UrbanWater

Urban Water 3 (2001) 205-216

www.elsevier.com/locate/urbwat

Case study

Application of geophysical methods to evaluate hydrology and soil properties in urban areas

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Received 10 March 2000; received in revised form 21 March 2001; accepted 18 June 2001

Abstract

Municipal activities continuously change soil properties and hydrology yet direct destructive sampling to monitor these changes is troublesome in urban areas. Electrical geophysical methods provide the means to investigate hydrological conditions and subsurface properties without soil disturbance. Methods of self-potential, electrical profiling, vertical electrical sounding, and non-contacting electromagnetic profiling were applied to urban soils in Astrakhan', Russia, and Kiev, Ukraine. Depth to the groundwater table, salinity of soils and groundwater, and soil profile organization were estimated with the methods. The methods ensure quick yet non-destructive estimation of soil and hydrological conditions in cities assisting with successful restoration and preservation of municipal constructions. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Electrical and electromagnetic surveys; Geophysics; Groundwater table; Soil physical properties; Urban soil hydrology

1. Introduction

Urban soils are highly disturbed, consist of mixed genetic horizons and non-soil materials, and have hydrological properties different from those of natural soils (Craul, 1990). Construction activities in modern cities change soil, geological, and hydrological conditions and often cause dramatic changes in groundwater level (Cox & Hillier, 1994; Lerner, 1996). Rising groundwater destroys buildings and causes landslides (Lerner, 1996); therefore, timely soil and hydrological information is essential to prevent destruction. Important information includes stratification of water-bearing and impermeable horizons, location of water recharge and discharge areas, and estimation of groundwater levels. Obtaining the hydrological information with conventional methods, such as drilling and excavation, is destructive and, therefore, difficult and prohibitive in most urban areas. Rapid and non-destructive methods for the investigation of soils and hydrological conditions are highly desirable in modern cities.

Conventional geophysics offers remote and non-destructive methods for evaluation of the deep subsurface. Electrical geophysical methods are extensively used for oil, gas, and coal exploration. Methods, such as four-electrode electrical profiling (EP), vertical electrical sounding (VES), ground-penetrating radar (GPR), and electromagnetic induction (EM) methods became increasingly popular in soil and environmental studies. The EP and EM methods were used for evaluating soil salinity (Rhoades, 1979; Rhoades, Shouse, Alves, Manteghi, & Lesch, 1990), assessing quality of forest soils (McBride, Gordon, & Shrive, 1990). and mapping aquifers located at large depths (Dodds & Ivic, 1990). GPR was utilized for mapping preferential water flow paths and perched water locations (Arcone, Lawson, Delaney, Strasser, & Strasser, 1998). Self-potential (SP) method was used to measure electro-filtration potentials to locate water leakage on the submerged slopes of earth dams and groundwater seepages (Corwin, 1990). The VES method was used to investigate stratification of soils and sediments and to estimate their hydraulic conductivity (Mazac, Cislerova, Kelly, Landa, & Venhodova, 1990) and texture (Banton, Seguin, & Cimon,

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PII: S1462-0758(01)00042-5

1997). Barker (1990) utilized VES to outline a landfill with a 40 m fill.

The electrical geophysical methods, which permit evaluation of various soil properties, are promising for application in urban areas. However, the arrays used in previous studies were preferentially adapted to evaluate deep (>50 m) geological profiles with thick (> 1 m) layers, which usually have uniform resistivity within a strata and high differences in electrical resistivity (ER) between adjacent strata. Researchers have also reported some failures of the methods used to investigate shallow subsurface and to evaluate very thin (3-30 cm) soil horizons, which generally have lower contrast in ER than geological strata (Pellerin & Allumbaugh, 1997). In addition, most conventional geophysical methods are labor-intensive, time-consuming, and difficult to operate. Therefore, geophysical methods should be carefully chosen, designed, and adapted for shallow environmental application in urban areas.

In this study, we utilize the geophysical methods of VES, EP, SP, and non-contact electromagnetic profiling (NEP) to evaluate properties of urban soils. The objectives of the study are to modify the conventional geophysical equipment for shallow subsurface investigation, to test the suitability of the methods for measuring soil properties and groundwater fluctuation, and to find advantages and limitations of the proposed methods.

2. Methods

The VES, EP, and SP methods evaluate parameters of the stationary electrical fields. The VES and EP measure ER of soil layers at any depth when a constant electrical field is artificially created on the surface. The SP method measures the naturally existing stationary electrical potentials on the soil surface. All the methods of stationary electrical fields require electrodes to be planted in the soil surface and, therefore, can be only used in urban areas within lawns, orchards, parks, etc. The NEP method, on the other hand, does not require a physical contact with the soil surface and can be used to measure parameters of non-stationary electromagnetic field in soils covered with firm pavement.

2.1. VES and EP methods

The VES and EP methods used in this study are based on four-electrode array, where four electrodes A, B, M, and *N* are set in a row in *AMNB* sequence. The electrical current (I) is applied to outer *A* and *B* electrodes and the potential (dU) is measured between inner M and N electrodes. The bulk soil ER is then calculated as the potential over current times a geometric coefficient, which can be obtained for arrays of different electrode configuration with existing formulas (Keller & Frischknecht, 1966; Barker, 1989). The array for VES consists of a series of electrodes *AMNB* with the gradually increasing distances among the electrodes (Banton et al., 1997) to increase the depth of sounding.

We developed an electrode array for the VES method, as a combination of Schlumberger and Wenner (Parasnis, 1997) arrays to obtain detailed characteristics of relatively shallow subsurface. Our array utilizes smaller distances among the electrodes than those usually applied in conventional geophysics (Table 1). Since soils generally have higher horizontal anisotropy in ER of the layers than have geological strata we provided from 2 to 4 replications with different [MN] distances for a [AB] distance (Table 1). These replications were then averaged to yield a single VES profile corresponded to the center of the array, for one sounding location. With a center-symmetric array (i.e. *AM* = *NB* and *AN* = *MB),* which we apply, the measured with VES apparent (bulk)

Table 1
Electrode spacing and calculated geometric factor (K) of the electrode array used for soil VES in the study

A B/2 (cm)	MN/2 (cm)	K
10	5	0.24
15	5	0.64
22	5	1.21
30	5	2.75
45	5	6.28
60	5	11.23
15	10	0.20
22	10	0.64
30	10	1.26
45	10	3.02
60	10	5.50
90	10	12.60
120	10	22.46
180	10	50.74
60	30	1.41
90	30	3.80
120	30	7.10
180	30	16.78
240	30	30.00
360	30	67.39
120	60	2.32
180	60	7.53
240	60	12.56
360	60	33.90
480	60	59.30
180	90	4.20
240	90	8.63
360	90	2 1.20
480	90	38.80
720	90	89.80
480	240	11.30
720	240	30.00
1000	360	25.17
1500	360	66.05

ER is usually represented as a function of the half of the distance between the current electrodes, i.e. ER = f(AB/2) (Beck, 198 1). Thus, from the Table 1, values for similar AB/2, but different *MN/2* are averaged to give values of ER = *f(AB/2)* function at *AB/2* equal 10, 15, 22, 30, 45, 60, 90, 120, 180, 240, 360, 480, 720, 1000, and 1500 cm. This technique helped reduce noise in soil VES, which are inevitably very noisy (e.g. Fig. 3) since they are measured at small distances between electrodes close to the surface that is dry and has high horizontal anisotropy. To obtain more reliable data for 1-D profile distribution of ER in soils VES data can be further smoothed prior to interpretation.

Since the experimental ER = *f(AB/2)* function lucks continuity, no analytical expression exists for the function; therefore, the data were analyzed with the numeric analyses for the extremes of first- and second-order. Due to measurement error and high anisotropy of soil properties, the results from raw data usually show first-order extremes almost at every *AB/2*. To obtain the function reflecting more general change in vertical resistivity distribution the data were smoothed by moving average technique. Usually one or two level smoothing was enough to obtain representative VES curve for most soils. Further smoothing is not relevant, since it considerably changes experimental data, especially first surface value, and leads to unreliable interpretation. To reduce changes in a data we suggest fixing the values at first and last *AB/2,* as well as extreme values in original experimental data, but smooth the values at other *AB/2*.

The smoothed data were then interpreted to derive thicknesses of the layers and their ER from a VES profile. The interpretation is based on the solution of Laplace equation as found by Stefanesku and Schlumberger (1930) for a media composed of horizontal isotropic or anisotropic layers. The solution exists through introduction of a special kernel function (Koefoed, 1979; Pekeris, 1940), which relates electrical potential on the surface of the media with composition of the media, and Bessel function (Zdanov & Keller, 1994). We adapted simple computer algorithm for the interpretation of soil VES, which consist of three steps. First, data are smoothed and normalized (recalculated) to equal interval in AB/2. Second, kernel function is calculated from the data using Hankel transformation and Bessel function (Zdanov & Keller, 1994). Finally, the kernel function is interpreted to derive layers' resistivities and thicknesses using Pekeris recursive method (Dimri, 1992; Pekeris, 1940). A solution for VES using kernel function is an ill-posted mathematical problem and an error in the measured ER for the first (surface) layer highly changes the results of the interpretation. Since an error in experimental data measured on very small distances among electrodes is inevitable, our algorithm for soil VES interpretation has embedded check-up of the measured resistivity of first layer based on asymptotic properties of the kernel function and consequent correction of the apparent resistivity for the surface layer if the correction is necessary. The algorithm is developed in dialog form, which allows an operator interactively participate in interpretation process. As an end result of the interpretation the layers' thicknesses and resistivities are reported together with the errors of interpretation to help operator select the best possible interpretation results through trial-and-error process. This algorithm for computer interpretation of VES allowed division of extremely noisy near-surface VES profiles into separate layers with an error of 2-100% or 1-6 cm compared with the depths of soil horizons measured in open pits. Noteworthy, a number of computer algorithms have been developed for deep geophysical sounding (e.g. Rijo, Pelton, Feitosa, & Ward, 1977; Ward, 1990) and were evaluated by us for application to soil VES profiles, but they were not robust enough for extremely noisy soil VES data.

An automatic commutator for 34 four-electrode combinations was designed and made by the authors specifically for shallow soil studies. The VES equipment built by us utilizes reduced size and weight of electrodes, decreased input voltage required for sounding, and different interchangeable arrays for a single commutator box. The electrodes are conveniently mounted on the arrays with pre-set distances among electrodes. Such features considerably reduced weight of the VES equipment, prolonged life of the batteries, and allowed easy transporting and installing the equipment by one operator. Thus, time required to set up an array and measure a detailed VES profile at one location was reduced to lo-15 min. This equipment is convenient for research in urban areas since it provides detailed information about the topsoil layer yet does not require much surface space to plant electrodes.

The EP, also called a four-electrode probe, is a simplified version of the VES with one or two arrangements of AMNB electrodes (Rhoades, 1979). After a pre-estimation of the depths of different horizons in soils within a study area using the VES method, the most informative combinations of AMNB electrodes can be chosen. The subsequent EP measurements with the selected AMN B combinations allow developing a large-scale map of the bulk soil ER within an area.

2.2. SP method

The method of self-potential is used to investigate streaming (infiltration) and diffusion-adsorption potentials of the natural stationary electrical fields, which develop when water flows through porous media. The SP method evaluates directions and intensities of shallow (within 8 m) water flow (Corwin, 1990). Since the SP method is a passive potential field technique, the array parameters cannot be changed for various depths of investigation as in the VES method. Therefore, the SP method provides only near-surface information, which often reflect the subsurface water flow and other hydrological properties.

The SP method utilizes two electrodes (trailing and leading), a voltmeter, and connecting wire. We used a combination of fixed-base (or total field) and gradient (or leapfrog) measurement procedures. The combined procedure reduces errors associated with varied electrode polarization at different locations in the gradient method and minimizes length of wires necessary for the fixed-base method (Corwin, 1990). The procedure is described as follows. The trailing electrode is first installed in a place with the relatively high potential, for example, in a wet clay layer or in an illuvial (B) horizon of a soil profile. The leading electrode is placed on the soil surface at any desirable location. The potential differences between the leading and trailing electrodes are measured in nearby locations by moving of the leading electrode. Then the trailing electrode is re-installed in one of the previous locations of the leading electrode and the potential differences are measured around the new location of the trailing electrode. The procedure is repeated until the electrical potential is measured in all desirable locations with sufficient replication. All the potential differences are recalculated as if they were measured with the only moving leading electrode and the trailing electrode fixed at the first location, i.e. standardized by potential at the first location of the trailing electrode.

The usage of non-polarizing electrodes is mandatory in the SP method (Corwin, 1990). The non-polarizing electrode consists of a metal element immersed in a solution of salt of the same metal with a porous membrane between the solution and the soil. Because such electrodes easily break we adopted firm non-polarizing electrodes (carbon cores from exhausted electrical cells) (Pozdnyakov, Pozdnyakova, & Pozdnyakova, 1996). The electrodes were calibrated against standard electrodes used by Corwin (1990).

The data obtained with the SP method are contoured to produce iso-potential maps of the measured areas. The maps are interpreted qualitatively using correlation between the observed contour pattern and information about seepage areas, flow paths, and other sources or quantitatively implying geometric source and analytical models (Corwin, 1990: Sundararajan, Srinivasa Rao, & Sunitha, 1998). In this study we used qualitative interpretation based on principles described by Corwin (1990). Negative potential anomalies indicate the locations of intensive infiltration. Increases in the electrical potential along the groundwater flow and seepage areas are characterized by the positive potentials. In urban areas considerable electrical potential anomalies might also arise around buried corroded metal constructions or electrical wires. These anomalies have a distinct point or line signature and often their effect can be calculated and removed from the total measured electrical potential if the research is focused on estimation of hydrological anomalies (Corwin, 1990).

2.3. NEP method

The principle of the NEP is analogous to the EM techniques (Corwin & Rhoades, 1984). Variety of EM equipment is commercially available (Borchers, Uram, & Hendrickx, 1997; Cook & Walker, 1992). In those methods an alternating current from 0.11 to 56.3 kHz passes through a coil, generating an electromagnetic field, which in turn induces current flow in the soil. This current generates a secondary magnetic field that is sensed by a second coil. The strength of the secondary magnetic field varies in a linear fashion with the soil electrical conductivity or resistivity. Transmitting and receiving coils for some equipment models are mounted on the plastic rod and can be carried by one person. In other models separate coils are carried by two operators. Inter-coil spacing varies from 1 to 400 m (depending on model) with coils arranged coplanar (Cook & Walker, 1992; Jong, Ballantyne, Cameron, & Read, 1979). The EM sensors are advantageous over DC ER surveys since they do not depend on a sensor-soil contact. Therefore, (i) measurements can be taken almost as fast as one can move from one measurement location to another, (ii) the large volume of soil that is measured reduces the variability so that relatively few measurements yield a reliable estimate of soil resistivity, and (iii) measurements in relatively dry, stony, or covered soils are possible. Disadvantages of the methods include: (i) continuous measurements in most models are impossible, (ii) most systems cannot utilize variable inter-coil spacing and/or frequencies, (iii) it is difficult to evaluate effective sampling volume for different models.

The advantages of the NEP technique are that it automatically records continuous profiles of ER and allows easy changing inter-coil spacing to survey different soil depths (Pozdnyakova, Pozdnyakov, & Karpachevsky, 1996). NEP utilizes much larger electromagnetic coils (Fig. l(a)). A generator constantly excites electromagnetic field through the two radiating antennas, which compose transmitting coil (Fig. 1 (b)). These two radiating antennas are fixed with 2 m distance between them. Antennas are made with multiply (>lOO) segments of isolated electrical cable in the form of a “broom” (Fig. 1 (a)). Such construction ensures good contact with the ground essential for formation of electromagnetic field with the stable parameters in soil. Receiving coil is formed by a receiving antenna and an operator, who walks along the measured profile and carries all the NEP equipment. Parameters of a secondary electrical field created in the soil are received by

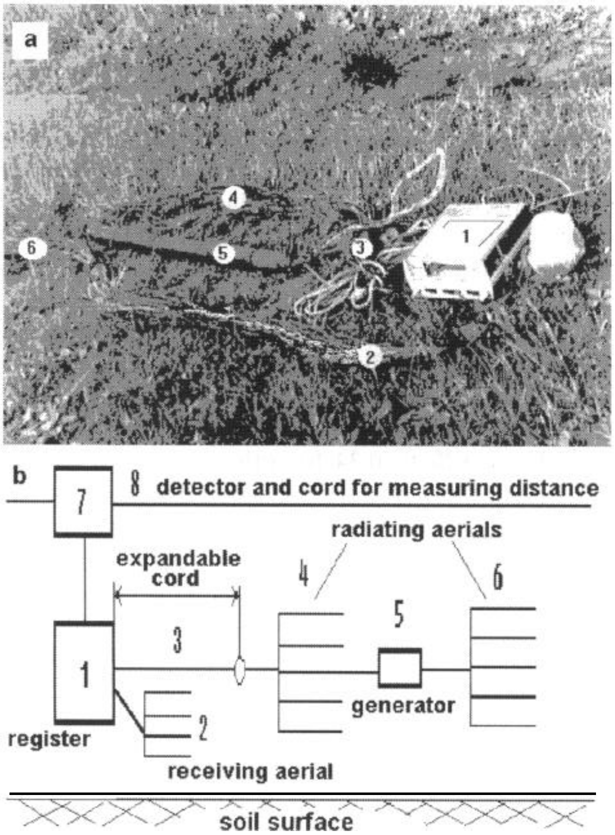

Fig. 1. Photo (a) and scheme (b) of the NEP: (I) receiver-register block, (2) receiving aerial, (3) cord, (4 and 6) radiating aerials, (5) generator of electromagnetic waves of 12.5-14.5 kHz frequency, (7) detector for measuring the distance, and (8) cord for measuring the distance.

the receiving coil and automatically recorded in a graphical form of continuous ER profile in the receiver-register block. The NEP equipment operates on user-defined frequencies of the primarily electromagnetic field within the range from 12.5 to 14.5 kHz. The depth of the electromagnetic profiling can be easily changed by changing the distance between radiating and receiving antennas. The minimal depth of 0.4 m can be investigated at a 5 m spacing between radiating and receiving antennas. Maximum depth of NEP survey is 20 m. NEP profiling can be conducted in synchronous and non-synchronous regimes. Synchronization of the resistivity profiles is provided automatically when the detector for measuring distance is turned on (Fig. l(b)). Non-synchronous regime provides more flexibility and allows operator to adjust measurement density in specific parts of profile by varying walking speed. Operator also visually investigates recorded ER profiles during the measurements and can mark recognition pickets right on the drafted electrical profiles. The NEP can be implemented directly through a firm pavement (asphalt, concrete, etc.) anywhere in urban areas.

The methods described above have different advantages and limitations. Therefore, no single method could be a priori recommended for the investigation of urban soils. Three methods of the stationary and one method of the non-stationary electrical fields were tested in urban areas to evaluate physical and hydrological properties of the soils.

3. Case studies

3.1. Volga delta and Astrakhan' city, Russia

The groundwater table rises steadily in the Volga delta at the rate of 0.5 m/yr because of irrigation and rising level of the Caspian Sea. The highly saline groundwater enhances secondary salinity in the area. More than 1080 km^2 of arable lands were abandoned in 1991, attributable to the high groundwater table; the abandoned territory has been increasing by 30 km^2 each year until 1999.

Not only the farming lands but also the urban areas in the Volga delta suffer from the destructive activity of rising saline groundwater. The groundwater caused visible destruction of more than 20% of the buildings in Astrakhan' city as for 1996. The natural hazardous groundwater conditions in Volga delta were further aggravated in the urban areas by uncontrolled leakage from the canals and domestic water supplies. One hundred and eighty stationary monitoring wells were set up in Astrakhan' city in 1994 to measure groundwater fluctuations. Nevertheless, the number of wells was not enough to provide detailed information about groundwater table for the entire city, especially when groundwater rising was influenced simultaneously by many factors and, therefore, unpredictable. The methods of VES and NEP were tested in 1995 for detail outlining of the groundwater table within a representative part of Astrakhan' city (Fig. 2). The study area was located in the centre of Astrakhan' with a large change of elevation, which induced a high variation of groundwater table within the area.

The measurements in Astrakhan' city were compared with analogous measurements in surrounding agricultural areas. The NEP method was used to outline the areas with hazardous rising saline groundwater during irrigation practices. The VES was applied to estimate depth and thickness of the layers with different salinity in profiles of alluvial soils (Salic Fluvisols, FAO-UNESCO; Fluvaquents and Aquic Torrifluvents, USA Soil Taxonomy) of the delta. The geophysical methods were tested against conventional analyses of soil samples. Samples were collected with an auger from different soil depths and analyzed in the laboratory for total soil salinity, pH, and compositions of CO_2^{-2}, SO_4^{-2}, NO_3^-, Ca^{+2}, Mg^{+2}, Na^+, and K^+ ions. The groundwater table was recorded from the stationary monitoring wells installed prior to the geophysical surveys.

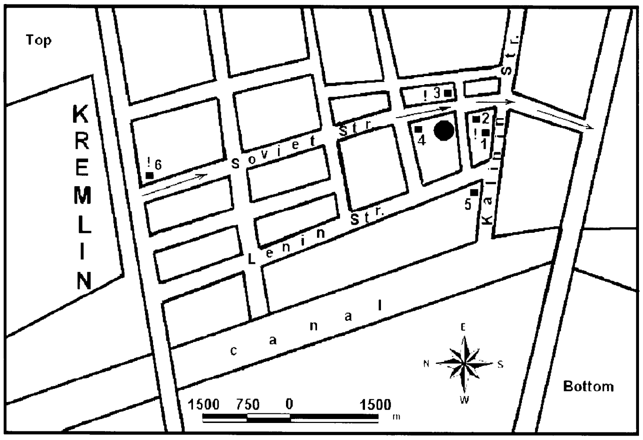

Fig. 2. Scheme of the investigated area in Astrakhan', Russia: the numbers show VES locations; (!) marks stationary monitoring wells, arrows indicate the NEP routes, and black circle represents Dramatic Theatre with active drainage. Height difference between top and bottom of the hill is about 12 m.

Profiles of alluvial soils in delta Volga consist of thin layers of silt, clay, and sand. The VES array constructed by us was not sensitive enough to distinguish thin (<3 cm) soil layers of different texture in a soil profile. Only water and salt content distributions within the soil profile caused considerable differentiation of the ER in the soils the Volga delta. Since evaporation in the delta is five times higher than precipitation, the water content and salt distributions within soil profiles are determined solely by saline groundwater. The soil profile can be generally divided into the top unsaturated layer with high resistivity and the bottom layer saturated by saline groundwater with low resistivity.

Considering the high distinction in ER between unsaturated and saturated zones, the VES method was applied for detection of groundwater table. The approximate location of the groundwater table can be estimated during the VES measurements directly in the field by observing the VES curve, finding the first *AB/2* with the low resistivity (3-20 Ω m), and multiplying it with an empirical coefficient (Fig. 3). This coefficient was about 0.32 for the investigated soils as was derived from the parallel observations in the monitoring wells and varied from 0.28 to 0.34 for other soil types (Barker, 1989; Pozdnyakov et al., 1996). Observation of the VES curve and approximation of the groundwater table during real-time field measurements is a valuable feature allowing change locations of future VES based on the results from the previous ones. To determine the transition between top layer with high resistivity and bottom layer with low resistivity (i.e. groundwater table) more accurately VES data were post-processed in the laboratory by with interpretation algorithm described in Methods section. Compared with the groundwater tables measured in wells, the relative errors of the VES estimation were from 0 to 14.5%, with an average of 7.25% (Table 2). The VES measurements indicated that the depth of groundwater table decreased downhill for

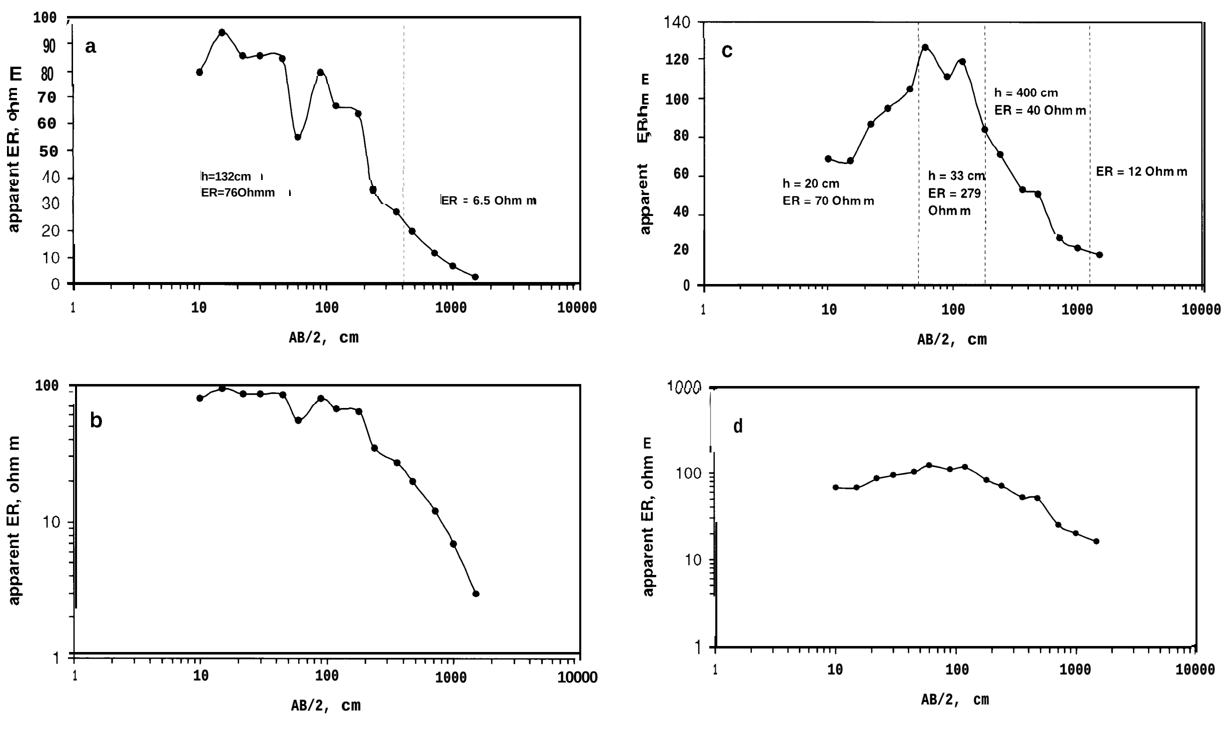

Fig. 3. Sample profiles of soil ER measured by VES in Astrakhan', Russia. VES at location 3 (a and b) and location 6 (c and d). Thickness (h) and resistivity (ER) shown for the layers are derived through computer interpretation.

Table 2
Estimation of groundwater table with the VES in Astrakhan city and surrounding farmlands

Location	Groundwater table		Relative estimation error (%)
	Real (well) (cm)	Estimated (VES) (cm)	
1. Astrakhan'	59	51	13.5
3, Astrakhan	132	132	0
6. Astrakhan'	482	453	6
1. farmland	219	237	8.2
2. farmland	115	129	12.2
3, farmland	247	255	3.3
4. farmland	238	225	0.5
5, farmland	160	153	4.4
6, farmland	117	134	14.5
8, farmland	138	124	10
Mean			7.25

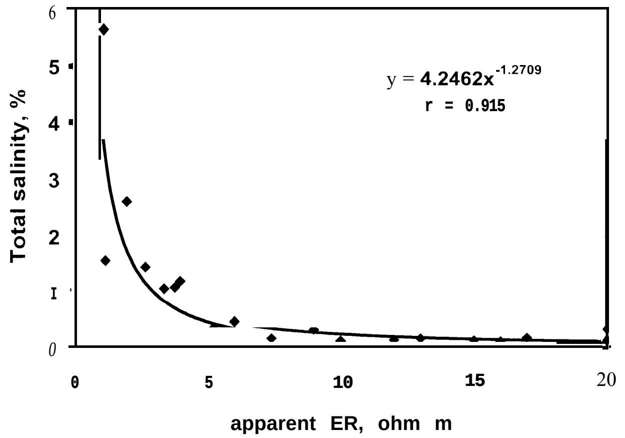

Fig. 4. The relationship between the ER measured in situ by VES method and the total salt content in soils of Volga delta, Russia (include soils from Astrakhan' City and surrounding farmland).

the investigated area in Astrakhan' city (Figs. 2 and 3). The groundwater level detected by VES was 0.51, 0.84, 1.32, and 4.53 m for the locations 1, 4, 3, and 6, respectively (Table 2, Fig. 2).

The differentiation of salinity in the unsaturated zone of the soil profiles was revealed by small fluctuations in measured ER in upper part of the VES profiles (Figs. 3(a) and (c)). We thoroughly interpreted the VES results to estimate the layers with different resistivities for 12 soil profiles from the agricultural irrigated fields surrounding the city. The total salt content was measured in soil samples collected from the layers of soil profiles as shown in Table 3 (columns 1 and 2) for an example profile. The interpretation of apparent VES data outlined three layers with different resistivities for the same soil profile (Table 3, columns 3 and 4). In the column 5 weighted averages for the outlined soil layers were recalculated from the total salt contents in Table 3 (column 2). Data of recalculated total soil salinity and VES ER were combined from the layers of all 12 soil profiles to obtain a relationship between ER and total salt content (Fig. 4). The correlation coefficient (r) was calculated for the linearized power relationship as 0.915. Data for the soil layers with resistivity higher than 20 Ω m were excluded from the correlation analyses because they mainly corresponded to non-saline and very low saline soils with the total salt content <0.3%. For quick delineation and estimation of salinity in a soil profile from the VES data we can consider that a resistivity of 10–20 Ω m corresponds to a total salt content between 0.3% and 0.5% (low and medium saline soil) and a resistivity <3 Ω m indicate that the total salt content in soil is > 1% (high saline soil).

Table 3
Example of evaluating salinity in soil layers with the vertical electrical sounding (VES)

Depth (m)	Total salinity (%)	Results of interpretation		Recalculated salinity for interpretation layers (%)
		Layer depth (m)	ER (Ω m)	
0-0.02	0.092	0–0.17	98	0.074
0.02-0.05	0.087			
0.05~0.20	0.068	0.17-0.74	15	0.095
0.20-0.40	0.07			
0.40-0.70	0.112			
0.70–1	0.117	0.74–2.55	12	0.117

Although the determination of the groundwater table and evaluation of soil salinity by the VES method is much faster than by conventional drilling methods, it still requires considerable time to cover a large area. In practice, to outline the area where the groundwater table or salinity is higher than safe levels, sometimes, is more important than to determine the exact groundwater tables at individual locations. The NEP method can be used to outline areas where groundwater table is higher than a threshold level. The threshold value is determined by the distance between the radiating (6) and receiving (2) coils (Fig. 1(b)). The 9 m inter-coil distance is set to measure the ER within the top 1 m layer, while the 16 m distance can be used to evaluate 2.2 m laver.

NEP helped to outline the areas with different groundwater tables created within one field by rising of water level due to irrigation. Fig. 5(a) shows an area where saline groundwater has risen. The groundwater table was higher than 1 m on the part 1 of the field and higher than 2.2 m overall the field as confirmed by NEP in Fig. 5(b). The groundwater was at 0.58 m in the part 1 of the field as measured with VES and in the well at location 10 (Fig. 5). The overall salinity of the soil within the field can also be characterized by the NEP profiles. The ER of high saline soils of rural areas around Astrakhan' city measured with NEP was about

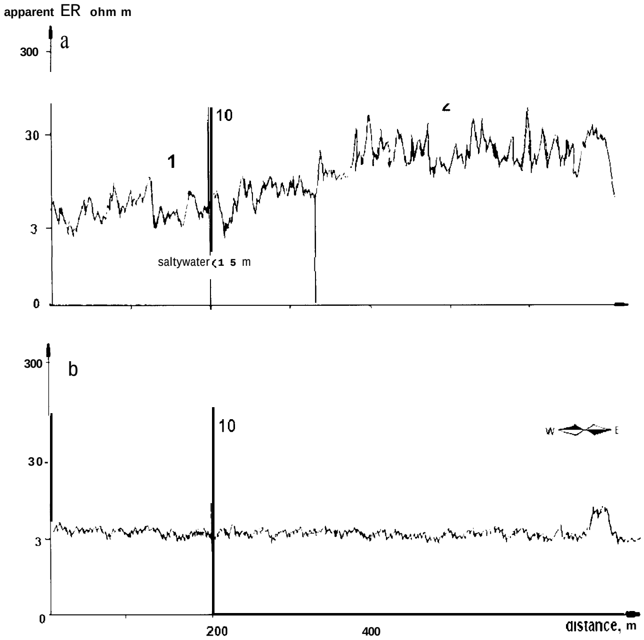

Fig. 5. NEP of low-saline Aquic Torrifluvent on the field with VES 10, Tabola area, indicating the change in ER with rising groundwater: (a) distance between antennas 9 m (profiling depth about 1.2 m) and (b) distance between antennas 16 m (profiling depth about 2.2 m).

1 Ω m. The ER of medium and low saline soils was about 3 Ω m in wet conditions and almost 30 Ω m in dry conditions. Non saline soils have ER measured with NEP more than 30 Ω m regardless of water content.

The principles of estimating groundwater table and soil salinity developed in agricultural and rural areas in the Volga delta were applied to characterize NEP profiles measured in Astrakhan' city. A general decrease of the resistivity downhill was revealed by the NEP at Soviet Street (Fig. 6). Profile A indicated that the saline groundwater has risen higher than 1 m to the surface at the bottom of the hill (Fig. 6). whereas at the top, near the Kremlin, groundwater table was deeper than 4 m, as indicated by the VES measurement (Fig. 3(c)). Low ER (3-30 Ω m) of the soil at the bottom of the hill as measured by 9 m array shows that the top 1 m of the soil is non-saline or of low salinity. The drop of ER to almost 1 Ω m as measured with the 16 m array at the bottom of the hill indicated that there is highly saline groundwater within 2.2 m from soil surface (Fig. 6, Profile B). Notably, the NEP profiles designated even local fluctuations of the groundwater table. For example, the area near the Dramatic Theatre was drained by the specially constructed active drainage as shown by the resistivity increase in Fig. 6. Local increases in ER were observed on the crossroads (Fig. 6). These increases appeared, probably, due to draining effect of sand and cloth isolations of the pipes gathering under the crossroads. Such detailed outline of the subsurface ER was obtained by the NEP method in <30 min and corresponded with VES measurements and data from the stationary wells located nearby (Figs. 2 and 3). Noteworthy, VES application as well as conventional boring for evaluation of groundwater table is restricted in cities to the areas with open soil surface. Supplemental NEP profiles provide continuous and detailed hydrological information about the soil subsurface even through the concrete pavement.

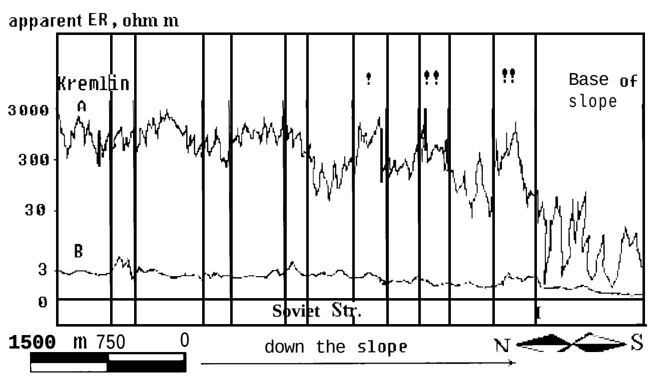

Fig. 6. Profiles of ER measured by the NEP along the slope in Astrakhan', Russia: profiling with (A) 9 m distance between aerials and with (B) 16 m distance between aerials. Vertical lines show location of crossroads. The single exclamation mark indicates local increase of resistivity near the Dramatic Theatre. The double exclamation marks indicate increase of resistivity at the crossroads in the low part of the hill.

3.2. Kiev, Ukraine

Case study in Kiev, Ukraine features investigation of localized hydrological problem caused mostly by urbanization of the area, as opposite to the extend areas with rising groundwater table in Volga delta induced by both natural and human factors. Hazardous hydrological situation caused by unknown factors appeared in Kiev-Pechersk Lavra (Kiev, Ukraine) near The Church of Holy Cross Elevation in 1987 (Fig. 7). Kiev-Pechersk Lavra is a center of Russian Christianity since IX century. The Church of Holy Cross Elevation was built in 1700 above the holy caves, a place of pilgrimage of Russian Christians since XI century. The caves store historical and art treasuries, such as XI century frescoes, living cell of Russian first annalist Nester, and the burial niches with the remains of civil and religious leaders.

Lavra is located on the high bank (near 200 m height) of the Dnipro river. The core of the bank is formed by limestone, which is covered by Quaternary deposits of loamy sand and sandy clay loam textures. The soil within a Patriarch garden was classified as eroded ordinary chernozems (Haplic Chernozems, FAO-UNESCO; Argiudolls, USA Soil Taxonomy). The caves are formed naturally in limestone and extend 228 m in length, with various depths from 5 to 20 m.

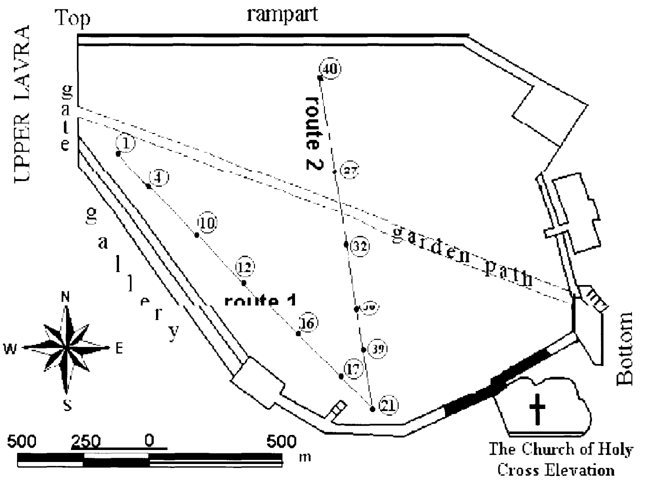

Fig. 7. Scheme of the investigated area within Patriarch garden, Kiev, Ukraine: the numbers in circles show VES and boring locations, lines are routes for EP investigation (Route 1 from VES 1 to VES 2 1 and Route 2 from VES 27 to VES 21), and the shaded area near the church is a concrete wall. Height difference between top and bottom of the hill is about 28 m.

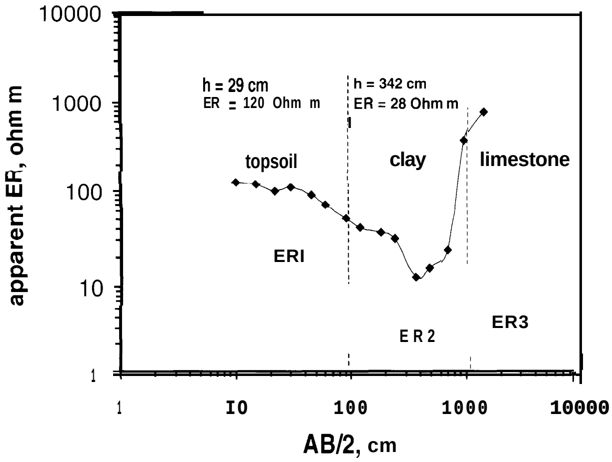

Fig. 8. Typical distribution (VES 4) of ER within soil profile measured by VES in Patriarch garden, Kiev, Ukraine. Thickness (h) and resistivity (ER) for the layers are derived through computer interpretation.

The groundwater penetrated in the caves and partly destroyed wall frescoes and other masterpieces in the caves and church interiors. To prevent groundwater seepage into the caves, a concrete tier wall was built around the church in 1988 (Fig. 7). Unfortunately, the activity did not change the hazardous situation. Therefore, it was necessary to further analyze hydrological conditions in the Patriarch garden. The methods of EP, VES, and SP were applied in 1990 to investigate and solve the problem. The results obtained with the methods were tested against the data from soil cores.

The problem area was located on a hill far above the groundwater table. Therefore, the problem was thought to be attributable to temporary subsurface water flow fed by precipitation. Excess water accumulated in subsurface in spring because of snow melting and in summer during intensive rainfalls. Due to the hill topography, water could accumulate in soil covering the whole territory of Upper Lavra and then flow into the Patriarch Garden within shallow soil subsurface (Fig. 7). We used the VES and EP methods to investigate the properties of water-bearing and impermeable layers essential for the development of the subsurface water fluxes. The directions and intensities of the fluxes were evaluated with the SP method.

The VES and EP methods revealed complex stratification of the hill slope in the Patriarch garden near The Church of Holy Cross Elevation (Fig. 7). All the VES curves revealed three-layer soil profile with apparent $ER_1 > ER_2 < ER_3$ (Fig. 8). The top layer was represented by the eroded Chernozem of coarse textures with ER (ER_1) about 125 Q m for loamy sand and about 50 Ω m for sandy clay loam. The second layer was a thick clay layer (up to 4 m) with low ER (ER_2) from 12 to 26 Ω m. The clay was saturated and gleyed in some places, which was indicated by 2 Ω m resistivity. The third layer with the resistivity (ER_3) about 1000 Ω m was horizontally deposed sandstone. The results of sounding were verified with boring at the same 12 locations (Fig. 7).

Soil thickness was only about 20 cm (VES 1, Fig. 7) on the top of the hill, but it increased downhill up to 2 m (VES 21, Fig. 7). Along the same direction the texture in surface soil layer changed from loamy sand (VES 4) to clay loam and clay (VES 17 and 2 1). That change in the texture of the first layer was reflected with the decrease in ER (ER_1) measured by the EP along the Route 1 (Fig. 7). The ER was about 100 Ω m for peaty sand at the top part of the Route 1 (VES 4), then decreased to 65 Ω m for sandy loam (VES 12), and further decreased to 35 Ω m on the surface and to 7 Ω m on the 0.5 m depth (VES 21) for topsoil of clay texture.

The low ER (6-28 Ω m) for the *AB/2* from 3.6 to 7.2 m for the second layer shown that clay did not bear any intrusions of sand or sandy loam, which was verified with boring (Fig. 8). Therefore, water flow inside second layer was impossible. The water flow could be formed only in the topsoil over the layer of impermeable clay.

Although undetectable on the surface, three gullies were revealed in the second layer of impermeable clay by the VES and EP methods. The subsurface water flow could be formed in such gullies. The first gully was detected near the gallery wall along the Route 1. The subsurface water flowed in the gully from the Upper Lavra downhill. Waterproof clay occurred on the surface about 6 m apart from the gallery wall (VES 12) causing bend of the subsurface water flow toward the Church of Holy Cross Elevation. The second gully formed along the garden path, which was indicated by non-decomposed plant debris deposited here. Narrow (about 17 m) band of raw organic litter mixed with sand of 30 cm depth was formed along the garden path

(Fig. 7, VES 1, 27, and 32). This indication of starting wetland formation on such steep slope designated that water saturation had occurred here for at least ten years. The second gully was also directed toward the Church of Holy Cross Elevation. The third gully was formed near the rampart and separated from the first and second gullies. Thus, the stratification of the investigated area with the EP and VES methods shows three possible ways for water flow in the soil: (1) near the gallery, (2) along the garden path, and (3) near the rampart.

The method of self-potential was used to estimate water flow directions and intensities through the measured variation in electrical potential on the soil surface. An iso-potential map (Fig. 9) was produced from the electrical potential measurements on a 5 x 10 m grid; 299 locations were measured with five replications. Three major iso-potential areas can be detected from Fig. 9. Two areas with negative potentials were found near rampart and along the gallery (including the garden path) and indicated the areas of water infiltration into the soil and development of groundwater flow (Fig. 9, I-III). The third area with positive potentials outlined the seepage zone near The Church of Holy Cross Elevation (Fig. 9, V). The most negative potentials (-250 mV) along the garden path indicated the most intensive subsurface water flow in this area (Fig. 9, IIA, IIBl, and IIB2). The -250 mV iso-potential area developed in surface peaty sand with ER (ER_1) about 170 Ω m. The less negative potentials (- 150 mV) and, therefore, the less intensive water flow occurred near the gallery (Fig. 9, IA and IB). The same negative potential areas were detected in the middle of the garden path and near the rampart (Fig. 9, IIIA, IIIB, and IV). The seepage area was outlined by the 0 mV iso-potential near The Church of Holy Cross Elevation (Fig. 9, V). The seepage area was enriched with clay material from the soil surface and had ER about 5 Ohm. The percentage of clay in the soil increased toward the corner of the church along with the electrical potential.

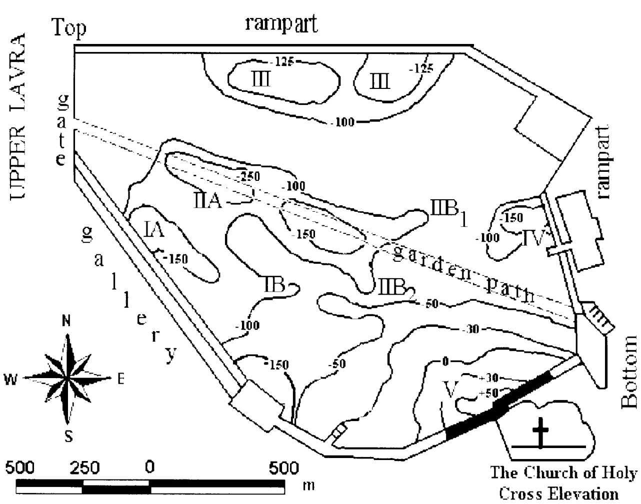

Fig. 9. Results of the SP measurements within Patriarch garden, Kiev, Ukraine. The curves are iso-potential lines. The numbers (I and II) and letters (A and B) indicate two fluxes with water flow from A to B areas; numbers III and IV indicate zones of infiltration: and number V shows seepage.

The measured electrical potentials were not corrected for the topography effects. Electrical potentials generally tend to become more negative with an increasing elevation; thus the most negative potentials in this case were found near garden path somewhat uphill from the seepage. The topographic effects on potentials measured with SP methods are generally thought to be caused by the down slope movement of subsurface water (Cull, 1985) and are largest in the areas with volcanic geology and large elevation change reaching maximum 3 mV per meter of elevation as reported by Corwin and Hoover (1979). Thus, the topography effects for our change of elevation within Patriarch Garden of about 28 m could possibly explain potential variability of maximum 84 mV, but the data shown differences in electrical potential up to 300 mV. Nevertheless, the topography effects on measured potential are mainly due to water moving in soil downhill and our primary objective was to detect the directions and intensities of water flow in soil subsurface.

The directions of water flow were predicted from the directions of increase in electrical potential. Three main water flux directions were detected by SP method: flux I near the gallery, flux II along the garden path, and flux III near the rampart (Fig. 9). Flux I was formed in thick loam sand about 1.5 m depth and characterized by a stable slow rate. Flux II could be highly intensive during rainfalls, since it was formed in coarse sand layer with a thickness about 0.3 m. Further downhill flux II was separated into two sub- fluxes (IIB_1 and IIB_2). Fluxes IB and IIB_2 merged during the intensive precipitation and seeped near the church infiltrating into the holy caves. Flux III was separated from fluxes I and II and did not influence the seepage near The Church of Holy Cross Elevation.

To protect the church, the following procedures were proposed based on our geophysical exploration near the architecture memorial. First, a hedge should be constructed across the gate to the garden to prevent the surface water flow to the Patriarch Garden from the pavement of Upper Lavra. Second, a small dike should be built perpendicular to the gallery and the garden path to direct subsurface water flow from fluxes II and I into the drain system. Third, to enhance evapotranspiration, trees and bushes with the intensive transpiration ability, such as willows and poplars, should be planted along the gallery and rampart, especially in the areas indicated by low potentials. All the measures were implemented in 1990 and still (personal communication with the church officials in 2000) provide adequate preservation for the church and the surrounding caves. The cost of the proposed measures was about one twentieth of the previous construction of concrete wall, which, nevertheless, did not solve the problem of water penetration into the caves.

4. Conclusions

Hazard hydrological conditions, such as spatial and temporal groundwater fluctuations, cause problems in many cities. Geophysical methods of stationary and non-stationary electrical fields can be used to evaluate hydrological situations and soil physical properties quickly and non-destructively. Various geophysical methods, such as VES, EP, SP, and NEP, were applied in urban areas of Kiev, Ukraine and Astrakhan', Russia, to detect subsurface soil and hydrological properties. Vertical electrical sounding was successfully utilized to delineate preferential water flow paths in stratified soil profiles as well as to determine saline groundwater table in a uniform soil. The method of self-potential revealed the directions and intensities of the subsurface water fluxes. The methods of the electrical and electromagnetic profiling (EP and NEP) were used to outline areas with different subsurface resistivities, which indicated different hydrology conditions in soils. Particularly, the NEP could outline saturated areas even through firm pavement materials. Thus, geophysical methods of the stationary and non-stationary electrical fields are convenient and powerful tools to investigate hydrology and soil properties and develop plans for building maintenance in urban areas.

Acknowledgements

This research was partly funded by the Russian Fund of Base Researches (RFBR), Ukrainian Orthodox Church Committee, and Russian Institution of Land and Ecosystem Monitoring. Authors deeply appreciate suggestions of anonymous reviewers on improvement of this manuscript.

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