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ARRANGING CONTROL OVER NON-CENTRALIZED WATER SUPPLY UNDER THE RISK OF GROUNDWATER DYNAMICS DISTURBANCE IN KARST TERRITORIES

Dr. Oleg R. Kuzichkin
Belgorod State University, Russian Federation
ORCID: 0000-0003-0871-8896
oldolkuz@yandex.ru
Ph. D. Roman V. Romanov
Vladimir State University named after Alexander and Nikolay Stoletovs, Russian Federation
ORCID 0000-0003-2736-2565
romanov.roman.5@yandex.ru
Ph. D. Nikolay V. Dorofeev
Vladimir State University named after Alexander and Nikolay Stoletovs, Russian Federation
ORCID 0000-0001-5029-7103
DorofeevNV@yandex.ru
Drado. Anastasia V. Grecheneva
Belgorod State University, Russian Federation
ORCID: 0000-0002-7341-5237
nastena07_93@mail.ru
Ph. D. Gleb S. Vasilyev
Belgorod State University, Russian Federation
ORCID: 0000-0002-7341-5237
vasilievgleb@yandex.ru

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Abstract

Presently, the use of non-centralized water supply in remote communities is the only possible option. In this case, monitoring water quality of water supply sources is a relevant and quite complicated task, especially when there are active karst processes and difficult groundwater conditions in the area of localities. Application of analytical algoristic-type water supply models under the risk of groundwater dynamics disturbance is not efficient. Major qualitative and even qualitative changes of groundwater conditions may occur between design moments, underestimation of which in expectation-driven design models may result in serious geoecological issues. This paper studies and justifies the use of the method of arranging adaptive dynamic hydrogeological control of the area of non-centralized water supply based on the identification of key zones of geodynamic karst monitoring and use of the methods of electrical express-monitoring of water resources. Identification of key zones is based on integrated analysis of available groundwater information that describes changes in groundwater hydrodynamic conditions in time during karst forecasting. It has been justified that the development of karst-suffosion processes is accompanied by much more intense dynamic changes in local areas of geologic environment compared to its summary variation intensity. Thus, information on the occurrence of destructive groundwater processes by way of selective geodynamic monitoring may be obtained much earlier than with environmental geodynamics monitoring as a whole. Experimental hydrogeological control activities of an area of non-centralized water supply have been conducted on a locality with the active manifestation of karst processes in the area of Pooksky right bank karst in Nizhny Novgorod region.

Keywords

Karst – Non-centralized water supply – Water quality – Hydrogeological control – Electrical express

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Introduction

Review of problems and methods of hydrogeological control in karst territories

Presently, water supply in the areas remote from major built-up areas relies on the use of water resources by means of non-centralized water supply (springs, wells, holes). Non-centralized water supply in remote communities is the only option in many cases. Reliable and high-quality water supply to these communities is a relevant task, especially when there are active karst processes. In these cases, the task is complicated by difficult groundwater conditions in the territory of localities and high vulnerability of karst groundwater to pollution due to its unique hydrogeological structure[1].

Karst water exchange systems differ from similar systems in insoluble rocks with a number of peculiar properties that are in charge of high natural and man-induced vulnerability of groundwater resources, their extremely low self-cleaning and pollutant dispersion ability. Cavitation distribution in the geologic environment is normally accepted as chaotic, cavitation and permeability parameters are averaged within the limits of certain sampled reservoir volume based on experimental data (borehole, geophysical and laboratory) and estimates[2]. Groundwater hydrology of karst territories has pronounced features[3], which makes these assumptions inapplicable to most practical tasks. The main difference of karst reservoirs from non-karst rock reservoirs is that their storage potential and filtration properties feature high spatial inhomogeneity and anisotropy. Despite a high share of karst channels in the overall volume of soluble rock cavitation (normally, in the range of 0.05-3%), they conduct 94-99% of the groundwater flow[4]. Groundwater speed in karst channels is 3-7 sequences higher than in non-karst water-bearing systems of an intense water exchange zone; normally, it amounts to hundreds and thousands meters a day. We should also mention the complex nature of the problem of conservation of underground drinking water supply sources in the regions of karst process development. If centralized water supply is used, water inlets are protected by establishing drinking water protection areas with special sanitary and epidemiological conditions to avoid water quality degradation of centralized domestic water supply sources and ensure the protection of waterworks[5]. In Russia, the project of the drinking water protective area and centralized drinking water supply system is agreed upon with the territorial subdivision of the federal executive body in charge of sanitary and epidemiological welfare of the population and consumer protection and is approved by executive state government bodies of constituents of the Russian Federation or local government bodies[6]. The border of the first conservative belt for groundwater intakes is set at no less than 30 m from the intake if protected

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[1] V. A. Korolev, The monitoring of the geological environment (Moscow: MGU, Russia, 1995) y A. I. Pecherkin, Geodynamics of sulfate karst (Irkutsk University Press, 1986).

[2] A. B. Klimchuk & S. V. Tokarev, "Recommendations for the protection of underground sources of drinking water supply in karst regions", Speleology and karstology, num 12 (2014): 5 – 16.

[3] V. N. Dublyansky & T. Z. Kiknadze, Hydrogeology of the Karst of the Alpine folded region of the USSR (Moscow: Science, Russia, 1984); A.B. Klimchuk, "Main features and problems of karst hydrogeology: speleogenetic approach". Speleology and karstology, num 1 (2008): 23 – 46 y D.C. Ford & D.W. Williams, Karst geomorphology and hydrology (London: Unwin Hyman, England, 1989)

[4] S. H. Worthington; D. C. Ford & P. Beddows, Porosity and permeability enhancement inunconfined carbonate aquifers as a result of solution. Speleogenesis: Evolution of Karst Aquifers. (2000).

[5] The Water Law of the Russian Federation of 03.06.2006 N 74. Retrieved 19.05.2018 from: http://www.consultant.ru/document/cons_doc_LAW_60683

[6] Special technical regulations "On drinking water and drinking water supply" Project N 284071-4. Chapter 3, Article 8. Retrieved 19.05.2018 from: http://docs.cntd.ru/document/902015702

groundwater is used and at no less than 50 m if poorly protected groundwater is used. Protected groundwater comprises head and free-flow middle water that is not supplied by overlying poorly protected water-bearing formations. Poorly protected groundwater comprises groundwater and middle water obtained from overlying poorly protected water-bearing formations via water courses and bodies by way of direct hydraulical connection[7]. However, territories with developed karst processes always meet the criteria of poorly protected groundwater and first belt border extension to 50 m does not ensure better groundwater protection. In non-centralized water supply is used, protection of sources is more of a recommendation. It is a duty of owners that must develop and fulfill a monitoring program including water use safety improvment activities.

Regulations of most countries with a large proportion of karst territories differentiate approaches to groundwater and water intake conservation in karst reservoirs. The approach applied to fractured reservoirs is the one that best matches their individual hydrodynamic features (degree of manifestation of continuous or discrete medium properties). For karst reservoirs, regulations of many EU member states prescribe a special approach to water intake protective zones that takes into account particular groundwater hydrology of the karst. The most representative legislation is that in Slovenia where about 95% of drinking water supply relies on underground sources[8].

European program COST Action 620 resulted in the elaboration of the European approach to assessing groundwater vulnerability in karst conditions in certain regions[9]. Methods in use are based on special (adapted to karst conditions) techniques of assessing groundwater vulnerability. The most well-known methods are KC used as the basis of the European approach and PI[10]. KC method[11] assesses resource vulnerability based on map data. PI method is based on protective function parameters of layers above the saturated zone and infiltration conditions. It ranks territories by five vulnerability grades. Infiltration conditions take into account the structure of topsoil, subsoil and zone made up of non-karst deposits and unsaturated zone of karst rock[12]. Water-bearing formation protection is estimated based on the statistical assessment by groundwater parameters of jointing distribution and spatial distribution of karst rocksand their height as well as annual average inflow and artesian pressure in a water-bearing formation[13].

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[7] Sanitary rules and norms 2.1.4.027-95 Zones of sanitary protection of water supply sources and water pipelines for domestic and drinking purposes. Sanitary rules and regulations. Retrieved 19.05.2018 from:http://docs.cntd.ru/document/1400014

[8] M. Brenčič; G. Prestor; B. Kompare; H. Matoz & S. Kranic, "Integrated approach to delineation of drinking water protection zones", Geologija, num 52 (2009): 175 – 182.

[9] F. Zwahlen, Vulnerability and risk mapping for the protection of car bonate (karst) aquifers; Final report COST Action 620, European Commission, Directorate (Belgium, 2004).

[10] N. Goldscheider; M. Klute; S. Sturm & H. Hotzl "The PI method: a GIS - based approach to mapping groundwater vulnerability with special consideration of karst aquifers". Z Angew Geol, 463 (2000): 157–166.

[11] J. M. Vias; B. Andreo; J. M. Perles; F. Carrasco & I. Vadillo, "Proposed method for groundwater vulnerability mapping in carbonate (karstic) aquifers: the COP method: application in two pilot sites in southern Spain", Hydrogeol J., num 14 (2006): 912–925.

[12] COST 65 Hydrogeological aspects of groundwater protection in karstic areas, Final report. European Commission, Directorate–General XII Science, Research and Development, Report EUR 16547 EN. 1995. Retrieved 19.05.2018 from: https://www.cordis.europa.eu/publication/rcn/199511660_en.html

[13] N. Ravbar & N. Goldscheider, "Comparative application of four methods of groundwater vulnerability mapping in a Slovene karst catchment", Hydrogeology J., num 17 (2009): 725–733.

EPIK method based on a vulnerability mapping concept using a multi-attribute method may be of use to assess vulnerability of non-centralized water supply sources[14]. EPIK has been developed to assess internal groundwater vulnerability to surface contamination and to determine protected zones in karst territories for groundwater forecasting. The method is based on mapping of the vulnerable territories where water supply relies on wells or holes. The method uses a geoinformation system (GIS) that simplifies vulnerability mapping. GIS uses digital topographical model analysis thus enabling automatic classification of infiltration conditions. Four attributes of a karst water-bearing formation are considered: Epikarst, Protective cover, Infiltration conditions, Karst network development. Each of the four attributes is divided into classes mapped across the study area. Next, attributes and their classes are weighed. Attribute maps are overlaid to obtain the final vulnerability map. The vulnerability map is used to define exact zones and elaborate groundwater conservation recommendations.

However, this approach has major drawbacks for the territories with the aggressive hydrogeological manifestation of karst processes and high technogenesis level under the risk of groundwater dynamics disturbance[15]. In this case, EPIK ignores possible aggressive dynamics of karst processes that may instantly change forecast groundwater conditions in the territory, as is the case with the unpredictability of dolines in the conditions of a covered karst[16]. In this regard, application of analytical algoristic-type water supply models under the risk of groundwater dynamics disturbance is not efficient. Major qualitative and even qualitative changes of groundwater conditions may occur between design moments, underestimation of which in expectation-driven design models may result in serious geoecological issues.

Principles and peculiarities of geoecological monitoring of non-centralized water supply in karst territories of Russia

About 35% of the Russian population consume drinking and sanitary water from natural freshwater sources[17]. According to rules and regulations, only water of the first water-bearing formation may be used in non-centralized water supply systems. Use of the second water-bearing formation (saturated with calcareous rocks) is legitimate for centralized water supply systems, while unauthorized use and production of water resources of the second water-bearing formation is a violation of law[18].

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[14] N. Dörfliger; P. Y. Jeannin & F. Zwahlen, “Water vulnerability assessment in karst environments: a new method of defining protection areas using a multi-attribute approach and GIS tools (EPIK method)”, Environ Geol, num 39 (1999): 165–176.

[15] R. Sharapov & O. Kuzichkin, Monitoring of Karst-Suffusion Formation in Area of Nuclear Power Plant. Proceedings of the 7th 2013 IEEE International Conference on Intelligent Data Acquisition and Advanced Computing Systems (IDAACS) (Germany, 12 – 14 September 2013)

[16] A. V. Grecheneva; N. V. Dorofeev; O. R. Kuzichkin & V. T. Eremenko, Organization of geodynamic monitoring on the basis of the geoelectric method. GeoBaikal 2016 – 4th International Conference: From East Siberia to the Pacific - Geology, Exploration and Development 4 (22 – 26 August 2016, Irkutsk, Russia)

[17] A. P. Demin, “The dynamics of water consumption by the population of Russia (1970- 2000)”, Water supply and sanitary, engineering, num 11 (2002): 9-13 y B. C. Ovodov, Agricultural water supply and watering. 3rd ed (Moscow: Kolos, Russia, 1984).

[18] Law of the Russian Federation of February 21, 1992 No. 2395-1 «On the Subsoil». Retrieved 19.05.2018 from: http://www.consultant.ru/document/cons_doc_LAW_343 y Law of the Russian Federation of February 21, 1992 No. 2395-1 «On the Subsoil». Retrieved 19.05.2018 from: http://www.consultant.ru/document/cons_doc_LAW_343

In this case, monitoring water supply is a relevant and quite complicated task, especially when there are active karst processes and difficult groundwater conditions in the area of localities.

Small localities and non-centralized water supply facilities normally use monitoring systems to control groundwater quality parameters and identify regions with different groundwater conditions. These systems have been built subject to availability of observation stations (wells, holes), analysis of water from which helps these systems monitor water resource pollution parameters and changes in the level of a water-bearing formation[19]. Monitoring organization is regulated by water resource internal monitoring authorities[20]. The biggest freshwater resources are found within the zone with free water exchange. In the territories with karst processes, this zone is unstable in terms of geodynamics, which is due to structural parameters of soil permeability and many aeration zones[21]. In this case, monitoring water quality of water supply sources is a relevant and quite complicated task, especially when there are active karst processes and difficult groundwater conditions in the area of localities. There were cases of abnormal local and regional changes in groundwater dynamics in these territories – water disappeared from wells and holes, entire lakes disappeared or, by contrast, glade areas were suddenly flooded (territory of Pooksky karst, Nizhny Novgorod region of Russia)[22].

Geoecological monitoring of groundwater dynamics implies control of a set of parameters:

- groundwater trends (space-time variations of the groundwater level);
- groundwater temperature trends;
- groundwater chemistry (mineralization, electrical conductivity, oxidation-reduction potential, acidity, toxicity, suspended solids and dry residual)[23].

An additional task of local groundwater parameter monitoring systems is data collection and presentation in bulletins that report yearly changes in geologic environment in the territory belonging to a particular regional center of Russia[24].

Rules for technical operation of water supply and sanitation systems in populated areas. Retrieved 19.05.2018 from: http://docs.cntd.ru/document/1200079794/ y Regulations on the procedure for licensing the use of subsoil. Decree of the Supreme Council of the Russian Federation. Retrieved 19.05.2018 from: http://www.consultant.ru/document/cons_doc_LAW_852/

[19] M. A. Somov & L. A. Kvitka, Water supply (Moscow: INFRA-M. Russia, 2014).

[20] V. M. Shestakov; I. K. Nevecherya & I. V. Avilina, The method of estimating groundwater resources in coastal water intake sites (Moscow: KDU, Russia, 2009).

[21] A. D. Abalakov, Ecological geology (Irkutsk: Publishing house of Irkut, Russia, 2007).

[22] V. V. Tolmachev; G. M. Troitsky & V. P. Khomenko, Engineering and construction development karstovannyh territories (Moscow: Stroiizdat, Russia, 1986);

[23] GOST 17.1.3.06-82. Protection of Nature. Hydrosphere. General requirements for the protection of groundwater. Available online: http://docs.cntd.ru/document/1200004387 (accessed on 19 May 2018); S. V. Temerev; V. M. Belov & V. P. Smagin, Water analysis. Altai State University (Barnaul: Publishing house of AltSTU, Russia, 2002) y Sanitary rules 2.1.5.1059–01. Hygienic requirements for the protection of groundwater from pollution. Retrieved 19.05.2018 from: http://docs.cntd.ru/document/901794517

[24] M. V. Androsov; A. L. Bazhaykin & I. Yu. Bortnik, Comment to the Federal Law of January 10, 2002 N 7 "On Environmental Protection" (Publisher: Norma, INFRA–M, Russia, 2014) Retrieved 19.05.2018 from: http://www.consultant.ru/cons/cgi/online.cgi?req=doc&base=CMB&n=18086#03288064267016071

Regulations for water management at non-centralized water supply facilities set out the main water use rules, except for the requirements to monitoring and inspection frequency.

As the Federal Law "On subsurface resources" does not prohibit groundwater production using private hole targets (wells, holes), the main concern in these cases is boring depth intractability. Sometimes, failure to comply with engineering requirements to well arrangement resulted in unintentional and unauthorized water intake from deep artesian springs, legitimate consumers of which are centralized water supply systems. Violation of the rate of exploitation affects detrimentally the second-level water-bearing formation that provides large regional centers with drinking water.

According to the law[25], the volume of water resources that a user may produce on his/her plot within a local non-centralized water supply system amounts to 100 l^3/day. Registration and monitoring of compliance in these cases imply constant control of the water-bearing formation level, which is quite complicated due to the lack of real-time tracking systems. If non-centralized water supply is an object of entrepreneurial activity to supply drinking water to a local community, according to regulations[26], the responsible person (entrepreneur) must continuously monitor the quality of water before it enters water supply sources. To this end, work programs must be elaborated and approved by sanitary and epidemiological supervision authorities and local government bodies. As is often the case, water quality control rules and regulations are not observed to the full and issuing and signing reports is a formality. This is due to the inaccessibility of water quality control tools in terms of cost or operational parameters (well drilling, fitting chemical-analysis laboratories, etc.).As was said earlier, lack of regulations for the established frequency of water intake for water quality control turns this process into something arbitrary, individual, and non-recurring or not occurring at all.

Fig. 1
Example of refuse dumps in dolines in the territory of localities

P. G. Lakhno, Energy Law of the Russian Federation. Formation and development (Publishing house of Moscow University, 2014).

[25] Law of the Russian Federation of February 21, 1992 No. 2395-1 «On the Subsoil». Retrieved 19.05.2018 from: http://www.consultant.ru/document/cons_doc_LAW_343

[26] GOST 17.1.3.12–86 General rules for the protection of water from pollution during drilling and production of oil and gas on land. Hydrosphere. Retrieved 19.05.2018 from: http://docs.cntd.ru/document/1200004385

We should also mention a problem typical of rural settlements – unauthorized refuse dumping on the outskirts of localities. As experience shows, dumps are arranged in natural depressions – ravines, dried-up riverbeds, etc. or in dolines (if any).Figure 1 shows an example of illegal dumps in dolines in localities with non-centralized water supply (Chud village of Nizhny Novgorod region, Russia, coordinates:N 55° 46' 3.36" E 42° 19' 44.4"). In some cases, these karst formations have direct channels that connect them with water-bearing beds used for water supply.

As was said before, if karst processes may become more intense, geoecological monitoring must be arranged in predefined points based on current groundwater data and prognosis in addition to routine procedures of water intake and analysis from non-centralized sources. In certain periods, groundwater parameters must be continuously monitored locally using data of regional monitoring networks.

Statement of study tasks

This article studies and justifies the use of the method of arranging adaptive dynamic hydrogeological control of the area of non-centralized water supply based on the identification of key zones of geodynamic karst monitoring and local geoecological monitoring based on the electrical express-monitoring method.

The proposed approach to arranging non-centralized water supply geoecological monitoring in localities in karst territories implies solving of the following tasks[27]:

- identification of key groundwater processes in a controlled territory that require groundwater and geodynamic monitoring in geologic environment based on the analysis of karst process conditions;
- choice and definition of methods to record and define monitored parameters;
- definition of bottlenecks and elaboration of reliable algorithms to identify hydrogeodynamic changes;
- assessment and analysis of identified abnormalities based on the models in use;
- forecast of potential irreversible catastrophic changes of groundwater conditions of non-centralized water supply utilization.

Materials and methods

Groundwater observation methods

Structure and algorithms of space-time processing of hydrogeological control data

Automated hydrogeological control systems are built around a possibility in principle to assess and make a geodynamic forecast based on local observations of individual isolated geodynamically active zones[28]. Individual medium volumes have their own natural pace and their geodynamics is determined by own technogenesis-complicated natural

[27] A. A. Orekhov & N. V. Dorofeev, “Development of software architecture for the automated monitoring of water objects”, Algorithms, methods and systems of data proc., num 24 (2013): 60–68.
[28] N. V. Dorofeev; O. R. Kuzichkin & V. T. Eremenko, The method of selection of key objects and the construction of forecast function of the destructive geodynamic processes. 16th International Multidisciplinary Scientific GeoConference SGEM, Bulgaria, 28 June – 7 July (Albena, Bulgaria, 2016).

conditions[29]. Still, they feature certain properties and characteristics that enable their description as a separate hydrogeodynamic object that belongs to a certain model class. In general, if the hydrogeological environment is described as an aggregate of large and small medium volumes (objects), individual hydrogeodynamic objects may be singled out that determine one or another process. This enables a focus on local geodynamic disturbances identified during the generalized assessment of hydrogeological environment and potential negative scenario forecasting.

Intensity of summary medium variations is much lower compared to the intensity of geodynamic changes of individual objects[30]. Thus, monitoring of hydrogeodynamic active zones (objects) identified yields information about possible catastrophic changes earlier than when medium geodynamics is monitored as a whole. The most promising methods for the arrangement of automated monitoring of geodynamic objects are electrical environment probing methods that ensure effective arrangement of groundwater object observations, state assessment, and development forecast thanks to their high technological effectiveness.

The authors have elaborated and used the geoelectric monitoring system for hydrogeological environment geodynamic zones. Figure 2 shows the generalized structure of the geoelectric data space-time processing system that describes the main processes of geoelectric data processing during geodynamic monitoring in the system elaborated[31].

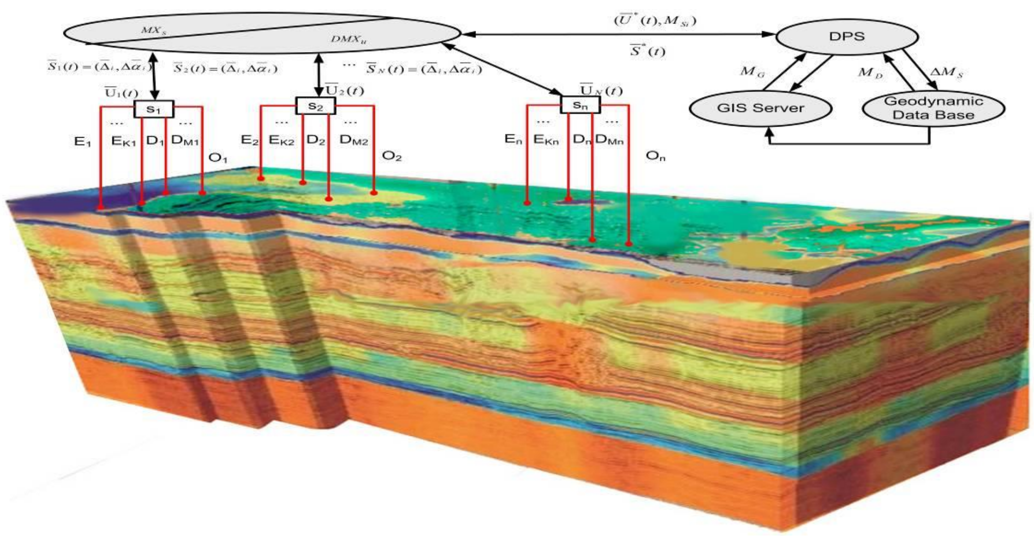


Fig. 2
Geodynamic monitoring geoelectric data space-time processing system

[29] R. Sharapov & O. Kuzichkin, "Geodynamic Monitoring in Area of Nuclear Power Plant". Applied Mechanic and Materials, num 492 (2013): 556–560.
[30] Yu. O. Kuzmin, Modern geodynamics and assessment of geodynamic risk in subsoil use (Moscow: Mountain Book, Russia, 1999).
[31] R. V. Romanov; O. R. Kuzichkin & A. V. Tsaplev, Geoecological Control of the Aquifer in the Decentralized Water Supply Systems of the Local Level. The 8th IEEE International Conference on Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications (IDAACS), Poland, 24 – 26 September (Warsaw, Poland, 2015).

The geodynamic monitoring geoelectric data space-time processing system is initialized based on the generation of model parameter vector $\mathbf{M}_S$ for the hydrogeological environment inspection zone. These model parameters are based on preliminary geological survey data in line with the Geodynamic Data Base $\mathbf{M}_D$ and GIS Server data $\mathbf{M}_G$:

$$\mathbf{M}_S = F_m(\mathbf{M}_D, \mathbf{M}_G). \qquad (1)$$

GIS data is used to determine geodynamic monitoring points (geodynamic monitoring objects) O_i and decompose model parameters $\mathbf{M}_S$ by model parameters of objects $\mathbf{M}_{Si}$:

$$\mathbf{M}_S \to (\mathbf{M}_{S1}, \mathbf{M}_{S2}, ..., \mathbf{M}_{SN}), \qquad (2)$$

where N is the total number of monitored objects.

Control signals for the initial setup and positioning of measuring geoelectric systems are generated:

$$\overline{\mathbf{U}}_i(t_0) = F_U(\mathbf{M}_{Si}, \overline{\mathbf{U}}^*(t_0)), \qquad (3)$$

where F_U is forming functionality of initial positioning by control vector $\overline{\mathbf{U}}^*$ by the by the geodynamic monitoring geoelectric data space-time processing system in the starting point $t = t_0$. Further on, measuring geoelectric systems operate directly in semi-automatic mode under the following algorithm:

$$\overline{\mathbf{U}}_i(t) = \overline{\mathbf{U}}_i(t_0) + \Delta\mathbf{U}(\mathbf{M}_{Si}, \Delta\overline{\alpha}_i) + F_U(\Delta\mathbf{M}_{Si}, \overline{\mathbf{U}}^*(t)), \qquad (4)$$

where $\Delta\mathbf{U}(\mathbf{M}_{Si}, \Delta\overline{\alpha}_i)$ is current control of electric installation positioning by hydrogeodynamic variation vector $\Delta\overline{\alpha}_i$; $\Delta\mathbf{M}_{Si}$ is model correction.

Data processing in geodynamic monitoring points O_i is based on fundamental principles of geodynamic monitoring inverse solution [9]:

$$(\mathbf{M}_{Si}, \Delta\overline{\alpha}_i, \mathbf{E}_i) = \mathbf{A}^{-1}(\mathbf{D}_i), \qquad (5)$$

where $\mathbf{D}_i$ is observed data vector;

$\mathbf{E}_i = \Psi(\overline{\mathbf{U}}_i(t), \mathbf{M}_{Si})$ are parameters of probing field source defined by the set model and control signal;

$\mathbf{A}^{-1}$ is inverse problem operator.

It should be noted that geoelectric data is often recorded with the noise determined both by interference in measuring channels and specific climatic and industrial factors. In this case, inverse solution implies determination of the model of object $\mathbf{M}_{Si}$ subject to geodynamic changes $\Delta\overline{\alpha}_i$ that would generate prognosis $\widetilde{\mathbf{D}}_i$ that matches best the data observed:

$$\widetilde{\mathbf{D}}_i = \mathbf{A}\ (\mathbf{M}_{Si}, \Delta\overline{\alpha}_i),\ \left\|\mathbf{D}_i - \widetilde{\mathbf{D}}_i\right\|^2_{\mathbf{L}_2} = \overline{\Delta}_i \to \mathbf{min}, \qquad (6)$$

where $\mathbf{A}$ is direct problem operator.

Intended use and operating principle of virtual multiplexer ($\mathbf{MX}_S, \mathbf{DMX}_\mathbf{U}$) is a correlation of geodynamic data flows $\overline{S}^* = ((\overline{\Delta}_i, \Delta\overline{\alpha}_i)\ \ i = \overline{1}, \overline{N})$ and control signals by the geodynamic monitoring geoelectric data space-time processing system with a data processing set (DPS).

Geoelectric express-monitoring method

A possibility in principle to use geoelectric methods to design a hydrogeological control system lies in the fact of the water specific conductivity-mineralization characteristic and, correspondingly, acquisition of data on the hydrogeological structure of the study medium. Besides, according to the state standard[32], specific conductivity recording at hydrogeological control objects is a part of the mandatory work program of water quality control.

When used for medium groundwater parameter monitoring, geoelectric methods have a number of advantages over other geophysical methods as the specific conductivity of water-saturated rocks is very different from that of dry rocks[33]. It is of importance that the same rock may have different specific conductivity depending on its mode of occurrence, internal structure, temperature, fillup with salt water. This rock property defines use efficiency of electric exploration methods to assess groundwater conditions of study media.

Natural environmental waters may be viewed as a mix of electrolytes (sodium, potassium, calcium, chlorine, sulfate, hydrocarbonate ions) that have strong and weak electrical properties. Unlike water of water-bearing formations, surface water is characterized by the prevailing content of inorganic compounds. We should also mention some ions that, due to their low concentration, do not produce material effect on water electrical conductivity parameters: Fe(II), Fe(III), Mn(II), Al(III), NO_3^-, NO_2^-, PO_4^{3-}, HPO_4^{2-}, $H2PO_4^-$[34]. However, reliability of water mineralization parameterization based on its specific

[32] GOST 17.1.3.07–82 Hydrosphere. Rules for water quality control of water objects and waterways. Retrieved 19.05.2018 from: http://docs.cntd.ru/document/gost-17-1-3-07-82

[33] R. V. Romanov; O. R. Kuzichkin & A. V. Grecheneva, “Geoecological control of the aquifer in a non–centralized water supply system at the local level”, Fundamental and applied problems of technology and technology, num 311 (2015): 137–142.

[34] Atlas of natural and man–made hazards and risks of emergencies in the Russian Federation (Publishing House Russian Academy of Sciences, 2005).

conductivity values deteriorates due to the complex chemical composition of surface water, sulfate ions in which have various electrical conductivity values, which determines a considerable range of degrees of conformity of the water mineralization level to electrical conductivity parameters[35]. The trial-and-error method is commonly used to make up for this drawback and determine the total mineralization: Values of the quantity of hydrocarbonates and chlorides available from experiments must be added to the calculated value of the quantity of sulfates (table 1).

Salt content (mg/dm³)	λ, mS/cm²			Salt content (mg/dm³)	λ, mS/cm²		
	Hydro-carbonates	Chlorides	Sulfates		Hydro-carbonates	Chlorides	Sulfates
1.0	81.90	108.80	103.80	8.6	73.58	102.44	85.52
2.0	80.10	107.30	99.20	10.0	72.70	101.80	83.90
3.0	78.80	106.20	95.70	11.0	72.10	101.40	82.90
4.0	77.70	105.30	93.00	12.0	71.50	100.90	82.10
5.0	76.50	104.50	91.00	13.0	71.10	100.60	81.20
6.0	75.70	103.80	89.20	14.0	70.30	100.20	80.50
7.0	74.80	103.30	87.60	15.0	70.10	99.80	79.70
8.0	74.00	102.80	80.30	20.0	68.20	98.30	76.30

Table 1
Dependence of group mean equivalent electrical conductivity (λ) at 18ºC on salt content in a solution

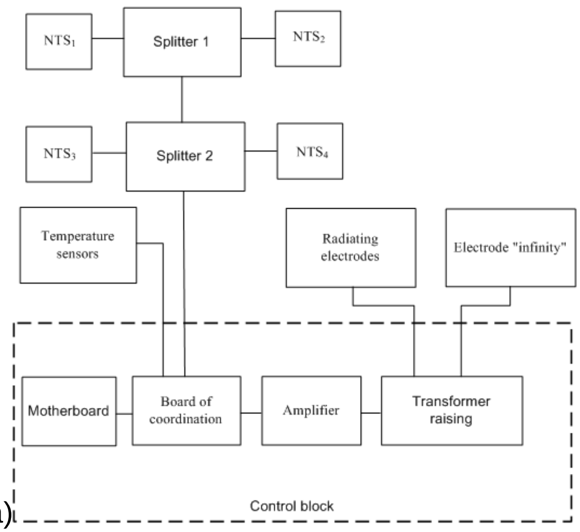
Underground water mainly comprises inorganic compounds; specific conductivity is a measure of its total ion concentration. Solid part of water consists of principle ions: Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, CO_3^{2-}, HCO_3^-. Increase in the water salt content results in enhanced interionic interactions. Velocity of ionic migration decreases as a result of cataphoretic effect. Electrical conductivity of water systems increases with temperature rise as it brings about a decrease in their viscosity and increase in dissociation rate. The result of assessing total mineralization of water based on its specific conductivity is not quite unambiguous. The main problems in these cases are caused by big variations in surface water chemical composition that results in varying electrical conductivity of different salts. This is why mineralization and electrical conductivity vary widely. However, practical application of the hydrogeological control system takes temperature effect into account and additional water sample analysis is expected in case of considerable electrical conductivity variations[36].

[35] Accelerated methods of quality control of natural wastewater and distilled water according to their electrical conductivity data. Guidelines. Retrieved 19.05.2018 from: http://tatarstan.regnews.org/doc/ae/tt.htm

[36] R.V. Romanov, Data processing in automated control systems of the aquifer of non-centralized water supply. Collection of proceedings on the materials of the 7th All–Russian Scientific and Practical Conference with international participation, Russia, 10-12 April (Saratov, Russia, 2015)

Hardware of the geoelectric monitoring system

The geoecological monitoring system designed contains non-contact differential electric field transformer transducers at data collection points[37]. Besides, the system in basic configuration comprises a control unit, set of radiating electrodes, including an electrode positioned far from the analyzed site ("infinity"), temperature and moisture sensors and intermediate communications equipment. The functional chart of the local water-bearing formation geoecological monitoring system for non-centralized water supply is shown in figure 3a, while figure 3b shows the system's layout.



a) b)

Fig. 3
System of local water-bearing formation geoecological monitoring

As the system has a big footprint, cable lines are used to connect measuring and intermediary devices to the control unit and to supply these devices. Industrial or dedicated protocols are used as data protocols; for example, RS-485 may be used as an interface. All system components are controlled by the "Control unit" that operates under algorithms (1-

[37] A. A. Orekhov, "Research and development of software and hardware complex for environmental monitoring of surface and groundwater on the basis of the method of geoelectric control", Scientific notes of the Russian state hydromet. Un, num 28 (2013): 72–77.

6). It consists of the following components: motherboard, board of coordination, amplifier, transformer raising. The board of coordination is used to interface the control unit and industrial interface. Besides, the matching unit generates a reference probing signal that comes to the amplifier and then to the transformer for further enhancement and galvanic isolation.

This measuring equipment enables simultaneous recording of electrical conductivity of a water-bearing formation and its level with reference to measuring sensors.

Territory and conditions of experimental studies

Geotechnical conditions of karst development in the study area

Carbonate (limestone, dolomite) and sulfate (gypsum, anhydrites) rocks are soluble (karsting) rocks found in Nizhny Novgorod region of Russia. When karst rocksare represented by carbonate and sulfate rocks, karst is classified as carbonate-sulfate. According to[38], karst rocksin Nizhny Novgorod region normally occur at a depth of up to 70-75 m, mostly to the south of the Volga river.

Carbonate karst is common in the south of the region (Pervomaysk, Diveevsk, Voznesensk districts, Sarov, etc.). Carbonate-sulfate karst prevails in the rest of the karst territory (Dzerzhinsk, Nizhny Novgorod behind the river, Pavlovo, Arzamas districts, etc.). Gypsum karst (in its pure form) is not commonly spread (can be found in Dzerzhinsk, Pavlovo, etc.) The total area of karst territories in Nizhny Novgorod region is about 20,000 sq. km (27% of the total region area). As a result of irregular karst activity and varying thickness of covering deposits, karst occurrence above ground (sinks, gaps, sink lakes, kettles, etc.) is found over an area of about 13 th. sq. m. Surface karst occurrence is confined to river valleys and watershed depression areas. Consequently, they are mainly found on the right bank of the Volga river (at the Balakhna – Nizhny Novgorod section), in basins of Oka, Tyosha, Seryozha, Kudma, Pyana, Alatyr and other smaller rivers of this part of Nizhny Novgorod region with a broad range of sparsely populated localities that use non-centralized water supply[39].

According to groundwater studies, the following conventional karst development types are found in Nizhny Novgorod region subject to their geological structure. These types are mainly determined by geological section types conventionally named Dzerzhinsk-Nizhny Novgorod, Arzamas-Pavlovo and Vyksa-Pervomaysk. The study area belongs to the Arzamas-Pavlovo geological section[40] (figure 4).

[38] Territorial building norms 22-308-98 Engineering surveys, design, construction and operation of buildings and structures in the karst areas of the Nizhny Novgorod region (Russia, 2012).
[39] A. A. Shilnov, “The influence of karst on the formation of natural landscapes of the Tesha-Seryozhinsk natural area”, Ecology and conservation, num 5 (2002): 96–99.
[40] Atlas of natural and man–made hazards and risks of emergencies in the Russian Federation (Publishing House Russian Academy of Sciences, 2005)

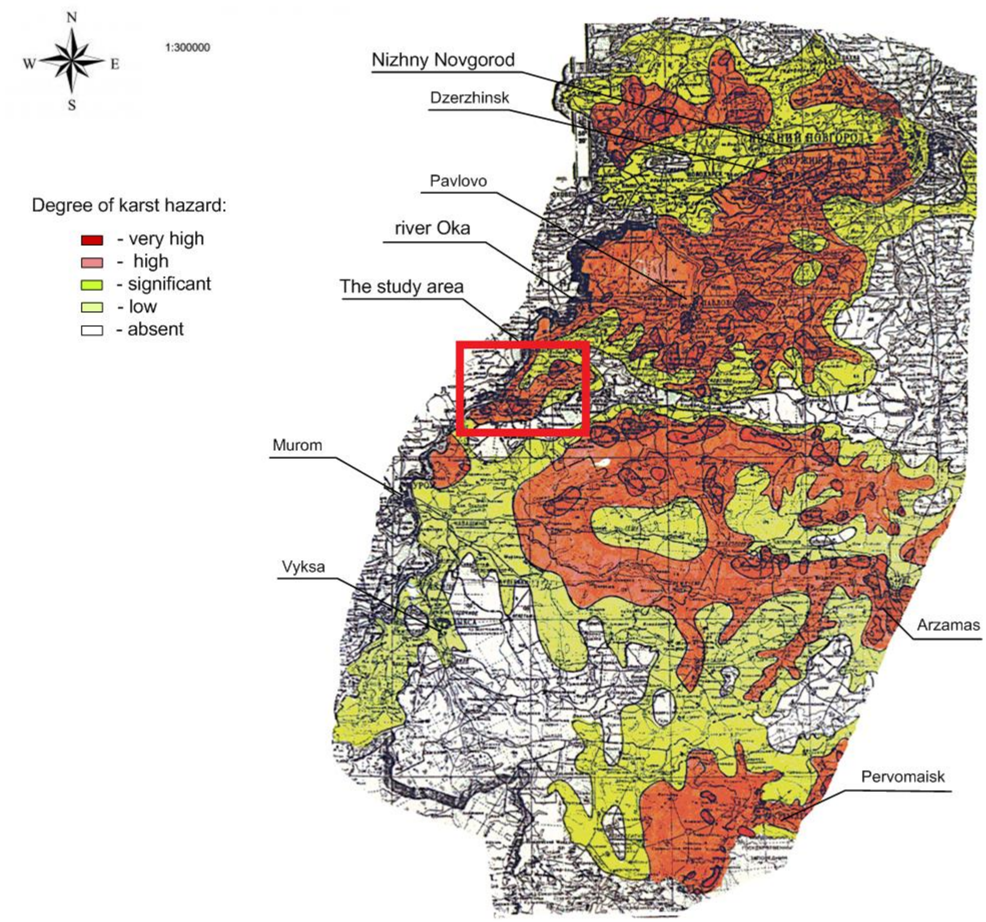


Fig. 4
Map of karst regions of north-western spurs of the Volga upland within confines of Nizhny Novgorod region (coordinates: N 55° 46' 3.36'' E 42° 19' 44.4'')

In the Arzamas-Pavlovo geological section type, soluble karst rocks (limestone, dolomite, gypsum, anhydrite) normally occur relatively close to the earth surface. Areas where karst rocksoccur at a depth of up to 60 m are less frequent. In most cases, karst rocksare concealed under Quaternary and Permian loam soils. Along river valleys, karst rocksoccur directly under Quaternary alluvial deposits, on valley sides, they sometimes crop out. Carbonate-sulfate karst prevails; purely carbonate or sulfate karst is less common. Quaternary deposits are represented by eluvio-diluvial loam soils, loess loams of problematic origin, fluvio-glacial deposits and in river valleys – by alluvial sandshale deposits. The thickness of Quaternary deposits ranges from 0 to 30 m. Tatarian Upper Permian are the underlying rocks represented by clays, marl, silty rocks. Their thickness ranges from 0 to 50 m.

Kazanian Upper Permian deposits that commonly underlay Tatarian clays are represented by limestone with dolomite streaks. The thickness of Kazanian deposits reaches 15 m. In some parts, Kazanian deposits are absent. They are normally characterized by selective or volumetric solution. Rocks are cleaved, often broken down to ballast, debris, limestone-dolomitic powder, completely dissolved occasionally with the formation of cavities of varying height filled with water or foreign matter. Height of recorded cavities is from 0.2 to 3.0 m.

Gypsum and anhydrites of Lower Permian Sakmarian contacting with overlying Kazanian and Tatarian Upper Perm deposits in the region are most prone to dissolution with the formation of flaws and cavities. Cavity height is from 0.2 to 7.0 m. Artesian aquifer, with the blocky part of gypsum-anhydrite mass as the confining layer, is confined to limestone and dolomite and where they are absent – to the roof of gypsum-anhydrite mass.

According to the karst hazard map, the study area lies close to the border of the so-called "non-hazardous" and "potentially hazardous" territory and may be classified as moderately hazardous[41]. According to conclusions of PNIIIS JSC (2008-2009), the study site is situated in the territory of potential development of highly dangerous natural and human-induced processes (hazard level I), while in terms of doline formation intensity, the site belongs to grade V-VI that matches low probability of caving[42].

According to the current classification, karst process of the study region is of carbonate-sulfate covered type. With this type of karst, karst territories are very sensitive to geologic environment pollution, including groundwater as a result of various karst manifestations (sinks, uneven yielding of foundations, setting, also related to gypsified soils, karst sinkholes, etc.). Consequently, water use zones in this territory have a complex hydrogeological structure prone to possible changes and high probability of water leaks from reservoirs and water use channels. Major sinkholes from very big depths have occurred in the study area. For example, a sinkhole 45 m in diameter (2005, near Bolotnikovo village of Vacha district of Nizhny Novgorod region). This sinkhole resulted in complete disappearance of water from a lake (also of doline origin) in two-three hours.

Characterization of non-centralized water supply of the study area

Underground water of the study area is confined in deposits of quite considerable stratigraphic range from Sakmarian to Quaternary deposits. Their study depth was conditioned by the need for detailed study of peculiarities of karsting Sakmarian-Upper Kazanian deposits and associated groundwater. Only two layers are used for water supply of localities:

- Quaternary alluvium aquifer;
- impervious locally low-yield Don moraine aquifer.

The Quaternary alluvium aquifer is confined to the valleys of the Oka, Tyosha rivers and their confluents Bol. Kutra, Muromka, and Led. Alluvial formations of bottomland and terraces above the flood-plain are water-bearing. They are almost entirely made up of sand of varying fractional makeup and clay content. Sand permeability ranges from 2 to 12 m/day. Layer water is unconfined; it has a common hydrostatic surface. Its occurrence depth ranges from fractures of a meter to 12 m, which is mainly due to the lie of the ground. The thickness of the alluvial water-bearing formation ranges from 16 to 24 m. On top of the alluvial section (above the water-bearing formation roof) where loam streaks and lenses are often found, there is a chance of formation of temporary groundwater. According to the data of the isolated wells used for non-centralized water supply, well yields range from 2.8 to 5.7 l/s. When the level decreased from 1.8 to 6.5 m, specific yields amounted to 0.31-2.0 l/s.

[41] Report of Institute for Engineering Surveys. Zoning of the territory of the Nizhny Novgorod region on the development of especially dangerous natural and technogenic processes (2009).
[42] V. V. Tolmachev, About a technique of the quantitative estimation of the natural factors influencing formation of karst sinkholes. Collection of MIIT. Volume 273 (Russia, 1968).

Water transmissibility was 31-200 m^2/day. The layer has fresh sulfate-carbonate water with mineralization of 0.2-0.5 g/l. In the areas of hydraulic connection with confined salt water of underlying deposits, alluvium water mineralization increases to 0.9-1.6 g/l. This water has sulfate composition. The groundwater is mostly recharged by way of precipitation infiltration. Water is discharged into the river network. In spots, the layer is recharged with confined water coming from underlying Urzhumian and Kazanian-Sakmarian strata, within paleovalleys and areas of occurrence of Holocene alluvium of the Oka river directly on the sulfate-carbonate rock mass.

The impervious locally low-yield Don moraine aquifer combines aqueoglacial (super-moraine) and glacial deposits (moraine) made up of fine silty sand with uneven clay content with ballast inclusions and drift clays containing sand and ballast lenses. The total thickness of deposits ranges from 0 to 18.0 m, the thickness of watered rocks is low; sometimes it reaches 15.0 m. Deposit water is unconfined or little confined. The occurrence depth of watered rocks varies from fractures of a meter to 6.5 m depending on the lie of the ground. Interbedded water is characterized by poor water abundance. It serves as a water supply source for local communities that use wells up to 5.0 m deep. In terms of its chemical composition, it is hydrocarbonate calcic water with the mineralization of 0.05-0.48 g/l. As we have mentioned earlier, in the territory of the localities, water is often exposed to pollution with domestic waste. The layer is recharged by way of precipitation infiltration. Water is discharged via the ravine-gully network in the form of little springs and water holes.

Temporary groundwater is often formed in local areas in top layers underlying drift clays. This water contributes to waterlogging and formation of small suffusion catholes.

In the study area, non-centralized water supply is mainly arranged using wells in the territory of localities that are used for drinking water supply (figure 5a). Artificial and natural reservoirs are used for domestic water supply; most of these reservoirs are of karst origin (figure 5b). As we mentioned earlier, some households have their own stripped wells.

a) 

b) 

Fig. 5
Typical sources of non-centralized water supply in the study area: a) Drinking well; b) Domestic water supply reservoir.

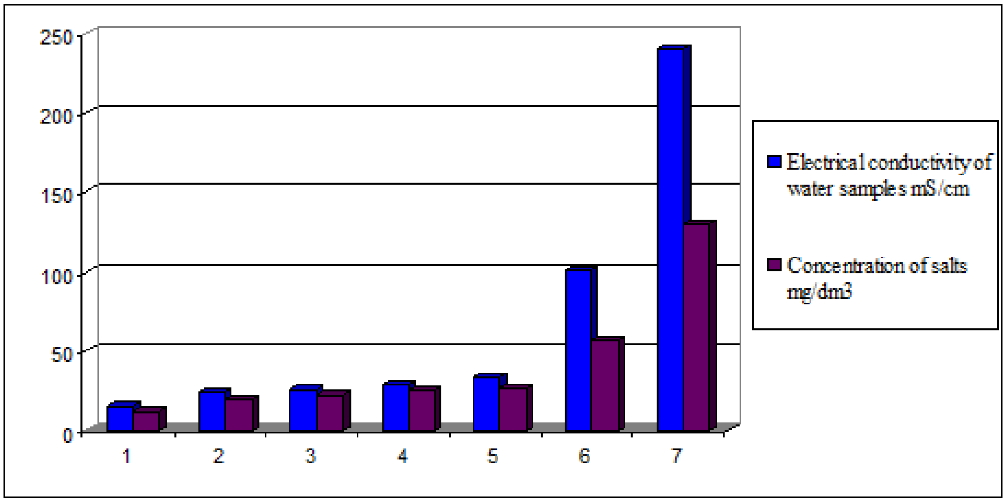
The purpose of the experimental work in Chud village of Nizhny Novgorod region was to arrange monitoring observations using the elaborated system of dynamic hydrogeological control of the area of non-centralized water supply based on the identification of key zones of geodynamic karst monitoring and local hydrogeological control based on electrical methods.

Results

Figure 6a shows results of assessing electrical conductivity parameters in the water samples taken from non-centralized water supply sources, Oka river and its confluents in the study area.

Figure 6b shows data of downhole observations and data obtained using the method of multifrequency vertical electrical sounding at a water intake of the non-centralized water supply of the study area when testing the hydrogeological control measuring system[43].

[43] V. V. Tolmachev, About a technique of the quantitative estimation of the natural factors influencing formation of karst sinkholes. Collection of MIIT. Volume 273 (Russia, 1968).



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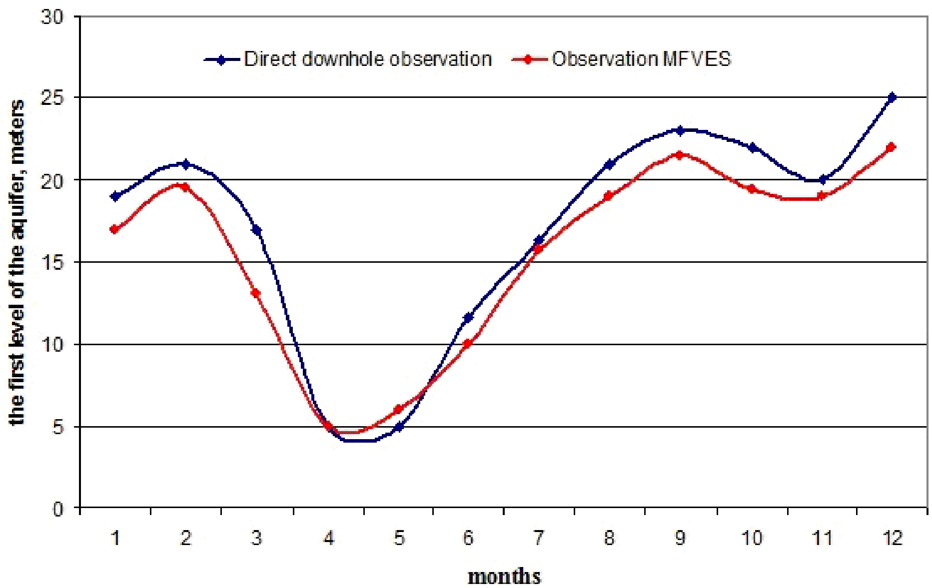


b)

Fig. 6
Results of assessing water-bearing formation level and concentration of salts using electrical conductivity express-monitoring

The experiments conducted in Chud village of Nizhny Novgorod region allowed to locate the main sources of non-centralized water supply in Chud village and identify key points of territory hydrogeological control with division of the karst massif into the area of precipitation and surface water infiltration and inflow, groundwater flow area and area of karst water discharge beyond karst rocks (figure 7).

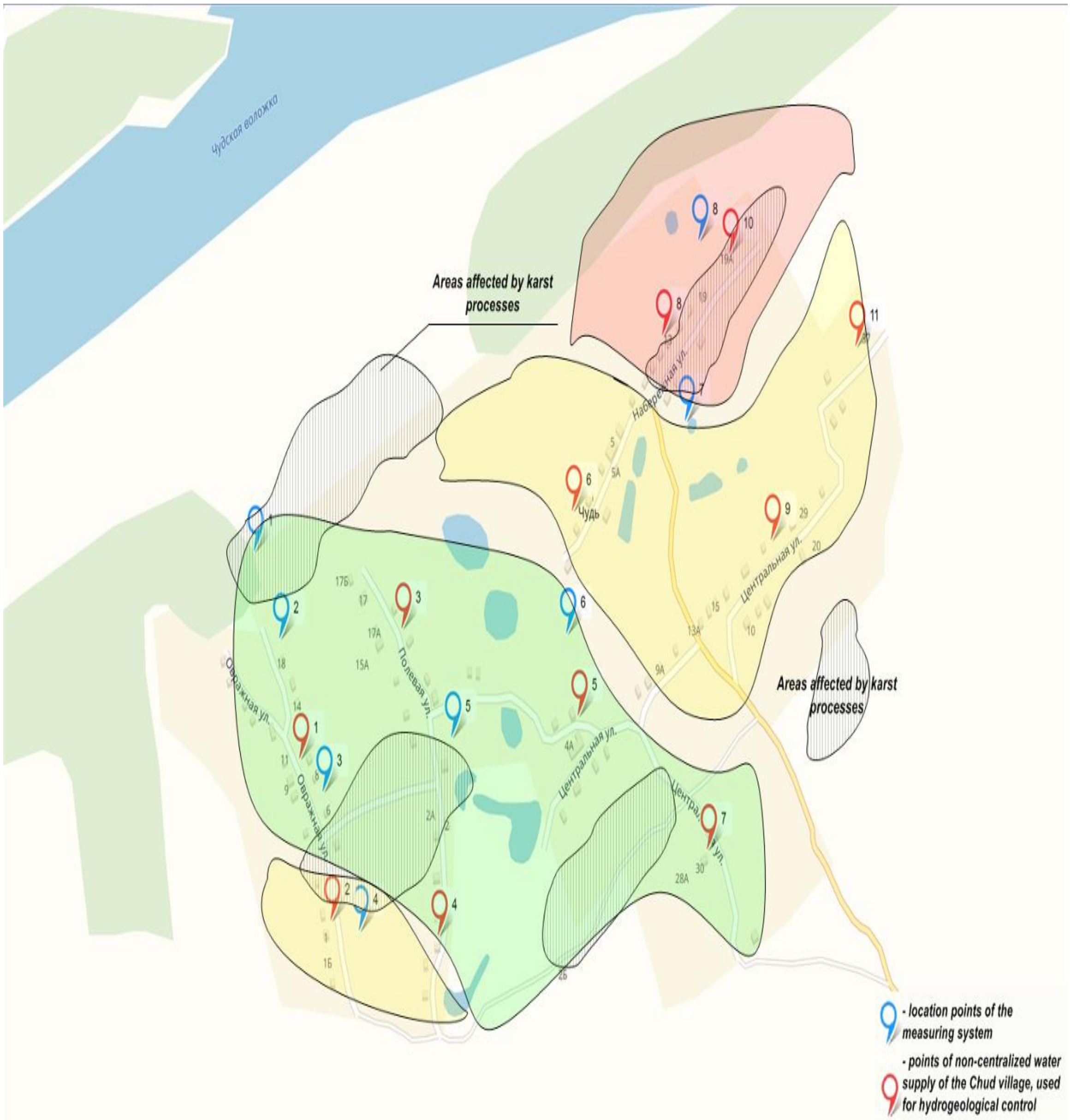


Fig. 7
Layout of the main points of non-centralized water supply and hydrogeological control system deployed (coordinates: N 55° 46' 3.36'' E 42° 19' 44.4'')

Monitoring observations were performed from February to September 2017 at eight local monitoring points using a two-pole equipotential unit. Besides, downhole observations were performed in a keyhole near point 3 for additional control of data acquired. Table 2 provides averaged monthly data on mineralization at observation points.

Months	Mineralization, mg/dm^3; numbers of observation points										
	1	2	3	4	5	6	7	8	9	10	11
March	264	441	290	189	296	400	297	1,203	486	1,030	443
April	380	458	340	195	304	559	300	1,570	650	1,500	590
May	391	460	345	200	317	700	316	1,510	781	1,662	722
June	320	446	243	177	209	626	266	1,375	720	1,549	662
July	267	412	204	163	192	570	257	1,210	670	1,451	620
August	280	437	281	167	280	600	260	1,340	688	1,480	652
September	307	446	290	184	294	653	285	1,310	689	1,509	703

Table 2
Experimental mineralization data

Figure 8 shows a bar chart of mineralization change assessment by observation points; figure 8b shows a bar chart of water-bearing formation level assessment for the period of observations based on geoelectric measurements.

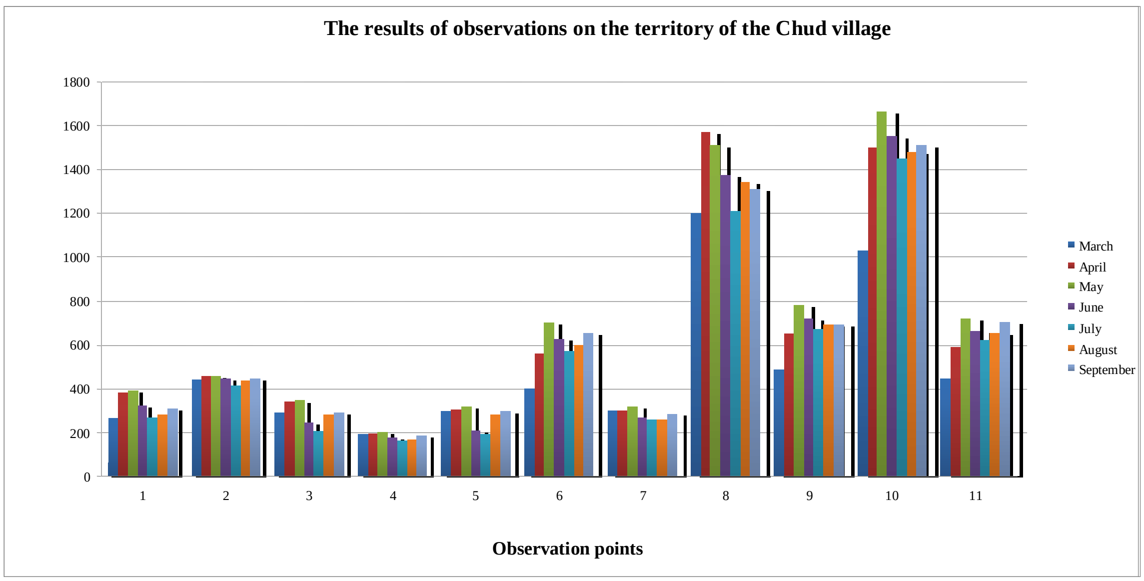
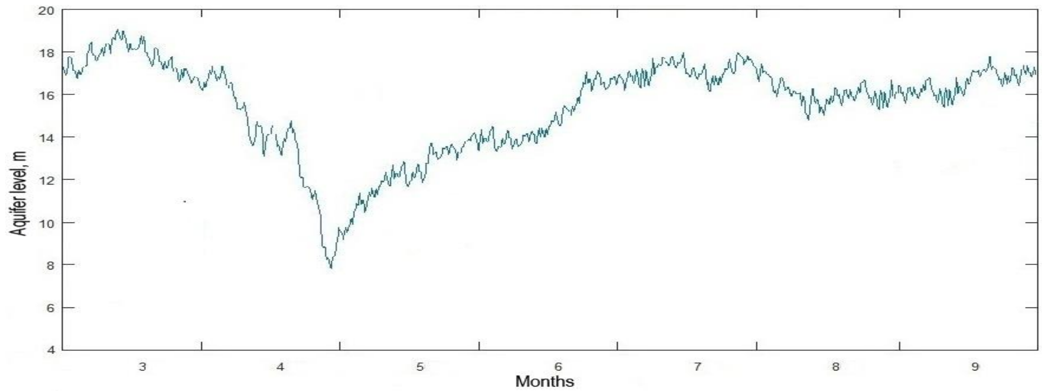
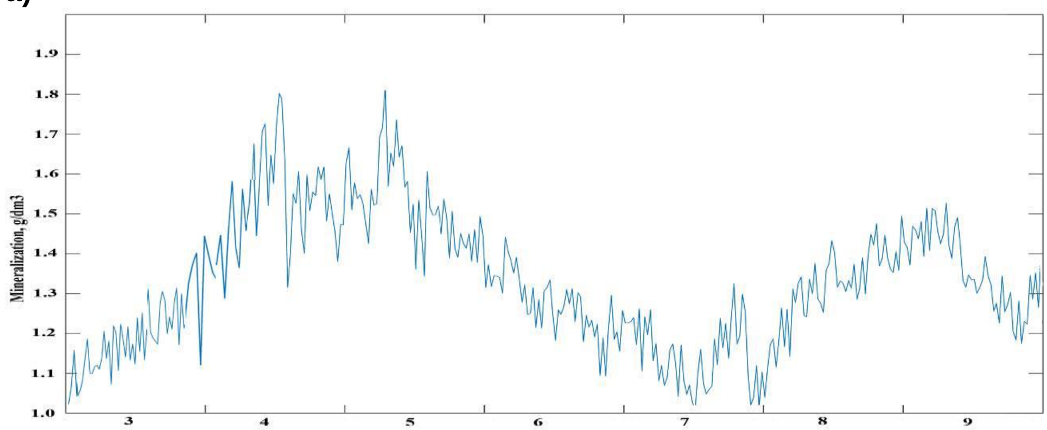


Fig. 8
Bar charts of mineralization change assessment by observation points

Figure 9 shows comparative data of direct and downhole observations of the water-bearing formation level and mineralization of water used for drinking water supply.



a)



b)

Fig. 9
Data of direct and downhole monitoring observations of the water-bearing formation level and mineralization of water used for drinking water supply (point 8).

Discussion

The preliminary hydrogeological survey was conducted at the chosen site with the determination of karst water movement conditions related to lithologic heterogeneity of the massif, its rock diversity, depth of erosion and degree of karst development.

The studies conducted using the electrical express-monitoring method elaborated to interpret and analyze hydrochemical and electrochemical monitoring data have shown high effectiveness of the method. Benchmarking of data in figure 6 shows that the discrepancy of the data of direct downhole observations and measurements using the method under study does not exceed 12%.

Data of monitoring observations shows that water sources recharged by the zones of surface circulation and vertical descending circulation are used as household water supply in the study area. Precipitation or snowmelt water drains off the rock surface and if there is grass-lined karst, it is taken up through inflow and infiltration by cracks, swallow holes and sinkholes. Covered karst prevails in the south-eastern part of the area and here, water drains off towards holes, hollows, karst ditches and other negative forms where is it taken up by cracks and sinkholes. When wells are used for drinking water supply, melting water and precipitation movement along vertical cracks must be taken into account as, according to the data of monitoring observations, near-surface zones with excessive fissuring are widely spread in and are typical of this territory.

Use of strippers drilled to the first water-bearing formation is the best option for water supply. However, the size of the zone of karst water level seasonal fluctuations must be considered; based on observation data, it may reach 8 m. Apparently, under certain conditions of karst process development in the study area, the use of these sources for drinking water supply during spring and fall low-water is problematic to local communities. This is confirmed by the data of monitoring observations (figure 9). Yet, this period is quite short (15-30 days a year at the best of times) and may be easily identified using the hydrogeological control system elaborated.

Effects of the karst water horizontal circulation zone, which represents the karst water layer and a part of the water-bearing system with concentrated flow towards discharge areas of the Oka river, include unstable discharge of karst water into other water-bearing formations that are also used for non-centralized drinking and domestic water supply of some households. Skipping the question of the legality of the use of these wells, we should mention considerable mineralization of this water and, consequently, the hazard of its use for drinking water supply due to the unpredictability of karst process intensification in the study area.

Conclusion

The studies conducted have shown that the development of karst-suffosion processes is accompanied by very intense and dynamically unstable hydrogeological variations in local areas of the geologic environment in the study area. Monitoring observations in Chud village over a half-year have helped identify three major water use zones with regard to the effects of karst processes. Figure 7 shows safe drinking water use zone (shown in green), zone with critically disturbed groundwater dynamics in terms of water use with undesirable water use for drinking water supply (shown in red) and restricted water use zone with temporary restriction in spring and fall low water (shown in yellow). Therefore, regular work must be conducted in localities of the territory using the hydrogeodynamic monitoring system elaborated over at least 5 years (recommended karst monitoring period) or more often if surface manifestations of karst processes in the territory become more active. Besides, such systems yield the information on the occurrence of destructive groundwater processes by way of selective hydrogeodynamic monitoring at the initial stage of their manifestation. However, in this case, more detailed models of the area monitored using fixed basic stations that yield background groundwater parameters of the regional level must be elaborated and used.

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