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Irrigation efficiency under a flat rate sprinkler system on heterogeneous soils – a pedotransfer-based comparison

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Abstract: ***Irrigated fields in complex landscapes are often characterized by topographical changes with small scale heterogeneity of soil properties. In terms of a precision irrigation management it is necessary to achieve an accurate determination of these spatial variations to enhance irrigation efficiency. The practical implementation of precision irrigation must be focused on characterizing spatial variation of soil properties that relate to the water supply of plants. This paper outlines the differentiated impact of irrigation on heterogeneous soil site conditions. The object of this research was to assess the effect of a homogeneous sprinkler irrigation application on heterogeneous types of soil substrates. A simultaneous flat-rate irrigation event on 31 heterogeneous soils with significant differences in the terms of soil texture has been simulated numerically through a model approach (FRIS = Flat-Rate Irrigation Simulation) as presented in this paper. Measurements of volumetric soil water contents are often used in irrigation management for scheduling water applications. However, soil water tension is the major control factor in site-specific irrigation and plays a vital part in the soil-water-nexus. For that reason the implementation of 31 soil-specific pedotransfer functions (PTFs) is one core element of this simulation. The transfer functions were determined statistically via corresponding nonlinear regression functions. Most of the already existing 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 regression-based PTFs in FRIS 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. The PTFs presented within FRIS may help to optimize existing irrigation strategies and simulation approaches concerning the consideration of similar soil textural differences. The results of FRIS show that irrigation efficiency is directly influenced by the existing site specific properties. The different types of soil texture seem to be a suitable key factor for improving water use efficiency in irrigation management.***

Keywords: irrigation management, precision irrigation, simulation, soil texture, soil-water-nexus.

1. Introduction

In times of climate change irrigation of agricultural areas is often linked with the constraint of water saving. Conversely, many cash crops require large amounts of water to ensure profitable harvesting. In the context of climatic changes a significant increase in global agricultural evapotranspiration is expected within the next decades [1-3]. Due to the fact that more than 40% of the global food production comes from irrigated agriculture [4] the water consumptions associated with the agricultural practice of irrigation is the focus of increasing attention [5].

At present many growers in the world base their irrigation scheduling and management on intuition or simple qualitative criteria. Over-irrigation or under-irrigation is the consequence of these traditional methods. But to maintain or increase agricultural production, new irrigation systems will need to provide higher water use efficiency than those traditional methods [6]. In connection with the global problem of water scarcity and the dwindling of fresh-water resources water-saving irrigation management is becoming a key technology in agriculture [7], [8].

Improvements of irrigation efficiency (IE) can be achieved by technical, agronomic and managerial approaches [9-11]. Other approaches are focused on crop-based methods [8], [12]. McCarthy et al. [13] have recently reviewed the current state of applications of advanced process control in irrigation. To find the optimal water use efficiency is also required by the policy directives and the corresponding administrative requirements [14], so that there is a pressing need for irrigation to improve IE. A coordinated combination of irrigation methods and site specific scheduling is required to achieve sustainable improvements in IE [15], [16]. Precision irrigation (PI) adheres to this recommendation by optimizing the water use efficiency with different technical approaches. Ideally PI makes it possible to apply relatively low amounts of water, so that soil water is maintained at constant levels [17].

Special techniques like variable flow rate sprinkler systems are becoming increasingly important for PI [7], [18]. The term and intention of PI evolved from precision agriculture and precision farming in the context of sustainability [19] with the aim to take site-specific conditions into consideration.
Furthermore there exist many models, tools and technologies to help farmers to decide about optimal water management and IE by special configurations of their irrigation systems [17], [20-27]. Subbaiah [28] has recently reviewed models for predicting soil water dynamics during trickle irrigation.

But above all correct irrigation management requires the consideration of the complex interaction between irrigation water and agricultural soil [29]. As noted by Sadler et al. [30] the soil moisture has a major effect on crop performance and maps of volumetric soil water content would be valuable for developing efficient irrigation management [31]. In PI-management the volumetric water content is often measured with multisensory capacitance probes like FDR-type probes and TDR probes or by different in-situ sensors for scheduling the irrigation [11], [32-35]. But the sole measurement of volumetric water content is not very constructive for optimal PI and IE. Actually soil water tension and the field capacity (FC) have much more practical significance for PI and IE than the often measured volumetric water content. A tensiometer-based automation of irrigation management is the best way to achieve soil- and crop-specific irrigation with the maximum of water use efficiency, but it is mostly too expensive and impractical within a framework of irrigation management. Therefore often the soil moisture content is used as regulating and controlling parameter for irrigation scheduling. In literature it is often mentioned that there is a great need for the development of low-cost and non-intrusive sensors for the monitoring of soil moisture [17], but the soil specific matric potentials are mostly neglected in PI-strategies [36]. Innovative and advanced PI-technologies like evenly distributed sensor systems can be applied across different levels of irrigation management, but the need of a corresponding basic soil research is often marginalized. Ganjegunte et al. [26] underlined that soil water sensors absolutely need soil site-specific calibration to improve their accuracy. So apart from new techniques and models in irrigation the site-specific management of irrigation also requires the knowledge about site-specific soil conditions. Soil varies spatially in field capacity, soil texture and other physical characteristics within small scales. But only few configurations of precision irrigation systems take into consideration variables that could affect hydraulic properties of soils [7], [26], [37]. To quantify all soil variations is a big challenge and mostly not feasible. Soil properties vary substantially in all vertical and horizontal directions. However, soil texture is a key factor for many physical characteristics which are relevant in irrigation management. Moreover, soil texture is an easily measurable parameter, which can be estimated in field by finger test or quantitatively by laboratory methods.

This report compares the efficiency of flat rate irrigation on 31 heterogeneous soil textures with a pedotransfer-based simulation approach.

2. Materials and Methods

2.1 Pre-Computing of soil-specific parameters and transfer functions for FRIS-algorithms

Based on 6352 data sets from different federal states of Germany an estimation framework for the deduction of different soil-physical parameters was developed in 1994 by the AG BODEN [38], [39]. The average pF-values which are given in the German Guidelines for Soil Mapping GGSM [38] and defined in DIN 4220 are based on a medium soil bulk density of about 1.5g/cm^3. This data base was used for building the regression models.

Due to the fact that GGSM gives the corresponding ψ_m-(θ)-values pedospecifically but only for specified fix pF-values (-∞, 0.5, 0.8, 1.5, 1.8, 2.5, 2.8, 3.5, 3.8 and 4.2), it was necessary to enhance the data density by using a procedure of interpolation. Therefore the corresponding $\psi_m(\theta)$-polynomes were interpolated linearly piecewise. Based on this process of interpolation it was possible to calculate the missing values θ_{pFVx} of the corresponding pF-value for each step between pF 0.001 and pF 4.2 with a step-size of pF 0.1 for every kind of soil texture.

The PTFs used are based on nonlinear regression functions which were calculated on the basis of the GGSM-data explained above. The computed soil-specific model parameters of the regression functions are listed in table 1. These regression models were computed with PASW Statistics®. The datasets used were prepared by using EXCEL® and the free software programming language of R.

These functions 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.

2.1 Structure of FRIS

The simulation was performed on 31 virtual soil sites (VSS), each with different compositions of grain-size fractions and soil textures (Fig. 2). The irrigation rate was adjusted with 7 mm/h over a period of 5 h.

At the start of the simulation the water in all soils is bonded with 1200 hPa (= start value SV). So the agricultural water stress is equal at all simulated soil sites (Fig. 1). The deciding key factor for the IE of the subsequent irrigation is the type of soil texture.

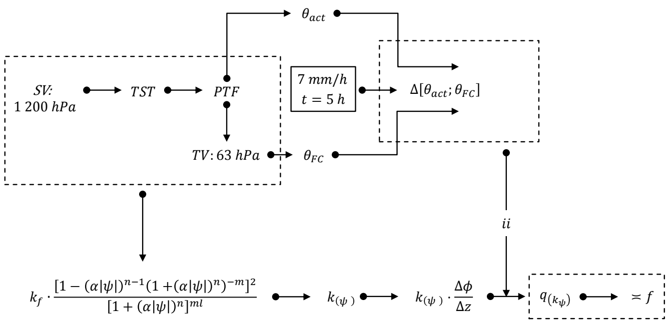

Figure 1: Simplified structure of the FRIS-model

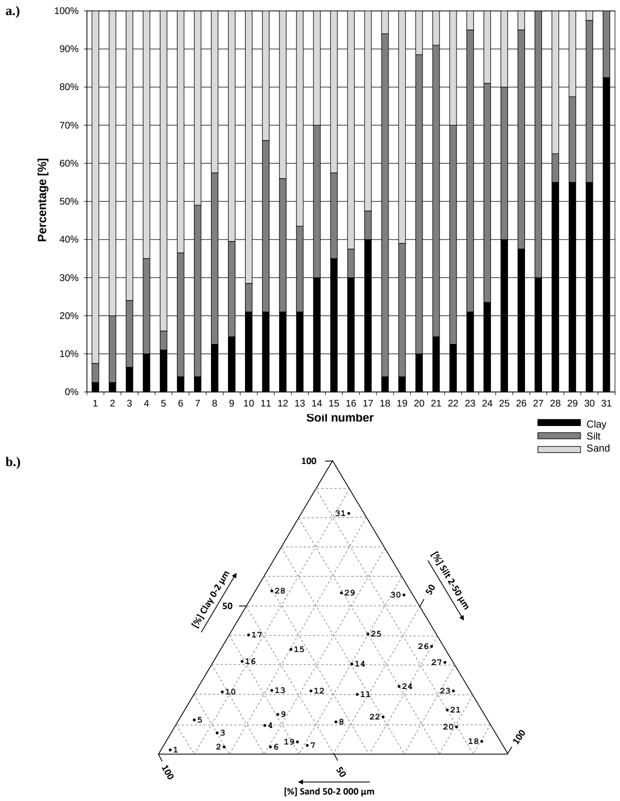

Figure 2: Composition of soil textures of the 31 VSS (a) and position of the 31 VSS in the soil textural triangle (b)

In FRIS the unsaturated hydraulic conductivity as a function of the soil matric potential is calculated through soil specific pedotransfer functions (PTFs) (Tab. 1) by including the parameters of van Genuchten [40] (Tab. 2).

The corresponding soil specific volumetric water contents (in figure 2 described by θ_{act} for the actual volumetric water content and by θ_{FC} for the volumetric water content at the point of soil specific field capacity) are transferred via the corresponding PTFs mathematically into the corresponding soil specific water tensions.

According to [41] and [42] the water flux $q_{(K\psi)}$ in FRIS is computed by using the corresponding hydraulic gradients (soil surface as level of reference). Due to the fact that in its simplest form the Green and Ampt equation for infiltration rate f can be written as

$$f = -Ks \cdot \frac{dh}{dz} \quad (1)$$

it was possible to estimate f in the unsaturated soil at field capacity. Therefore in FRIS K_S has been substituted by $K\psi$ at 63 hPa as corresponding value of matric potential at field capacity. By these model specific algorithms and parameters FRIS calculates the IE for the 31 virtual soil sites with the given irrigation rate of 7 mm/h over an irrigation period of 5 h.

3. Results

The simulation results show the variation of the irrigation efficiency at the 31 VSS. The simulated values of volumetric water contents at 1200 hPa and 63 hPa are depicted in figure 3. Quantitative information about the real water demand for FC can also be taken from there. It is reflected in the corresponding curves that there are significant variances concerning the differentiated and soil specific water demand to the target value of 63 hPa. The discrepancy between θ_{act} and θ_{FC} increases according to the VSS-specific desorption characteristics with increasing content of clay. Accordingly also the calculated volumetric demand of water is increasing.

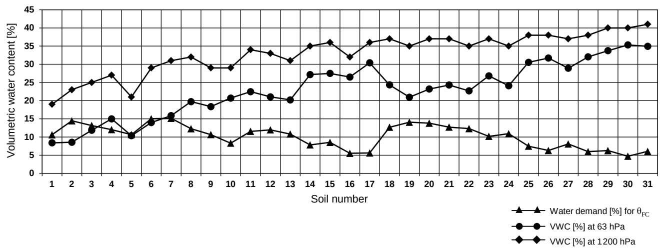

Figure 3: Volumetric water contents at simulated stress point (1200 hPa) and at point of simulated field capacity (63 hPa) with the calculated soil-specific water demand.

The grading of volumetric water contents at the 1200 hPa-level is nearly congruent to the grading at the 63 hPa-level. In line with expectations the grading of the water demand paints a different picture, because of the texture-specific controlling. Differences in the site specific water demands which are needed to achieve the corresponding water content at the point of field capacity are becoming obvious.

Irrigation efficiency is directly influenced by the existing site specific properties. Figure 4 represents the respective soil depths of all virtual soil sites which have been filled up to field capacity (θ_{FC}) after the simulated irrigation period. An irrigation depth of >25 cm has been displayed by FRIS only for VSS 1. The effectiveness of the simulated flatrate irrigation is highest at VSS with favorable compositions of the sand and loam fraction (sand texture: VSS 1; loam-sand texture: VSS 2; sand-loam texture: VSS 6, VSS 7, VSS 19; loam texture: VSS 8). Two significant outliers belong to the sandy clay-loam soil texture (VSS 16) respectively to the silty fraction (VSS 18).

RENGER et al. [43] have criticized the pF-data of GGSM because of the used medium bulk density of 1.5 g/cm^3 and pointed out that this may cause misjudgments in clayey soils and in pure sand soils. This could also explain the outliers observed in figure 4.

Table 1: Calculated soil-specific model parameters of the (nonlinear) regression based PTFs

Soil-Nr.	b_1	b_2	b_3	b_0	R^2	***F***	α
1	-0.5048	0.0192	-2.52E-04	6.1112	0.978	523.99	0.001
2	-0.4931	0.0194	-2.65E-04	6.0432	0.974	447.31	0.001
3	-0.4836	0.0168	-2.18E-04	6.8071	0.996	2791.18	0.001
4	-0.4194	0.0127	-1.57E-04	7.0379	0.999	8808.9	0.001
5	-0.5121	0.0180	-2.31E-04	6.7027	0.996	2671.92	0.001
6	-0.4419	0.0150	-1.98E-04	6.8627	0.997	4014.37	0.001
7	-0.4266	0.0143	-1.91E-04	6.9951	0.998	5281.6	0.001
8	-0.3005	0.0069	-7.81E-05	6.9314	0.995	2376.2	0.001
9	-0.3009	0.0058	-5.37E-05	6.9958	0.997	4454.68	0.001
10	-0.2225	0.0013	7.71E-06	7.0796	0.997	3450.93	0.001
11	-0.2349	0.0031	-2.68E-05	7.0862	0.984	729.83	0.001
12	-0.2616	0.0042	-3.76E-05	7.0928	0.985	763.43	0.001
13	-0.2686	0.0041	-3.23E-05	7.1096	0.980	595.45	0.001
14	-0.0988	-0.0026	3.25E-05	7.0138	0.993	1797.22	0.001
15	-0.1026	-0.0021	2.38E-05	7.0018	0.992	1441.87	0.001
16	-0.0235	-0.0071	9.35E-05	6.9392	0.989	1058.11	0.001
17	0.0384	-0.0079	8.01E-05	6.9466	0.977	508.95	0.001
18	-0.3002	0.0090	-1.24E-04	6.8656	0.985	773.65	0.001
19	-0.2968	0.0081	-1.07E-04	6.7177	0.981	627.16	0.001
20	-0.2960	0.0085	-1.16E-04	6.8307	0.977	506.99	0.001
21	-0.2825	0.0079	-1.11E-04	6.8542	0.975	467.81	0.001
22	-0.2754	0.0069	-9.12E-05	6.8460	0.985	777.1	0.001
23	-0.2465	0.0063	-9.32E-05	6.9286	0.985	783.54	0.001
24	-0.2133	0.0028	-3.13E-05	7.0193	0.990	1187.94	0.001
25	-0.1114	-0.0009		7.2715	0.970	593.71	0.001
26	-0.0874	-0.0014		7.2915	0.946	323.16	0.001
27	-0.0439	-0.0046	5.45E-05	6.9100	0.983	686.33	0.001
28	-0.0801	-0.0016		7.2600	0.923	222.25	0.001
29	-0.0518	-0.0021		7.2073	0.936	270.18	0.001
30	-0.0226	-0.0026		7.1660	0.934	259.73	0.001
31	-0.0326	-0.0024		7.1374	0.934	260.44	0.001

Table 2: Parameters of van Genuchten [40] used in FRIS

Soil-Nr.	***n***	***K_S [cm/d]***	***m***	***α***	***l***
1	1.5754	340	0.3652	0.0874	0.5
2	1.4370	127	0.3041	0.0679	0.5
3	1.2642	98	0.2090	0.0786	0.5
4	1.2204	65	0.1806	0.0476	0.5
5	1.2253	118	0.1839	0.1214	0.5
6	1.2813	59	0.2195	0.0264	0.5
7	1.2750	38	0.2157	0.0167	0.5
8	1.2330	28	0.1889	0.0176	0.5
9	1.1765	42	0.1500	0.0428	0.5
10	1.1391	42	0.1221	0.1080	0.5
11	1.1258	23	0.1117	0.0314	0.5
12	1.1158	23	0.1038	0.0360	0.5
13	1.1149	36	0.1031	0.0498	0.5
14	1.1023	13	0.0928	0.0123	0.5
15	1.0883	10	0.0811	0.0151	0.5
16	1.2300	38	0.1870	0.0270	0.5
17	1.2300	11	0.1870	0.0270	0.5
18	1.3448	13	0.2564	0.0034	0.5
19	1.2513	22	0.2008	0.0090	0.5
20	1.2535	12	0.2022	0.0076	0.5
21	1.2252	12	0.1838	0.0085	0.5
22	1.2123	20	0.1751	0.0132	0.5
23	1.1744	13	0.1485	0.0091	0.5
24	1.1261	16	0.1120	0.0133	0.5
25	1.0833	7	0.0769	0.0084	0.5
26	1.0928	9	0.0849	0.0075	0.5
27	1.1052	12	0.0952	0.0198	0.5
28	1.2300	5	0.1870	0.0270	0.5
29	1.0628	6	0.0591	0.0331	0.5
30	1.0939	3	0.0858	0.0033	0.5
31	1.0816	3	0.0754	0.0068	0.5

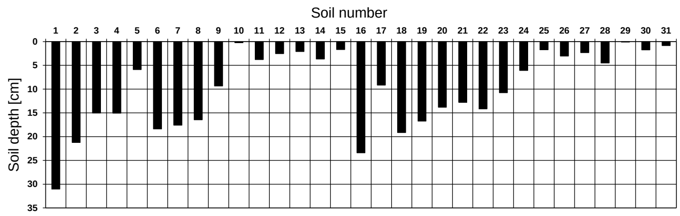

Figure 4: Specific soils depths with θ_{FC} of the VSS after the simulated irrigation period.

The quantification concerning the corresponding parts of the really used and the excess of irrigated water at the end of the simulated irrigation period is depicted in figure 5. Under the simulated conditions soil sites with high contents of silt and clay are characterized by high rates in the excess of irrigated water.

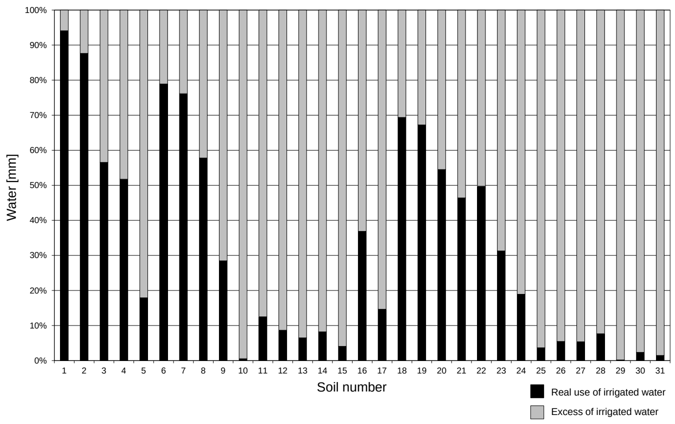

Figure 5: Really used and excess of irrigated water at the end of the simulated irrigation period.

4. Discussion

As the presented simulation has shown, without any information about soil texture differences it is impossible to manage spatial variability of different soil sites in the sense of PI and IE. But usually, in most cases irrigated fields are treated by the growers as homogeneous management zones [17]. Spatial information about soil textural differences both in horizontal and vertical dimension by sound scientific soil mapping, may provide a valuable management tool for improving IE and optimizing PI.

The discrepancy between the curves of θ_{act} and θ_{FC} and the calculated increase of the volumetric water demand in figure 3 is explained by the soil-specific desorption characteristics with increasing contents of silt and clay.

Account needs to be taken of the fact that a simulation of vertical soil water dynamics in the soil-water-nexus will always be associated with some uncertainty. In general soils with high contents of clay are greatly affected by soil physical changes when the soil got dry [37]. Especially crack spaces cause a bypass flow with an incalculable hydrological behavior [44-47]. The average pF-values which are given in the guideline for soil mapping [38] and defined in DIN 4220 [48] and which form the base for the pedotransfer functions presented here, are based on a medium bulk density of about 1.5 g/cm^3. This may cause misjudgments in clayey soils and in pure sand soils, which has been criticized by Renger et al. [43]. This could explain the outliers observed in figure 4.

Soil sites with high percentages of small-grained and fine textures show high rates in the excess of irrigated water (figure 5). This is mainly attributable to reduced hydraulic conductivities under saturated conditions (table 2), because in FRIS hydraulic conductivities and infiltration characteristics of irrigated water is controlled by PTF and particularly by the well-established parameters of van Genuchten [40].

The PTFs presented within FRIS help to optimize existing irrigation strategies and simulation approaches concerning the consideration of similar soil textural differences. It must be pointed out that a correct quantification of irrigation-influenced soil water state and soil water flux is a nearly intractable problem – not least because tillage and farm-traffic affects soil infiltration with significant effects on irrigation performance [49]. There exist many approaches and numeric models in soil science, soil physics and soil hydrology for the mathematical description of processes in the unsaturated zone, but PI requires information with a higher accuracy. Moreover, each model postulates abstractions and rationalizations of natural conditions and interactions. However, soil properties are only one part in the nexus of plant, soil and water. For the efficient use of irrigation water it is indispensable that core competencies of engineering, agriculture, crop science and soil science must be combined. There are still no numerical solutions for an exact PI-support, so that PI will also always depend on the experience and expertise of the growers.

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