Electrical characteristics of soils as affected by hydromorphic salinization (case study of the Upper Volga region)

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Abstract. The relationships between the electrical resistivity and the properties of hydromorphic saline soils forming in a humid climate were established. The salinity factor turned out to be the most significant for the value of electrical resistivity compared to soil texture and organic matter content.

1. Introduction
The electrical resistivity (ER) or electrical conductivity (EC) is used in soil science primarily to identify heterogeneities of soil properties. Geospatial resistivity survey is applied to diagnose the spatial variability of soil properties correlated to electrical parameters. Soil electrical properties are influenced by a complex interaction of edaphic properties including salinity, saturation, water content, bulk density, organic matter, cation exchange capacity, clay percentage and mineralogy, and temperature [1-3].

In salt-affected soils of arid and semi-arid regions salinity is one of the main factors that influence the spatial variability of soil ER. Salinity can be measured directly through geospatial on-site measurements of soil electrical resistivity. In humid climate conditions studies conducted so far [4] indicate that soil ER is influenced by a large set of the above mentioned physicochemical parameters. Spatial heterogeneities of these soil properties are successfully diagnosed using non-destructive mapping technique of vertical electrical sounding and horizontal electrical profiling. The surveys, depending on the areas heterogeneities can be performed at different scales resolution from the centimetric scale to the regional scale. The stronger the variability of soil property, the easier is its electrical detection [4, 5]. Furthermore, similar ER values may be caused by different soil properties [1]. Thus, one of the major problems associated with this diagnostic approach is to allocate ER variability to the one from a number of essential factors if these factors are not of sharp contrast. In that case, experimental ER data provides uncertainty of the estimate. An understanding of the factors that determine ER variability is particularly a complex problem. At a higher level of resolution, such as a soil pit, the gradations of the factor that can be fixed may be less contrasting, and the corresponding variation of the studied trait is more noticeable in the electrical profile of the soil.

The main idea of the underlying studies is to reveal the dependence of ER on basic properties of hydromorphic soils under variable salinity, texture and organic matter.

2. Materials and methods
2.1. Study area
The samples were collected from 17 soil pits at The Upper Volga region in the central part of the Russian plain. The study area is located between 58°36’N, 38°42’E and 57°07’N, 39°42’E (figure 1).

The climate is temperate with the average annual rainfall between 500 and 600 mm throughout the area. Average annual temperature is 3.4 °C. The parent materials for the studied soils are lake-glacial and alluvial sediments. Soils investigated in this study have high water tables of about 0.3–1.0 m. The peculiarity of groundwater within the sampled areas is the high mineralization from 1 to 14 g/L. Shallow saline ground water causes forming saline soil spots. It should be noted that soils in the region are of typical low groundwater salinity. Thus, soils of the saline spots are rather scarce and unique compared to the surrounding zonal and intrazonal soils expanding under humid climate conditions [6, 7 and references therein].

2.2. Sampling and analyses
Field studies were designed to characterize ER and basic soil properties, which could potentially affect ER. At each of the 17 soil sampling locations within the 3 study sites, ER were measured on-site on soils of undisturbed compaction. ER serves as a surrogate to characterize the spatial variation of those soil properties that are found to influence ER within a field [2]. The survey was carried out at comparable soil water content and temperature. The ER values were measured by means of a portable LandMapper device (LandViser, LLC) with a 4-electrode array (in-field ER). Measurements were conducted in 6 points within each horizontal 5 cm layer from surface to a depth of the groundwater table. The in-field ER data obtained were further averaged on the thickness of the soil horizon.

A total of 86 samples were analysed in the laboratory. The soil sample was saturated with distilled water and put into a conductivity cell. Measuring ER in a water-saturated soil paste (ERp), allows you to abstract from the influence of soil moisture content since the electrical resistivity is almost independent of the water content in the gravitational water range [8 and references therein]. The ERp were measured by LandMapper (LandViser, USA). To estimate salinity using ground-truth data the soil samples were analysed for soluble cations and anions in the 1:5 soil-water extracts. To analyse soluble Na, K, Ca and Mg in soil extracts inductively coupled plasma-atomic emission spectroscopy (ICP-AES) was used. Chloride in soil extracts was analysed using potentiometric titration with AgNO₃. Sulphate ion was determined after precipitation via 10% BaCl₂. Carbonate and bicarbonate ions were determined by titrimetric method. Total salt content was determined by summarizing soluble
cations and anions. Soil particle size fractions were evaluated by the pipette method after dispersion in sodium pyrophosphate. Organic matter was measured by dry oxidation on a LECO CHN628 device.

To find out the relationship between ER and basic soil parameters, methods of statistics were subsequently undertaken. Variance of a set of values expressed in percent was eliminated after the Fisher's transformation, which converts the sampling distribution of the Pearson correlation into a normal distribution.

3. Results and discussion
According to the IUSS WRB [9], the studied soils can be classified as Fluvisols, Gleysols and Umbrisols, Solonchaks. The soils have high water tables and the presence of gleying features, at least in the lower part of the profile. The results for the soils used in this study are presented in table 1.

| Statistical parameter | In-field ER (Ohm·m) | ERp (Ohm·m) | Sand (2–0.063mm) (%) | Silt (0.063–0.002 mm) (%) | Clay (<0.002 mm) (%) | Organic matter (%)<sup>a</sup> | Salt content (%) |
|-----------------------|---------------------|-------------|----------------------|--------------------------|---------------------|-----------------------------|-----------------|
| Maximum               | 71.6                | 47.1        | 89                   | 74                       | 40                  | 19.9                       | 2.93            |
| Minimum               | 0.8                 | 0.4         | 2                    | 9                        | 2                   | 1.1                        | 0.02            |
| Mean                  | 16.3                | 15.3        | 39                   | 46                       | 15                  | 5.1                        | 0.47            |
| Median                | 10.9                | 10.1        | 35                   | 53                       | 15                  | 3.6                        | 0.19            |
| DV                    | 7.9                 | 8.0         | 23.4                 | 18.1                     | 7.7                 | 5.5                        | 0.1             |
| CV, %                 | 72.9                | 79.6        | 60.6                 | 39.0                     | 50.8                | 46.0                       | 75.3            |

<sup>a</sup> Only for organic horizons (N=54).

The soils in the study sites are generally loamy to sandy. Only rarely do clay soils present. The average clay content is 15% (table 1). The textural vertical differentiation in the soil profiles is mainly due to lithological heterogeneity. The considered soils also differ significantly in the amount of soluble salts (0.02–2.93%), with the mean of 0.47% and a median of 0.19%. According to the salt concentration, slightly and moderately saline soils are mainly distributed, however there are also non-saline soils and extremely saline soils.

The statistical characteristic of the data sample showed that the in-field ER varies widely from 0.8 to 71.6 Ohm·m and the ERp varies from 0.4 to 47.1 Ohm·m. The average in-field ER and ERp were of 16.3 and 15.3 Ohm·m, respectively, with the similar median of about 10 Ohm·m (table 1). In 59 of the 86 samples studied, the ER values measured in the cell do not exceed 20 Ohm·m. In these samples, the salt content is more than 0.15%. The highest values of resistivity (more than 20 Ohm·m) are mainly typical for the soils with salt content less than 0.1%. Drastically decreasing ERp and in-field ER occurs responding to increasing salt content. In the saline soils with salt content greater than 0.5%, the ERp and the in-field ER do not exceed 10 Ohm·m. It can be seen that the data both on the ER and on the salt content show the similar variation. The coefficients of variation are greater than 70%. However, there also were non-saline soils with the low ER. Therefore, it can be concluded that, in these cases, the ER was not associated with soil salinity and should be explained by the other reasons. For example, loamy and clayey soils and sediments, where ground waters are close to the surface, may have ER of 30–50 Ohm·m [1].

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The studied soils are rich in organic matter associated with hydromorphic processes, which are thought to be a factor limiting organic matter mineralization. When saline soils develop under arid conditions, they are typically very low in organic matter, but, when they form under humid conditions, the top layers are relatively high in organic matter [10]. In soils containing larger amounts of organic matter, wettability and water flow are expected to affect the in-field ER and ERp relationship [11].

To identify the basic properties of the soil, which in our case study determine electrical parameters, correlations were calculated (table 2).

| Criterion   | In-field ER | Sand  | Silt  | Clay  | Organic matter | Salt content |
|-------------|-------------|-------|-------|-------|----------------|--------------|
| In-field ER | 1           | 0.022 | -0.021 | -0.018 | -0.333<sup>b</sup> | -0.501<sup>a</sup> |
| ERp         | 0.754<sup>a</sup> | -0.029 | -0.018 | 0.124 | -0.373         | -0.571<sup>a</sup> |

<sup>a</sup> Correlation is significant at the 0.01 level (2-tailed, N = 86).

<sup>b</sup> Correlation is significant at the 0.05 level (2-tailed, N = 54).

The correlation coefficients indicate a complex relationship between the magnitude of the resistivity and the physicochemical parameters of the soil. On poorly drained elements of the relief of the humid zone, the moisture content in hydromorphic soils at the beginning of summer is in the range of a weak influence on the resistivity value. Therefore, the high correlation (R = 0.75) was observed between the in-field ER, measured in the soil horizons of the undisturbed profiles, and the ERp, measured in a water-saturated soil paste. However, trying to relate laboratory tests on remoulded soils to their in-situ resistivity cannot be based solely on moisture content, since, in the field, soil samples may have identical moisture contents but different degrees of compaction [12]. Besides the effect of soil compaction violation the difference in both mean and extreme values of the ERp and the in-field ER (table 1) may be explained by the heterogeneity of the soil within a horizon. Also, it has been reported [11], that in water-saturated soils the geometry and topology of the aqueous phase contribute to the soil electrical conductivity, and the major factors affecting the relationship between the in-field EC and the EC of a soil solution are porosity, particle shape, particle-size distribution, tortuosity of porous and granular media.

When identifying the basic soil properties, which determine the ER, it was revealed that there was no significant correlation between the soil texture and the electrical parameters. Significant but weak correlation was established with organic matter content. These results suggest that salinity plays a major role in forming electrical properties even though soils under humid climate conditions. However, it should not be excluded the influence of organic matter and soil texture on electrical properties of slightly saline soils.

4. Conclusion
For the hydromorphic soils with varying degrees of salinity forming under humid climate conditions, a higher significant correlation was established between ER and salt content. There is no significant correlation between soil texture and electrical parameters. A significant but weak correlation with organic matter content was revealed.

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