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The organisation of control over non-centralized water supply under the risk of groundwater dynamics disturbance in karst areas

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Abstract

The use of non-centralised water supply in remote settlements is currently the only possible option. Monitoring the water quality of such supply sources is a complicated task in such areas, especially when there are active karst processes and difficult groundwater conditions. The application of deterministic analytical models of water supply under the risk of disturbance to groundwater dynamics is not efficient. Significant quantitative and even qualitative changes in groundwater conditions may take place between the calculated points, and the underestimation of these changes in expectation-driven computation models may result in serious geoecological issues. This research studied and justifies the use of adaptive dynamic hydrogeological control in an area of non-centralised water supply based on the identification of key zones of geodynamic karst monitoring and the electrical express-monitoring of water resources. The identification of key zones is based on an integrated analysis of available groundwater information that describes changes in groundwater hydrodynamic conditions at the time of the karst forecast. The development of karst-suffusion processes is accompanied by more intense dynamic changes in local areas of geologic environment compared to the general variation in intensity. Information about the occurrence of destructive groundwater processes by means of selective geodynamic monitoring may thus be obtained much earlier than with environmental geodynamics monitoring as a whole. The experimental hydrogeological control of an area of non-centralised water supply was conducted on the right bank of the Oka River in Nizhny Novgorod region, a locality with an active manifestation of karst processes. Structure and algorithms of space-time processing of hydrogeological control data developed by authors have been used. The approach based on multifrequency vertical electrical sounding (MFVES) method has shown good correspondence with direct borehole observation when measuring depth of the first aquifer. Zones of unsafe water use have been revealed. The results demonstrated the effectiveness of the proposed method and the need for further regular observations of destructive groundwater processes by means of selective hydrogeodynamic monitoring.

Key words: *electrical express-monitoring method, hydrogeological control, karst, non-centralised water supply, water quality*

INTRODUCTION

The supply of water in areas remote from large communities currently relies on non-centralised water sources (springs, wells, boreholes). Such a non-centralised water supply is the only option for remote communities in many cases. The supply of reliable and high-quality water to these communities is important, especially when there are active karst processes. In such cases, the task is complicated by difficult groundwater conditions in the land, and the high vulnerability of karst groundwater to pollution due to its unique hydrogeological structure [MESTER *et al.* 2017; PECHERKIN 1986; STEVANOVIC, DRAGISIC 1998].

Karst water exchange systems differ from those in insoluble rocks due to a number of special properties that determine the high natural and anthropogenic vulnerability of groundwater resources, and their extremely low ability for self-purification and the dispersion of pollutants. The distribution of cavitation in the geologic environment is normally accepted as chaotic, and cavitation and permeability parameters are averaged within the limits of sampled reservoir volumes based on experimental data (borehole, geophysical and laboratory) and computations [KLIMCHOUK, TOKAREV 2014]. The groundwater hydrology of karst territories has pronounced features [DUBLYANSKY, DUBLYANSKY 2000; FORD, WILLIAMS 1989; ROMANOV *et al.* 2020], which makes these assumptions inapplicable to most practical tasks. The main difference between karst reservoirs and non-karst rock reservoirs is that their storage potential and filtration properties involve high spatial inhomogeneity and anisotropy. Despite a large proportion of karst channels in the overall volume of soluble rock cavitation (normally, in the range of 0.05–3.00%), they conduct 94–99% of the groundwater flow [KHASANOVA *et al.* 2019; WORTHINGTON *et al.* 2001]. Groundwater speed in karst channels is 3–7 orders higher than in the non-karst aquifer systems of an intense water exchange zone; normally, it amounts to hundreds and thousands of meters a day.

We should also note the complex problem of conserving underground drinking water supply sources in regions of karst process development. If a centralised water supply is used, water inlets are protected by establishing drinking water protection areas with special sanitary and epidemiological conditions to avoid degradation of the water quality in centralised domestic water supply sources and to ensure the protection of waterworks. In Russia, a project to protect the drinking water area and the centralised drinking water supply system is coordinated by the territorial subdivision of the Federal Executive authority for the 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 authorities. The first security border for groundwater intake is set at no less than 30 m from the intake if protected groundwater is used, and at no less than 50 m if poorly protected groundwater is used. Protected groundwater comprises pressure and non-pressure inter-formation waters that are not fed from overlying insufficiently protected aquifers. Poorly protected groundwater is groundwater and inter-formation water obtained from overlying poorly protected aquifers via watercourses by means of a direct hydraulic connection. Areas with developed karst processes always meet the criteria of poorly protected groundwater, however, and a first security border extension to 50 m does not ensure better groundwater protection. If a non-centralised water supply is used, the protection of sources is more of a recommendation. It is the duty of owners to develop and follow a monitoring program, including safety improvement activities for water use.

Regulations in most countries with a large proportion of karst territories differentiate between approaches to groundwater and water intake protection 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 properties of the environment). The regulations of many EU member states prescribe a special approach to water intake protective zones for karst reservoirs that takes into account the particular groundwater hydrology of the karst. The most representative legislation is that in Slovenia, where about 95% of the drinking water supply relies on underground sources [BRENČIČ *et al.* 2009].

The European COST Action 620 program resulted in the elaboration of the European approach to groundwater vulnerability assessment in karst conditions in certain regions [ZWAHLEN 2003]. The methods in use are based on special (adapted to karst conditions) techniques for groundwater vulnerability assessment. The most well-known methods are karst control method (KC), used as the basis of the European approach, and protective cover and infiltration capacity method (PI) [GOLDSCHEIDER *et al.* 2000]. The KC method assesses resource vulnerability based on map data [VÍAS *et al.* 2006]. PI method is based on the protective function parameters of layers above the saturated zone, as well as infiltration conditions. It ranks territories by five vulnerability grades. Infiltration conditions take into account the structure of topsoil, subsoil, the zone composed of non-karst deposits and the unsaturated zone of karst rock. Aquifer protection is estimated based on the statistical assessment of the spatial distribution of karst rocks and their height, as well as the annual average inflow and artesian pressure in the aquifer [RAVBAR, GOLDSCHEIDER 2009].

The EPIK (epikarst, protective cover, infiltration conditions, and karst network development) method, based on a vulnerability mapping concept using a multi-attribute method, may be of use to assess the vulnerability of non-centralised water supply sources [DOERFLIGER *et al.* 1999]. 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 the vulnerable territories where water supply relies on wells or boreholes. The method uses a geographic information system (GIS) that simplifies vulnerability mapping. GIS uses digital topographical model analysis, enabling the automatic classification of infiltration conditions. Four attributes of a karst aquifer are considered: the epikarst, protective cover, infiltration conditions, and karst network development.

Each of the four attributes is divided into classes mapped across the study area. The attributes and their classes are then weighed. Attribute maps are overlain to obtain the final vulnerability map. The vulnerability map is used to define specific zones and to make groundwater protection recommendations.

This approach has major drawbacks for areas with an aggressive hydrogeological manifestation of karst processes and high level of technogenesis under the risk of groundwater dynamics disturbance [SHARAPOV, KUZICHKIN 2013]. In this case, EPIK ignores the potentially aggressive dynamics of karst processes that may instantly change forecast groundwater conditions in the territory, as is the case with the unpredictability of sinkhole formation in the conditions of covered karst [GRECHENEVA *et al.* 2016]. In this regard, the application of deterministic analytical models of water supply under the risk of groundwater dynamics disturbance is not efficient. There may be major quantitative and even qualitative changes in groundwater conditions between the calculated points. Underestimation of these changes in expectation-driven computation models may result in serious geoecological issues.

Some 35% of the Russian population uses drinking and sanitary water from natural freshwater sources [DEMIN 2000; OVODOV 2004]. Rules and regulations specify that only water from the first aquifer can be used in non-centralised water supply systems. The use of the second aquifer (saturated with limestone rocks) is legitimate for centralised water supply systems, but the unauthorised use and production of water resources from the second aquifer is a violation of the law (subsoil). In this case, monitoring the water supply is an important and relatively complicated task, especially when there are active karst processes and difficult groundwater conditions in the area of karst manifestations.

Small settlements and non-centralised 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 the availability of observation stations (wells, boreholes), the analysis of water from which helps these systems to monitor the pollution parameters of water resources and changes in aquifer level [SOMOV, ZHURBA 2008]. The organisation of monitoring is regulated by the internal monitoring authorities of water resources [ZEKTSER *et al.* 2004]. The biggest freshwater resources have been found within zones with free water exchange. In territories with karst processes, this zone is unstable in terms of geodynamics, due to structural parameters of soil permeability and many aeration zones [ABALAKOV 2007]. In this case, monitoring the water quality of water supply sources is an important and relatively complicated task, especially when there are active karst processes and difficult groundwater conditions in the area of karst manifestations. There have been cases of abnormal local and regional changes in groundwater dynamics in these territories – water disappearing from wells and boreholes, entire lakes disappearing or, by contrast, glade areas that were suddenly flooded – right-bank karst area of the Oka River, Nizhny Novgorod region of Russia [TOLMACHEV 1986].

Geoecological monitoring of groundwater dynamics requires the control of a set of parameters:

- groundwater trends (space-time variations of the groundwater level);
- groundwater temperature trends;
- groundwater chemistry (mineralisation, electrical conductivity, oxidation-reduction potential, acidity, toxicity, suspended solids and dry residual) [NOLLET, DE GELDER 2000].

An additional task when monitoring local systems of groundwater parameters is data collection and its presentation in bulletins that report yearly changes in the geologic environment in the territory belonging to a particular regional centre of Russia [ABANINA, ZENYUKOVA 2006].

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

As the Federal Law of the Russian Federation “On subsoil” [Zakon RF 1992] does not prohibit groundwater production using private hole targets (wells, boreholes), the main concern in these cases is the lack of control over boring depth. Failure to comply with engineering requirements for good arrangements have sometimes resulted in unintentional and unauthorised water intake from deep artesian springs, only legitimate consumers of which are centralised water supply systems. Violating the rate of exploitation is detrimental to the second-level aquifer that provides large regional centres with drinking water.

The volume of water resources that a user may consume on their property within a local non-centralised water supply system is 100 dm^3 per day. The registration and monitoring of compliance to rules in these cases implies a continuous control of the aquifer level, which is quite complicated due to the lack of real-time tracking systems.

If a non-centralised water supply is the object of entrepreneurial activity for the supply of drinking water to a local community, then regulations state that the responsible person (entrepreneur) must continuously monitor the quality of water before it enters water supply sources. Work programs should be developed and approved for this purpose by the bodies of sanitary and epidemiological supervision, as well as local authorities. As is often the case, water quality control rules and regulations are not fully observed, so that 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, exploitation of chemical-analysis laboratories, etc.). As noted earlier, a lack of regulations for the established frequency of water intake for water quality control turns this process into something arbitrary, individual, and nonrecurring, or not occurring at all.

We should also note a problem that is common in rural communities – unauthorised refuse to dump on the outskirts of settlements. As experience shows, dumps are arranged in natural depressions – ravines, dried-up riverbeds, and so on, or in karst sinkholes (if any). Photo 1 shows an example of illegal dumps in sinkholes in areas with a non-centralised water supply (Chud village in the Nizhny Novgorod region, Russia, coordinates: 55°46'3.36" N,

Photo 1. Examples of garbage dumps in sinkholes in the area of the settlements (phot. *R. V. Romanov*)

42°19'44.4" E). In some cases, these karst formations have direct channels that connect them to aquifers used for water supply.

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

This study examined and justified the use of adaptive dynamic hydrogeological control in an area of non-centralised water supply based on the identification of key zones of geodynamic karst monitoring and local geoecological monitoring, using the electrical express-monitoring method.

The proposed approach to arranging non-centralised local geoecological monitoring of the water supply in karst territories requires solving the following tasks [OREKHOV 2013]:

- identification of key groundwater processes in a controlled territory that require groundwater and geodynamic monitoring in a 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 the development of reliable algorithms to identify hydrodynamic changes;
- assessment and analysis of identified abnormalities based on the models in use;
- forecast of potential irreversible catastrophic changes of groundwater conditions.

MATERIALS AND METHODS

GROUNDWATER OBSERVATION METHODS

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

Automated hydrogeological control systems are made for assessment and geodynamic forecasting based on local observations of separate isolated geodynamical active zones [DOROFEEV *et a*l. 2016]. Separate fragments of the environment have their own natural pace, and their geodynamics is determined by their own technogenically-complicated natural conditions [SHARAPOV, KUZICHKIN 2014]. Despite this, they involve 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 fragments (objects), separate hydrogeodynamic objects that determine one or another process may be identified. This enables a focus on local geodynamic disturbances identified during the generalised assessment of the hydrogeological environment and potential negative scenario forecasting.

The intensity of aggregate variations in the environment is much lower than the intensity of geodynamic changes in individual objects [SASHOURIN *et al*. 2018]. Monitoring separate hydrodynamically active zones (objects) thus yields information about possible catastrophic changes earlier than when the environment is being monitored as a whole. The most promising methods for the arrangement of automated monitoring of geodynamic objects are electrical environment probing methods that ensure the effective organisation of groundwater observations, assessment and forecasting thanks to their high technological effectiveness.

The authors elaborated and used the geoelectric monitoring system for geodynamic zones of hydrogeological environment. Figure 1 shows the generalised structure of the geoelectric data space-time processing system that describes the main processes of geoelectric data processing during geodynamic monitoring in the developed system [ROMANOV *et al*. 2015].

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

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

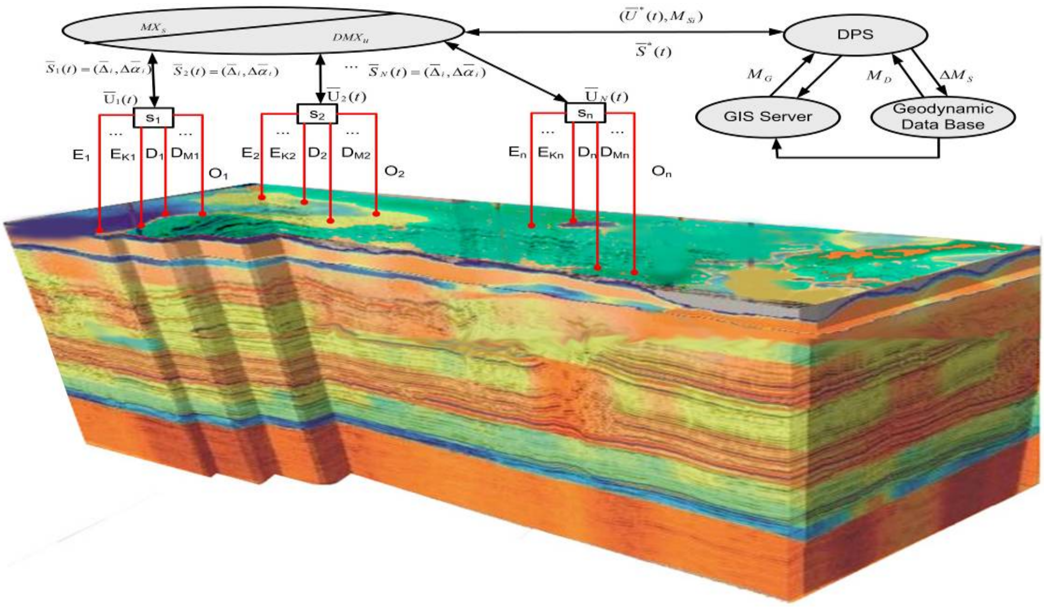

Fig. 1. Space-time processing system of geoelectric data of geodynamic monitoring; source: ROMANOV *et al*. [2015], modified

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

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

Where N is the total number of monitored objects.

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

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

Where F_U is a forming function of the initial positioning by control vector $\overline{\mathbf{U}}^*$ at the starting point of the monitoring process $t = t_0$. Further on, geoelectric measuring systems operate directly in the semi-automatic mode under the following algorithm:

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

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

Data processing in geodynamic monitoring points O_i is based on fundamental principles of geodynamic monitoring inverse problem [ROMANOV *et al*. 2015]:

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

Where: $\mathbf{D}_i$ is an observed data vector; $\mathbf{E}_i = \psi\left(\overline{\mathbf{U}}_i(t), \mathbf{M}_{Si}\right)$ are the parameters of probing field source defined by the set model and control signal, and $\mathbf{A}^{-1}$ is an 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, the inverse problem solution implies the determination of the model of the object $\mathbf{M}_{Si}$ subject to the geodynamic changes $\Delta\overline{\alpha}_i$ that would generate the forecast $\widetilde{\mathbf{D}}_i$ that best fits the observed data:

$$\widetilde{\mathbf{D}}_i = \mathbf{A}(\mathbf{M}_{Si}, \Delta\overline{\alpha}_i), \left\|\mathbf{D}_i - \widetilde{\mathbf{D}}_i\right\|^2_{L_2} = \overline{\Delta}_i \to \mathbf{min} \quad (6)$$

Where: $\mathbf{A}$ is a direct problem operator.

The intended use and operating principle of the virtual multiplexer ($\mathbf{MX_S}$, $\mathbf{DMX_U}$) is a correlation of geodynamic data flows $\overline{\mathbf{S}}^* = \left((\overline{\Delta}_i, \Delta\overline{\alpha}_i) i = \overline{1, N}\right)$ and control signals by the monitoring system with a data processing set (DPS).

Geoelectric express-monitoring method

The use of geoelectric methods to design a hydrogeological control system means that the specific electrical conductivity of water can be determined – including the mineralisation characteristics and, accordingly, data about the hydrogeological structure of the medium under study. According to the state standard [GOST 17.1.3.07–82], the specific conductivity recording of hydrogeological control objects is part of the mandatory work program for water quality control.

When used for 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 [ROMANOV *et al*. 2015]. It is important that the same rock may have different specific conductivity depending on its mode of occurrence, internal structure, temperature, fillup with saltwater. This property of rocks defines the efficiency of electric exploration methods for assessing the state of groundwater environments.

Natural environmental waters may be seen as a mix of electrolytes (sodium, potassium, calcium, chlorine, sulphate, hydro carbonate ions) that have strong and weak electrical properties. Unlike water from aquifers, surface water is characterised by the prevailing content of inorganic compounds. We should also note some ions that, due to their low concentration, do not have a significant effect on the electrical conductivity parameters of water: Fe(II), Fe(III), Mn(II), Al(III), NO_3^-, NO_2^-, PO_4^{3-}, HPO_4^{2-}, $H_2PO_4^-$. The reliability of water mineralisation assessment based on its specific conductivity values deteriorates due to the complex chemical composition of surface water, and sulphate ions which have various electrical conductivity values. The trial-and-error method is commonly used to determine total mineralisation: the quantity of hydrocarbonates and chlorides available from experiments must be added to the calculated quantity of sulphates (Tab. 1).

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

Salt content ($mg \cdot dm^{-3}$)	λ ($mS \cdot cm^{-2}$)		
	hydro-carbonates	chlorides	sulphates
1.0	81.90	108.80	103.80
2.0	80.10	107.30	99.20
3.0	78.80	106.20	95.70
4.0	77.70	105.30	93.00
5.0	76.50	104.50	91.00
6.0	75.70	103.80	89.20
7.0	74.80	103.30	87.60
8.0	74.00	102.80	80.30
8.6	73.58	102.44	85.52
10.0	72.70	101.80	83.90
11.0	72.10	101.40	82.90
12.0	71.50	100.90	82.10
13.0	71.10	100.60	81.20
14.0	70.30	100.20	80.50
15.0	70.10	99.80	79.70
20.0	68.20	98.30	76.30

Source: own study.

Underground water mainly contains inorganic compounds; specific conductivity is a measure of its total ion concentration. The solid part of water consists of principal ions: Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, CO_3^{2-}, HCO_3^-. An increase in the water-salt content results in enhanced interactions between ions. The velocity of ionic migration decreases due to the cataphoretic effect. The electrical conductivity of water increases with temperature as its viscosity decreases, and the degree of dissociation increases. The results of a total mineralisation assessment of water based on its specific conductivity are not entirely unambiguous. The main problems in these cases are caused by large variations in the chemical composition of surface water, which results in the varying electrical conductivity of different salts. This is why mineralisation and electrical conductivity vary widely. Practical applications of the hydrogeological control system take the temperature effect into account, however, and additional water sample analysis is expected in cases of considerable electrical conductivity variation.

The hardware of the geoelectrical monitoring system

The geoecological monitoring system developed includes non-contact differential electric field transformer sensors (NTS) at data collection points. The system in its basic configuration also comprises a control unit, a set of radiating electrodes, including an electrode positioned far from the analysed site ("infinity"), temperature and moisture sensors and intermediate communication equipment. The functional scheme of the local geoecological monitoring system of the aquifer used for non-centralised water supply is shown in Figure 2 shows the system layout.

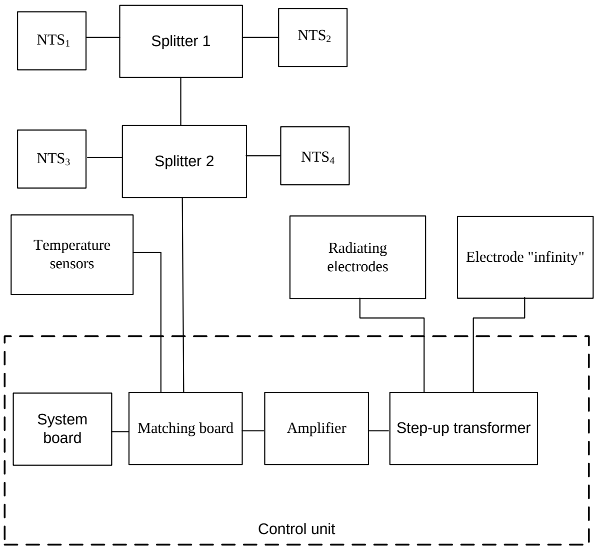

Fig. 2. Local geoecological monitoring system of the aquifer; source: own elaboration

As the system has a large 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", which operates under algorithms (1–6). This consists of a system board, matching board, amplifier, and step-up transformer. The matching board is used to interconnect the control unit and industrial interface. 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 the simultaneous recording of electrical conductivity of the aquifer, and its level with reference to measuring sensors.

TERRITORY AND CONDITIONS OF EXPERIMENTAL STUDIES

Geotechnical conditions of karst development in the study area

The soluble (karstic) rocks found in the Nizhny Novgorod region of Russia are carbonate (limestone, dolomite) and sulphate (gypsum, anhydrites). When karst rocks are represented by carbonate and sulphate rocks, the karst is classified as carbonate-sulphate. According to territorial building norms [SNIP 1999], karst rocks in the 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-sulphate 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 common (it can be found in Dzerzhinsk, Pavlovo, etc.) The total area of karst territory in Nizhny Novgorod region is about 20,000 km^2 (27% of the total region area). As a result of irregular karst activity and the varying thickness of covering deposits, karst above ground (craters, sinkholes, karst lakes, hollows, etc.) is found over an area of about 13,000 m^2. Surface karst is confined to river valleys and watershed depression areas, and consequently, it is mainly found on the right bank of the Volga River (at the Balakhna – Nizhny Novgorod section), in the basins of Oka, Tyosha, Seryozha, Kudma, Pyana, Alatyr and other smaller rivers of the part of Nizhny Novgorod region with a broad range of sparsely populated settlements that use non-centralised water supplies.

According to groundwater studies, the following karst development types are found in the Nizhny Novgorod region, subject to their geological structure. These types are mainly determined by geological section types such as Dzerzhinsk-Nizhny Novgorod, Arzamas-Pavlovo and Vyksa-Pervomaysk. The study area belongs to the Arzamas-Pavlovo geological section (Fig. 3).

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

The 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 characterised by the selective or volumetric solution. Rocks are cleaved, often broken down to ballast, debris, limestone-dolomite powder, or occasionally completely dissolved with the formation of cavities of varying height filled with water or foreign matter. The heights of recorded cavities range from 0.2 to 3.0 m.

Gypsum and anhydrites of the Lower Permian Sakmarian in contact with overlying Kazanian and Tatarian Upper Perm deposits in the region are the most prone to dissolution and the formation of caverns and cavities. Cavity height is from 0.2 to 7.0 m. Artesian aquifers, for which the monolithic part of the gypsum-anhydrite stratum is a water seal, are confined to limestone and dolomite, and, where they are absent, to the roof of the gypsum-anhydrite stratum.

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 [Tolmachev, Leonenko 2005]. According to the conclusions of PNIIIS JSC (2008–2009), the study site is situated in a territory of potential development for highly dangerous natural and human-induced

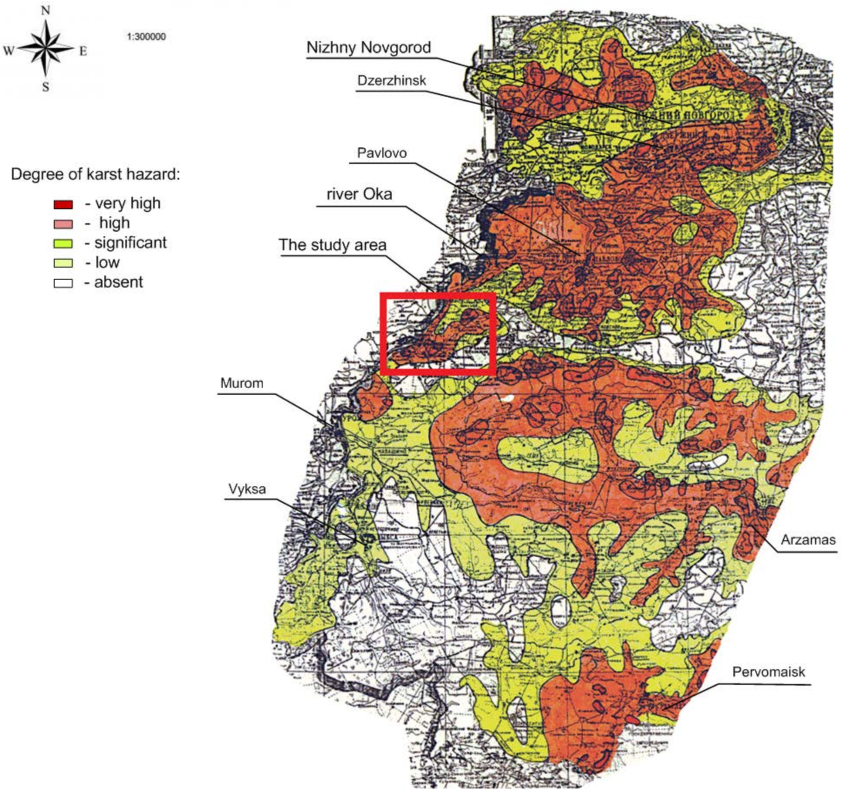

Fig. 3. Map of karst regions of north-western spurs of the Volga Upland of Nizhny Novgorod region (coordinates: N 55°46'3.36" E 42°19'44.4"); source: own elaboration

processes (hazard level I), and in terms of sinkhole formation intensity, the site is grade V–VI, which means a low probability of caving.

According to the current classification, the karst process of the study region is of the carbonate-sulphate covered type. Such 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 a high probability of water leaks from reservoirs and water use channels. There have been major sinkholes from great depths in the study area, for example, a sinkhole 45 m in diameter in 2005, near Bolotnikovo village, in the Vacha district of the Nizhny Novgorod region. This sinkhole resulted in the complete disappearance of water from a lake (also of karst origin) in two to three hours.

Characterisation of the non-centralised water supply of the study area

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

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

The Quaternary alluvium aquifer is confined to the valleys of the Oka and Tyosha Rivers and their confluence the Bolshaya Kutra, Murom, and Led. Alluvial formations of the bottomland and terraces above the flood-plain are water-bearing. They are almost entirely composed of sand in different granulometric compositions and clay content. Sand permeability ranges from 2 to 12 $m \cdot day^{-1}$. Layer water is unconfined; it has a common hydrostatic surface. Its depth ranges from fractures of a 1 to 12 m, which is mainly due to the ground relief. The thickness of the alluvial aquifer ranges from 16 to 24 m. On top of the alluvial section (above the aquifer roof) where loam streaks and lenses are often found, the formation of temporary groundwater is possible. According to data from the isolated wells used for the non-centralised water supply, well yields range from 2.8 to 5.7 $dm^3 \cdot s^{-1}$. When the level decreased from 1.8 to 6.5 m, specific yields amounted to 0.31–2.0 $dm^3 \cdot s^{-1}$. Water transmissibility was 31–200 $m^2 \cdot day^{-1}$. The layer has fresh sulphate-carbonate water with mineralisation of 0.2–0.5 $g \cdot dm^{-3}$. In the areas of hydraulic connection with confined saltwater in underlying deposits, alluvium water mineralisation increases to 0.9–1.6 $g \cdot dm^{-3}$. This water has a sulphate composition. The groundwater is mostly recharged through the infiltration of precipitation. Water is discharged into the river network. In small areas, the layer is recharged with confined water from underlying Urzhumian and Kazanian-Sakmarian strata, within Palaeolithic valleys and areas of Holocene alluvium of the Oka River, directly on the sulphate-carbonate rock mass.

The impervious local low-yield Don moraine aquifer combines water-glacial (super-moraine) and glacial deposits (moraine) made up of fine silty sand with uneven clay content, with ballast inclusions, and drift clays containing a 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 slightly confined. The depth of watered rocks varies from fractures of a 1 to 6.5 m depending on the ground relief. Interbedded water is characterised by poor water abundance. It serves as a water supply source for local communities which use wells up to 5.0 m deep. In terms of its chemical composition, it is hydrocarbonate calcic water with mineralisation 0.05–0.48 $g \cdot dm^{-3}$. As noted earlier, water is often exposed to pollution from domestic waste in the territory of the karst manifestations. The layer is recharged by the infiltration of precipitation. Water is discharged via the ravine-gully network in the form of little springs and water holes.

Temporary groundwater is often formed at local sites in the upper layers of underlying drift clay. This water contributes to waterlogging and formation of small suffosion hollows.

In the study area, non-centralised water supply is mainly arranged using wells in the territory of karst manifestations (Photo 2a). Artificial and natural reservoirs are used for domestic water supply; most of these reservoirs are of karst origin (Photo 2b). As we noted earlier, some households have their own low-yield wells.

Photo 2. Typical sources of non-centralised water supply in the study area: a) drinking well (phot. *R. V. Romanov*); b) domestic water supply reservoir (phot. *N. V. Dorofeev*)

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

RESULTS

Figure 4a shows the assessment results for the electrical conductivity parameters of the water samples taken from non-centralised water supply sources, in the Oka River and its confluence in the study area. Figure 4b shows data from borehole observations and data obtained using the multifrequency vertical electrical sounding (MFVES) method at a water intake for the non-centralised water supply when testing the hydrogeological control measuring system.

The experiments conducted in Chud village in the Nizhny Novgorod region allowed the location of the main sources of non-centralised water supply in the village and identification of the key points of hydrogeological control with the division of the karst massif into an area of precipitation and surface water infiltration and inflow, a groundwater flow area, and an area of karst water discharge beyond karst rocks (Fig. 5).

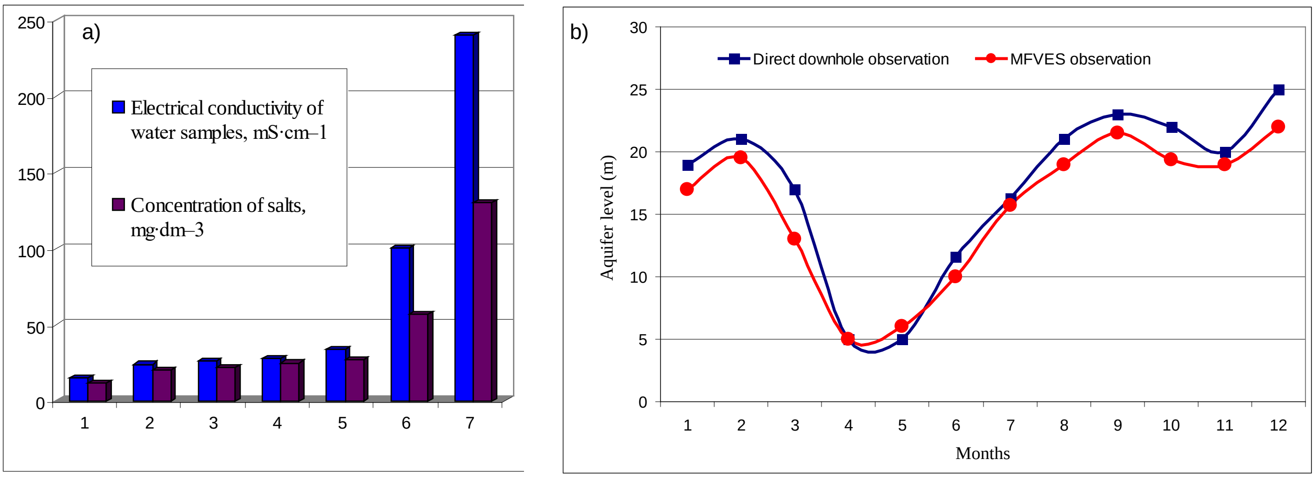

Fig. 4. Aquifer level and mineralisation using express-monitoring of electrical conductivity in the studied area: a) electrical conductivity of water samples and concentration of salts b) depth of the first level of the aquifer acc. to data from borehole observations and data obtained using the multifrequency vertical electrical sounding (MFVES) method; source: own study

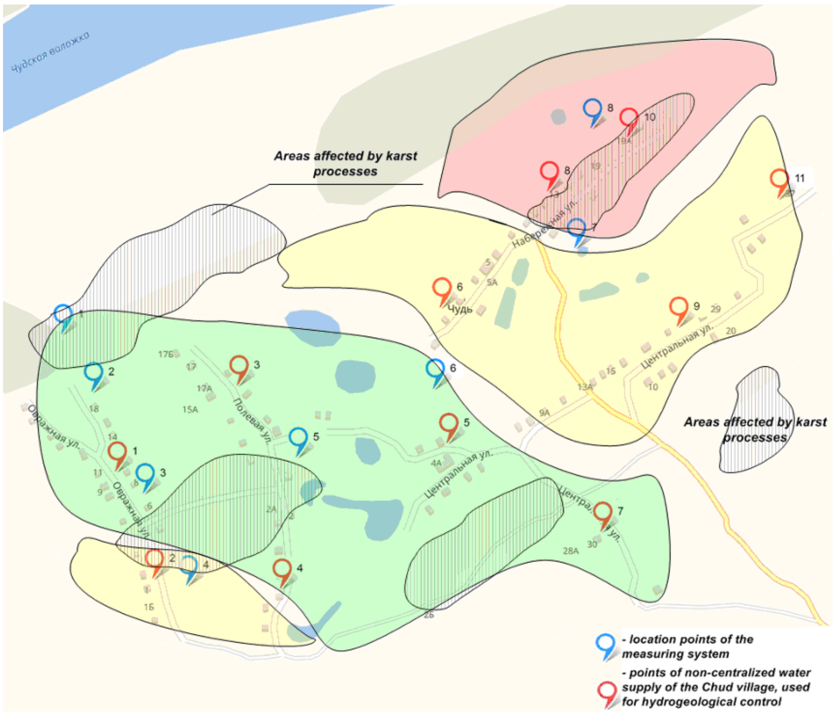

Fig. 5. The layout of the main points of non-centralised water supply and hydrogeological control system deployed (coordinates: N 55°46'3.36" E 42°19'44.4"); source: own study

Table 2. Experimental mineralisation data

Month	Mineralisation (mg·dm^{-3}) at observation point										
	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

Source: own study.

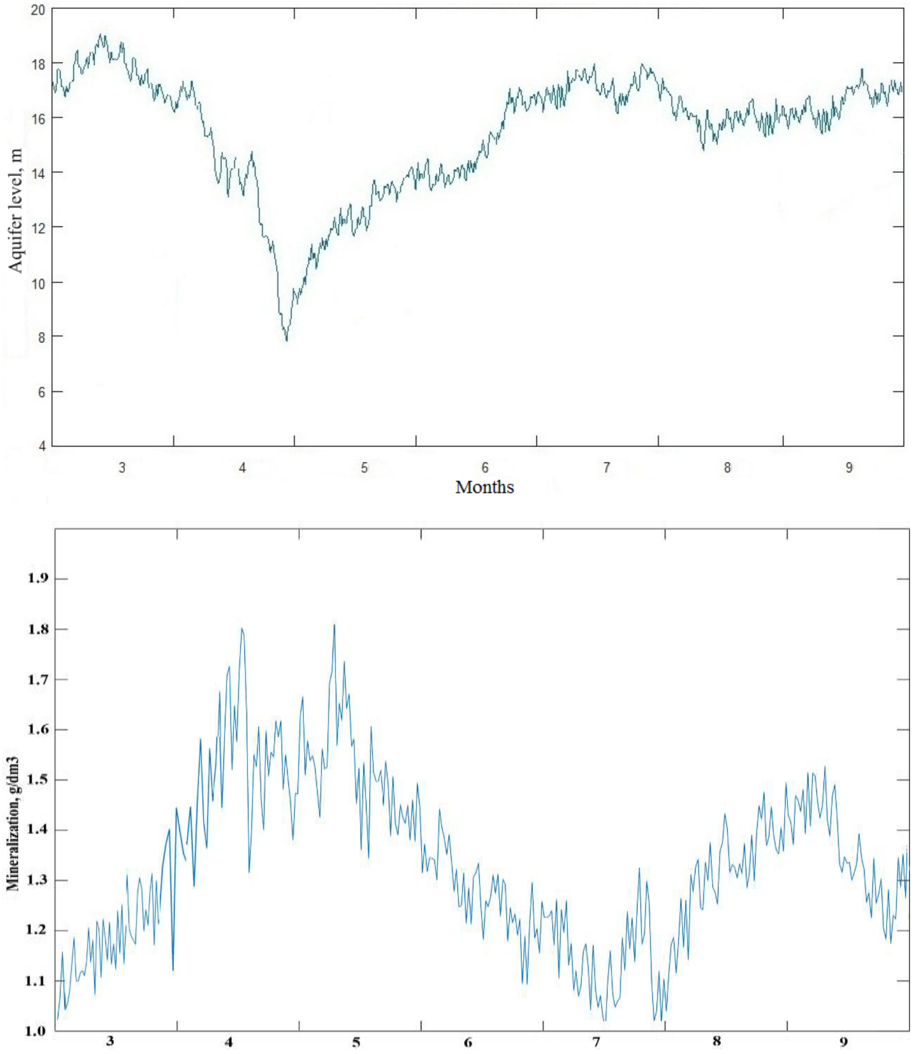

Fig. 6. Data from direct and borehole observations of an aquifer used for drinking water supply (point 8): a) of the level, b) of mineralisation; source: own study

Monitoring observations were performed from February to September 2017 at eight local monitoring points using a two-pole equipotential unit. Borehole observations were also performed in a borehole near point 3 for the additional control data acquired. Table 2 provides the averaged monthly data for mineralisation at the observation points.

Figure 6 shows comparative data for the direct and borehole observations of the level and mineralisation of an aquifer used for drinking water supply.

DISCUSSION

A preliminary hydrogeological survey was conducted at the chosen site to determine the karst water movement conditions related to the lithologic heterogeneity of the massif, its rock diversity, depth of erosion and degree of karst development. The studies were conducted using the developed electrical express-monitoring method to interpret and analyse hydrochemical and electrochemical monitoring data. Studies have shown the high effectiveness of the method. The comparative analysis of data in Figure 4 shows that the discrepancy between the data for direct borehole observations and measurements using the method understudy does not exceed 12%.

Data from the monitoring observations show 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 meltwater flows from the surface of rocks, and in the presence of grassy karst, it is absorbed through the inflow, as well as infiltration cracks and sinkholes. Covered karst prevails in the south-eastern part of the area, and here water drains off towards hollows, karst ditches and other negative forms where it is taken up by cracks and sinkholes. When using wells for drinking water supply, it is necessary to take into account the movement of meltwater and precipitation along vertical cracks, since, according to monitoring observations, surface areas with excessive fracturing are widespread and characteristic of this territory.

The use of low-yield boreholes drilled to the first aquifer is the best option for water supply. However, the size of the zone of karst water must be considered; based on observation data, seasonal fluctuations of its level may reach 8 m. 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 apparently problematic for local communities. This is confirmed by the data from the monitoring observations (Fig. 6). This period is quite short (15–30 days a year at most), however, and can be easily identified by the developed hydrogeological control system.

The effects of the horizontal circulation zone of karst water, which represents the karst water layer and a part of the aquifer with the concentrated flow towards discharge areas of the Oka River, include the unstable discharge of karst water into other aquifers that are also used for non-centralised drinking and the domestic water supply of some households. Ignoring the question of legality in the use of these wells, we should note the considerable mineralisation of this water and, consequently, the hazardous nature of its use as a drinking water supply due to the unpredictability of karst process intensification in the study area.

CONCLUSIONS

This study has 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. Monitoring observations in Chud village for over half a year has helped to identify three major zones of water use with regard to the effects of karst processes. Figure 5 shows the safe drinking water use zone (shown in green), a zone with critically disturbed groundwater dynamics with undesirable water use for drinking water supply (shown in red), and a restricted water use zone with temporary restrictions during spring and fall low water (shown in yellow). Regular work must, therefore, be conducted in an area of karst manifestations using the hydrogeodynamic monitoring system developed, at intervals of 5 years at most (recommended karst monitoring period) or more often if surface manifestations of karst processes in the territory become more active. Such systems also yield information about the occurrence of destructive groundwater processes by means of selective hydrogeodynamic monitoring at the initial stage of their manifestation. In this case, however, more detailed models of the monitored area using fixed basic stations that yield background groundwater parameters of the regional level must be developed and used.

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