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SPATIAL VARIABILITY OF SOIL WATER CONTENT AND SALINITY IN A SEMI-ARID AGRICULTURAL FIELD

Rumslig variabilitet av markvattenhalt och salinitet i ett semiaritt fält

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Abstract

One technique for collecting rainwater and prevent soil erosion applied on large areas in Tunisia involves the use of soil ridges (1–1.5 m high). These contour ridges are constructed parallel to topographical isolines. The effects of the contour ridges on the soil water content (θ) distribution, bulk soil salinity σ_a, and soil water salinity (σ_w) were investigated in the catchment of El-Gouazine in central Tunisia. In total 258 measuring points were obtained in an 80 m x 120 m area. Spatial maps of σ_w, σ_a, and θ displayed essentially a random variation and no apparent pattern within the sampling area. A geostatistical analysis, however, displayed spatial correlation for all variables. A variational analysis displayed small measurement errors as compared to small-scale variation in the soil. A potential risk with soil ridges could be salt accumulation just upstream the ridges, however, no such effect could be observed in the studied area.

Key words – Spatial variability, semi-variogram, Tunisia, semiarid, contour ridges

Sammanfattning

En teknik för att förhindra yterosion och samla ytavrinning är bygga jordvallar (1–1,5 m höga) parallellt med höjdkurvorna. Denna teknik används över stora områden i Tunisien. I denna studie undersöks hur dessa jordvallar påverkar ytjordens rumsliga variabilitet av markvattenhalt (θ) och salinitet, dels uttryckt som jordens totala elektriska konduktivitet (σ_a) och dels som porvattnets elektriska konduktivitet (σ_w). Totalt mättes dessa parametrar i 258 punkter i ett 80 x 120 m stort område i El-Gouazine i centrala Tunisien. De tre parametrarna uppvisade en till synes slumpmässig rumslig variabilitet, men en geostatistisk analys visade ett rumsligt beroende. En variationsanalys visade på små mätfel i jämförelse med småskalig rumslig variation. En potentiell risk med jordvallarna är att salt ska ackumuleras i det översta jordlagret just uppströms vallarna. I vår studie kunde dock ingen förhöjd salinitet påvisas.

1 Introduction

Since ancient times, farmers, and herders in the Mediterranean have, under widely varying ecological conditions, attempted to "harvest" water to secure or increase agricultural production (Prinz, 1998). The collection and concentration of rainfall and its use for irrigation of crops, pastures, and trees for livestock consumption and household purposes are called rainwater harvesting (Siegert, 1994). Among the different methods for harvesting the so called "macrocatchment water harvesting", which is water collection from long slopes, is a popular technique. In this method, runoff from hill slope catchments is conveyed to cropping areas located below the hill by using small banks of soil (1–1.5 m high) denoted as soil contour ridges. The function of this arrangement is to hold back surface runoff water so as to make the water infiltrate and reduce erosion. Up to

2001 about 900 000 ha farming land were protected by this technique (Nasri, 2002). However, the hydrological effects of this system are still to a major extent unknown. For example, there might be a potential risk of salt buildup just upstream the ridges where the infiltration and evaporation are greatly increased.

Geostatistics is a methodology for the analysis of spatially correlated data. The characteristic feature is the use of semi-variograms or related techniques to quantify and model the spatial correlation structure. It helps to determine the optimum size of spatial grids for a specific hydrological modeling. It gives also a view of how a specific measurement at a point is related to the area surrounding it.

There are several examples of studies of the spatial variability of soil moisture. Nyberg (1996) sampled 60 evenly spread nodes and up to a dozen non-regular nodes twice using 0.15 m long vertically installed time domain reflectometry probes. This experiment was carried out in a 0.63 ha spruce-covered sandy-silty soil in Sweden for sampling soil moisture. A spherical semi-variogram with a range of 20 m was successfully fitted to the sampling estimates. Western and Grayson (1998) used time domain reflectometry for measuring surface soil moisture across 10.5 ha in the Tarrawarra catchment in temperate southeastern Australia (clay-loam pasture for cattle grazing). These measurements were made at 13 occasions on 500 nodal locations forming 10 x 20 m^2 grids. Western et al. (1998) indicated that the lack of spatial correlation depicted in some previous studies may be due to sampling spacing greater than the range over which correlation existed or because sampling size was too small to reliably estimate the spatial correlation. Anctil et al. (2002) characterized fine scale patterns of organic soil moisture content in the top 0.05 m by means of semi-variogram modeling. Soil moisture values were found to be normally distributed and were not significantly correlated with the soil organic matter content. They found many similarities between their exponential semi-variograms and the variograms from a study conducted in mineral soil (Western et al., 1998), except for the much higher sills associated with organic soils.

The objective of the present study is to analyze spatial variation of surface soil water content and salinity levels of both soil and soil water to examine the effects of comprehensive changes in soil surface characteristics. This is done in a catchment where soil contour ridges were constructed to cover the major parts of the surface area. Especially, the possible effect of salt buildup near the soil ridges was investigated. Measurement points were taken in a 80 x 120 m large area. The smallest distance between two points was 0.02 m. A geostatistical analysis is done to study the characteristics of the mentioned variables and to reveal effects of the implemented rainwater harvesting system. The fine spatial resolution of our measurements allowed for an analysis of the partition between uncertainty and errors in the measuring techniques and real small-scale variability.

2 Materials and methods

2.1 Experimental Conditions

The hilly catchment of El-Gouazine is situated in the center of the Tunisian Dorsal mountains, 50 km northeast of Kairouan. The climate is semiarid with cool winters and hot summers (Gounot and Le Houerou, 1967). Annual rainfall is erratic and varies from 200 to 800 mm with a median rainfall of 358 mm (Ousseltia, during 47 years). Most of the soils are developed on quaternary deposits (silt and sand), often with calcareous crust. The elevated parts are on geological calcareous outcrops from the end of the cretaceous era (Nasri and Zante, 1998). A typical soil profile of the area contains, 0 to 0.30 m: plowing layer to 0.12 m, silty clay, fine subangular blocky structure, many fine roots, some calcareous pseudo-mycelium and soft nodules; 0.30 to 0.95 m: silty clay, angular blocky structure when wet, massive when dry, some calcareous nodules, hard consistence, no roots; >0.95 m: sandy clay loam, firm to friable consistence, fine pores. The experimental field area is an agricultural field used by local farmers for mainly wheat and vegetable crops. At the time of measurements, however, the field lay fallow.

2.2 Measurements of θ, σ_a, and θ

Observations of field soil water content (θ) and soil salinity levels were made in an area covering two soil ridges (80 x 120 m). The location of the sampling area is shown in Figure (1a). Measurements of bulk soil electrical conductivity (σ_a) and apparent dielectric constant (K_a) were taken at 258 points with time domain reflectometry (TDR). The TDR measured K_a was converted to θ using the general calibration function presented by Topp et al. (1980). Also, soil solution electrical conductivity (σ_w) samples were taken at the same points with a Sigma Probe (at 10 measurement points Sigma Probe readings were not possible due to too low water content). About 50% of the samples were taken near the ridges to have a more detailed view on conditions in this area. About 50 samples were taken along one line across the northern ridge with a spacing of 0.1–0.5 m to study conditions before and after the ridge in detail. Thirteen samples with 0.02 m spacing were taken to investigate the effect of small-scale variation. In all points, three measurements of K_a, σ_a, and σ_w were taken and averaged. In one point, measurements were repeated 30

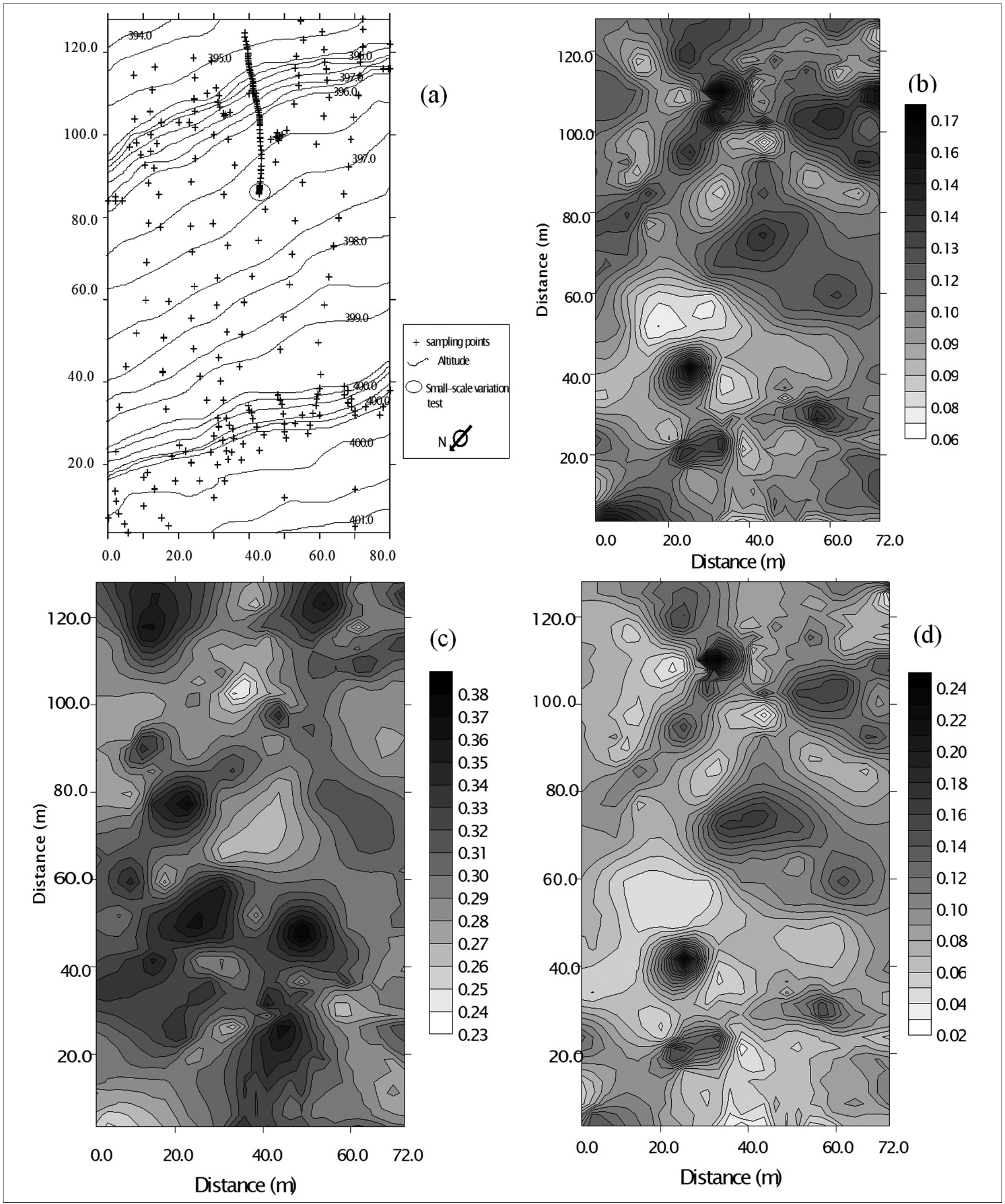

Fig. 1. a) *Topography and measuring points in the study area. b) Spatial distribution of water content* (θ) *m^3 m^{-3}. c) Spatial distribution of soil water salinity* (σ_w) *in dS m^{-1}. d) Spatial distribution of bulk soil salinity* (σ_a) *in dS m^{-1}.*

times and the standard deviation was calculated to investigate the effect of measurement error. The altitude of sampling points was measured with a standard leveling instrument

The σ_a and K_a measurements were taken by a Tektronix 1502C metallic TDR cable tester (Tektronix, Beaverton, OR). This was connected to a laptop computer via an RS232 interface. Estimates of K_a and σ_a were calculated from the TDR trace using the WinTDR program (developed by the Soil Physics Group at Utah State University). A three-rod probe was used, 0.1 m in length, a wire diameter of 0.003 m, and a wire spacing of 0.05 m (Soilmoisture Equipment Corp., Santa Barbara, CA).

The σ_w measurements were taken by a Sigma probe instrument type EC1 (Delta-T Devices Ltd., Cambridge, UK). The Sigma probe is a relatively new dielectric technique that uses the K_a and σ_a measured at a specified frequency (30 MHz) for calculating the σ_w. The sensor consists of a 0.105 m rod, 0.005 m in diam. At the end of the rod there are two electrodes (0.015 m long) separated by an isolating material. The rod is connected to a handle with built in electronics. The Sigma probe is connected to a hand held data logger (Psion Workabout) and gives readings of temperature and σ_w. The Sigma probe measures a few cm^3 of soil whereas the TDR measures a soil cylinder of approximately 0.05 m diameter and 0.1 m in depth (distance between the rods and their length), i.e., the measurement volume is about 200 cm^3.

The TDR probes were pushed down vertically from the soil surface and, thus, the TDR measurements represent the average σ_a and θ for the uppermost 0.1 m of the soil profile. In order to get a comparable σ_w measurement, the Sigma probe measurements were made at 0.05 m depth through the same position as the middle rod of the TDR probe.

2.3 Geostatistics

Geostatistics can be applied to situations where local variance of sample values depends only on the relative spatial distribution of these samples (e.g., Clark, 1987, Webster and Oliver, 1990, Söderström, 1992). In the simplest case, there is no trend in the population that affects values within the scale of interest. The semi-variance $\gamma^*_{(h)}$, which is the local variance determined from the average difference squared between each pair of samples for a given (lag) distance of separation (*h*), can be calculated as:

$$\gamma^*_{(h)} = \tfrac{1}{2}\, \eta\, \Sigma\, ((X_i) - (X_{i+h}))^2 \qquad (1)$$

where η is the number of pairs of samples separated by the distance *h*, X_i is the value at point i and X_{i+h} is the value at point separated from *i* by a distance *h* (e.g., Söderström, 1992). Results of $\gamma^*_{(h)}$ were plotted against *h* to produce experimental semi-variograms onto which a model could be fitted. The geostatistical analyses were performed on a PC using the Geo-EAS software (version 1.2.1), which is public domain from the Environmental Monitoring Systems Laboratory, U.S. EPA (Englund and Sparks, 1988).

Table 1. *Basic statistics of the measurements.*

	θ [m3 m^{-3}]	σ_a [dS m^{-1}]	σ_w [dS m^{-1}]
Min	0.059	0.018	0.228
Max	0.201	0.352	0.395
Mean	0.107	0.090	0.301
Standard deviation	0.023	0.041	0.032

3 Results and discussion

Some basic statistics of the measurements can be found in Table 1. Maps of θ, σ_a, and σ_w were produced using kriging. Figure 1b shows the spatial distribution of θ in the upper 0.10 m of the soil. This ranged from 0.059 m^3m^{-3} in the middle part of the area to 0.201 m^3m^{-3} near the northern ridge. There appears to be no clear spatial pattern regardless of topography and location of the soil ridges. Instead the θ pattern seems random. In general, however, individual points of lower soil water content appear in the area between the two ridges. Also σ_w and σ_a (Figs. 1c and 1d) displayed an essentially random spatial behavior. The topsoil within the entire area can be considered as non-saline. The range in σ_w (0.22 to 0.40 dS/m) was much smaller than the range in σ_a (0.018 to 0.352 dS/m). One reason for this could be due to the fact that the Sigma probe over-estimates small values of σ_w.

A geostatistical analysis shows that significant spatial correlation was present. Figure 2 shows the experimental variogram for θ and a best fit exponential model. A sill and constant variance are reached at about a range of

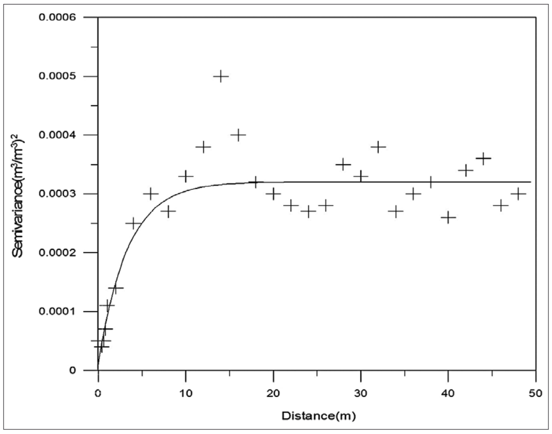

Fig. 2. *Experimental variogram for water content* θ *with the best fit exponential model.*

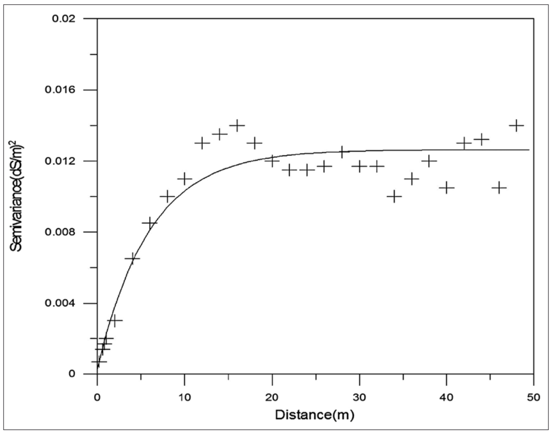

Fig. 3. *Experimental variogram for soil salinity (σ_a) with the best fit exponential model.*

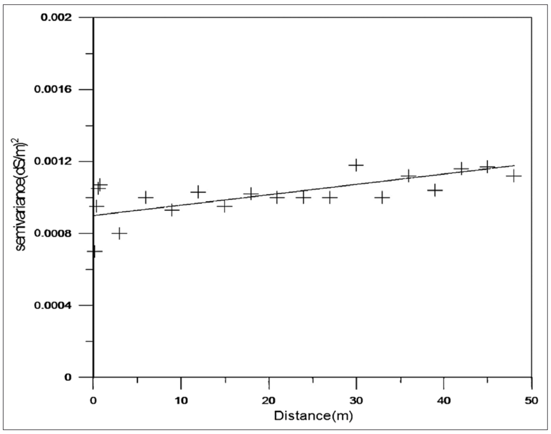

Fig. 4. *Experimental variogram for soil water salinity (σ_w) with the best fit linear model.*

18 m. A similar model could be fitted to σ_a (Fig. 3). Here, a range of about 24 m was found. For σ_w (Fig. 4), however, the best fit model was linear. According to the figure no sill or range with constant variance could be found. Instead the variance was unbounded within the specific area.

There are numerous studies of the spatial variability of θ presented. Nyberg (1996) found a similar range in his water content measurements, however, these ranges are smaller than those found by Anctil et al. (2002) and Western et al. (1998) (31–60 m). Our observed sill and nugget were considerably lower than previous reported values (e.g., Anctil et al. (2002); Western et al. (1998)). However, when comparing these parameters we need to normalize the values against the average values. Our average θ (0.107 $m^3\ m^{-3}$) was considerably lower than those in the studies of Anctil et al. (2002) and Western et al. (1998) (0.20–0.50 $m^3\ m^{-3}$). When we normalize the sill and nugget for our data we find that the sill value is in the same range as those found in Anctil et al. (2002) and Western et al. (1998). Our nugget, however, is still around 10 times smaller than the ones presented in the previous studies. For σ_w an unbounded range was found. Also, for σ_w, the large nugget value indicated a large sum of measurement errors and small-scale variation. The reason for the differences in the semi-variograms of σ_a and σ_w could be explained by i) the σ_a is highly correlated with θ (r=0.93) while σ_w is less correlated with θ (r=–0.51), and ii) the of σ_a and σ_w readings are taken by different instruments with totally different measurement volumes.

With our data set we can also evaluate the potential risk of salt accumulation just upstream the contour ridges. In arid and semiarid areas, a salt crust is often found at the soil surface due to the upward water flow caused by the high evaporation rate. During heavy rainstorms this salt crust will be eroded and dissolved by overland flow. The overland flow will be detained by the ridges and subsequently infiltrate. Thus, salt will be transported by the overland flow and accumulate upstream the ridges. When the water has infiltrated salts will again be transported due to the upward flow caused by the evaporation. In order to analyze our data, it is essential to understand the theoretical relationship between our parameters. The σ_a, of the soil depends mainly on three variables; θ, σ_w, and a geometry factor, which accounts for the complex geometry of the soil matrix (Mualem and Friedman, 1991). The σ_a is also affected by the surface conductivity of the soil matrix (σ_s). For unsaturated soils Rhoades et al. (1976) described the σ_a as;

$$\sigma_a = \sigma_w(\theta)\ T(\theta) + \sigma_s \qquad (2)$$

where $T(\theta)$ is the transmission coefficient. Rhoades et al. (1976) proposed a linear relationship between $T(\theta)$ and θ, i.e., $T(\theta) = a\theta + b$, where a and b are soil specific parameters. These parameters can be assumed constant within the area. From equation (2) we can see that a large σ_a does not necessarily mean that the soil contains more salt compared to a point with lower σ_a if the latter point has lower θ. In our data set we found a high correlation between θ and σ_a. This means that the σ_w is fairly uniform within the area. This is also reflected in the Sigma probe measurements in the low standard deviation of the σ_w measurements. Local areas with high σ_w were found, but these were located both upstream and downstream the ridges as well as in the area between the ridges. However, these areas seemed to coincide with areas of low θ, which is also reflected by the negative

Table 2. *Variogram model parameters.*

	θ $(m^3/m^3)^2$	σ_a $(dS/m)^2$	σ_w $(dS/m)^2$
Sill	$3.5 \cdot 10^{-4}$	0.013	–
Range (m)	18	24	–
Nugget	$2.6 \cdot 10^{-5}$	$30 \cdot 10^{-5}$	$90 \cdot 10^{-5}$

Table 3. *Estimated errors and small-scale variation.*

	θ $(m^3/m^3)^2$	σ_a $(dS/m)^2$	σ_w $(dS/m)^2$
Small-scale variation (n = 13)	$3.8 \cdot 10^{-5}$	$15 \cdot 10^{-5}$	$77 \cdot 10^{-5}$
Error (n = 30)	$0.07 \cdot 10^{-5}$	$0.23 \cdot 10^{-5}$	$0.83 \cdot 10^{-5}$
Σ	$3.87 \cdot 10^{-5}$	$15.23 \cdot 10^{-5}$	$77.83 \cdot 10^{-5}$

correlation between these two parameters (r = –0.51). This is likely to be caused by salt accumulation due to evaporation.

Table 2 gives a summary of all model parameters and Table 3 shows the results of estimated errors and small-scale variation. According to Table 2 σ_a can only be estimated with a precision (the nugget effect) of one order of magnitude compared to θ with the present methods. This is not surprising sine σa is highly dependent not only on θ but also on σ_w and $T(\theta)$ (see equation 2). The inherent spatial variability of σ_a may therefore be said to be much larger as compared to θ. The precision of σ_w estimations on the other hand was three times less than that for σ_a. The precision in observations (nugget effect) is the sum of errors and small-scale variation in the observation method. By studying Table 3 and comparing the precision with the nugget in Table 3 some interesting information emerges. For all three investigated variables the nugget was in the same order as the sum of small-scale variation and errors. Also, for all three variables the small-scale variation was one to two orders of magnitude larger as compared to the error component. Consequently we may safely conclude that the reason for the nugget effect was mainly due to variation in the small-scale and not due to errors in the observations. Due to the difference in sampling volume (about 100 times larger for θ and σ_a compared to σ_w) it was reasonable to expect larger small-scale variation for σ_w.

4 Summary and conclusions

Soil water content (θ), bulk soil salinity (σ_a), and soil water salinity (σ_w) were sampled in an agricultural area in central Tunisia employing soil contour ridges for rainwater harvesting. The purpose was to examine the effects of the ridges on the spatial distribution of the parameters. In total, 258 measuring points were obtained in an 80 x 120 m^2 area. In order to study the small-scale variability in detail, some measurement points were taken as close as 0.02 m. Spatial maps of all variables appeared to display a random behavior regardless of topography. A geostatistical analysis, however, displayed significant spatial correlation. Both θ and σ_a displayed a range of 18–24 m. The range of θ was found to be similar to the ones presented in a study by Nyberg (1996), however, larger values have been presented by Anctil et al. (2002) and Western et al. (1998). Our observed sill was in the same range as the ones in Anctil et al. (2002) and Western et al. (1998) when data were normalized against the average θ. Our nugget, however, was about ten times smaller than those found in Anctil et al. (2002) and Western et al. (1998). One reason for the difference might be that our measurement points were located much closer to each other than in the previous studies. For σ_w an unbounded range was found. Also for σ_w, the large nugget value indicated a large sum of measurement errors and small-scale variation. The reason for the differences in the semi-variograms of σ_a and σ_w could be explained by i) the σ_a is highly correlated but σ_w is less correlated with θ, and ii) the of σ_a and σ_w readings are taken by different instruments.

A specific study of small-scale variation and errors allowed an analysis of the cause of variation for the different variables. The error in the estimation method was shown to be small for the TDR measured variables (θ and σ_a) and slightly higher than σ_w measured by the Sigma probe. The observed nugget effect was thus mainly due to small-scale variation. The σ_a displayed an order of magnitude larger small-scale variation as compared to θ with the same observation volume. The Sigma probe measured σ_w was about 20 times higher compared to θ, the probable cause for this is the much smaller sampling volume of the Sigma probe.

No apparent effects of the constructed soil ridges on surface soil water and salinity could be found in the studied area. However, it might be wise to perform a similar study in other areas with more saline soil.

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