Stockholm Junior Water Prize 2013

Russian Federation

Geophysical Methods of Ground Water Monitoring

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Summary

Implementation of Federal long-term development program “Securing drinking water supply for population of the Russian Federation” (1998) requires continuous monitoring of water reservoirs, used as drinking water sources by 16 million residents of rural communities in Russia. Geophysical methods help to identify persistent sources of pollution of these reservoirs by tracing directions of groundwater migration. These methods include electric resistivity exploration, electric tomography, and electric charge method. Modern geophysical methods of environmental monitoring may be effectively used to monitor the state of water reservoirs, urban and rural infrastructure, transportation networks and residential properties. These state-of-the-art methods also offer opportunities for professional development of well-educated and creative young people.

My pilot project was implemented in a small village of Kireevka in Rostov region, where I demonstrated possible approaches to optimization of various engineering and research techniques of assessment of environmental risks in drinking water supply sector. In particular, I implemented a novel method of joint interpretation of results of electric tomography and electric charge measurements. This research project was conducted upon the request of the village residents who expressed concerns about construction of new gas station near the water well. I conducted a geophysical survey of the area around the well to assess the risks of potential infiltration of oil products from the gas station in drinking water. The direction of laminar groundwater flow was established by a sanitary-topographic survey of geological structure of the area around the well. Using electric tomography and electric charge methods, I concluded that the new gas station could not be the source of well water pollution. At the same time, computer analysis of field measurements detected other potential sources of well water pollution, which originated in the communal sector (toilets, waste damps and drains). The results of my project were communicated to the local residents and local self-governance authority.

INTRODUCTION

Federal long-term development program “Securing drinking water supply for population of the Russian Federation” was adopted in 1998 with the goal to enhance supplies of drinking water with standard quality. About 80,000 rural settlements in Russia with total population of 16 million people currently use local (decentralized) sources of potable water. About 9 million people drink water which does not meet drinking water quality standards. Consumption of this water contributes to unfavorable sanitary-epidemiologic situation in many rural settlements.

Several normative documents require continuous monitoring of all sources of potable water in the Russian Federation (State Standard 2761-84, Sanitary Norms and Regulations 2.1.4.1074-01 and 2.1.4.1075-02) [1, 2].

The object of my study was the main water well in Kireevka village of Rostov region. The study was conducted in July-September of 2012. This water well is used as the primary source of drinking water by most residents. The new gas station was constructed within 48 meters from the well early in 2012. Despite the claims of the gas station owner about environmental safety of this property, local residents expressed concerns about potential contamination of their source of drinking water with oil products. They asked my teacher and me to assess the risks of groundwater contamination and to confirm or disprove their concerns (Annex 1).

Infrastructure development often creates environmental risks for drinking water reservoirs in rural settlements in Rostov region and in other regions of the Russian Federation.

Sanitary-topographic survey of drinking water sources provides the basis for hygienic assessment of water safety. Although laboratory tests confirm the presence (or absence) of water pollutants, they cannot predict future risks of water contamination. Geophysical exploration is a noninvasive method which produces regular and detailed data on geological structure of the study area. Geophysical monitoring methods (electric resistivity exploration, electric tomography, and electric charge method) are used to detect the direction of groundwater migration and thus help to reconstruct long-term dynamics of potential sources of water contamination.

The project goal was to assess the potential for contamination of the source of drinking water in Kireevka village by using modern noninvasive methods.

This goal could be achieved through the following steps:

1. Conduct geophysical measurements and elucidate information on geological structure of the area around the water well;
2. Determine the direction of laminar groundwater flow which supplies the well;

3. Conduct sanitary-topographic survey of the well and determine potential sources of water contamination;
4. Inform Kireevka residents about the project findings.

1. DESCRIPTION OF PROJECT SITE

1.1 General geographic and geological characteristics

The project site lies is the eastern part of Kireevka. The village is situated 7 km away from the town of Shakhty and is accessible by Shakhty – Belaya Kalitva motorway (Figure 1). The village was built on the south-east slope of Donetsk Range. The relief is flat with mild slopes facing the river valleys which are formed by prairie gullets with flat ramps. Absolute elevations are 95-105 m. Man-made features include gob piles 15-25 m in height.

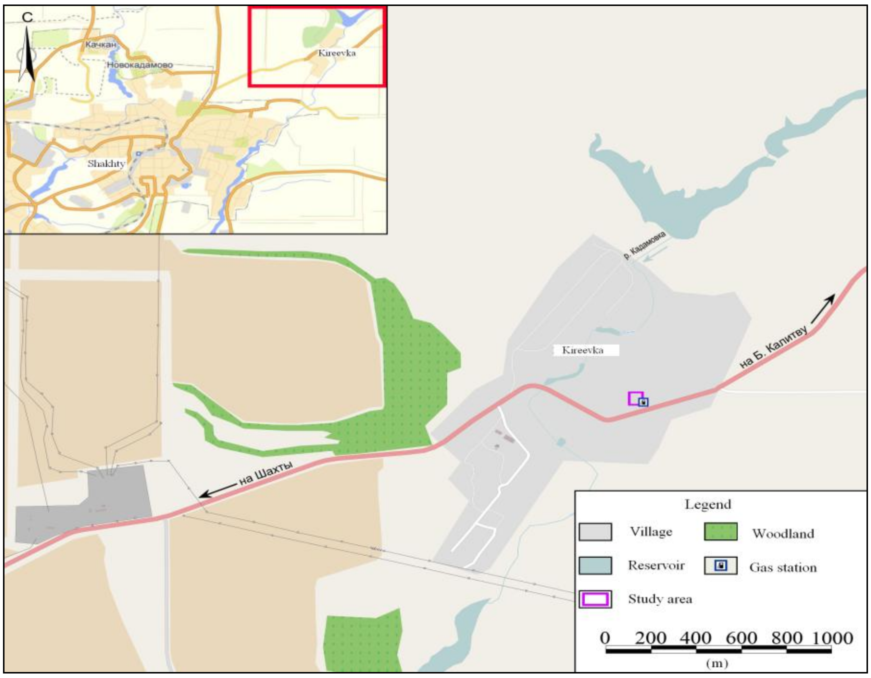

Fig.1. Map of study area

Local climate is moderately continental. Annual mean temperature is 9.3ºC. Prevailing winds have eastern direction. Annual precipitation is 400-450 mm with seasonal maximum in spring and autumn (up to 300 mm). The land is covered with grass and bush with occasional man-made forest belts with acacia, oak, poplar and pine stands.

Local hydrology: The project site lies in the watershed of Kadamovka river which originates in the south slope of Donetsk Range and flows south-west, falling into Tuzlov river near Novocherkassk city. Local river system is Kadamovka→Tuzlov→Aksay→Don. Kadamovka river carries large quantities of suspended solids.

Ground waters which supply the main well in Kireevka flow in the geological stratum of Quarternary period. The sediments are comprised of aeolian diluvial loess-type loams, alluvial sands and sand clays which cover more ancient strata. The sediment layer is several meters in depth and sits on the confining bed of cavernous Neogene and Paleogene limestone and shell rocks (Figure 2).

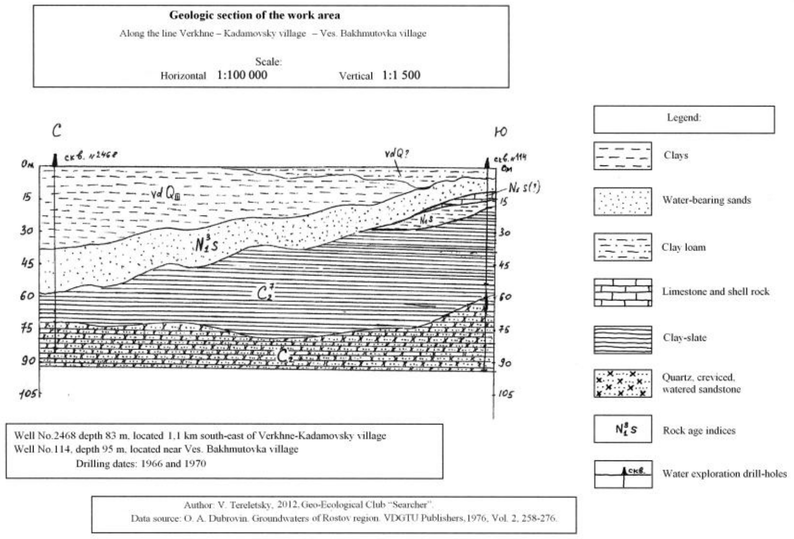

Fig.2. Geologic section of the work area

1.2 Sanitary-topographic description of project site

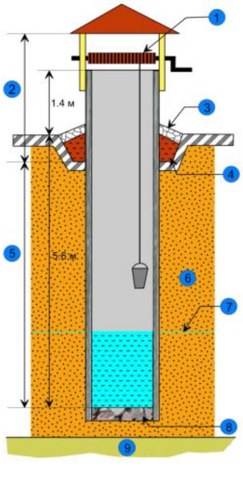

Fig. 3. Scheme of water well

1. Hoist
2. Headwall
3. Stone riprap
4. Clay lock
5. Shaft
6. Waterbearing rock
7. Groundwater level
8. Gravel
9. Confining bed

The well is located in the eastern part of Kireevka and is supplied by ground waters. Water level stays nearly constant all year round at the depth of 3.8 m. Total depth of the well is 5.6 m. The walls are lined with concrete rings with above-ground height of 1.4 m (Figure 3). A clay lock protects the well from melt waters. The well was constructed 40 years ago and is repaired every 2 years. The inner walls have occasional cracks but there is no risk of collapse. I did not observe any dirt or accumulation of periphytic microorganisms on the inner walls. The well water is transparent, odorless, and tasteless. It does not contain suspended solids.

Infiltration of water pollutants from the surface is quite likely because the village does not have centralized sewerage. Geologic and environmental forecast should consider all possible ways of migration of pollutants. I considered the following potential sources of pollution: gas station, toilets, waste drains and cesspits within 50 m from the well.

2. METHODS AND INSTRUMENTS

2.1 Theoretic foundations

Electric tomography utilizes electric resistivity method for for geophysical exploration at small depths. Electric tomography has advanced since wide-scale adoption of personal computers in mid-1980s, and especially during the last 5 years. Lomonosov Moscow State University initiated use of electric tomography in Russia, and Lengiprotrans Institute (St.-Petersburg) was the first Russian company which implemented this method in geophysical exploration.

Electric resistivity exploration devise has two pairs of electrodes (feeding pair and measuring pair). The feeding pair of grounded electrodes A, B passes direct current with certain intensity. The measuring pair of electrodes M, N measures the voltage produced by this current (Figure 4). The research area below the devise center spans the depths down to approximately one-half of the devise length (AB/2). Electric field on the ground surface depends upon the distribution of unit electric resistivity in the geologic section near the installation [3]. Based on the voltage measurements (ΔU, mV) and current intensity (I, mA), apparent resistance of geologic section (ρk) is calculated as $\rho k = K\frac{\Delta U}{I}$, where K is the coefficient determined by the positions of the electrodes. As the distance between the electrodes increases, this coefficient and the depth of the research area also increase.

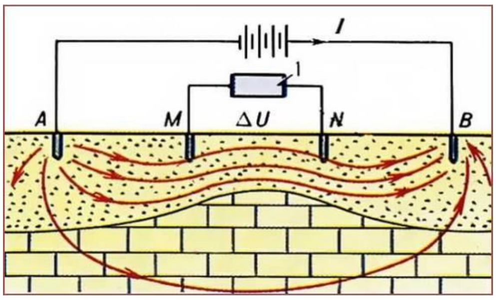

Fig. 4. Installation for electric resistivity exploration:
A, B – feeding electrodes;
M, N - measurement electrodes; 1- meter

Electric tomography is high-resolution geologic exploration method which involves field measurements, data processing and interpretation [4]. Usually the same fixed positions of feeding electrodes (A, B) and measurement electrodes (M, N) are used many times to increase measurement density. Data interpretation involves 2D and 3D models of complex geologic structures.

Electric charge method was introduced in 1919-1922 by N. Lundberg and K. Zundberd in Sweden and K. Shlumberge in France. A. Semenov was the first researcher who used this method for geologic surveys in Russia (1930). This method was used mainly for lode exploration, and only rarely in hydrogeology. I could not find any publications in the international and domestic literature published during the last decade which mentioned this method. Electric charge method involves grounding one pole of the current supply directly in the analyzed body while the other pole is grounded beyond the research area. The distance between the poles must be large enough to neglect the influence of the electric field of the second pole on the measurement results. Passage of current between the poles creates electric field in the conducting body. Equipotential surfaces of this field repeat the contours of this body. The position and geometry of the conducting body are determined by measuring surface electric potential [5]. Electric charge method is used in exploration of copper-sulphide ores, magnetite, anthracite, graphite, etc. It is also used in hydrogeology for detection of direction and velocity of groundwater flow.

I used artificial medium with high ion conductivity as the analyzed body. For this purpose, I put some cooking salt in the well. Infiltration of saline water through the ground increased its conductivity and showed the direction of groundwater flow. Regularly repeated measurements of electric potential were used to reconstruct the direction of groundwater flow within the research area (Figure 5).

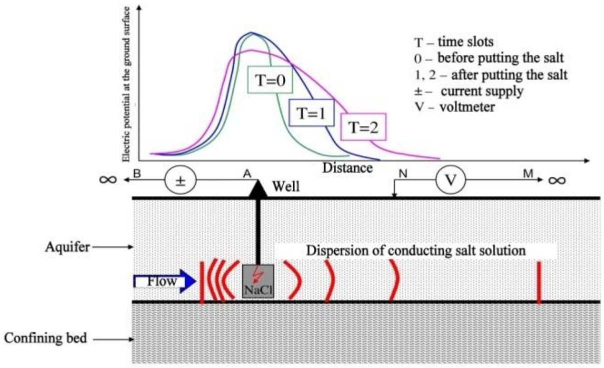

Fig. 5. Hydrogeology modification of electric charge method
(*A, B – feeding electrodes;M, N - measurement electrodes)*

2.2 Methods of field measurements

Electric tomography. The first stage of my project involved sanitary-topographic survey of the water supply source. I studied the condition and structure of the well, drew its scheme (Figure 3), detected potential sources of ground water pollution by visual examination of the adjacent area. I used a bearing circle for topographic mapping of detected objects and drew the chart of the research area (Figure 6).

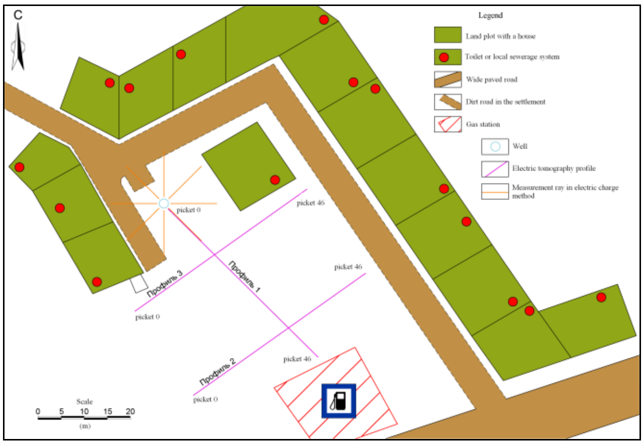

Fig.6. Scheme of the actual material

The positions of geometric profiles for electric tomography were selected to gain information about the geometry and depths of geologic heterogeneities of the sections between the potential sources of pollution and the well. Such heterogeneities may hinder or obstruct groundwater flow and therefore should be accurately described. I prepared three profiles for electric tomography measurements. Profile 1 stretched from the well to the gas station. Profiles 2 and 3 were oriented perpendicularly to profile 1 to assess heterogeneities in two directions of the geologic section. Each profile had the length of 46 m. Separate set of profiles was used in electric charge method. These profiles were the eight arms radiating from the well (Figure 6) at 45º angles. Each arm had the length of 7-10 m. The measurement points (pickets) were spaced regularly at 1 m distances along each arm and numbered.

The second stage consisted of preparations to geophysical measurements. Tape-line and flaggings were used for topographic positioning of the profiles. After positioning the profiles were picketed and marked on the chart with the bearing circle.

A three-electrode installation with multi-channel receiving line was used for electric tomography measurements (Figure 7) along the three profiles (Figure 6). I used ERA-MAX meter manufactured by NPP ERA (St.-Petersburg), serial number MV06, tested in May 2013 (Figure 8). Similar instruments for electric tomography are produced in Sweden by ADEM (Terrametr LS) and in France by IRIS Instruments (SYSCAL).

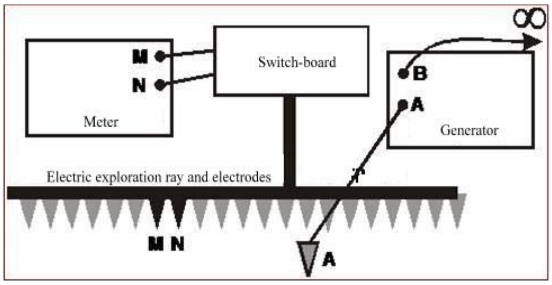

Fig. 7. Multichannel electric exploration devise

Fig. 8. Electric exploration meter ERA-MAX

Three-electrode geometry must meet the following condition on the distances between the electrodes: AM<AN<1/5AB. Therefore, the voltage between the receiving electrodes M, N is determined by the feeding electrode A, and the influence of the feeding electrode B could be neglected because the distance to this electrode is much greater (I assumed that this electrode was infinitely distant).

A 24-channel receiving line was lain along the profile at this stage. The first channel (or electrode) was placed at 0 m picket; the distance between regularly spaced receiving electrodes was 2 m. The feeding electrode B was placed 200 m away from the profile line and grounded. An extension reel connected the remote electrode with the power generator. The feeding electrode A was consecutively placed at each picket beginning at 0 m picket and ending at picket 46. The feeding current was stabilized by the generator after placing the feeding electrode at each location. The voltage in the receiving line was measured after stabilization of the electric field. An automatic switch was used for commutation between the receiving channels. A series of ten measurements across both sides was recorded at each position of the feeding electrode A. This method produced an equally spaced grid of measurements over the whole geologic section (Figure 9). The maximum diversity of the installation was 21 m, which allowed to analyze geological structure down to the depth of 7 m [6].

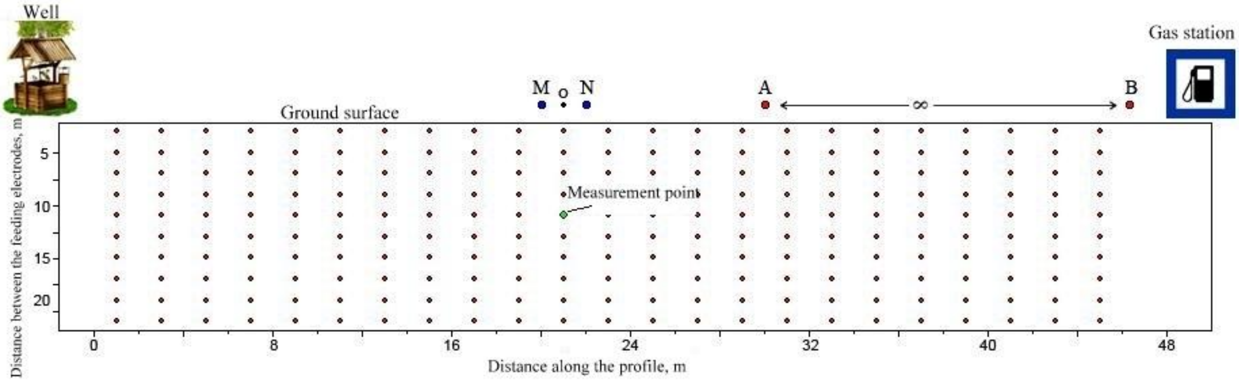

Fig. 9. Schematic of electric tomography measurements

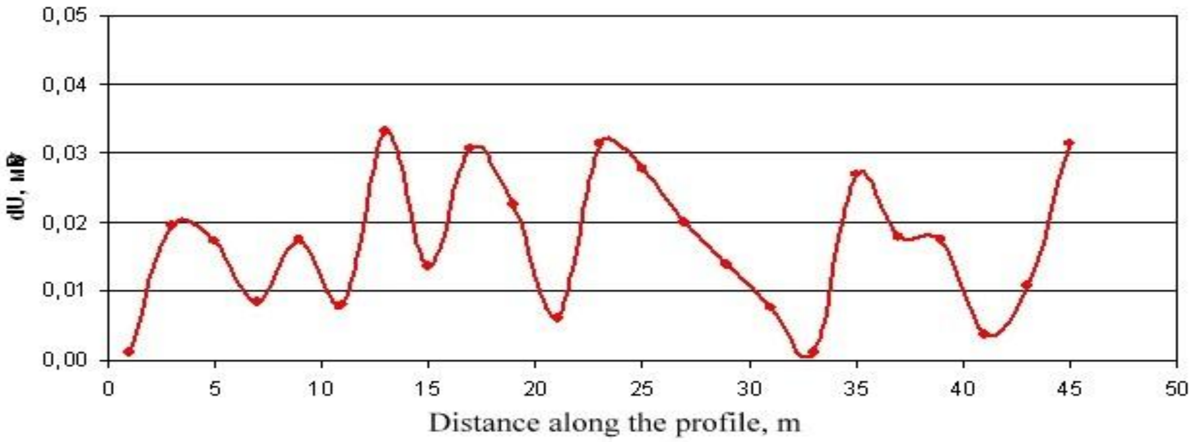

Fig. 10. Electric field noise level at frequency 4.88 Hz along Profile 1

Alternative current with frequency 4.88 Hz and nominal current intensity 20 mA was used for measurements. At this frequency, the electric noise within the profile was minimal and varied between 0.001 and 0.036 mV (Figure 10). The level of effective signal was at least 2 mV. The results of measurements were stored in memory of ERA-MAX meter and processed with the personal computer. Quality control was assured through a series of repeated (control) measurements [7]. The number of control measurements was about 10% of total number of measurements. An estimated mean square error (MSE) of measurements was 2.4%.

Electric charge method. The measurement system consisted of four steel electrodes. Two feeding electrodes generated electric field in the formation within the research area; two receiving electrodes measured distribution of electric potential of this field.

One feeding electrode (A) was placed on the well bottom; the other (B) was grounded 100 m away from the well with an extension reel. This distance was greater than the well depth by a factor of 20, and the influence of electrode B on the electric field near the well could be neglected. The electric field near the well could be approximated as the field of point source A. Receiving electrode M was grounded 100 m away from the well in the opposite direction from electrode B. This geometry allowed to perform measurements only by changing the position of the other receiving electrode N.

At the first step, the baseline distribution of electric potential near the well was measured. For this purpose, I stabilized electric current with the intensity 50 mA and frequency 4.88 Hz between the feeding electrodes. This frequency was used to minimize electric noise. I measured electric potential at each picket with ERA-MAX meter. Equipotential lines from the point source A made almost perfect circles.

At the second step of the experiment, I placed a cheesecloth bag with cooking salt into the well. The salt dissolved and the charged particles (ions) were carried by groundwater flow, thus forming a high conductivity “charged body” [8]. The measurements of electric potential were repeated 4 and 8 hours after “charging” the well with the salt, along the rays at each picket. I recorded the measured values and did quality control measurements as recommended in [7]. The number of control measurements was 15% of the total number of measurements. Estimated MSE of measurements was 1.8%

2.3 Processing of field measurements

Data processing consisted of two steps. At the first step (preliminary processing), I converted the electrode numbers along each ray in the metric coordinates on the profile and calculated standardized signal using the formula $Res = \Delta U/I$. At this stage, I deleted from the dataset several incorrect measurements which had errors due to weak grounding of the electrodes. This procedure increased overall quality of the data.

The second step was to solve the inverse problem of geophysics: given the contours of the electric field, I had to reconstruct the shape of the charged body. I used ZondRes2D software released by Alexander Kaminsky (Zond Software, St Petersburg) [9]. This numeric algorithm approximated the geologic medium with a grid of uniform rectangular cells. Solution of the inverse problem involved optimization of the model parameters [4]: with the length of the study area 46 m and the depth 7 m, optimal cell dimensions were 1 m in length and 0.5 m in height. The optimal model of the geologic medium was selected by iterations. At each iteration, specific resistance values of each cell (unit resistance values) were calculated to match the measured and simulated contours of electric field (Figure 11). Each simulation experiment involved 8-10 iterations. Relative closing error between the measured and simulated values of electric potential after the iterative cycle was 2.7 - 4.1%.

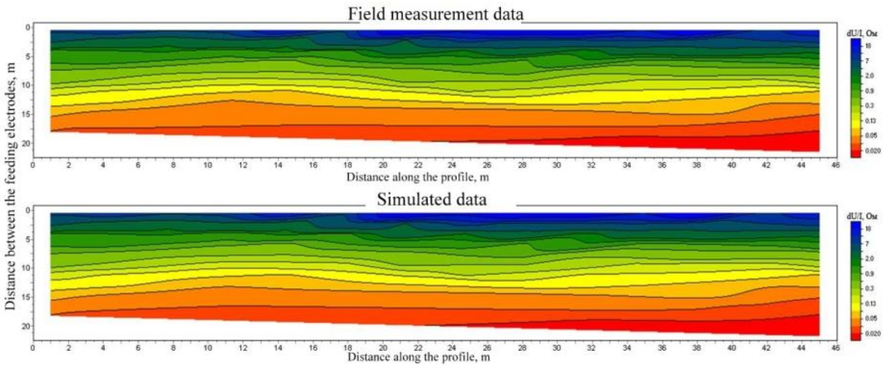

Fig. 11. Pseudosections of normalized signal after model selection and schematic of geoelectric section

The results of electric tomography measurements were presented as two-dimensional geo-electric sections of unit electric resistance (Figure 12). The reference values of unit electric resistance of main geologic formations are specified in Table 1.

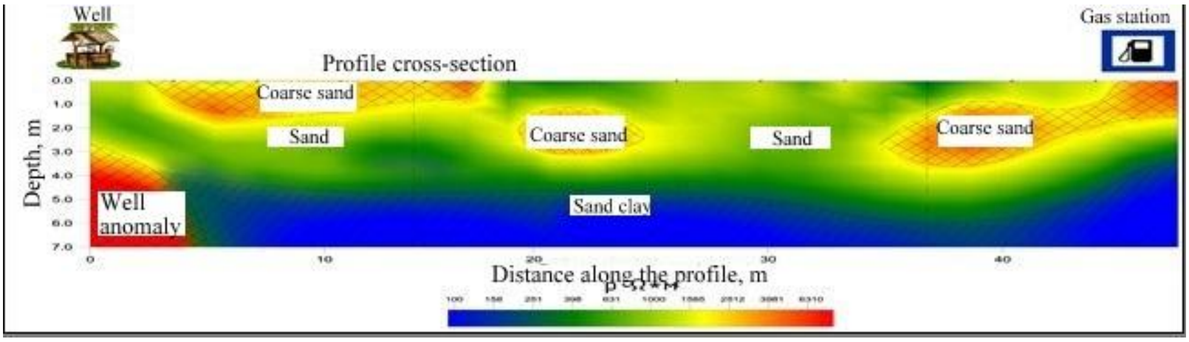

Fig.12. Geologic section.

Table 1.

Geo-electric properties of main formations in the study area

Geologic formation	Specific electric conductivity, Ohm×m
Loam	25–70
Sand	75–160
Coarse sand	≥200

Equipotential contour lines were drawn at different times after putting the salt in the well. This mapping procedure was used to detect the direction of ground water flow by electric charge method (Figure 13).

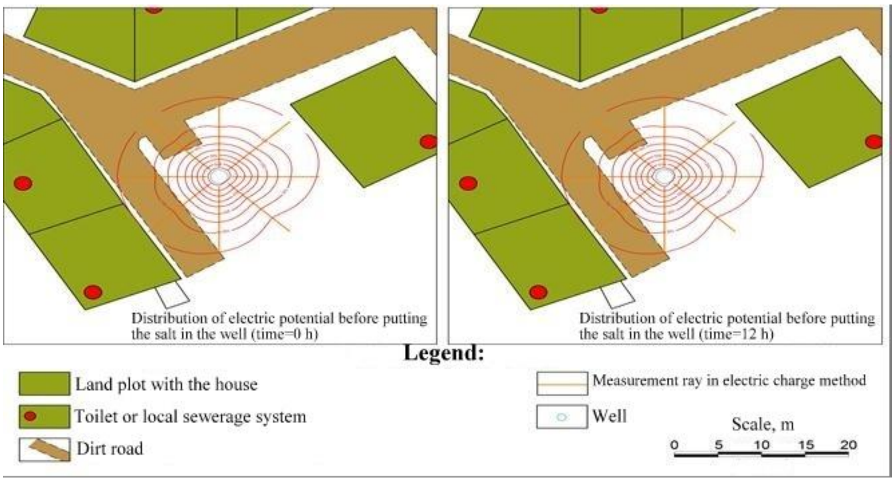

Fig. 13. Dynamics of distribution of electric potential

Surfer (Golden Software) graphic package was used for calculations and mapping. Figure 14 shows that the equipotential lines slightly change over time. The lines stretch in the direction of groundwater flow repeating the contours of the “charged body”. To visualize the direction of groundwater flow, I calculated the normalized change in electric potential relative to the baseline, and expressed it as a percentage:

$$U_n = \frac{U_{12h} - U_{baseline}}{U_{baseline}} \times 100\ \%,$$

where U_n is normalized change in potential (%); $U_{baseline}$ (mV) is electric potential before putting the salt in the well; U_{12h} (mV) is electric potential 12 hours after putting the salt in the well.

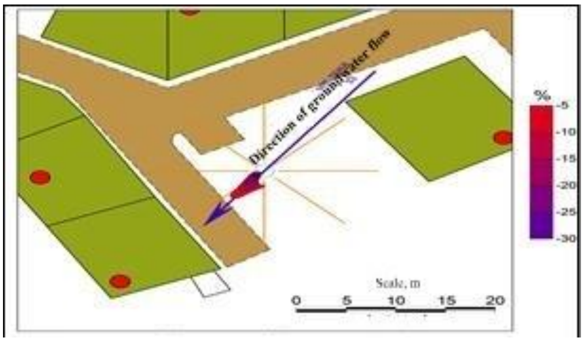

Fig. 14. Direction of laminar flow.

3. RESULTS AND DISCUSSION

The novelty of my approach stemmed from the combined application of two methods of electric exploration, which produced high-confidence characteristics of the study area. I consider this as my personal input in electric exploration methodology.

Sanitary-topographic survey of the well was used to detect potential sources of water pollution. I identified and mapped the nearby toilets, local sewerage tanks and the gas station as potential sources of water pollution (Figure 6). Infiltration of hazardous substances from these sources in the groundwater may contaminate the well. Geologic and environmental forecast considered the following aspects:

1. Hazardous substances are dispersed in the environment and transported by groundwater over long distances.
2. The direction of groundwater flow does not necessarily follow the relief of the area, because this direction is determined by geometry of the confining bed and its cross-sectional heterogeneities.
3. The direction of groundwater flow and filtration coefficient (water conductivity) of the rock are the key parameters in the forecast of potential water contamination.

Electric tomography was used to reconstruct geometry and chemical composition of quaternary sediments in the section of the aquifer (Figure 12). I used archive data on geologic composition of the area and a geologic manual [10] to determine the composition of sediments. My findings may be summarized as follows:

1. The upper layer of the section (down to the depths of 5-6.5 m) is composed by wet sands, presumably fine-grained, with specific electric resistance 75-160 Ohm×m. This layer contains the lenses of coarse sands with thickness 1.7-2.8 m and specific electric resistance more than 200 Ohm×m. The horizontal length of the lenses is 4.5-11.6 m. The boundaries between fine-grained and coarse sands are quite sharp and distinct. The sands usually have very high water conductivity.
2. Along the breached boundary, the sands are confined by underclay with specific electric resistance 25-70 Ohm×m. Low resistance values indicate groundwater confining properties of this layer. The clay layer mildly slopes in south-west direction and has nearly constant thickness.

The results of geologic survey confirmed that geological structure of waterbearing sands was rather complex and non-uniform. Nevertheless, the absence of patches with low water conductivity indicated linear character of ground water flow.

At the first glance, the distribution of electric potential cannot provide reliable information on the direction of groundwater flow, as the contour lines have not changed much over time (Figure 13). Nevertheless, the normalization procedure relative to the baseline makes it possible to accurately predict this direction (Figure 14). Electric charge method was implemented to show that electric conductivity of groundwater increased after putting the salt in the well. Increase in electric conductivity was confirmed by a 5-20% decrease in electric potential. Near the well potential decreased by 20-30%. Compared to the mean square error of 2.4%, this decrease is highly significant.

CONCLUSIONS

This study was the first one to implement a combination of electric tomography and electric charge methods with the aim to detect the direction of ground water flow within the study area (Figure 15). The results of the study indicated that the gas station could not pose risks of contamination of drinking water in the well. At the same time, project results indicated several previously unknown potential sources of contamination: local sewerage to the north-east from the well. The owners of household sewerage systems have been informed about these risks and the need to use these systems in a responsible manner. The concerns of Kireevka residents have been duly answered.

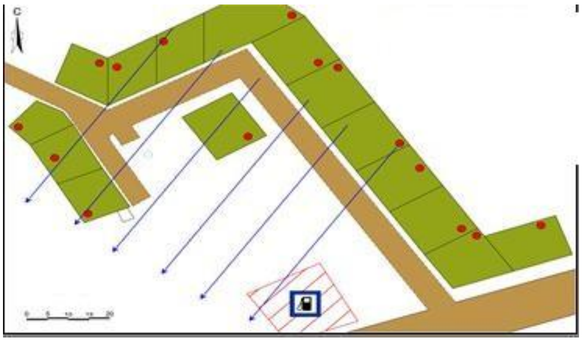

Fig. 15. (C) Forecast of groundwater flow

RECOMMENDATIONS

1. A combination of electric tomography and electric charge methods should be used in environmental risks assessment during land use planning and design of new infrastructure objects: gas stations, warehouses, etc. The proposed methodology can provide the basis for communication of information about potential risks of contamination of open reservoirs to local residents who drink water from these reservoirs.

2. Ministry of Natural Resources of the Russian Federation and Ministry of Science and Education of the Russian Federation should set up a mobile unit for geophysical research, with the goal to advance and disseminate state-of-the-art methods of remote assessment of environmental quality among young Russian and foreign scientists.

LITERATURE

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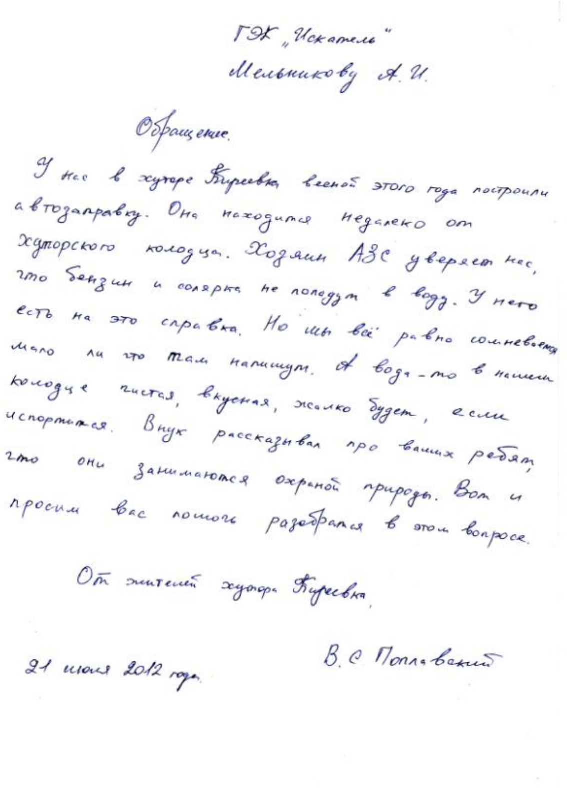
Annex.1.



ГЭК „Искатель“
Мельникову А. И.

Обращение.

У нас в хуторе Киреевка весной этого года построили автозаправку. Она находится недалеко от хуторского колодца. Хозяин АЗС уверяет нас, что бензин и солярка не попадут в воду. У него есть на это справка. Но мы всё равно сомневаемся мало ли что там напишут. А вода-то в нашем колодце чистая, вкусная, жалко будет, если испортится. Внук рассказывал про ваших ребят, что они занимаются охраной природы. Вот и просим вас помочь разобратся в этом вопросе.

От жителей хутора Киреевка.

21 июля 2012 года.

В. С Поплавский

Petition to Geo-Ecological
Club “Searcher”

A new gas station was built in our village Kireevka last spring. This station is situated not far from the water well. The gas station owner has assured us that gasoline and solar oil would not come into the water. He has a relevant certificate. Nevertheless, we still have our doubts, because one might have written many things in such certificate. The water in our well has always been pure and tasty, we would so much regret if it gets spoilt. My grandson told me about your kids, that they are engaged in nature conservation. So we are asking you to look into the matter.

On behalf of Kireevka residents,

V. S. Poplavsky

July 21, 2012