OPTIMIZING IRRIGATION EFFICIENCY THROUGH THE CONSIDERATION OF SOIL HYDROLOGICAL PROPERTIES – EXAMPLES AND SIMULATION APPROACHES

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With 9 figures, 1 table and 1 photo
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Summary: Climate change is connected with a global increase in the use of irrigation. But irrigation is often practiced on very variable soils with the consequence of over- or under-irrigation. The efficiency of irrigation techniques is closely connected with soil hydrological and soil physical interactions in the main root zone. In irrigation practice the deciding and often site-specific soil properties are usually not taken into consideration. This paper will emphasize the importance of soil texture in terms of improving irrigation by summarizing some results of longtime studies about soil water dynamic under the influence of irrigation. Furthermore, the paper presents possibilities of optimizing irrigation on the basis of two simulation approaches. In the first simulation approach a multi-agent-based tool calculates soil specific and corresponding water tensions by using pedotransfer functions. This makes possible a quantification of the need for irrigation and the control of the irrigation system. By integrating the physical concept of soil water potentials, temporal and spatial soil water fluxes are used to schedule dynamic and precision trickle-irrigation. The second simulation approach calculates a field-irrigation with simultaneous consideration of the horizontal variability of soil properties. The irrigation is carried out in a site-specific way with high precision. Both approaches show that precision and soil specific irrigation is accompanied by a significant reduction of irrigation water and an improvement of irrigation efficiency.

Zusammenfassung: Der Klimawandel ist mit einer weltweit intensivierten Bewässerungspraxis verbunden. Allerdings wird die Bewässerung oft auf sehr stark differenzierten Böden praktiziert, so dass sich häufig Erscheinungsformen einer Über- oder Unterbewässerung zeigen. Die Effizienz künstlicher Bewässerungsverfahren ist damit eng an die bodenhydrologischen und bodenphysikalischen Wechselwirkungen im Bereich der Hauptdurchwurzelungszone geknüpft. Die darüber entscheidenden und oft sehr standortspezifischen Bodeneigenschaften werden in der aktuellen Bewässerungspraxis noch unzureichend berücksichtigt. Dieser Beitrag will einige Ergebnisse aus langjährigen Untersuchungen zur Bodenwasserdynamik unter Bewässerungseinfluss zusammenfassen und anhand von zwei Simulationsansätzen Möglichkeiten der Bewässerungsoptimierung aufzeigen. Im ersten Modellierungsansatz werden durch ein multi-agenten-basiertes Simulationstool substratspezifisch korrespondierende Wasserspannungen zeitgleich mittels regressionsbasierter Pedotransferfunktionen berechnet. Dies ermöglicht eine Quantifizierung der Bewässerungsnotwendigkeit und dient als Basis für die Steuerung des Bewässerungssystems. Über die Einbindung des bodenhydrologischen Potentialkonzeptes wird die vertikale Bodenwasserdynamik in ihrem raum-zeitlichen Verlauf beschrieben. Der zweite Modellierungsansatz kalkuliert eine Flächenbewässerung auf numerischer Basis unter Berücksichtigung der horizontalen Variabilität der Bodeneigenschaften. In einem virtuellen Bewässerungsfeld erfolgt die Verteilung der Wassermengen teilflächenspezifisch und bedarfsgerecht. Beide Ansätze zeigen, dass eine bodenspezifische und bedarfsgerechte Bewässerung mit einer signifikanten Reduzierung der Bewässerungsmenge und einer Optimierung der Bewässerungseffizienz verknüpft ist.

Keywords: Soil science, water economy, precision irrigation, soil texture, South Tyrol

1 Introduction and problem statement

Optimal irrigation is of critical importance for agriculture with decreasing freshwater resources in times of climate change. About 70% of the global water withdrawal and 85% of the consumptive water use is for irrigation (Meyer 2008; Evans et al. 2013). Approximately 40% of the total food production relies on supplemental irrigation (Lal 2012). Unfortunately water use efficiency (WUE) in the agricultural sector is very poor with more than 50% water losses (Hezarjaribi and Sourell 2007). This is unfavourable in terms of dwindling resources of freshwater and soil. Also the effects of global irrigation on the near-surface climate have recently been studied (Sacks et al. 2009) and the results emphasize the current significance of irrigation in the geosphere. So new adaptations in irrigation strategies will become more necessary than ever before to improve the performance of agricultural water use.

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Especially in (semi-)arid areas a successful cultivation of crops depends strongly upon solving irrigation application problems. Due to the increasing water shortage in such regions irrigation technique has become one of the most important factors of production in agriculture (Armindo et al. 2011). Hence strong and increasing efforts have been made in agricultural and soil science in the last 20 years and irrigation science has become a separate and innovative field of research also in physical geography and soil science (Barth et al. 1990). The water balance approach is not optimal but often used in irrigation modelling and simulation. Jones (2004) mentioned the need of a permanent recalibration of water balance based models. New approaches in agri- and horticulture like precision farming and precision irrigation (PI) require advanced sensing technologies for measuring soil and crop properties at the field scale (Sun et al. 2013). The main scope of all these approaches is to minimize water use and to maximize the WUE. Apart from the wastage of water, over-irrigation is also accompanied by problems of soil degradation like surface runoff, soil erosion and nutrient leaching.

Various methods like subsurface or root zone irrigation have been developed in the last decades to control the irrigation (James 1988; Ayars et al. 1999; Jones 2004). New methods in irrigation management are using crop-based methods by sensing the plant water-stress (measurement of plant water status, sap flow, xylem cavitation or stomatal conductance) for irrigation control (Fereres and Goldhamer 2003; Jones and Leinonen 2003; Smith and Baillie 2009). Jones (2004) reviewed and summarized various methods for irrigation scheduling based on the sensing of the plant response to water deficits and compared them with traditional water-balance and soil moisture-based approaches. Abidin et al. (2013) recently evaluated the capillary flow response in a soil-plant system for modified subsurface PI. Other innovations like partial root-zone drying PI inside the root zone have been developed (e.g. Dry and Loveys 1998; Stoll et al. 2000a, 2000b; Saeed et al. 2008; Xie et al. 2011).

Better results in PI might potentially be obtained by plant-stress methods combined with soil-water based methods because the soil water dynamic at irrigated sites is a decisive factor for irrigation efficiency (IE). However, important parameters like soil textures and corresponding water retention functions are unconsidered by most of the irrigation strategies so far although they could be responsible for pivotal soil hydrological properties. Selle et al. (2011) noted that at a farm scale, irrigation systems may be changed to match up more closely with soil hydraulic properties. Dabach et al. (2013) recently pointed out that very little work has been carried out to study the relationship between the scheduling, the threshold and the amount of irrigation that also takes into account site-specific soil properties. For example the modification of the WUE by soil texture has not been studied very extensively so far (Orfánus and Eitzinger 2010; Grashey-Jansen 2010, 2012). Comparatively few approaches in irrigation and irrigation modelling try to take different soil properties into account (e.g. Steppe et al. 2008; Grashey-Jansen and Timpf 2010; Gaudin and Gary 2012; Phogat et al. 2012; Dabach et al. 2013). Site-specific irrigation (SSI) has partially been achieved by the use of innovative technologies, but well-documented and proven water saving strategies using SSI are quite limited (Evans et al. 2008, 2013) A new and promising approach of soil physical based zoning of irrigation management using (spatial-)statistical methods was published by Jiang et al. (2011). The variable rate irrigation (VRI) seems to be the best in precision irrigation so far because it considers the fact that soil physical and hydraulic properties vary over time and space from site to site (Hedley and Yule 2009; Chávez et al. 2010; Evans et al. 2013). Combinations of SSI and VRI make it possible to meet the specific needs of crops in different zones within a field.

However, only quantitatively based information about actual soil water dynamics can deliver valuable data to optimize the volume and duration of irrigation. The plant-available water content (PAWC) between the wilting point (θ_{WP}) and the field capacity (θ_{FC}) is decisively influenced by the soil composition and can be perceived as the most important component for high irrigation efficiency and the WUE. But mostly the nonlinear relationship between the volumetric soil water content (SWC) and the soil water tension (SWT) is neglected. In fact, the amount of water is mostly given according to subjective irrigation schedules. So the main objective of SSI- and PI-techniques is to find the optimal strategy and schedule to enhance soil moisture distribution and WUE.

Sensors and sensor networks are particularly suitable here. There exist a lot of studies about special soil sensors like wired and wireless micro sensors and their application (Corwin and Lesch 2003; Adamchuk et al. 2004; Morais et al. 2004a, 2004b; Bogena et al. 2007; Sun et al. 2008; Pan et al. 2010; O'Shaughnessy et al. 2012). Sun et al. (2013) have studied a combined application of a dual-sensor vertical penetrometer for measuring volumetric soil water content by considering site-specific information of soil properties. Some approaches operate with soil moisture micro sensors in the rootstocks of crops to control and schedule the irrigation. The use of soil specific calibrated sensor networks may help to improve the realization of PI by varying irrigation intensity according to soil differences. A variable rate control of irrigation in accordance with soil properties is one of the most promising approaches in PI.

Apart from practical methods, efforts to improve irrigation efficiency can also profit from knowledge gained through model experiments. In the last 20 years many models have been developed in irrigation science to optimize crop yield and economic benefit (e.g. Srivastava and Patel 1992; Small and Rimal 1996; Teixeira et al. 1996; Kuo and Liu 2003; Mailhol et al. 2005). Mateos (2006) has compared different irrigation methods in a simulation study. Karamouz et al. (2013) developed a multi-dimensional agricultural optimization model to determine different factors like the optimal cultivated area, cropping pattern and irrigation efficiency considering limited water resources in a semiarid region.

This paper attempts to summarize extensive studies on soil water dynamics under the influence of irrigation which have been carried out in South Tyrol (Northern Italy) since 2003. In the first part of the paper the results of long-term field studies and statistical analysis of tensiometric measurements are presented. The results thus obtained then set off the development of modelling approaches with the objective to assess the irrigation schedule in relation to the given site-specific soil textures. In the second part this paper presents two general simulation approaches for PI which may be applicable to sites with surface irrigation.

2 Study area

The field studies focused on the Etsch-valley in the South Tyrolean irrigation region in Northern Italy which covers a land area of 18.500 ha. Orcharding (especially apples) is the dominant land use there. The average annual precipitation in the upper valley (Val Venosta) is about 500 mm per annum. The distribution of soil types within the region is very heterogeneous (Fig. 1). In general, hillsides are dominated by Leptosols and Cambisols. Most of the soils on the valley floor are gleyic Cambisols, partially calcaric Fluvisols or Gleysols (Grashey-Jansen and Schröder 2009). Many orchards in the study area are very close to the groundwater and reductive pedogenetic processes can easily be detected. Evidence of these processes is the presence of Gleyosols and other soil types with gleyic properties. Especially at valley bottom sites the groundwater is very close to the surface so that groundwater may rise capillarily and supply the tree roots sufficiently with water (Grashey-Jansen 2010, 2012).

Our own field studies have shown that the spatial variability of physical soil properties can vary significantly within small distances across irrigated fields. The results show a small scaled variation of soils at the study sites. Regosols, (gleyic) Cambisols, (calcaric) Fluvisols and Gleysols are the most common soil types in the region of measurement. Figure 1 depicts a highly simplified overview of the prevalent reference soil groups (RSGs) in the study area, according to the World Reference Base for Soil Resources (WRB). The soil horizons are mainly composed of sand or silty loam soil textures (Grashey-Jansen 2008a).

Because of the climatic conditions irrigation has always been regarded as necessary here, but the way irrigation is applied follows mostly subjective criteria. At many locations much more water is used for irrigation than the apple trees actually need. Nearly 90% of the orchards in this region are equipped with sprinkler overhead irrigation systems (Photo 1). With irrigation densities between 2 mm/h and 6 mm/h under a constant operating pressure these systems cause an uneven distribution of the irrigation water on the soil surface. Furthermore the losses of these sprinkler systems by evaporation and wind drift can be enormous and decrease the IE significantly (Grashey-Jansen and Timpf 2010; Stambouli et al. 2012).

Drip and trickle irrigation is gaining increasing importance in this region. But so far soil properties are not considered by both kinds of irrigation. The exemplary soil transects (Fig. 2) underline the vertical and horizontal heterogeneity of measured soil textures of two selected survey sites. These adjacent fields are irrigated with equal flat-rates of water and without any consideration of soil properties. Consequently the plant roots (main root-zone in 40 cm soil depth) are supplied by uneven amounts of water.

In the described region investigation sites were chosen to study and quantify the importance of soil properties for irrigation efficiency (Grashey-Jansen 2007a, 2007b, 2008a, 2008b, 2010, 2011, 2012; Grashey-Jansen and Eben 2009).

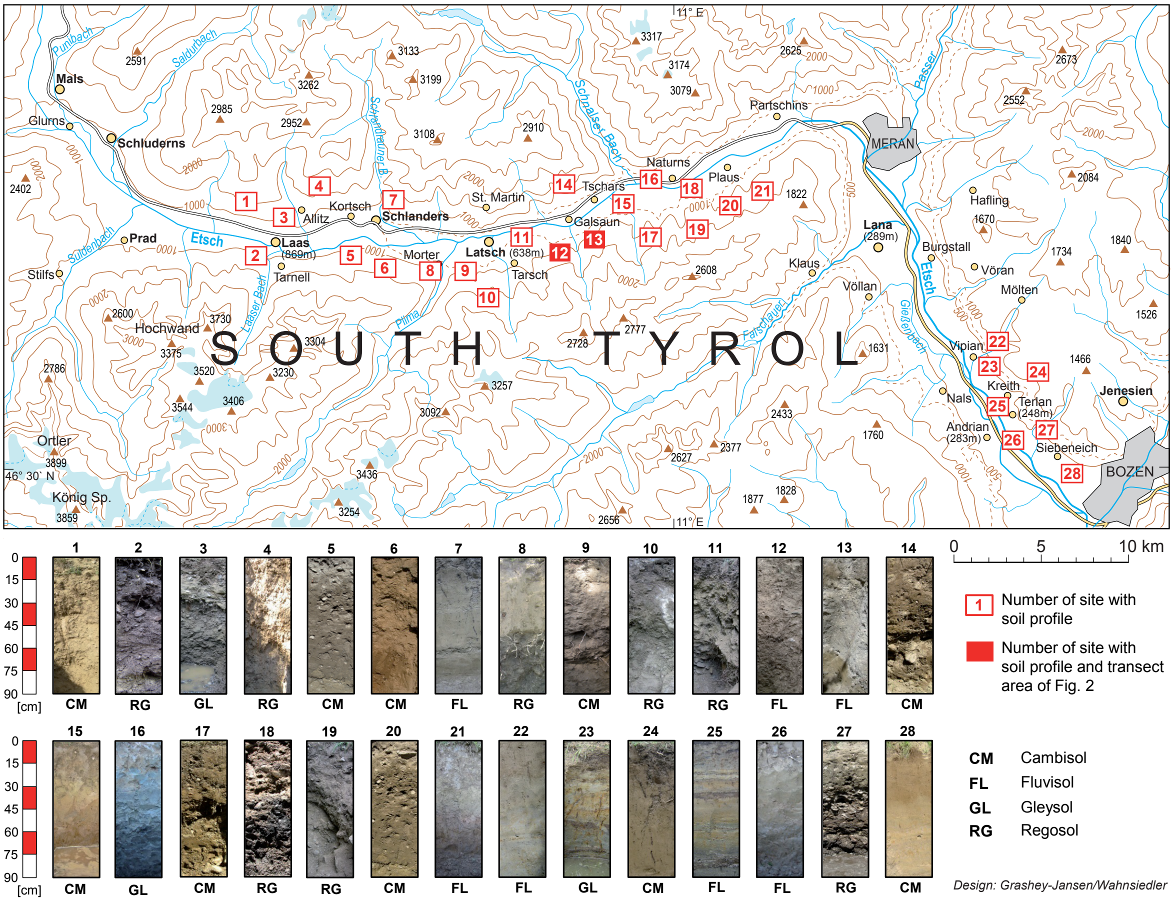

Fig. 1: Map of South Tyrol showing the course of the upper Etsch-Valley (including the Val Venosta in the upstream branch) and the location of the soil profiles considered in this study. Soil profiles corresponding to the numbers in the map are shown in the lower part of the figure. The classification of the reference soil groups (legend on the right-hand side) is according to the World Reference Base for Soil Resources (WRB; highly simplified without qualifiers and specifiers)

3 Materials and methods

3.1 Preliminary field and lab studies

The dataset for soil physical and statistical analyses was built by 131 seasonal time-series (April–November) of soil matric potentials in four different soil depths (20 cm, 40 cm, 60 cm and 80 cm) from 2003 to 2011.

The soil matric potential was chosen as parameter instead of the soil moisture because the SWT gives direct information about the PACW. Furthermore the water fluxes in soil depend on SWT. SWT was measured by tensiometric logger units (modified according to Thalheimer 2003, 2013) in a high temporal resolution of 1 hour at different soil sites and soil depths. Irrigation schedules were registered by pressure sensors in the water pipes. The resulting vertical water fluxes in the soils were calculated by the hydraulic gradients *i* according to Ehlers and Goss (2003) with the soil surface as reference level for the gravitational potential *z*:

$$i = \frac{\Delta\psi}{\Delta z} \qquad \text{(eq. 1)}$$

where:

- i hydraulic gradient
- ψ hydraulic soil water potential
- z gravitational potential

28 soil profiles were discussed according to the German Guideline for Soil Mapping (AG BODEN 2005). Furthermore, numerous soil auger drillings were carried out to get information about small scaled variations. The pedological field-research was complemented by particle-size analysis in the laboratory. The analysis for particles < 0.063 mm was done by the pipette method and for particles > 0.063 mm

Photo 1: Overhead sprinkler irrigation in the upper Etsch Valley (South Tyrol, Northern Italy). Common irrigation densities between 2 mm/h and 6 mm/h under a constant operating pressure. The potential loss of water through interception, evaporation and wind drift is obvious

by sieving (according to DIN 19683-1; DIN 19683-2; DIN 52098; DIN 66115-2). The soil samples were pre-treated with 30%-H_2O_2 (elimination of organic fractions) and with $Na_4P_2O_7 \cdot 10H_2O$ (dispersion medium).

3.2 Statistical analysis of time series

Concerning the measured SWT-data, inertia-influenced reaction speed and repetition pattern calculations of auto correlation functions (ACFs) were executed to identify location and depth specific properties (eq. 2). ACF is a set of correlation coefficients between the measured time series (tensiometric soil water potentials) and lags of itself over time.

$$r_k = \frac{\sum_{i=1}^{n-k} (x_i - \bar{x})(x_{i+k} - \bar{x})}{\sum_{i=1}^{n} (x_i - \bar{x})^2} \qquad \text{(eq. 2)}$$

where:
- x_i observation of input series, $i = 1 \ldots n$
- $\bar{x}$ average of the n obeservations
- r_k k^{th} lag sample autocorrelation

Due to the fact that ACFs estimate all correlations between x_i and x_{i+k}, additionally partial autocorrelation functions (PACFs) were calculated to get information about the signals after removing any linear dependence.

Relevant time-lags were calculated using cross correlation functions (CCFs) for all correlation pairs of measured tensiometric soil water potentials to quantify natural temporal delays within soil-hydrological processes as well as the relationships and reaction speeds connected with them:

$$r_{xy}(k) = \frac{C_{xy}(k)}{S_x S_y} \qquad \text{(eq. 3)}$$

where:
- $r_{xy}(k)$ Sample cross correlation coefficient at lag k
- S_x Standard deviation of series X
- S_y Standard deviation of series Y
- $C_{xy}(k)$ Sample cross covariance at lag k

The statistical analyses were performed using the proprietary software SPSS® and the free statistical software environment of R.

3.3 Deduced simulation approaches

The results thus obtained then set off the development of modelling approaches with the objective to assess the irrigation schedule in relation to the given site-specific soil textures.

3.3.1 MAPIS – Multi-agent precision irrigation simulation

The simulation approach MAPIS is based on a wireless soil-moisture sensor network and realized by the multi-agent toolkit SeSAm (= Shell for Simulated Agent Systems). SeSAm provides a generic environment for an agent-based modelling. Agent-based simulation is a relatively new paradigm in 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 (Wooldridge 2002). 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 (Grashey-Jansen and Timpf 2010).

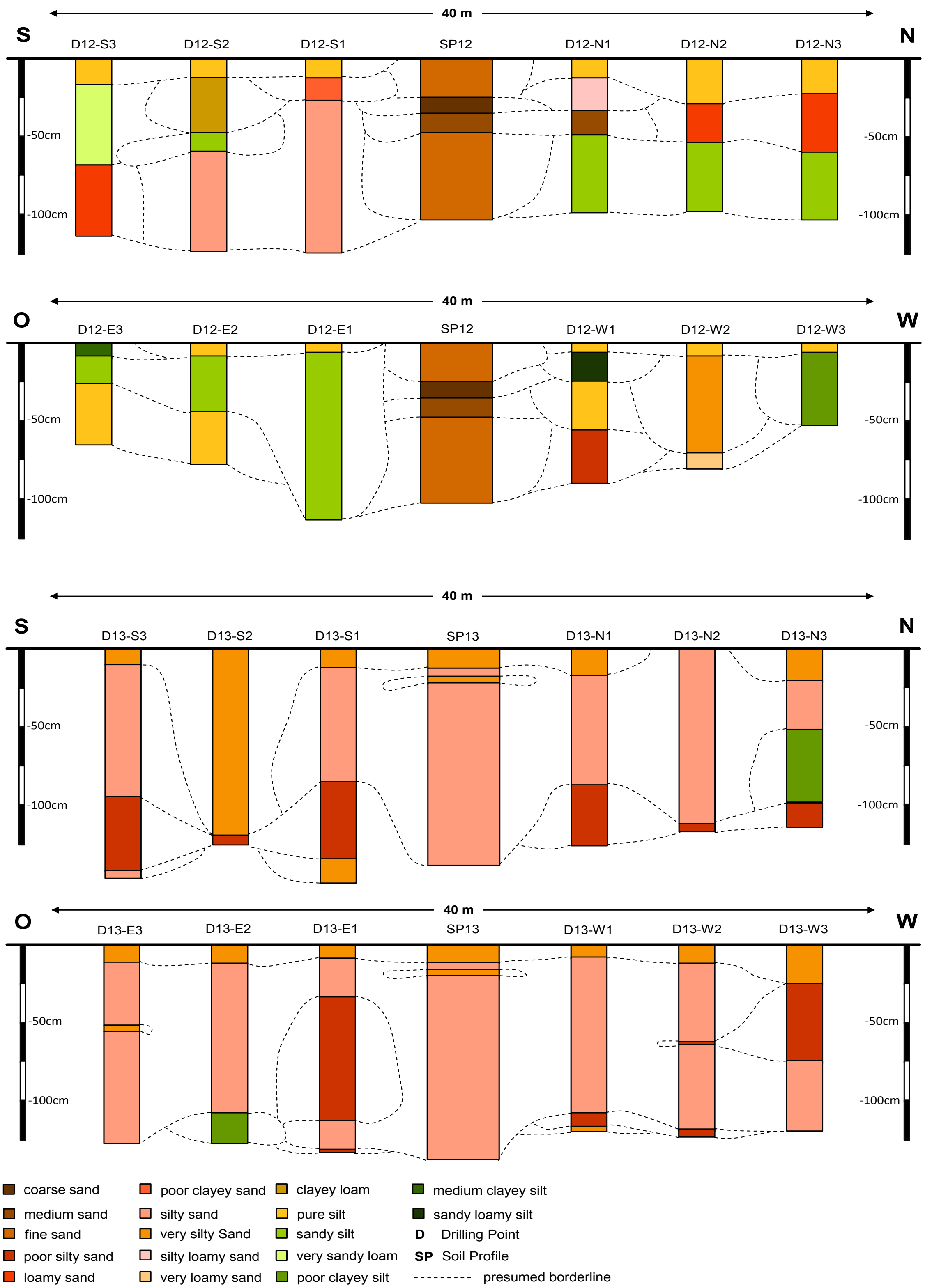

Fig. 2: Vertical cross-sections (North-South and West-East) showing the spatial heterogeneity of soil textures at sites 12 (top) and 13 (bottom) on the map in figure 1. Soil textures are named following the USDA soil classification. Dashed lines indicate a possible interpretation of the main units in the cross-sections

In MAPIS, based on a few soil moisture sensors which were installed at the horizon borders, the soil water tensions in the spaces between real sensor nodes are simulated. In this paper MAPIS is demonstrated by comparing two differently composed soil columns (Fig. 8a). The soil textures of these columns are depicted in figure 3.

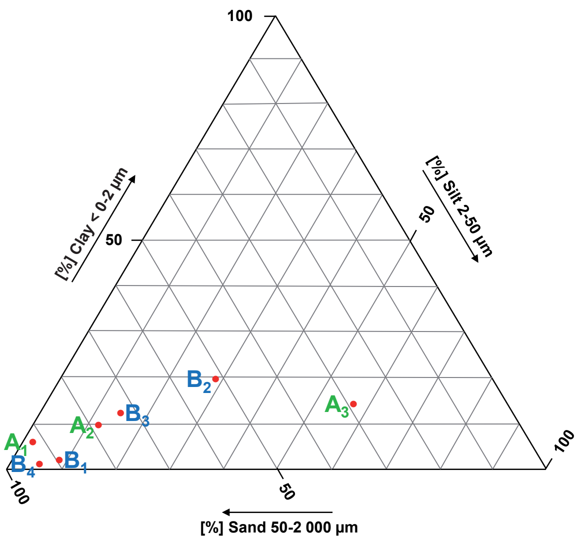

Fig. 3: Soil textural triangle showing the clay-silt-sand fractions observed at sites A (horizons A1 to A3) and B (horizons B1 to B4) considered for the analysis with MAPIS (cf. Fig.8)

The most important part of the model is the simulation of the soil water dynamics which determines the water volume available to the plant. Based on the real sensor nodes the moisture values in the spaces between these nodes are computed by using pedotransfer functions. This setup makes it possible to estimate the actual soil water dynamics with a minimal number of sensors.

Most of the already existing pedotransfer functions (PTFs) cannot be used for practical applications because they determine the physical relationships in a fragmentary way or just in the extremes which are of no relevance for the agricultural practice. The PTFs used in MAPIS (and also in GRIRIS; cp. 3.3.2) show sufficient accuracy in the range of pF 1.8 and 4.2 and therefore in that range of the water tension which is ecologically relevant for most cultured plants (Grashey-Jansen and Timpf 2010; Grashey-Jansen 2013). These PTFs describe the pedospecific water retention curves (pF-WC_θ) between pF 0.5 and pF 4.2, based on nonlinear regression functions (eq. 4-7).

$$PTF_{(A1;B1;B4)} = \{(-0.5688 \cdot \theta)+(0.0239 \cdot \theta^2)+(0.0003 \cdot \theta^3)+5.96\} \quad \text{(eq. 4)}$$

$$PTF_{(A2;B3)} = \{(-0.4931 \cdot \theta)+(0.0194 \cdot \theta^2)+(-0.0003 \cdot \theta^3)+6.0432\} \quad \text{(eq. 5)}$$

$$PTF_{(A3)} = \{(-0.2754 \cdot \theta)+(0.0069 \cdot \theta^2)+(-0.0001 \cdot \theta^3)+6.846\} \quad \text{(eq. 6)}$$

$$PTF_{(B2)} = \{(-0.2686 \cdot \theta)+(0.0041 \cdot \theta^2)+(-0.0001 \cdot \theta^3)+7.1096\} \quad \text{(eq. 7)}$$

Thereby volumetric soil water contents (measured by the sensor nodes) are transferred mathematically into the corresponding soil specific water tensions. Direction and rate of vertical soil water fluxes are quantified by considering the hydraulic gradients i with the soil surface as level of reference and the unsaturated hydraulic conductivity k(ψ) (eq. 8) with the parameters of van Genuchten (1980) (Tab. 1) according to Carsel and Parrish (1988) and Ehlers and Goss (2003).

$$k(\psi) = ks \cdot \frac{\left[1 - (\alpha|\psi|)^{n-1} \cdot \left(1 + (\alpha|\psi|)^n\right)^{-m}\right]^2}{\left[1 + (\alpha|\psi|)^n\right]^{ml}} \quad \text{(eq. 8)}$$

where:

$k(\psi)$	unsaturated water conductivity as a function of the soil water tension [cm/d]
ks	saturated water conductivity [cm/d]
ψ	soil water tension [hPa]
α, n, m, l	parameters of van Genuchten (1980) (cf. Tab. 1)

So the simulation calculates the necessary parameters based on measured soil moisture data and soil specific values. The intensity of irrigation is adapted to the soil specific field capacities. This makes possible a quantitative description of infiltration time

Tab. 1: Parameters of van Genuchten (1980) used in MAPIS

Soil	***n*** **(-)**	***m*** **(-)**	**α (cm⁻¹)**	***l***	***K**$_s$* **(cm d⁻¹)**
A_1; B_1; B_4	1.37136	0.270796873176992	0.184987	0.5	490
A_2; B_3	1.43704	0.304125146133719	0.067866	0.5	127
A_3	1.21234	0.175148885626145	0.013197	0.5	20
B_2	1.11493	0.103082704743796	0.049791	0.5	36

in the soil during the saturation process and also to estimate the actual water demand of the crops and the real need of irrigation in the progression of time. Finally, the model calculates an irrigation plan to ensure a water application which is efficient and meets the demands. Thus 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 MAPIS-setup has been described in detail with the similar model AQUASIM by Grashey-Jansen and Timpf (2010).

3.3.2 GRIRIS – Grid-based irrigation simulation

In GRIRIS soil moistures in the range of the measurement points are registered by wireless sensor nodes. In contrast to MAPIS, GRIRIS simulates soil water and irrigation demand in the horizontal dimension of the soil surface. So the heterogeneity of soil is limited to the horizontal direction in this model. In this approach it is assumed that the soil properties are consistent in the vertical soil profile without any vertical differentiation in the root zone (in this simulation: soil depth 0.3 m). The particle-size distribution of the virtual soil textures are depicted in figure 4.

In this example, GRIRIS was applied to compute irrigation requirements for a virtual test field (85 x 35 m). The nodes of each grid (5 x 5 m) are equipped with soil moisture sensors. The model works with two different modes of irrigation: the NPI-mode (with an undifferentiated and evenly distributed irrigation) and the PI-mode (with a differentiated precision irrigation which is adapted to the soil properties).

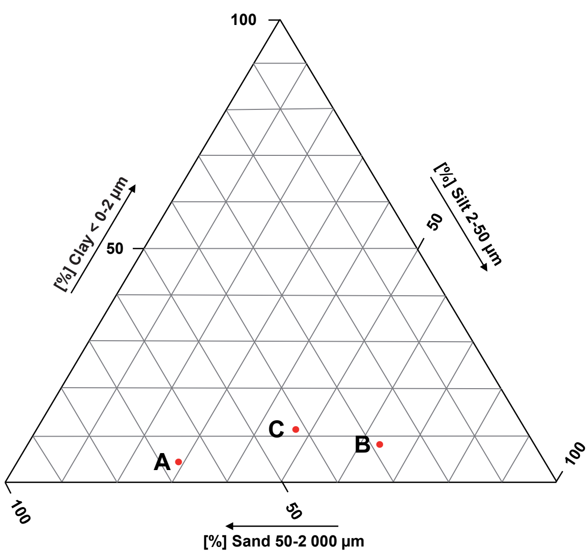

Fig. 4: Soil textural triangle showing the clay-silt-sand fractions in the simulation field considered for the analysis with GRIRIS (cf. Fig. 9)

The NPI-mode represents the most frequently applied practice so far. It is connected with an uncontrolled application of irrigation water. In contrast the amount of given water in the DPI-mode is controlled by the SWTs. The corresponding SWTs (as a control parameter for PI) are calculated by transfer functions and averaged for each grid in the network setup. The PTFs which are used by GRIRIS describe the pedospecific water retention curves (pF-WC_{θ}) between pF 0.5 and pF 4.2:

$$PTF_{(A)} = \{(-0.4419\cdot\theta)+(0.0151\cdot\theta^2)+(-0.0002\cdot\theta^3)+6.8627\} \text{ (eq. 9)}$$

$$PTF_{(B)} = \{(-0.3005\cdot\theta)+(0.0068\cdot\theta^2)+(-0.0001\cdot\theta^3)+6.9314\} \text{ (eq. 10)}$$

$$PTF_{(c)} = \{(-0.2754\cdot\theta)+(0.0069\cdot\theta^2)+(-0.0001\cdot\theta^3)+6.8459\} \text{ (eq. 11)}$$

A similar simulation approach for a larger irrigated field with a more detailed description of the setup has been recently presented by Grashey-Jansen (2013).

4. Results

4.1 Statistical signals in the field data

The ACF-results (mapped in figure 5) show a progressive inertia of soil water tensions with increasing soil depth (increasing of time lags ≥ 3 hours with increasing soil depth). The highest density of significant positive PACF-coefficients with time lags of 1 hour is depicted in a soil depth of 20 cm (Fig. 5a) and it increases with the soil depth (Fig. 5 b-d). This implies that the soil water tensions lose their dynamics with increasing soil depth because of the recessive influence of atmospheric parameters.

Figure 6 depicts the PACF-coefficients of 50 time series (measured in 20 cm soil depth) in context with the corresponding soil textures. 1-hour lags correspond primarily with the silty loam fraction while 2-hour lags and lags ≥ 3 hours correspond with the sandy loam fraction. This points out that the reaction of the soil water dynamic on exogene signals in sandy soil textures is more inert than in silty fractions. Effects of hysteresis must be responsible for these longer intervals of persistence: Properties of sand soils, like frequent changes of pore diameters and air-inclusions, encourage widening of hysteresis loops in the range of low soil water tensions (50–200 hPa) (Clausnitzer 1978; Ilnicki 1982).

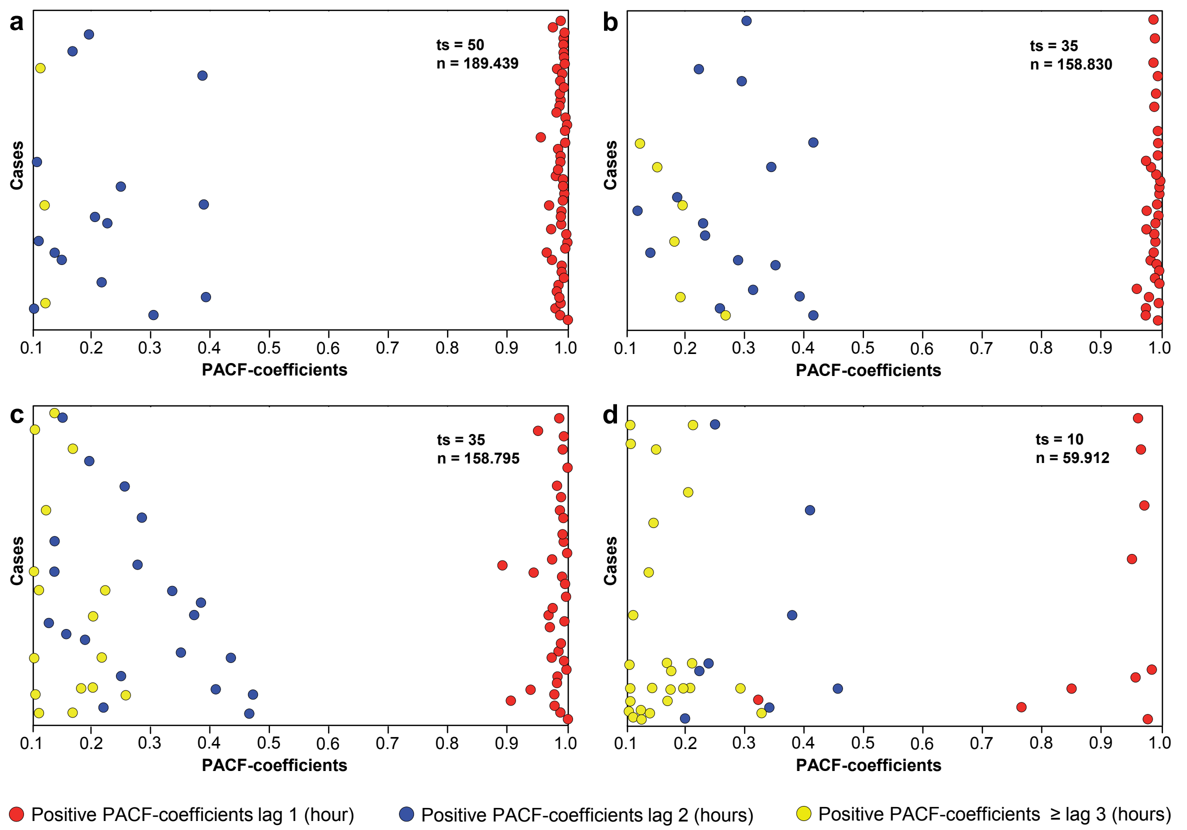

Fig. 5: Positive PACF-coefficients of measured SWT-series in different soil depths (a: 20 cm; b: 40 cm; c: 60 cm; d: 80 cm) and different time lags (hours). (ts: number of used time series; n: number of values). Level of significance between $\alpha \leq 0.001$ and $\alpha \leq 0.05$. Negative values are not depicted

Figure 7 shows the time lags of the irrigation signals between 20 cm and 40 cm and 20 cm and 60 cm soil depth of three different soil profiles, each composed of equal soil textures (Sa, LoSa, SiLo).

The time lags were calculated by cross correlations of 18 tensiometric time series captured at these locations. In contrast to the PACFs the shortest time lags can be detected for the sand profile (Sa). Irrigation signals need less than two hours to pass the soil depth of 60 cm due to higher ratios of macro and medium pores. In the loam sand profile (LoSa) signals show significantly longer time lags to reach the depth of 60 cm. The silty loam texture with a higher ratio of micropores in the third profile causes signal delays up to 23 hours.

4.2 Results of MAPIS

The result of MAPIS is an irrigation schedule for a dynamic (not intermittently) and soil specific application of irrigation water (Fig. 8).

Thereby the amount of given water varies during the irrigation without any interruption. The intensity and duration of PI is controlled by the soil specific SWTs. Thus the intensity of irrigation is variable during the period of irrigation (Fig. 8b) because each soil depth contains the amount of water which corresponds to its maximum volume of water content at field capacity. This explains the varying values of the effective water amount. So the soil specific influence becomes obvious.

In both cases the water quantities spent are in the range of 40 mm – thus they do not differ significantly from each other. This is a result of the fact that both soils (Fig. 8a) show similar cumulative pore volumes in their total soil profiles.

Due to the low hydraulic conductivity of the horizon B2 (sand clay loam) the time of irrigation takes about 15 h longer than at soil site A (Fig. 8c). Without considering these soil-site-specific attributes over-irrigation and an afflux of infiltrating water would have been the consequences. In the medium term this would cause an over-supply of irrigation water and root rot of the crops.

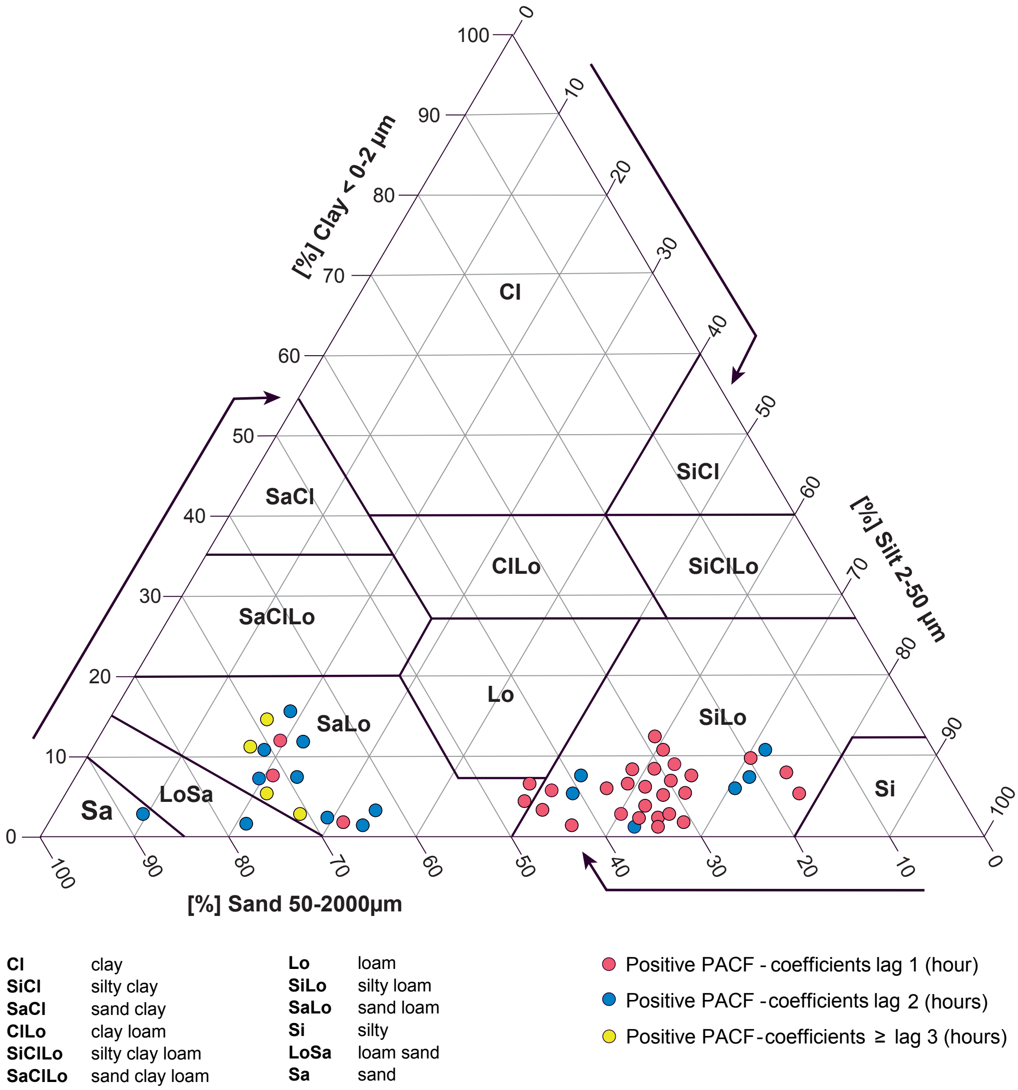

Fig. 6: Particle-size triangle with positive PACF-coefficients of measured SWT of 50 time series in a soil depth of 20 cm with different time lags. Level of significance between $\alpha \leq 0.001$ and $\alpha \leq 0.05$

4.3 Results of GRIRIS

In figure 9 the GRIRIS-simulation process is depicted for two different modes of irrigation:

PI-mode with a soil and site specific PI which is controlled by grid-specific soil water tensions (target value 150 hPa)

NPI-mode without considering any soil site specific variations and a flat rate of irrigation (30 mm) all over the field

The uneven distribution of the simulated SWCs and the transformed SWTs corresponds with the different soil properties in the grid-fields (cf. Fig. 4). The patterns of NPI- and PI-mode are subject to soil specific modification. This explains why the patterns of SWCs and SWTs are not congruent. In the PI-mode the volume of irrigation water in the soil corresponds to the site specific SWTs

In GRIRIS the water supply of plants and soils is controlled by SWT-values. It is obvious that over-irrigation in the PI-mode is prevented while some of the grid-fields in the NPI-mode are over-irrigated (hPa-values < 150). In the PI-mode all grids are filled up with water until a SWT-value of 150 hPa has been reached. So the field

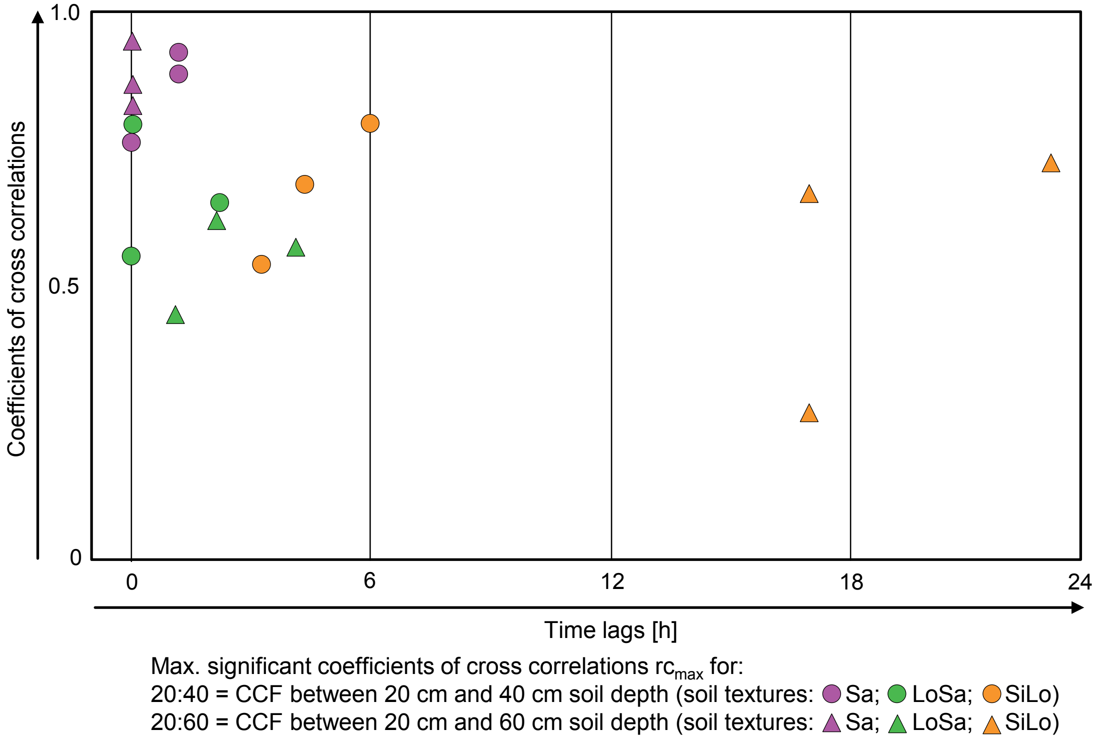

Fig. 7: Significant coefficients of cross-correlations in the 24-hour time frame of three uniform soil profiles. Level of significance α = 0.01

of the PI-mode shows a lower SWC than the field of the NPI-mode. For all grids in the PI-mode the target value of 150 hPa has been achieved, so that there are no zones of water stress. Thereby the result is significantly less water consumption in the PI-mode.

5 Conclusions

The presented results of the field studies and statistical analysis underline the significance and importance of soil texture concerning site specific and precision irrigation. Furthermore, the simulation approaches have shown that without a consideration of site specific soil attributes the IE may be unfavourable. The potential benefits of modifying irrigation according to soil differences by comparing uniform rate irrigation with variable rate irrigation scheduling are obvious. The approach of PI requires precise knowledge of soil properties. Vertical soil water fluxes in the unsaturated zone are very heterogeneous and complex. Naturally soil profiles are divided into different layers and horizons with specific hydraulic properties. The results of tensiometric time series analysis indicate that the pedological characteristics with their spatial variability decisively control the IE. Apart from atmospheric influences the dynamic of the irrigation water in soil is strongly influenced by soil texture and the composition of soil profiles. Infiltration rates and velocity of water fluxes are crucial components. Furthermore effects of hysteresis present a difficult problem in PI.

The practical implementation of a site specific irrigation management like MAPIS or GRIRIS requires related soil data. The spatial resolution required depends largely on the general genetic soil site conditions. Contrary to general conception our own investigations have shown that small scaled heterogeneity of soil sites can be met primarily in the area of fluvial sediments at valley plains and not on sloping locations (Grashey-Jansen 2008a, 2010, 2012). Consequently, the number of soil data that must be collected can be enormous. In these cases the effort must be balanced against the potential IE which may be achieved by a soil site specific irrigation. Furthermore, the spatial clustering of similar hydraulic soil properties in irrigated fields constitutes a constructive opportunity for improving PI and IE.

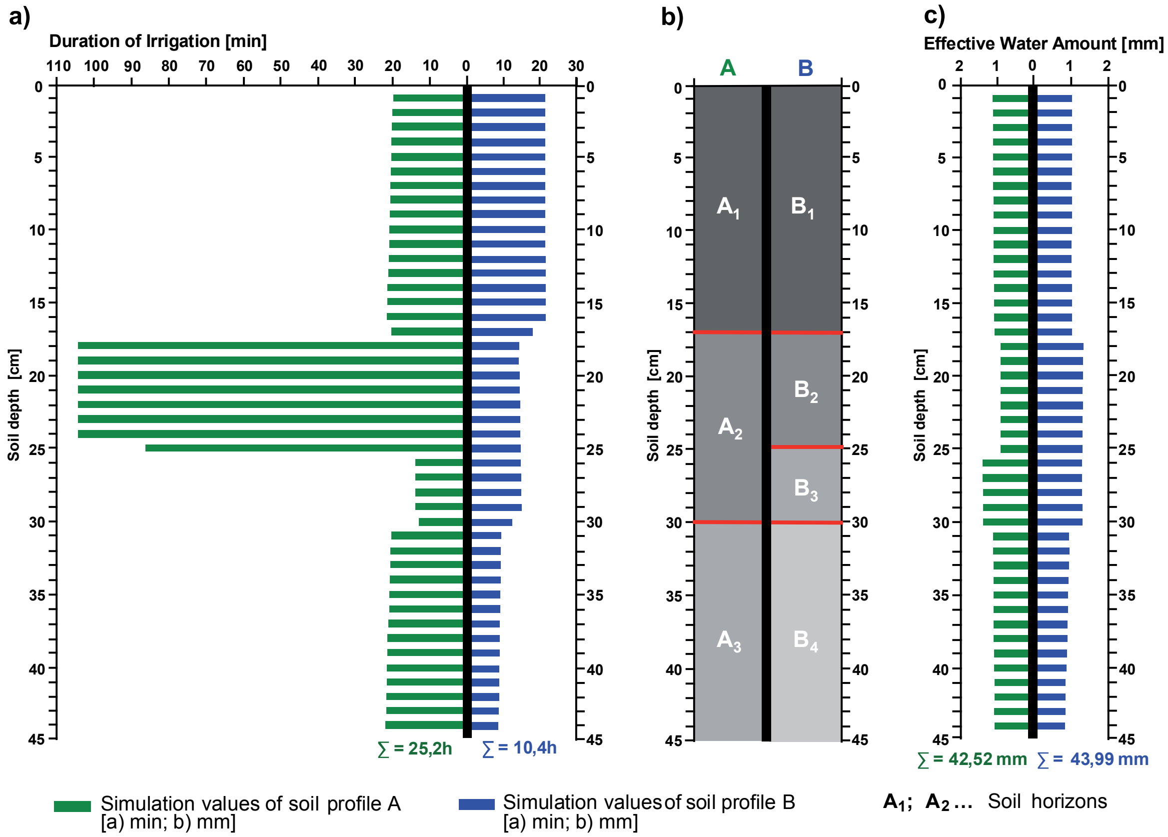

Fig. 8: Output of MAPIS-simulated irrigation schedule for two sample soil profiles A and B

However, due to the lack of available soil data, the practical implementation of MAPIS and GRIRIS seems to be impossible at the present time. Furthermore, it is to be noted that a simulation of vertical soil water fluxes in the soil-water-nexus on irrigated sites will never provide completely reliable data. In addition, there is also the fact that soil water dynamics on agricultural lands are decisively influenced by the processes in the system of the Soil-Plant-Atmosphere-Continuum (SPAC). So in a next step MAPIS or GRIRIS will have to be linked with suitable SPAC-models.

Farmers often request precise information about the duration and amount of irrigation. As irrigation and especially PI is not only determined by the water consumption of crops alone it is not possible to give exact values. But results of MAPIS and similar studies have shown that the combination of intermittent and dynamic water application by PI seems to be the best solution (Grashey-Jansen and Timpf 2010).

Both simulation approaches prove the possibilities of saving water by PI. However, the effective saving potential crucially depends on the respective weather conditions during the growing season. It is therefore impossible to give specific information about water saving rates. Our own comparative calculations with MAPIS for the region of study have shown an annual water saving potential of about 25 Mio m^3 for the whole irrigated area of South Tyrol (which is 56,000 ha with ~17,000 ha overhead sprinkler irrigation) by using a dynamic PI-technique instead of the common irrigation technique (the annual agricultural water use of South Tyrol is estimated at about 170–200 Mio m^3; Zebisch et al. 2011).

In all, the results show that greatest IE can only be achieved by a comprehensive consideration of soil properties. In this context the composition of grain sizes is one of the most important control factors for appropriate and precision irrigation. Similar researches confirm these conclusions (Grashey-Jansen 2008a, 2010, 2012; Grashey-Jansen and Timpf 2010) and emphasize furthermore the influence of soil bulk densities and contents of organic matter. Thereby the consideration of small scaled changes of soil properties in the horizontal and vertical dimensions will be a major challenge because minimal differences in spatial-temporal dynamics

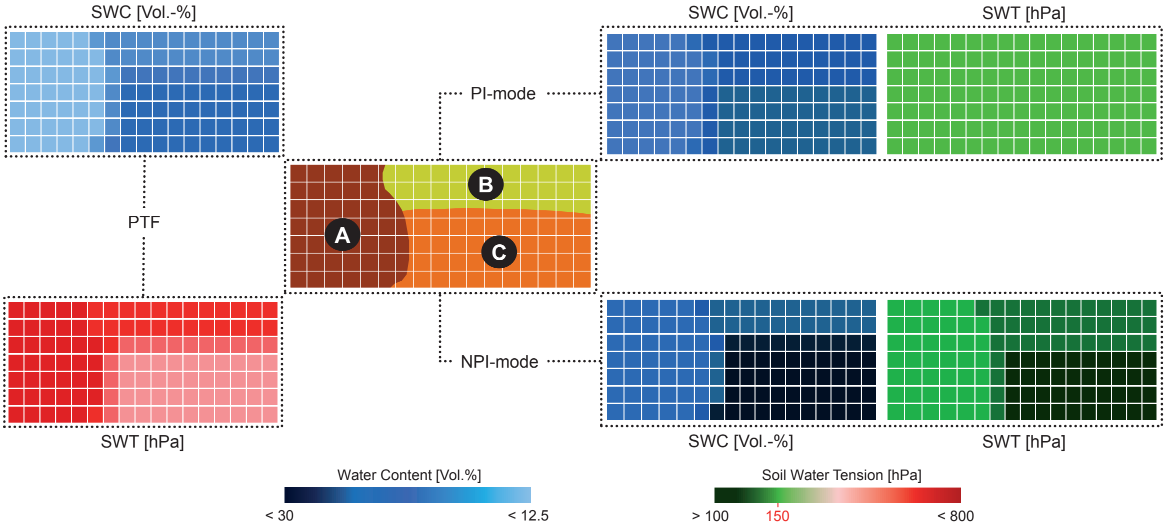

Fig. 9: Output of GRIRIS-simulated irrigation in a virtual test field with areas of different soil textures (A, B and C) in the PI- and NPI-mode

of water movement in soil sections may cause an under- or oversupply of irrigation water in the root zone with a significant reduction of IE.

6 Outlook

Nowadays there are many tools and techniques to assist farmers in PI – for example the use of soil specific calibrated sensor networks. But a sensor-controlled PI-system has also been faced with some restrictions so far, such as problems concerning a non-intermittent network communication, the electrical power supply of the sensor nodes and the comparatively high costs of installation and maintenance. So most of these methods are simply too complex and too expensive as yet. There exist only a few commercial sensors to control irrigation in a cost-efficient way.

Finally, there is still a gap between science approaches and the irrigation practice in the field: irrigation schedules in crop plantings are mostly based on measurements performed at a few sites disregarding the spatial variances of soil properties.

It is quite important to invest in water saving irrigation technologies. But the real WUE can only be achieved by an irrigation scheduling based on real-time soil moisture sensing that considers soil site specific conditions. Hence the delineation and mapping of soil management zones is indispensable for achieving a site-specific irrigation with a high WUE – so the subject of irrigation is also going to be an innovative field of research in physical geography.

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