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Hydrogeological monitoring of karst activity based on regime observations in the territory of karst lakes

Oleg R. KUZICHKIN[1) ✉], **Roman V. ROMANOV**[2)],
Nikolay V. DOROFEEV[2)], **Gleb S. VASILYEV**[1)],
Anastasia V. GRECHENEVA[1)]

[1)] Belgorod National Research University, 85 Pobedy St., 308015 Belgorod, Russia
[2)] Vladimir State University, Vladimir, Russia

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Abstract

This article shows that the most sensitive indicator of local and regional karst activity in territories of apparent karst processes is the behaviour of karst lakes. The authors propose a hydrogeological monitoring methodology for the karst process based on the phase-measuring geoelectric control method in the coastal zone of karst lakes. The geoelectric current control of hydrogeological changes in the medium at local levels uses a multi-frequency vertical electric sounding combined with a phase-measuring method of registering the geoelectric signal. These proven methods permit to distinguish variations of spatial parameters and the electric conductivity of several layers at a time. Moreover, they significantly increase the noise resistance and sensitivity of the measuring system. An adaptive algorithm function of the measuring complex for geoelectric monitoring of karst lakes' coastal zones was developed to control the operation of facilities and data collection systems. Based on an example of a lake where karst processes are active, the key zones of hydrogeological control were identified depending on karst manifestations. The research confirmed the possibility of local and regional monitoring of the development and forecasting of destructive karst-suffosion processes based on hydrogeological regime observations of karst lakes.

Key words: *data processing algorithm, geodynamics, geoelectric facility, hydrogeological monitoring, karst lake, phase-measuring method*

INTRODUCTION

The organisation of hydrogeological monitoring data from technical and life-sustaining facilities is essential, especially if the latter are situated in territories with probable karst processes. The designing of safety-sensitive facilities, such as nuclear power plants and hydro-technical facilities, requires thorough survey work and the development of a karstological monitoring system [Bonacci, Juračić 2010; Epure, Borda 2014; Šolar *et al.* 2007; Somaratne 2015].

An increase in the technogenic load leads to a change in the hydrogeological regime and a change in the mechanical stress fields. This also causes an increased rate of karst-suffusion processes. Considering the development of destructive karst-suffosion processes, the following dangerous situations can arise during the construction of certain safety-sensitive facilities:

- karst destruction in the soil base of buildings leads to the deformation of foundation elements that are responsible for the overall stability of the building;
- karst cavity developed may cause uneven deformations of the soil base, which can lead to the redistribution of loads in the building structure, formation of cracks and the destruction of individual elements;

- karst process proceeds unnoticed, while the surface of the karst remains stable until the elastic limit is reached; then, an abrupt collapse occurs leading to the destruction of buildings located near the karst cavity.

This is due to the fact that during exploitation, the massif of cavernous rocks acquires different hydrogeological properties compared to the same rocks that are not affected by the dissolving influence of moving groundwater. The development of karst forms is largely influenced by the hydrology of the karst water movement, which determines the topicality of hydrogeological monitoring [BOHACHENKO 2012; GOLDSCHEIDER, DREW (eds.) 2014; HAMDAN *et al.* 2010] and an estimation of the hydrogeological risk [LA VIGNA 2016; OLADUNJOYE, JEKAYINFA 2015; SCAIONI *et al.* 2015]. Additionally, karst development significantly influences the quality of groundwater [ANGEL *et al.* 2015; SOBEIH *et al.* 2017; SZYDLARSKI *et al.* 2017; WANG *et al.* 2016]. The type of karst is determined in the hydrodynamic zone, a zone where karst processes manifest themselves. When organising karst monitoring, two groups of interrelated tasks need to be considered. The first group includes control over geological and hydrogeological situations that promote the dissolution of rocks. The second group includes the identification of caverns and cavernous zones, survey of groundwater movement conditions and forecasting of further corrosion and suffusion.

The most sensitive indicator of karst activity in a surveyed area is the behaviour of karst lakes formed by depression processes (mainly interflow). In this case, surface water flowing into depressions are taken up by sinkholes and fed into the lakes. Karst processes lead to the intensification of interflow and disturb the zonal character of interflow distribution, which is determined by geographical zoning and results in redistribution of interflow in the neighbouring rivers within relatively limited areas. Based on the type of regime, the interflow in zones of karst depression lakes is similar to the river flow. It forms regional patterns of maximums and minimums and determines the intensity of karst processes at local levels [RAVBAR, GOLDSCHEIDER 2009]. Accordingly, karst lakes significantly influence (both locally and regionally) the development of destructive karst-suffosion processes [ANIKEEV *et al.* 2015]. This feature of karst lakes enables to organize regime geo-ecological monitoring that covers the development and forecasting of destructive karst processes at the regional level [LARSEN 2003].

Karst-forming processes are influenced by a combination of four main conditions:

- presence of soluble rocks;
- increased water permeability of rock massifs;
- presence of water exchange through the rock massif;
- water aggressiveness towards the rocks.

The lack of any of these condition prevents karst-forming processes.

The most common carbonate karst shows slow rock dissolution; and therefore, the karst forms (e.g. cavities and depressions of karst rocks), which are immediately associated with the rock dissolution under natural conditions, develop very slowly. This is why the development of new karst cavities, which are dangerous for constructions during their calculated life cycle, is considered improbable. However, there are cases when the speed of carbonate rock dissolution has been significantly accelerated due to leakage of industrial waters saturated with acids and organic substances.

The efficiency of hydrogeological monitoring depends on the accuracy and immediate estimation of destructive geodynamic development processes and their influence on the natural environment and life-supporting facilities. The key requirement is to obtain accurate and reliable information on the facility examined at the minimal technological expenditure. This requirement can be met by geoelectric control methods [CHEN *et al.* 2017; DONG *et al.* 2013; GRBIĆ *et al.* 2013; SONG *et al.* 2017] and electrical sounding [IRAWAN *et al.* 2015; KOLYUSHKO, RUDENKO 2017; OLADUNJOYE, JEKAYINFA 2015; OLAWUYI, ABOLARIN 2013; SANTOSA 2007]. While most approaches aim at researching global geodynamics [DOLOGLOU 2011; SOKOLOV *et al.* 2017], these methods allow control of the geodynamic processes and efficient response to unfavourable geodynamic changes at the local level [DOROFEEV *et al.* 2016; GRECHENEVA *et al.* 2016].

When we use a network for hydrogeological data collection, it is essential to select carefully local control points because of obvious limitations to the observation network. When establishing the data registration system, one should first consider the informative value of the hydrogeological data collected using the applied methods for local control. A comprehensive approach is necessary together with the selection of points that are the most sensitive to hydrogeological changes, including the coastal zone of a lake's hydrological discharge and the zone of active karst processes [KUZMIN 2015]. Furthermore, it is necessary to apply a highly sensitive method of registering the geodynamic changes in the hydrogeological medium with increased noise immunity. This research developed a phase-measuring method which offers geoelectric control of geodynamic changes and a system of hydrogeological monitoring of karst processes with high metrological characteristics [BYKOV *et al.* 2017].

The purpose of this paper is to present a technique of organising the hydrogeological monitoring of karst process based on a phase-measuring method of geoelectric and geodynamic control in the coastal zone of karst lakes.

MATERIALS AND METHODS

STRUCTURE OF THE MEASURING COMPLEX OF HYDROGEOLOGICAL MONITORING

The measuring complex of hydrogeological monitoring of the karst lakes coastal zone is uses a phase-measuring method of geoelectric and geodynamic control. Figure 1 shows the structure of the measuring complex located in the coastal zone of a karst lake. The key component is an electrolocation geoelectric facility which traces parameters of the vertical geological and hydrogeological section using a phase-measuring method of primary data collection and processing.

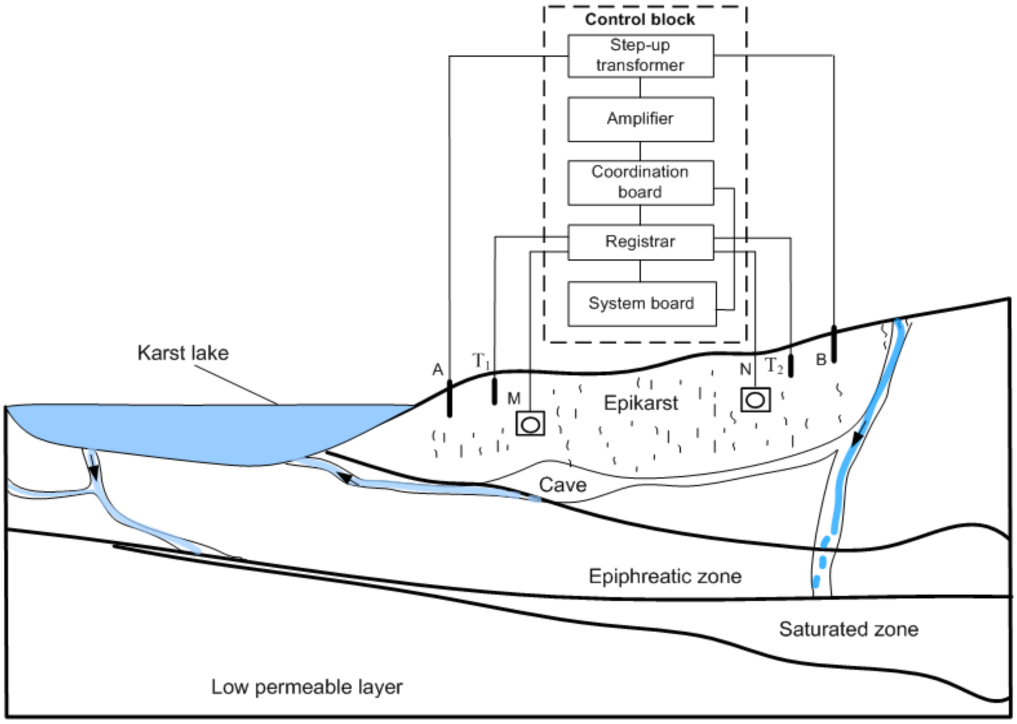

Fig. 1. Hydrogeological monitoring and measuring complex; source: own elaboration

The electrolocation facility consists of a control block, several pairs of emitting electrodes AB, sensors measuring electromagnetic field M and N, temperature sensors T_1 and T_2, and equipment that communicates with the registration post.

The coordination board is connected to a control block, sensors for geoelectric field measuring M and N, and temperature sensors T_1 and T_2; the coordination board also generates a sounding signal. The latter is supplied to emit electrodes via a step-up transformer to form the working voltage.

PHASE METHOD OF REGISTERING GEOELECTRIC SIGNALS

The geoelectric method of current control of hydrogeological changes in a medium at local levels is based on multi-frequency vertical electrical sounding (MFVES) (Fig. 2a), which is combined with a phase measuring that registers geoelectric signals (Fig. 2b).

The MFVES method can be used to distinguish variations of selected parameters and to determine the specific conductivity of several layers at a time. This constitutes a peculiar feature of the proposed approach [ROMANOV *et al*. 2015]. In addition, using the phase-measuring method for the registration of geoelectric signals enables a significant increase of sensitivity and noise immunity of the measuring system, which is essential when aquifers are examined using geoelectric methods.

When using the phase-measuring method with a bipolar source, signals of sources A and B are phase-shifted by $\pi/2$ relative to each other. It should be noted that in the case of a different location of the sensors and multi-polar sounding, phase shifts between testing signals may be different. Thus, in the observation point O, a signal is formed as a superposition of the medium responses to the signal from each source:

$$\overline{E}_x = \vec{E}_{Ax} + \overline{E}_{Bx} = \vec{E}^0_{Ax} + \Delta\overline{E}_{Ax} + \vec{E}^0_{Bx} + \Delta\overline{E}_{Bx}$$

$$\vec{E}_y = \Delta\overline{E}_{Ay} + \Delta\overline{E}_{By} \qquad (1)$$

Where: $\vec{E}^0$ = the normal signal in the absence of changes in the medium, $\Delta\overline{E}$ = the abnormal component of the electric field caused by geodynamic changes in the medium.

In this case, the registering of geoelectric signals is conducted via informative parameters, which are phases φ_x, φ_y of the elliptically polarised geoelectric field that can be determined based on the following equations:

$$\varphi_x = \arctan\left(\frac{E^0_{Ax} + \Delta E_{Ax}}{E^0_{Bx} + \Delta E_{Bx}}\right), \quad \varphi_y = \arctan\left(\frac{\Delta E_{Ay}}{\Delta E_{By}}\right) \qquad (2)$$

Geodynamic variations of the researched object are determined by shifting fictitious sources that leads to a misbalance of the measuring system. Then, the corresponding signal vector is registered. After preliminary processing, the signal of the fictitious source shifting can be presented as a model of an adaptive-multiplicative class [SHARAPOV, KUZICHKIN 2014]:

$$E_x(t) = \Delta E_x(t,T)(1 + \xi_x(t)) + E^0_x(t) \qquad (3)$$

$$E_y(t) = \Delta E_y(t,T)\big(1 + \xi_y(t)\big) + E^0_y(t) \qquad (4)$$

Where: $\Delta E_x(t,T)$ and $\Delta E_y(t,T)$ are signals of fictitious source shifting based on the temperature dependence of the contrast coefficient; $E^0_x(t)$ and $E^0_y(t)$ = the trend of signal shifting; $\xi_x(t)$ and $\xi_y(t)$ = multiplicative noises characteristic for the action of planetary and climatic factors; T = the summarised temperature.

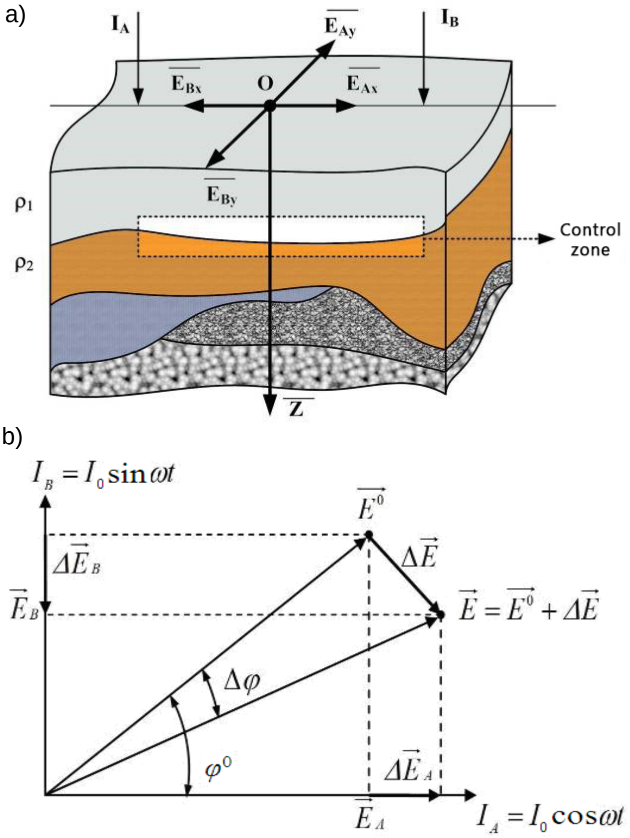

Fig. 2. Phase method of registering primary data for geoelectric control; I_A and I_B = current of the signal sources at points A and B, O = the observation point located at equal distances between points A and B, I_0 and ω = current amplitude and frequency, E = electric field strength, φ = phase of electromagnetic field, Δ = change of the corresponding parameter of electric field (strength or phase) due to geodynamics, E^0 and φ^0 = parameters of the normal signal in the absence of changes in the medium, ρ_1 and ρ_2 = specific resistivity of the medium 1 and 2, control zone is located at the intersection between two media, Z = strength of electric field along the vertical axis; source: own elaboration

In the case of insignificant shifting of the fictitious sources α^x_{jk} and α^y_{jk} and current balancing of the sounding signal poles of a multi-polar electrical facility, the resulting signal within the measuring system may be determined based on spatial transmitting functions $G_i(j\omega)$ and the geodynamic sensitivity of the measuring system β_{ij}:

$$E_{ix}(j\omega) = G_1(j\omega)\frac{\partial\beta_{ijk}}{\partial x}\alpha^x_{i1k}\left(1+\xi^x_{jk}\right) + \sum_{j=2}^{M} I_j \exp(j\varphi_j)\, G_j(j\omega) \sum_{k=1}\frac{\partial\beta_{ijk}}{\partial x}\alpha^x_{ijk}\left(1+\xi^x_{jk}\right) \qquad (5)$$

$$E_{iy}(j\omega) = G_1(j\omega)\frac{\partial\beta_{ijk}}{\partial y}\alpha^y_{i1k}\left(1+\xi^y_{jk}\right) + \sum_{j=2}^{M} I_j \exp(j\varphi_j)\, G_j(j\omega) \sum_{k=1}\frac{\partial\beta_{ijk}}{\partial y}\alpha^y_{ijk}\left(1+\xi^y_{jk}\right) \qquad (6)$$

Where $i = 1, \bar{N}$.

The system of equations (5) and (6) can be solved with regression expressions relative to the functions:

$$\theta^x_{ijk} = \Delta^x_{ijk}\left(1+\xi^x_{jk}\right)G_j(j\omega)\frac{\partial\beta_{ijk}}{\partial x},$$

$$\theta^y_{ijk} = \Delta^y_{ijk}\left(1+\xi^y_{jk}\right)G_j(j\omega)\frac{\partial\beta_{ijk}}{\partial y} \qquad (7)$$

with further elimination of tidal deformative noises and temperature correction of the results.

To monitor the geological medium at coastal zones of karst lakes, it is rational to use non-contact transformer electric field sensors [ROMANOV *et al.* 2015], which have no galvanic contact with the medium and enable to eliminate all types of excessive electrochemical noises.

FUNCTIONAL ALGORITHMS OF THE BASIC COMPONENTS OF THE MEASURING COMPLEX

The general function algorithm of the measuring complex for geoecological monitoring of karst lake coastal zones is shown in Figure 3.

After software is initiated, the first settings of the measuring complex are installed. Then, all devices connected to the system start to operate. The operator checks the functioning of all devices and connections. If all devices are ready, the operator transfers the system into an automatic mode. During the installation period t_G, a generator is started and the reference signal to the emitting electrodes is generated. After the transient processes have settled and the data reception regime is achieved, registering devices can start to operate, i.e. non-contact transformer sensors of an electric field and the temperature gradient sensor. After the set sounding time, t_p expires, the generator and registering devices are stopped.

The next repetition of this segment of the algorithm takes place after a preset period T_p. However, while waiting for the next stage of sounding, registered data undergo preliminary processing. Then, a set of data received from registering devices is formed. Next, results are corrected by the temperature factor, and the results of the geoelectric sounding are interpreted within the selected model [BYKOV, KUZICHKIN 2014; GRECHENEVA *et al.* 2016]. Their interpretation is based on well-known correlations that determine the depth and hydrogeological structure of the researched territory [KAZEEV, POSTOEV 2017; KHOMENKO, ALESHINA 2008; MILANOVIĆ 2000; MOLEK 2003]. The correctness of results interpretation depends on the degree of correspondence between the modelling method and geological objects and the accuracy of the qualitative estimation modelling. It is noted that despite the diversity and complexity of karst forms, the interflow structure (and accordingly, medium electric structure) and its first approximation can be performed with simple geoelectric models with the latter being geoelectric massifs with horizontal, vertical and inclined boundaries of media surfaces (tilted contact, step, horst, graben, funnel and the body of rotation).

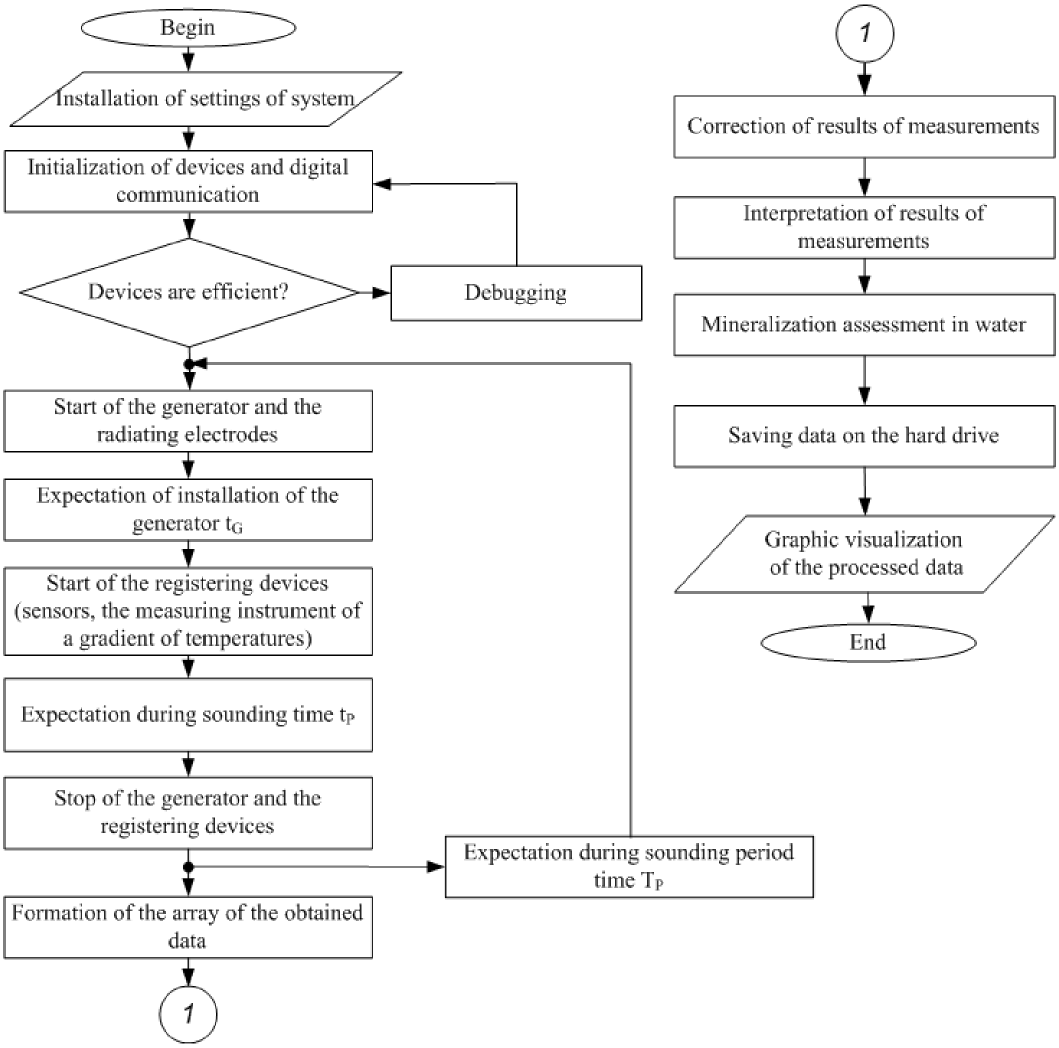

Fig. 3. The algorithm of the measuring complex; source: own study

HYDROGEOLOGICAL STRUCTURE OF THE RESEARCHED TERRITORY

Within the required depth of the studied section (up to depth of regional confining layer), the geological structure of the researched territory consists of the Dyas deposits and the Neogene and Quaternary formations. In the territory of Nizhny Novgorod region, karsting rocks are deposited at depths of up to 70–75 m and are mainly to the south of the Volga River. Accordingly, on the Earth’s surface and at foundations of buildings, karst is manifested predominantly in central, south-western and western parts of the Nizhny Novgorod region. The total area of the karst territories in the Nizhny Novgorod region is approximately 20,000 km^2 (27% of total area of region). Due to the uneven karst activity and varied thickness of mantle deposits, karst manifestations on the Earth’s surface (funnels, gaps, karst lakes, and hollows) are found on an area of approximately 13,000 km^2. In addition, karst manifestations tend to occur in river valleys and watershed depressions including the zones of karst lake flows.

In the studied territory, groundwater can be found in deposits of a rather large stratigraphic range from the Sakmarian to Quaternary stages. Their study depth was determined by the necessity to thoroughly research the features of karst Sakmarian and Lower Kazan deposits and connected groundwaters.

A hydrogeological monitoring was conducted in the coastal zone of the Lake Svyato (coordinates: N 55°46'3.36", E 42°19'44.4"). This is a large karst lake in the territory of the Nizhny Novgorod region (Russian Federation) of 20 m in depth. It was formed as a result of a merger involving several karst gaps, and it has rather steep sides 2–3 m high that are sharply cut with many promontories and bays. There are several large islands on the lake. The lake is moving within its bottom that consists of sand and a thick layer of silt, with water transparency up to 3 m.

This area was selected for monitoring because the most sensitive indicator of karst activity in this territory is the behaviour of karst lakes formed by depressive processes with the predominant underground flow. In this case, surface waters flowing into depressions are collected by sinkholes and feed the lakes. Karst processes intensify underground flow and disturb the zonal character of the underground flow distribution determined by geographical zoning. This leads to the redistribution of the underground flow in the nearby rivers within a relatively limited territory. Based on its regime type, the underground flow in the zones of karst depression lakes is similar to a river flow, forms regional patterns of maximums and minimums, and determines the intensity of karst processes at the local level. Accordingly, karst lakes significantly influence, both locally and regionally, the development of destructive karst-suffosion processes. This feature of karst lakes enables us to establish geoecological monitoring. The monitoring helps to forecast the initiation of destructive karst processes at the regional level.

RESULTS

To assess the development of karst processes in the territory concerned, we used a commonly known technique which helps to determine the presence and forecast surface karst manifestations. Using the results of a special land survey, conducted as an experiment by students and employees of the Murom Institute of Vladimir State University, and the Institute of the Earth Physics at the Russian Academy of Sciences in 2011–2012, a karst land spot was designated in the vicinity of the Lake Svyato in the zone of the lake discharge area of 0.7 km^2. The spot contained 97 craters of a total area 6,305 m^2. The crater density was 138 per 1 km^2, which translates into the crater coverage of approximately 90%. The average diameter of the craters was 8.1 m and the maximum diameter was 20.7 m. Results of the statistical analysis of the crater distribution with the breakdown by diameter are shown in Figure 4.

Figure 5 shows the territory with karst-suffosion processes.

The analysis can be used to allocate two control points at the coastal lake zone (Fig. 6). These are the key points (2 and 3) in the lake discharge zone with the top manifestation of karst processes and a reference point (1) for background measurements. The reference point was selected after considering water supply wells at a health camp. The data were used to exercise additional control.

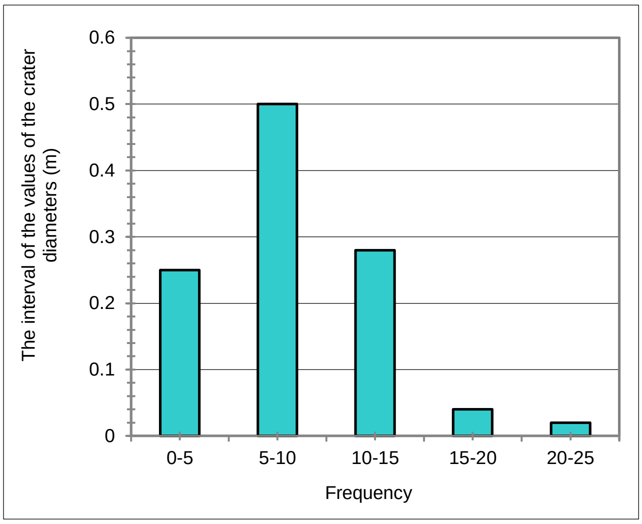

Fig. 4. Histogram of the karst crater distribution by diameter at the spot; source: own study

Before installing the hydrogeological observation system, detailed geoelectric research was conducted at selected key points, and a geoelectric section of the controlled zone was constructed, in which two water-bearing horizons were distinguished (Fig. 7).

Figure 8a shows the installation scheme for components of the information-technical complex and Figure 8b shows the appearance. The control of currents in emitting electrodes and the processing of signals received by noncontact transformer sensors take place at the control centre.

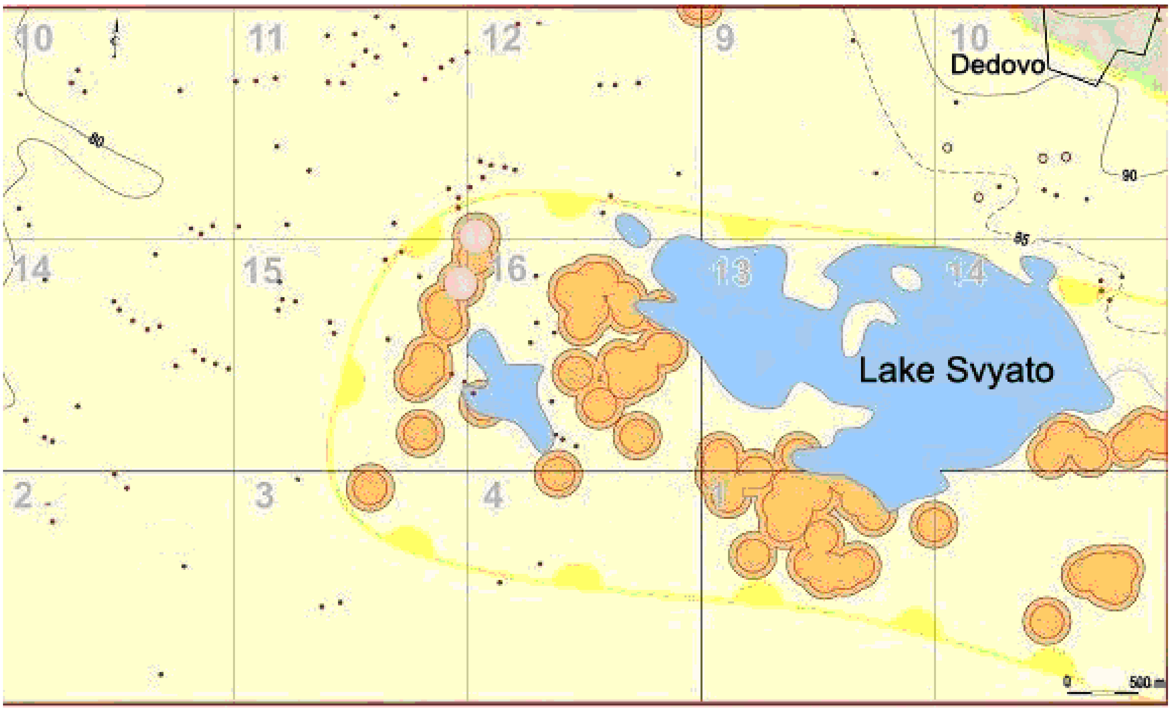

Fig. 5. Assessment of results within the area of karst processes (coordinates: N 55°46'3.36", E 42°19'44.4"); source: own study

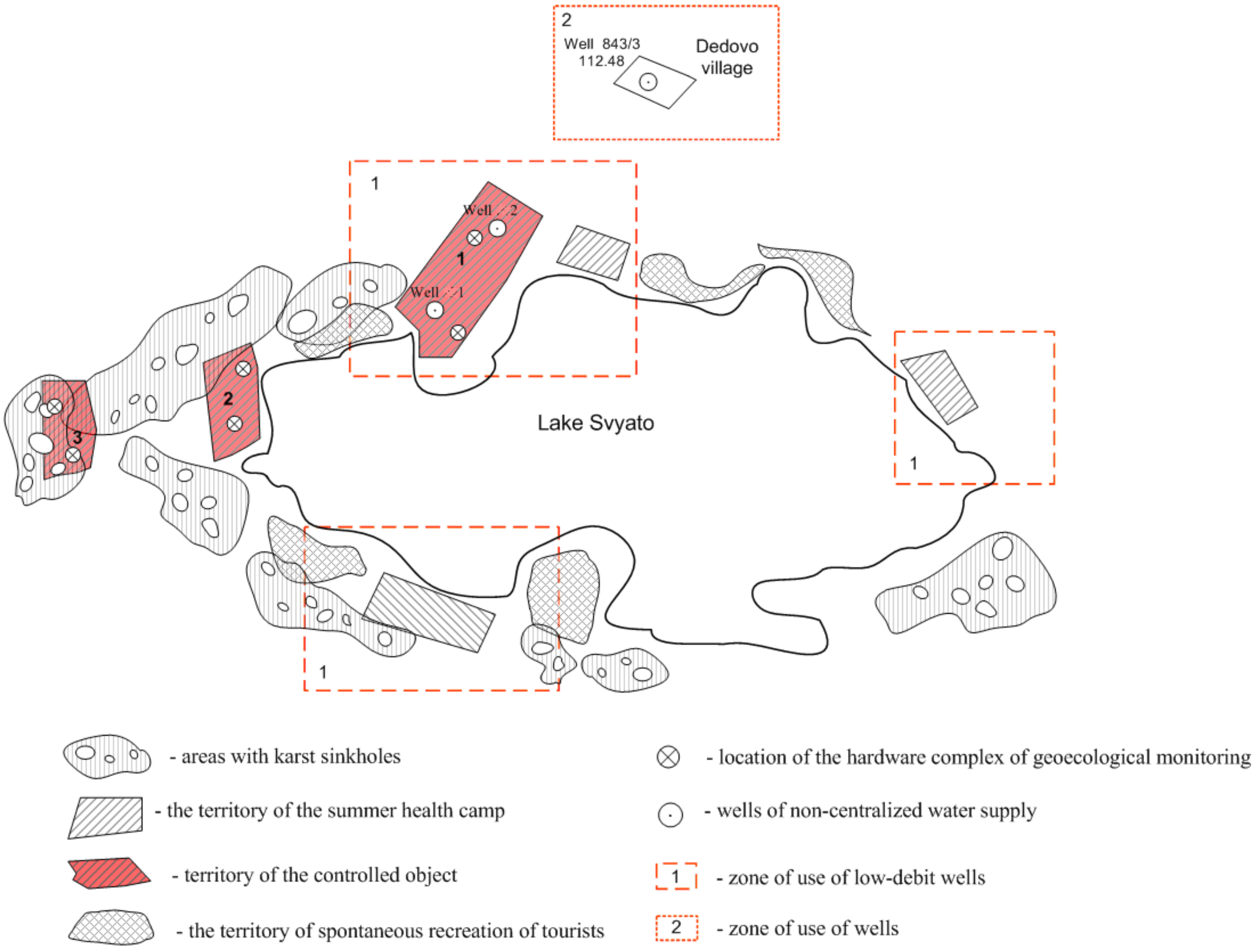

Fig. 6. Location of a hydrogeological observation system; source: own study

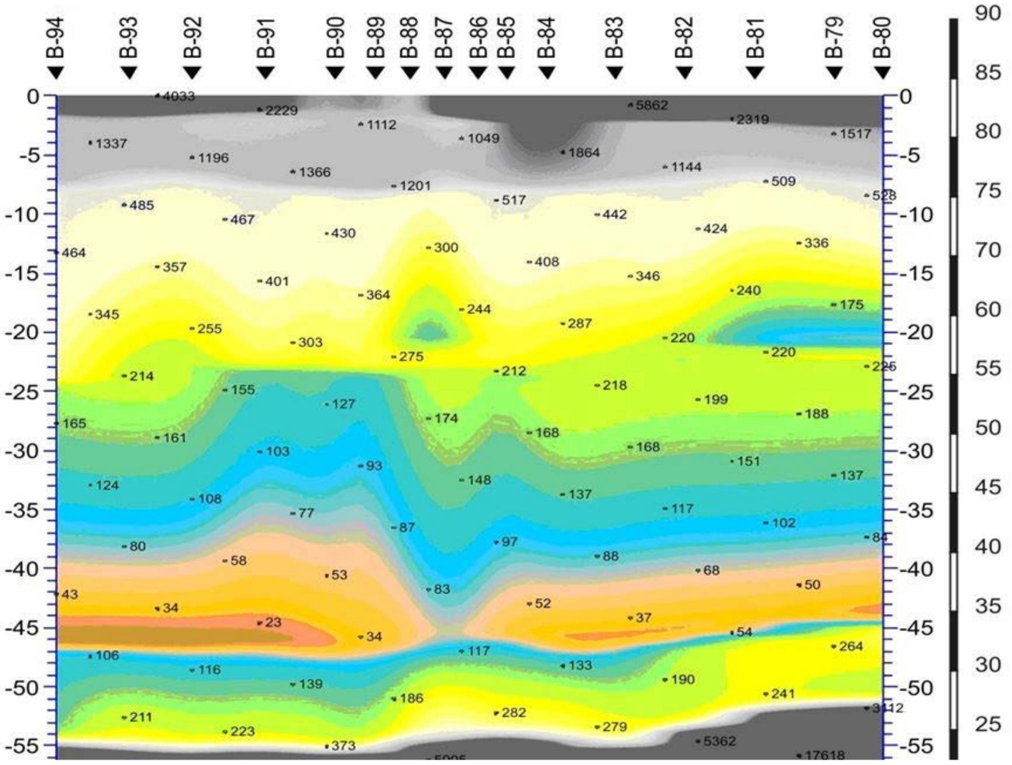

Fig. 7. Geoelectric section of the controlled zone; source: own study

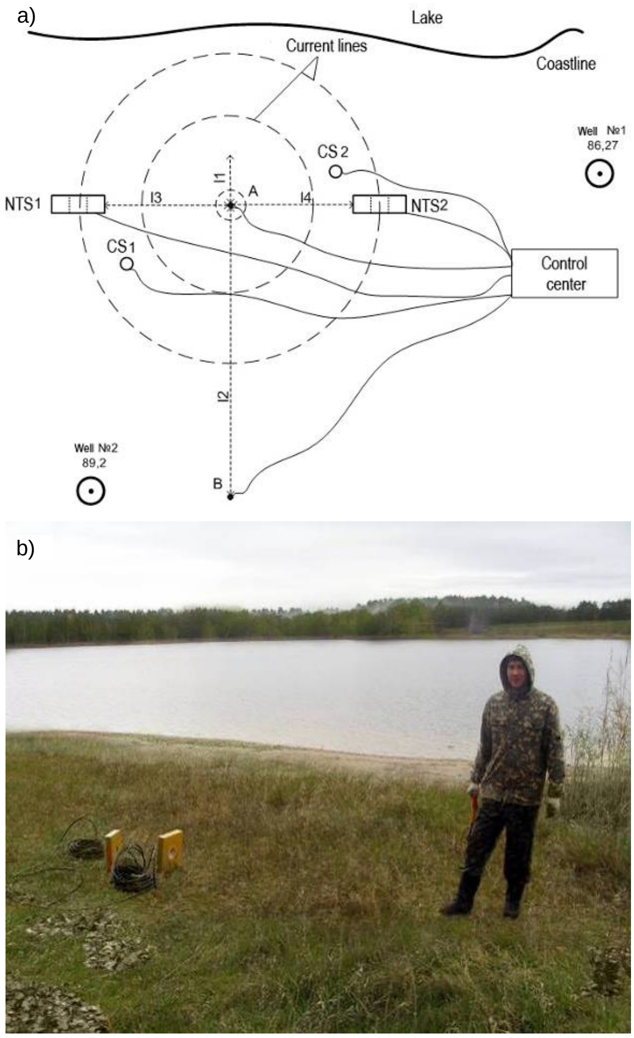

Fig. 8. The complex location on the reference hydrogeological control point: a) installation scheme, b) appearance; NTS = non-contact transformer sensors, A = emitting electrode and CS = current sensors; source: own elaboration

The measurement by the geoelectric system involved as follows: emitting electrode A was *l*1 = 5 m away from the lake coast*;* the first and second blocks of the non-contact transformer sensor (NTS1 and NTS2) were situated at distances *l*3 and *l*4 from the emitting electrode (given *l*3 = *l*4 = 30m); and electrode B was located at the largest possible distance (*l*2 = 250 m) from emitting electrode A.

In the main hydrogeological control zone, measuring sensors were deployed in accordance with the scheme shown in Figure 1, i.e. at two control points on the lake coast and 500 m away in the karst processes zone on the slope of an "active" karst crater (Photo 1).

Figure 9 shows data of calculated flow and geodynamic observations.

DISCUSSION

Observations were conducted from 1st May 2017 until 25th October 2017. Three zones were selected as observation points:

Photo 1. Installing the measurement system in the main control zone (phot. *R.V. Romanov*)

1 – the zone of reference hydrogeological observations in which the level and mineralisation regimes were measured in aquifers used for the non-centralised water supply;
2 – the zone of hydrological observations in the lake discharge areas where the level and mineralisation regimes of the aquifers were also measured;
3 – the zone of geodynamic measurements of karst processes.

The processing of control data was conducted with the use of a dedicated software by implementing algorithms described above.

According to control results (Fig. 7), the first aquifer belongs to Quaternary and alluvial sands, and the second aquifer belongs to crumbling and destructed rocks of the Kazan and Sakmarian stages. The area contains Quaternary alluvial deposits of the second terrace above the flood plain of the Tesha River. In the upper part of the layer, sands are fine-grained, deeper, and become anisomerous. In the source of the Lake Svyato and in the lake itself, water has very low mineralisation. According to the analysis, mineralisation is 0.008 $g \cdot dm^{-3}$. Based on its chemical composition, we deal with sulphate-calcium-magnesium water. The tests of water sampled from a well (18 m deep) in the territory of the Lake Svyato show that the waters are fresh and

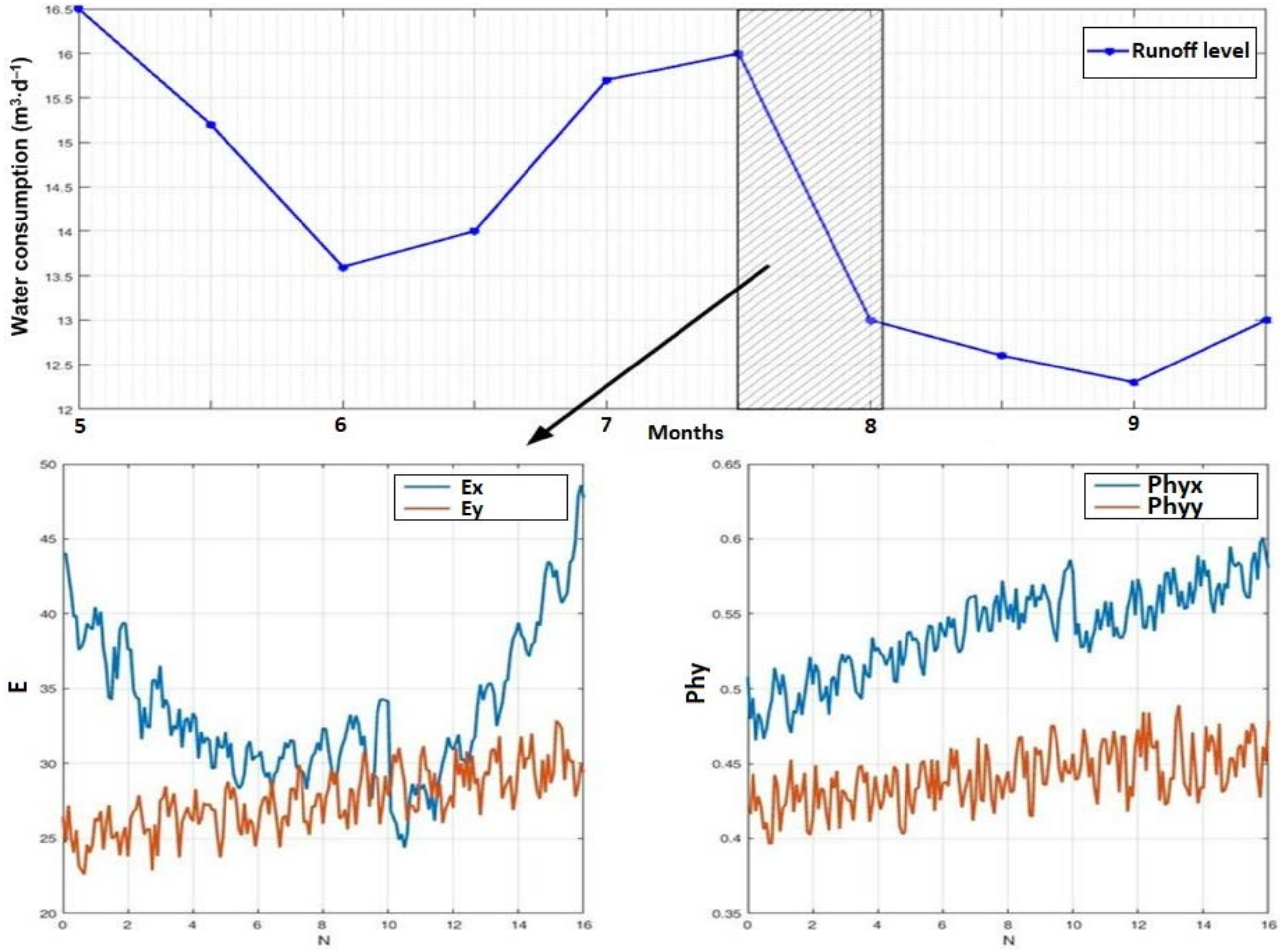

Fig. 9. Data of calculated flow and geodynamic observations; *Ex*, *Ey* = strength of electric field along *x* and *y* axes, respectively; *Phyx*, *Phyy* = phase components of electric field along the corresponding axis; source: own study

aggressive towards sulphates and carbonates. According to the chemical analysis, waters of the aquifer are sulphate-calcium-sodium. Furthermore, the mineralisation of the water solution is 0.07–0.23 $g \cdot dm^{-3}$. According to these data, the coastal zone waters are aggressive towards carbonates and unaggressive towards sulphate rocks.

The piezometric level of karst waters was very close to the level of ground above-karst waters. According to regime observations during the period, levels of ground above-karst waters exceed piezometric levels for the head karst waters alongside an increase in the general level of the first aquifer. Based on observations, the difference was from 0.7 to 1.6 m.

Figure 9 shows the period of geodynamic measurements in the third control point where the initiation of karst processes in the geodynamic control zone could be seen. It coincides with the change of the lake flow (count 10 in the graph of amplitude and phase data, which corresponds to the end of July).

CONCLUSIONS

The article presents research results and substantiation of the methodology for exercising the adaptive dynamic hydrogeological control over the territory of the Svyato karst lake in the Nizhny Novgorod region. This research distinguishes key zones of geodynamic karstological monitoring and applies a phase-measuring method of water resources geoelectric control.

Along with the hydrogeological monitoring system, the research has shown that karst is an active regulator of flow and significantly influences water exchange. Consequently, it also influences facilities located in the territory. The research determined hydrogeological conditions, volume, karst susceptibility, the degree of anisotropy of the aeration zone, and the presence of hydraulic interdependence between fissure-karst and river waters. This has been done based on the composition of karst rocks, conditions of their occurrence, and the structural-tectonic and neotectonic situation. The karst regulation of the flow is the process of forming and distributing surface and ground waters in time and space, in basins composed of easily soluble rocks. Therefore, the research confirmed the hypothesis that karst lakes significantly influence the development of destructive karst-suffosion processes (both locally and regionally). At the regional level, it is possible to establish the hydrogeological monitoring regime for the development and forecasting of destructive karst processes using the observation system operating in the vicinity of karst lakes.

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