Grid-based Simulation of a Lateral Move Irrigation System

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Abstract

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A central objective in irrigation science is the improvement of the water use efficiency (WUE). Mostly the focus is laid on improvements and innovations in irrigation technology. The characteristics of soils are often considered to be of secondary importance or totally disregarded. This paper reports on the simulation of a sensor network based irrigation system. The simulation was designed for a lateral move irrigation system with a notional irrigated area of 100 × 200 m. A grid-based network with soil specific calibrated and wireless moisture sensors (SMSN) captures the actual soil water content and calculates the corresponding water tensions simultaneously. The simulation in this paper is presented with two different modes of irrigation: the undifferentiated and evenly distributed irrigation (UDI-mode) and the differentiated precision irrigation (DPI-mode) which is adapted to the soil properties. The UDI-mode has been the most frequently applied practice so far and connected with an uncontrolled application of irrigation water. A supply under or over the real water demand of the plants is the consequence. In the DPI-mode the amount of given water is controlled by the soil water tensions (SWTs) calculated by pedotransfer functions (PTFs).

Keywords: irrigation technology; pedotransfer functions; precision irrigation; soil moisture sensors; soil water tensions; water use efficiency

The consequences of climate change require a more responsible and efficient handling of water resources – particularly in regions with freshwater scarcities. This demand is especially addressed to those involved in irrigated agriculture as the largest water-use sector. Approximately 70% of the global water withdrawal and 85% of the consumptive water use is for irrigation (Döll & Siebert 1999; Siebert *et al.* 2005; Goodwin & O'Conell 2008). Unfortunately, water use efficiency (WUE) in the agricultural sector is very poor with more than 50% water losses (Hezarjaribi & Sourell 2007). A major goal in most irrigation management is to optimize irrigation water use efficiency (IWUE) not only to produce high quality, high yielding crops, but also to ensure that runoff and leaching are minimized (Sadler *et al.* 2000; Al-Karadsheh *et al.* 2002; Chávez *et al.* 2010; Dursun & Ozden 2011).

Worldwide, overall IWUE is about 40%. So there is no doubt that introducing advanced technology such as innovative systems designed for precision irrigation (PI) can enhance efficiency from the current levels up to 80% (Schultz & De Wrachien 2002). PI is an important part of the concept of precision agriculture (PA) which was proposed by US agriculturalists in the 1990s. The traditional meaning of PI is to apply precise amounts of water to plants at precise locations (e.g. within the soil profile) and at specific times – but evenly distributed across the field (Smith & Baillie 2009). PI-techniques are still in the development stages and require a lot of experimental work to determine their feasibility and applicability (Al-Karadsheh *et al.* 2002; Almarshadi & Ismail 2011).

The need for irrigation may differ within small scaled zones of a particular field because of changes in soil properties like soil texture, soil bulk densities or contents of organic matter. Precision site-specific irrigation management requires precise knowledge of these soil properties and efficient methods to consider them by variable rates of irrigation. Consequently PI-systems need adjusted irrigation levels for effective action. Techniques of variable rate irrigation are a relatively new concept in agriculture (Sourell *et al.* 2004) and they require detailed knowledge of the physical and hydraulic properties of the soil horizons and their spatial-temporal variations. In principle, variable rate irrigation and the consideration of soil properties help providing economic and environmental benefits as well as providing spatial variation in yield and quality of irrigated crops (Buss *et al.* 2004). Gains in water use efficiency can only be achieved if water application is precisely matched to the spatially distributed crop water requirements and the different properties of soils (Chávez *et al.* 2010; Grashey-Jansen 2010, 2012). Due to the fact that mobile irrigation systems often traverse highly variable soils, dynamic and precision irrigation is an important and soil-based strategy for an improved use of global water and soil resources.

Detailed spatial temporal information is very expensive and time consuming to obtain and spatially detailed measurement of soil properties is still not practical (Starks *et al.* 2003). The best one can obtain (e.g. from existing soil survey databases) is the spatial distribution of soil textural classes. After all, the IWUE will benefit from it. Soil textural heterogeneity generally leads to variable water retention and yield within a field as crop productivity largely depends on the plant-available water (Mann *et al.* 2011). Hedley and Yule (2009) and Hedley *et al.* (2010) describe the potential benefits of modifying irrigation according to soil differences by comparing uniform rate irrigation with variable rate irrigation scheduling. For instance, it is possible to save water by using different watering times with variable intensities based on soil physical values. Basically, the delineation of irrigation management zones is the primary problem in PI-management. A promising approach of soil physical based zoning of irrigation management using (geo-)statistical methods has recently been published by Jiang *et al.* (2011).

With the availability of soil moisture sensors and stem water potential devices, it has become possible to irrigate at the exact time when water is needed by the plant (Leib *et al.* 2003; Morais *et al.* 2004b; Cardell-Oliver *et al.* 2005; Shatanawi 2005). But also only by the use of soil moisture sensors a PI can be achieved – on condition that the soil properties are well known. There also exist novel micro-electro-mechanical systems like micro-tensiometers for plants and soils but they are very expensive compared with microtechnical soil moisture sensors. The wireless communication of sensors has improved markedly in recent years (Morais *et al.* 2004a; Wang *et al.* 2006; Kim & Evans 2009; Rundel *et al.* 2009). New technologies made it possible to measure the soil moisture with very small sensors – even with wireless sensors and wireless networks (Morais *et al.* 2004a, b; Bogena *et al.* 2007; Dursun & Ozden 2011; Grashey-Jansen 2011). Grashey-Jansen and Timpf (2010) created an agent-based simulation of a soil dependent precision irrigation system. The model calculates an irrigation plan to ensure that water application is both 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 water applied during the irrigation process is subject to controlled dynamic fluctuations.

Soil moisture sensors and wireless sensor networks will become still more cheaper and smaller in the future (Mittelbach *et al.* 2011). Dursun and Ozden (2011) and Li *et al.* (2011) have lately presented an autonomous variable drip irrigation control system with an in-field soil property monitoring wireless sensor network. The non-invasive installation of a sensor system is very advantageous because of less maintenance and it provides measurement data in a high spatial and temporal resolution without an interruption or disturbance of the running agricultural operations in the field.

MATERIAL AND METHODS

Monitoring soil water content is important for optimizing irrigation and production. In the presented simulation soil moistures in the range of the measurement points are registered by wireless sensor nodes. But the use of nothing but soil moisture sensors is insufficient (Grashey-Jansen & Timpf 2010). Due to the fact that soil water content measurement in different soils may not correlate well with soil water potential the measured soil water contents are converted into the corresponding soil matric potentials. The water retention characteristics (WRC) were estimated by polynomial pedotransfer functions (PTFs).

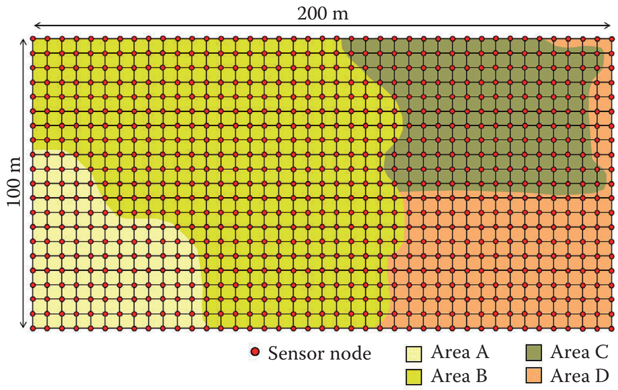

Figure 1. Virtual test field with areas of different soil types and sensor nodes on corner points of the grid fields

According to Zacharias and Wessolek (2007) the multi regression based parameter estimation method was used for deriving the WRCs. The PTFs used therefore describe the relationship between the water content θ as a dependent variable and the pF-value as an independent variable by nonlinear regressions of the third degrees (Grashey-Jansen & Timpf 2010; Grashey-Jansen 2011). Based on these values it is possible to specify the point in time as well as the duration of irrigation on the plant specific threshold value in the respective phenological stage.

Figure 1 shows the virtual simulation field (100 × 200 m) with a wireless installed soil moisture sensor network (SMSN) at the soil depth of 0.3 m (grid size 5 × 5 m). The grid lines mark the borderlines between the calculation fields. The heterogeneity of the soil is limited to horizontal direction in this model (areas A–D). For simplification, it is assumed that these conditions are consistent downward in vertical direction. The computing of the irrigation model was performed using the free programming language and software environment of R.

The simulation runs in two different modes: the UDI-mode (undifferentiated irrigation) with a flat rate of irrigation in the field and irrigation starting by a predefined time schedule or by subjective evaluation, and the DPI-mode (differentiated precision irrigation) when irrigation is controlled by the values of soil moisture and their corresponding water tensions in the root zone. The soil water tensions are calculated by the soil specific PTFs mentioned above (Figure 2). Each grid will be irrigated until the target value is reached.

RESULTS

The respective particle-size distributions of the simulated soils on areas A–D are depicted in the particle-size grading curve in Figure 3. The corresponding soil textures and water retention curves are shown in the soil-texture triangle in Figures 4 and 5.

Figure 6 shows the simulation process in both modes. The simulated soil water contents (SWC) in the root zone (soil depth 0.3 m) are unevenly distributed (Figure 6a) according to heterogeneous distribution of different soil textures (Figure 1) which is also reflected in the differentiated distribution pattern of soil water tensions (Figure 6b).

The initial values of soil water tension range between 600–800 hPa (Figure 6b). The nonlinear and pedospecific relations between the measured soil water contents and the corresponding soil water tensions are obvious: surface areas with higher values of SWC may nevertheless show high soil water tension (SWT)-values (e.g. discernible in

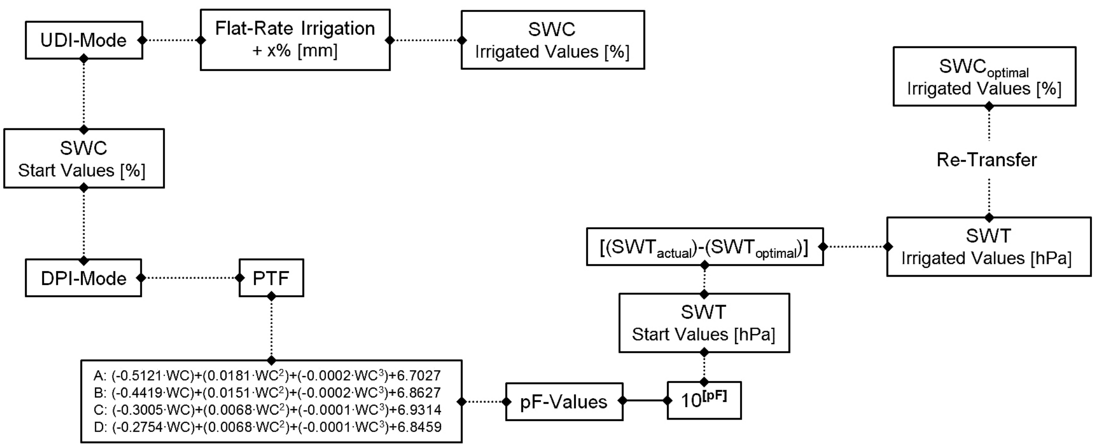

Figure 2. Simplified procedure of the grid-based simulation in the undifferentiated irrigartion (UDI)- and differentiated precision irrigation (DPI)-mode; SWC – soil water contents; SWT – soil water tension

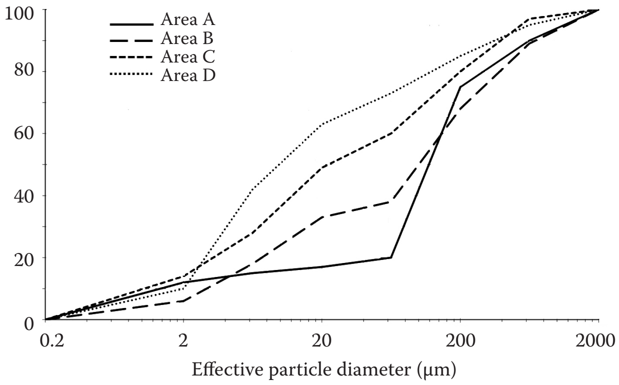

Figure 3. Particle-size grading curve of the respective particle-size distributions of the simulated soils on areas A–D

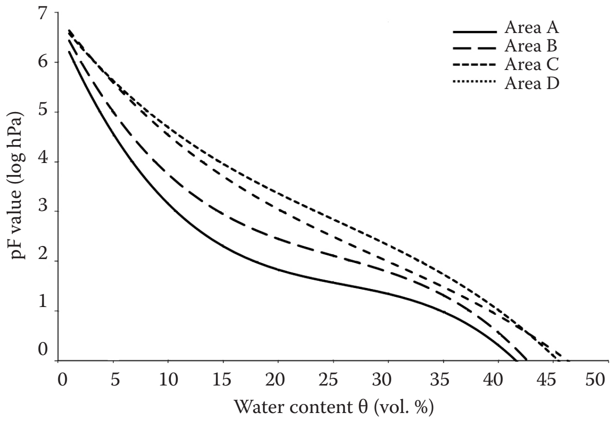

Figure 5. Corresponding water retention curves of the different soil textures

the lower left part of Figure 6b). The patterns of SWCs and SWTs are not congruent, but they are subjected to pedo-specific modification.

The irrigation simulation in the UDI-mode (Figure 6c) runs with a flat rate of 30 mm (10% for the replenishment of soil) and without any pedological differentiation. In the DPI-mode (Figure 6d) the volume of irrigation water corresponds to the soil specific water tensions in the root zone. This means that each grid is only irrigated until the target value of soil water tension (in this simulation 150 hPa) has been reached. Thus the water supply of soil and plants is controlled by the simultaneous values of soil water tensions, so that an over-irrigation in the DPI-mode is prevented. As a consequence the total area in the DPI-mode (Figure 6d) shows a much lower content of soil water than that in the UDI-mode (Figure 6c). Regarding the corresponding values of soil water tension, it is obvious that in the UDI-mode (Figure 6e) a major part of the area has been over-irrigated (values partially < 100 hPa). This oversupply of water (particularly in areas A and D) is not only a waste of water, but it also may have negative influence on plant growth. Only area B ranges in the defined optimum with an average soil water tension of 150 hPa. In the DPI-mode (Figure 6f) the target level of 150 hPa was achieved for all grids by precision irrigation. For the crops this means equal conditions of water tension in the whole irrigated area. This is a big advantage in the water supply of the crops over the UDI-mode. Moreover, this aim was achieved with less water consumption than in the UDI-mode. Figure 6g shows that for each grid the same amount of water was used for irrigation. In comparison to the DPI-mode (Figure 6h), much more water was used for the irrigation process. Based on a virtual cropland of 2 ha, the DPI-mode saves a water amount of 177 m^3 compared to the UDI-mode.

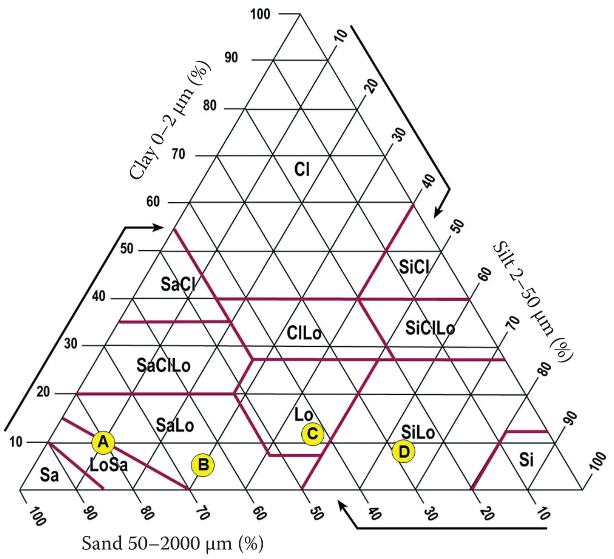

Figure 4. Soil-texture triangle of corresponding soil textures; A, B, C, D – areas
Cl – clay; SiCl – silty clay; SaCl – sand clay; ClLo – clay loam; SiClLo – silty clay loam; SaClLo – sand clay loam; Lo – loam; SiLo – silty loam; SaLo – sand loam; Si – silty; LoSa – loam sand; Sa – sand

DISCUSSION

For precision irrigation it is indispensable to mark out irrigation management zones. Soil variability is therefore the most important key factor. The knowledge of only the spatial distribution of soil water content is insufficient because the soil-depending water tension decides about the availability of water for plants. The presented irrigation model makes it possible to apply irrigation water to a given soil

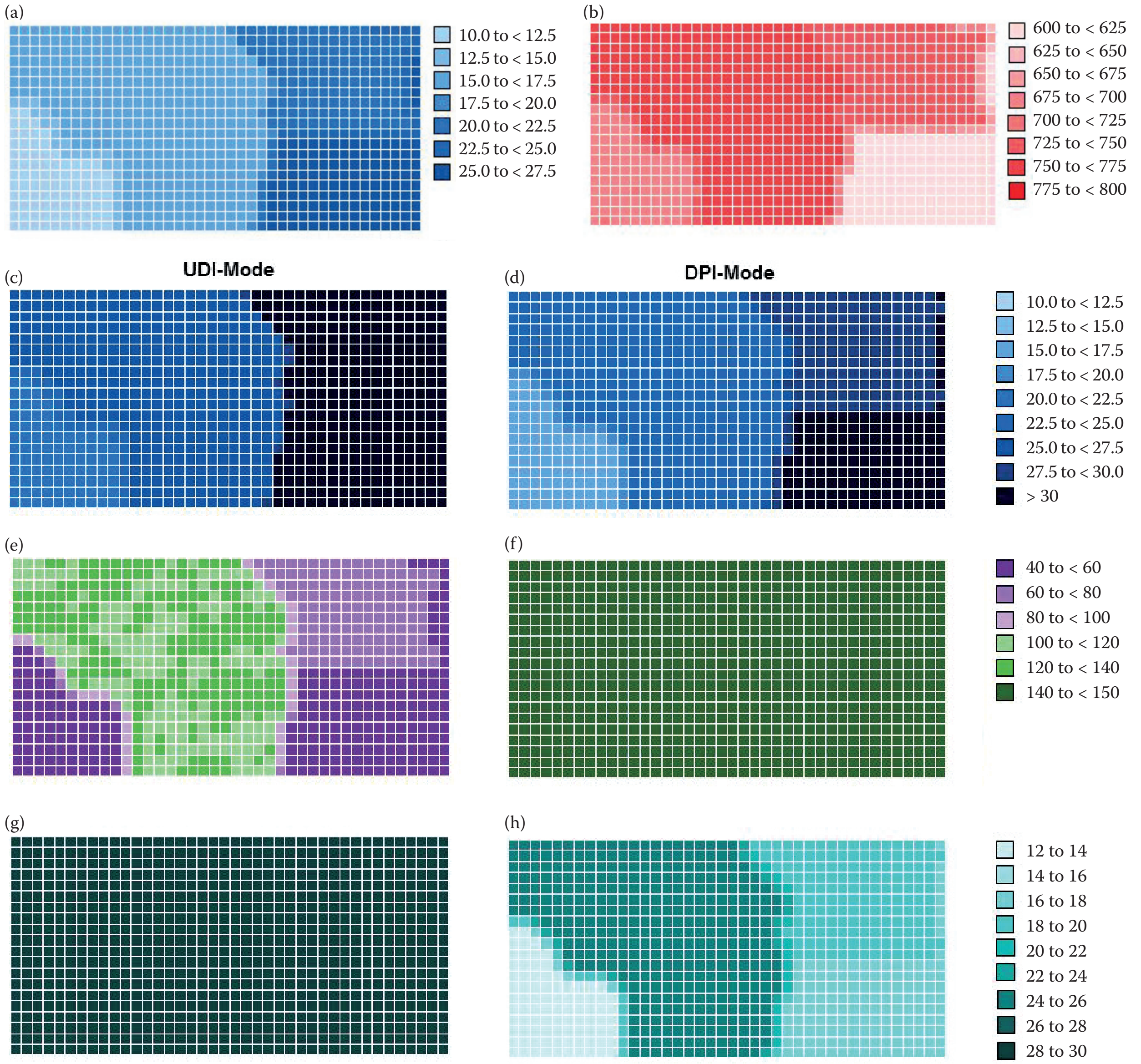

Figure 6. Simulation output of UDI- and DPI-mode; (a, c, d): water content (%); (b, e, f): soil water tension (hPa), (g, h): irigated water (mm)

site in a volume and at a time needed for optimum soil water supply for the crops.

The use of soil moisture sensors has many advantages like the possibility to read soil volumetric water content directly and the possibility of continuous measurement at the same location in a high temporal and spatial resolution. Water saving irrigation can be achieved by the use of simple soil moisture sensors in combination with the given knowledge of soil conditions. Compared with tensiometric sensors, the use of soil moisture sensors is less expensive. The efficiency of a sensor-controlled irrigation system can be optimized significantly by a grid-based distribution in the soil. The presented simulation approach is also compatible with special irrigation scheduling decisions and the use of irrigation management strategies such as regulated deficit irrigation or partial root zone drying.

Sensor-based irrigation using wired sensors with pedohydrological calibration is considered to be a suitable method even if the sensor-technology is still in development. In addition to the usage of wired sensors, 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.

The exact positioning (GPS-supported) and non-destructive installation of micro sensors is no more a problem. Thereby the construction of a wireless network is a desirable objective in agriculture.

However the possibilities of implementing have been associated with many restrictions as yet. An error-free communication between the wireless sensor-nodes and the control unit is still more difficult with the increasing soil depth. Furthermore, a stabilized electrical power supply of the wireless sensors is still a problem concerning sensor technology. Solar powering is not possible because of the subsoil installation of the sensor nodes and small celled batteries have limited lifetimes.

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