A COMPLEX APPROACH FOR SEDIMENTARY ARCHITECTURE MODELLING OF FLUVIAL SUCCESSIONS AND THEIR CONVERSION INTO HYDROGEOLOGICAL UNITS

Stefan Zeynelov[1], Daniel Ishlyamski[1], Bozhurka Georgieva[1]

[1]*University of Mining and Geology "St. Ivan Rilski", 1700 Sofia, stefan.zeynelov@gmail.com*

ABSTRACT. Often the clastic fluvial deposits demonstrate significant lateral and temporal variability that significantly impedes the correct evaluation and modeling of their hydrodynamic properties. On the basis of lithological studies and aerial and terrestrial photogrammetric documentation of representative logs and 2D outcrops of fluvial successions study the main lithofacies and architectural-element units are determined. The fluvial successions are converted into hydrogeological units after a detailed grain size analysis and a correlation between the obtained results and the hydraulic conductivities. The application of an integrated geophysical approach (incl. ground-penetrating radar, electrical resistivity methods, geomagnetics, kappametry, etc.) enables the development of specific for the investigated sites key techniques used for indirect mapping of fluvial successions and hydrogeological units. This is useful for their depth profiling and spatial mapping. The presented multi-disciplinary approach is developed for studying the Galata Formation in the area north of the Kamchia River firth.

Keywords: hydrogeological model, geophysical methods, hydrogeological units, water budget

КОМПЛЕКСЕН ПОДХОД ЗА МОДЕЛИРАНЕ НА СЕДИМЕНТНАТА АРХИТЕКТУРА НА АЛУВИАЛНИ ПОСЛЕДОВАТЕЛНОСТИ И ТЯХНОТО ПРИВЪРЗВАНЕ КЪМ ХИДРОГЕОЛОЖКИ ЕДИНИЦИ

Стефан Зейнелов[1], Даниел Ишлямски[1], Божурка Георгиева[1]

[1]*Минно-геоложки университет "Св. Иван Рилски", София 1700; stefan.zeynelov@gmail.com*

РЕЗЮМЕ.Кластичните алувиални отложения често показват значима изменчивост, както по площ така и в разрез, което значително затруднява коректната оценка и моделирането на филтрационните им свойства. На основата на литоложки изследвания, въздушна и наземна фотограметрична документация на представителни разрези и 2D разкрития на алувиални последователности се обособят главните съставни литофациални и архитектурно-елементови единици. Алувиалните последователности се привързват към хидрогеоложки единици, на базата на детайлен зърнометричен анализ и корелация на получените резултати с коефициентите на филтрация. Прилагането на комплекс от геофизични методи (георадар, електросъпротивителни методи, геомагнитни методи, капаметрия и др.) позволява разработване на специфични за обекта геофизични ключове за косвено картиране на алувиални последователности и хидрогеоложки единици. Това се използва при тяхното дълбочинно профилиране и площно картиране. Методиката е разработена за изследване на Галатската свита в района на север от устието на р. Камчия.

Ключови думи: хидрогеоложки модел, геофизични методи, хидрогеоложки единици, воден баланс

Introduction

The main objective of contemporary surveys in the field of petroleum geology and hydrogeology in continental successions is 3D geometrization and characterization of sedimentary bodies that are typified by specific porosity and permeability. For decades, a set of sedimentological field and laboratory methods has been used for this purpose, where the form and degree of exposure of the sedimentary outcroppings are of key importance for achieving credible results.

The combination of detailed lithofacial profiling and 2D mapping of outcrops with extensive detection of textures-indicators of sediment paleo-transport is the basis of the architectural-element analysis of fluvial successions - one of the most advanced 3D methods for facial and paleographic modeling, reconstruction and stratigraphic division of continental successions (Stoyanov and Ajdanlijsky, 2002; Ajdanlijsky and Stoyanov, 2003). Along with the many limitations associated with the nature of the outcropping of the investigated sedimentary successions, the application of this method is connected to the accessibility of these outcrops and the possibility of their detailed and extensive documentation.

Substantial progress in this area is the combination of relatively inexpensive modern Remotely Piloted Aircraft Systems (RPAS) and a standard high resolution camera (or other type of sensor), which emerges as a powerful tool for remote sensing. There are also a number of budget software solutions providing further processing of the information. Modern drones are an efficient and highly productive tool for near-terrestrial mapping and documentation of substantial in scale outcrops, which are otherwise inaccessible to conventional field methods. They also allow extremely high levels of detailization (Кисьов и Цанков, 2016).

Parallel to the development of computing machinery and measuring equipment, geophysical methods (electrical resistivity surveying, ground-penetrating radar, geomagnetic surveying, etc.) find wider application in detailed mapping of the near-surface geological section. Their geological efficiency is determined by the differentiation of rocks according to different physical properties (Димовски и др., 2007, 2014; Димовски и Стоянов, 2011; Стоянов, 2004; Stoyanov et al., 2017).

Methodology of geophysical research

Different geophysical methods (ground-penetrating radar, geomagnetic surveying, electrical resistivity surveying, kappametry, etc.) can be applied successfully for mapping of the near-surface geological section. The major advantage of these methods is that they are convenient non-invasive instruments for a relatively rapid and effective determination of the spatial boundaries of geological and hydrogeological units of different rank, as well as zones with different characteristics. The common scheme for their application to each specific subject involves three main steps:

- *Field measurements*. They are carried out on predefined profiles and/or areas covering characteristic parts or the whole area of the object under study. The depth of study is decisive for the choice of techniques and schemes used in field measurements.
- *Development of two-dimensional or three-dimensional computer models of the physical field,* based on the performed measurements. Based on the model solutions and depending on the method used, a series of surface maps at different hypsometric levels can be obtained and vertical sections of the geoelectric or geomagnetic field can be derived. The acquired distributions of the studied physical parameters (electrical resistivity, total vector of the geomagnetic field, etc.) are a function of the mineral composition, the granulometric characteristics and the geometry (architecture) of the studied geological bodies, the presence and the degree of their secondary alterations (weathering, cracking, karstification, compaction), the degree of water-saturation, the physical properties and chemical composition of groundwater, etc.
- *Interpretation of the computer models*. In the process of transformation of the geophysical models in geological and/or hydrogeological models, different approaches are applied, based on correlation dependencies and complex comparative analysis of model solutions with data from studies performed in the area under investigation - geological mapping, drilling, field tests, laboratory tests, etc. Depending on the applied geophysical method and on the character and required precision of the study, most common well-known relationships and theoretical dependencies are used, or transformation keys, ensuring high reliability and quality of interpretation, are developed for each specific object.

Basic geophysical methods for mapping of the near-surface geological section

The most suitable geophysical methods for mapping geological and hydrogeological units of different rank are electrical resistivity methods (electrotomography), ground-penetrating radar, geomagnetic methods and cappametry. Practice shows that their integrated implementation gives greater confidence in the analysis and interpretation of the results from the geophysical study.

Electrical resistivity methods. The resistivity methods and, in particular, electrotomography have a leading role in the geometrization of geological and hydrogeological units that compose the near-surface section. Their geological efficiency is determined by the differentiation of rocks according to their electrical properties and mainly the specific electrical resistance. The variations of this parameter are uniquely related to the degree of ionic conduction. In the near-surface geological section, the ionic conductivity is associated with the presence of a saturated porous media where the ground water acts as an electrolyte. Therefore, the influence of three factors should be taken into account when assessing the ionic conductivity: the porosity coefficient, the degree of saturation of the porous media with groundwater, and the specific electrical resistance of the groundwater (electrolyte), i.e. the degree of mineralization of groundwater. Research has shown that practically always a very good, even in many cases unambiguous, connection is present between the electrical resistance differentiation and the specifics of the studied near-surface geoelectrical section.

Ground-penetrating radar (GPR). The GPR uses radar pulses to image the subsurface. This nondestructive method uses high-frequency (usually polarized) radio waves, usually in the range of 10 MHz to 2.6 GHz. A GPR transmitter emits electromagnetic energy into the ground. When the energy encounters a buried object or a boundary between materials having different permittivity, it may be reflected or refracted or scattered back to the surface. A receiving antenna can then record the variations in the return signal. The principles involved are similar to seismology, except GPR methods implement electromagnetic energy rather than acoustic energy, and energy may be reflected at boundaries where subsurface electrical properties change rather than subsurface mechanical properties as is the case with seismic energy. The electrical conductivity of the ground, the transmitted center frequency, and the radiated power all may limit the effective depth range of GPR investigation. Increases in electrical conductivity attenuate the introduced electromagnetic wave, and thus the penetration depth decreases. Because of frequency-dependent attenuation mechanisms, higher frequencies do not penetrate as far as lower frequencies. However, higher frequencies may provide improved resolution. Thus, operating frequency is always a trade-off between resolution and penetration. The GPR registers changes in the electrical characteristics of the media (conductivity and dielectric permeability), which are directly related to the type of sediments, their humidity and porosity. In such a way, it reproduces in real time vertical sections (the so-called ground-penetrating radargrams), which reflect the geological, hydrogeological and anomalous conditions. Individual lines of GPR data represent a sectional (profile) view of the subsurface. Multiple lines of data systematically collected over an area may be used to construct three-dimensional or tomographic images. Data may be presented as three-dimensional blocks, or as horizontal or vertical slices. Horizontal slices (known as "depth slices" or "time slices") are essentially planview maps isolating specific depths. With the application of the ground-penetrating radar one can clearly localize lithological boundaries, inclusions, water-saturated zones, etc.

Geomagnetic surveying. The magnetic methods in geophysics enable the study of the geological structure based on the anomalies of the geomagnetic field. These anomalies are due to the varying content or absence of ferromagnetic minerals in sediment rocks. Under certain conditions, there is the possibility of depositing different ferromagnetic minerals in the riverbeds. Such are ferromagnetic magnetite, low-magnetic ilmenite, hematite and others. The iron-ore mineralization accumulated along the palaeochannels can be recognized using magnetic methods as low-intensive elongated anomalies, which repeat the form of the covered ancient riverbeds. Therefore, the geomagnetic method is very effective for the localization and geometrization of channel-belt bodies (some of the most attractive in terms of porosity and permeability building elements of fluvial clastic successions), in their lower part similar minerals are frequently present, formed as residual depositions. Because of its proven rapidity and effectiveness, the method can be used to localize the presence of hematite deposition, to track the route of paleoflows, etc.

Kappametry. The magnetic susceptibility depends on the type and quantity of magnetic minerals contained in the studied rock samples. This parameter is most often related to the presence of ferromagnetic minerals (iron oxides or sulphides such as magnetite and/or pyrrhotite). There is sometimes a strong dependence on some paramagnetic minerals (mafic silicates such as olivine, pyroxene, amphibolite, mica, tourmaline, and garnet) and very rarely diamagnetic minerals (calcite, quartz).The magnetic susceptibility (kappa) of the various rocks is related to their ability to "seal" the magnetic field of the Earth during their formation. For sediments, the magnitude of this parameter is in functional dependence on the physical prerequisites of their deposition. Fluctuations in the magnetic susceptibility values provide an appropriate tool for identifying cyclical changes in the physical processes of sedimentation, which are often associated with different climatic factors such as warming or cooling.

Aero-photogrammetry. The airborne photogrammetry deals with the determination of the shape, dimensions, position and other quantitative and qualitative characteristics of different objects on the Earth's surface according to photographic images made by an airborne device. There are geometric relationships between the objects in the area and their photographic image, as the photo is a central projection of the captured land surface. Nevertheless, photos can not be used directly for geodetic purposes.The different remoteness of the captured objects from the projection center (this can be associated with the center of the lens) is the reason for the different scale of the objects on the captured surface.

The main task of photogrammetry is the transformation of photographic images into plans and maps that are orthogonal projections of the captured land surface. With scale bars, basically a known distance of two points in space, or known fixed points, the connection to the basic measuring units is created. Algorithms for photogrammetry typically attempt to minimize the sum of the squares of errors over the coordinates and relative displacements of the reference points. This minimization is known as bundle adjustment and is often performed using the Levenberg–Marquardt algorithm. At least two photographic images are needed to generate a stereo model. It is necessary to capture a series of mutually overlapping photos along a predefined route in order to create the orthophoto mosaic. Common points are identified on each image. A line of sight (or ray) can be constructed from the camera location to the point on the object. The intersection of these rays (triangulation) determines the three-dimensional location of the point.

Interpretation of geophysical models

For the transformation of geophysical models into geological and/or hydrogeological models, the so-called geophysical keys are applied that are expressing the connection between the determined in the cross section zones, characterized by different physical properties, and their corresponding geological and/or hydrogeological units of different rank. Generally, when developing a geophysical key for a particular object, three different in degree of authenticity approaches can be applied. They are based on value tables, available lithology data and laboratory tests.

Approach 1. Using value tables. This is a very fast and inexpensive way for pre-processing the results of a geophysical study. In this approach, as a key for the transformation of a geophysical model into a geological or hydrogeological one are used published in specialized literature tables of values for the specific physical properties of the basic rocks, minerals and compounds, as well as data for rocks saturated with fresh, brackish or saline water (Daniels and Alberty, 1966; Keller and Frischknecht, 1981, Stoyanov et al., 2017). Unfortunately, the results of the interpretation are a little bit fairly accurate and usually variative, as the specific physical property values for different environments vary in wide and often overlapping boundaries (Tables 1, 2 and 3).

Table 1.
Specific electrical resistance of some basic rocks and chemical compounds (Keller and Frischknecht, 1981, Daniels and Alberty, 1966).

Material	Specific electrical resistance,Ω.m
Magmatic and metamorphic rocks	
Granite	$5x10^3 – 10^6$
Basalt	$10^3 – 10^6$
Shale	$6x10^2 – 4x10^7$
Marble	$10^2 – 2.5x10^8$
Quartzite	$10^2 – 2x10^8$
Sedimentary rocks	
Sandstone	$8 – 4x10^3$
Argillite	$20 – 2x10^3$
Limestone	$50 – 4x10^2$
Dispersive soils	
Clays	1 – 100
Alluvial sands and gravels	10 – 800
Water	
Groundwater	10 – 100
Sea water	0.2
Chemical compounds	
0.01M KCl	0.708
0.01M NaCl	0.843
0.01M CH_3COOH	6.13
Xylene	$6.998x10^{16}$

Table 2.
Criteria for estimating sea salt water intrusion in the region of the Nile delta – District Rashid, Egypt (Stoyanov et al., 2017)

Object of study	Water type	Resistivity (Ohm.m)
Unsaturated zone (dry sediments)	-	> 150
Aquitard (clay and silt)	-	2 – 10
Aquifer (gravel and sand layers)	fresh water	
	slightly brackish water	20 – 45
	moderately brackish water	10 – 20
	brackish water	5 – 10
	very brackish water	2.5 – 5
	saline (salt) water	< 2.5

Approach 2. Employing available lithology data. This is the most frequently used methodology for transforming geophysical sections into results that reconstruct the geological structure of the studied areas. For this purpose a complex analysis and interpretation of the obtained sections is performed and they are compared with the available information for specific elements of the geological structure derived on the basis of geological mapping and exploratory drilling data.

Approach 3. Using laboratory tests data. They can be applied for the development of a local geophysical key, which gives the direct connection between the determined in the section media characterized by different physical properties and their corresponding geological and hydrogeological units in the studied area.

For example, in case electrical resistivity measurements are performed, it is advisable to use the following general scheme. During the stage of geological mapping or exploratory drilling, representative soil samples are taken from each low-rank geological unit. In case of layers that are very heterogeneous with respect to their granulometric composition, sampling is desirable to cover all dominant varieties. Water samples having TDS corresponding to the natural background are also taken. In laboratory conditions, the electrical resistance is measured first when the soil samples are dry and later when they are saturated. Watering is performed using the available water samples. The values for the electrical resistivity determined in such a way are used as local criteria for the transformation of geoelectrical computer models into geological or hydrogeological models.

An essential element in this approach is the measurement of the electrical resistivity of dry and saturated soil samples. For this purpose a device was designed and constructed, in which the electrical resistivity of a small volume of the studied media can be modeled and measured (Стоянов, 2004). The device is a four-electrode geoelectrical column for measuring the electrical resistivity of dry and saturated samples (Figure 1).

Measurements are made applying standard resistivity meters used in field geoelectrical surveys or conventional electrical measuring equipment. The necessary requirement for this apparatus is to generate alternating current, thereby eliminating or limiting the polarization of the potential electrodes. The geoelectrical column is made of a thick-walled tube of electro-insulating material. The current and the potential electrodes (C1, C2, P1 and P2) are located in the central part of the column and represent aWenner-Alpha array. The column calibration constant is k = 0.054 m.

The sequence of operation for measuring the resistivity of dry and saturated samples is as follows. First, the column is filled and packed (without segregating) with sand having a

Table 3.
Values for the specific electrical conductivity and the dielectric constant of some basic materials.

Material	Specific electrical conductivity σ [S/m]	Dielectric constant ε_r
Air	0	1
Distilled water	10^{-4} – 3.10^{-2}	81
Sea water	4	81
Ice	10^{-3}	4
Granite(dry)	10^{-8}	5
Limestone(dry)	10^{-9}	7
Clay (wet)	10^{-1} – 1	8 - 12
Snow firn	10^{-6} – 10^{-5}	1,4
Sand (dry)	10^{-7} – 10^{-3}	4 – 6
Sand (saturated)	10^{-4} – 10^{-2}	30
Sediments(saturated)	10^{-3} – 10^{-2}	10
Sandy sediments (dry)	2.10^{-3}	10
Swamp forest and plain depositions	8.10^{-3}	12
Agricultural land and pastures	5.10^{-3}	13
Basalt(wet)	10^{-2}	8
Granite(wet)	10^{-3}	7
Clayey shale(wet)	10^{-1}	7
Sandstone(wet)	4.10^{-2}	6
Limestone(wet)	$2,5.10^{-2}$	8
Frozen soil / Permafrost	10^{-5} – 10^{-2}	4 – 8
Concrete (dry)		6
Concrete (wet)		2,5
Asphalt		3 – 5
PVC, plastics, rubber, latex, etc.		3
Sandy soils (dry)	$1,4.10^{-4}$	2,6
Sandy soils (wet)	$6,9.10^{-3}$	25
Clayey-sandy soils (dry)	$1,1.10^{-4}$	2,5
Clayey-sandy soils(wet)	$2,1.10^{-2}$	19
Clayey soils(dry)	$2,7.10^{-4}$	2,4
Clayey soils (wet)	5.10^{-2}	15

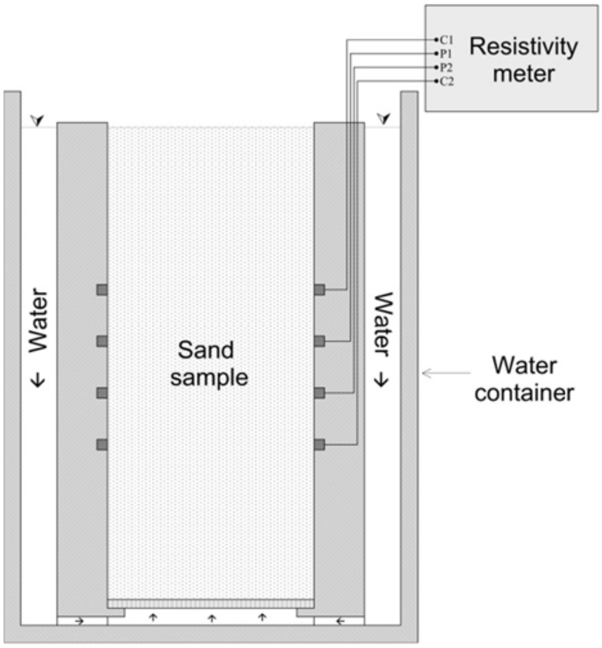

Fig. 1. General scheme of the four-electrode geoelectrical column (Стоянов, 2004).

known grain size and its resistivity is measured. The column is then placed in a higher container made of an electro-insulating material. The container is filled with water that penetrates along canals to the bottom end of the column and through the perforated base gradually saturates the built-in sample from the bottom upwards. The water inflow is stopped when the sand sample is completely saturated. This approach eliminates the presence of any unsaturated voids. Measurement is performed a few hours after the sample is saturated. It has been confirmed that this time is adequate to establish a relative physical-chemical equilibrium between the solid phase and the liquid phase and in such a way to ensure the reliability of the obtained result.

Principles for attachment of fluvial architectural units towards aquifer and aquitard layers and zones

The description and definition of architectural elements includes:

- Nature and morphology of confining surfaces;
- Unit scale: thickness, lateral development (parallel and perpendicular to the direction of the sedimentation paleo-transport);
- Surface geometry of the unit;
- Inner structure of the unit: lateral and vertical lithofacial assemblages and sequences, presence and orientation of low-rank erosion surfaces, orientation of the indicators of the sedimentary paleo-transport, interaction of bedding with respect to the limiting surfaces.

Based on the results from the performed grain-size analyses, the degree of sorting of the sediments in each separate lithofacies unit is determined. After that, this parameter is estimated for the architectural-element units that they compose. The representation and analysis of grain size data in standard phi-scale allows an accurate hydrodynamic and genetic interpretation of the established sedimentary bodies.

Employing connections, achieved by many authors, between granulometric composition and degree of sorting of sediments, on the one hand and hydraulic conductivity on the other, a correlation diagram (Figure 2) is compiled. It allows the lithofacies and architectural-element units to be interpreted as hydrogeological units (Stoyanov and Ajdanlijsky, 2002).

Using this correlation diagram, at first approximation, aquifers and zones with specific geometry and characteristics can be determined in the subsurface space of each particular studied site (Ajdanlijsky and Stoyanov, 2003). According to laboratory and "in situ" filtration and tracertests, values of hydrodynamic and migration parameters can be assigned to each layer and zone.

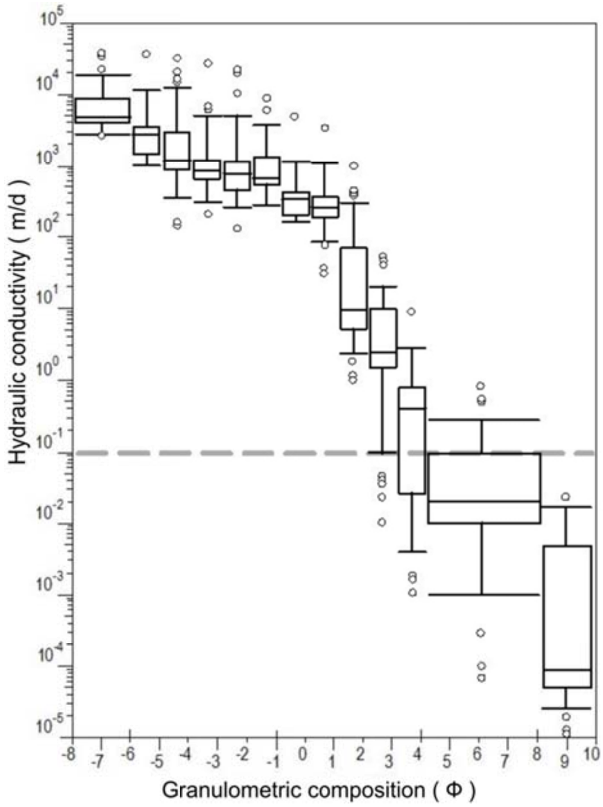

Fig. 2. Correlation box-diagram of the type of sediments and hydraulic conductivity. Dotted line shows the boundary between permeable and practically impermeable sediments. Circles show the values, typical for well-sorted and poorly sorted varieties (Stoyanov and Ajdanlijsky, 2002).

Conclusions

The main objective of the proposed approach is the formation of anoptimal complex of field sedimentological and geophysical methods for studying and 3D modeling of main lithofacies and architectural-element units and assessment of reservoir properties of young fluvial successions. It can be accompanied by an efficient and high-productive technique for near-terrestrial mapping and documentation of substantial in scale outcrops.

For this purpose, a variety of procedures aimed towards studying the near-surface geological section can be applied, including lithological analysis, geophysical methods, remote sensing, etc. They all are directed at:

- Development of specific detailed lithofacial sections and 2D profiles;
- Definition and documentation of architectural elements that are typical for terrestrial fluvial complexes;
- Precise 2D and 3D mapping of these elements in substantial in scale outcrops that are inaccessible for the application of conventional field methods;
- Characterization of the architectural units with regard to their reservoir properties;
- Tracing the units' boundaries by application of geophysical methods (ground-penetrating radar, electrical resistivity methods, geomagnetics, kappametry, etc.).

The presented complex approach is developed for studying the Galata Formation in the area north of the Kamchia River firth.

Acknowledgment

The presented complex approach for sedimentary architecture modelling of fluvial successions and their conversion into hydrogeological units is based on unpublished authors' work in the frames of the Contract No: FGE-216 / 2018. Contract topic: "A multi-disciplinary approach for sedimentary architecture modelling andevaluation of reservoir properties of fluvial successions", funded by the scientific-research fund of the University of Mining and Geology "St. Ivan Rilski" for 2018.

References

Димовски, С., Н. Стоянов, Ч. Гюров. Ефективност на електротомографията за детайлно геоелектрично картиране на приповърхностния геоложки разрез. – БУЛАКВА, 4, 2007. – 47-55. (Dimovski, S., N. Stoyanov, Ch.Gyurov. Efektivnost na elektrotomografiyata za detailno geoelektrichno kartirane na pripovarhnostnia geolozhki razrez. – BULAKVA, 4, 2007. – 47-55.)

Димовски, С., Н. Стоянов. Геоелектричен подход при изучаване на хидрогеложките условия в района на ДБО Асеновград. – Год. МГУ, София, 54, I, 2011. – 125-130. (Dimovski, S., N. Stoyanov. Geoelektrichen podhod pri izuchavane na hidrogeolozhkite usloviya v rayona na DBO Asenovgrad. – God. MGU, Sofia, 54, I, 2011. – 125-130.)

Димовски, С., Н. Стоянов, Х. Цанков, А. Кисьов. Комплексен геофизичен подход за локализиране на водопропускливи зони в земнонасипна стена на повърхностен водоем. – Год. МГУ, София, 57, I, 2014. – 89-94. (Dimovski, S., N. Stoyanov, H.Tsankov, A. Kisyov. Kompleksen geofizichen podhod za lokalizirane na vodopropusklivi zoni v zemnonasipna stena na povarhnosten vodoem. – God. MGU, Sofia, 57, I, 2014. – 89-94.)

Кисьов, А., Х. Цанков. Приложение на дистанционно управляеми летателни системи (ДУЛС) за дистанционни изследвания. –Сборник с доклади от XIV Национална младежка научно-практическа конференция, София, 2016. – 66-72.(Kisyov, A., H.Tsankov. Prilozhenie na distantsionno upravlyaemi letatelni sistemi (DULS) za distantsionni izsledvaniya. – Sbornik s dokladi ot XIV Natsionalna mladezhka nauchno-prakticheska konferentsiya, Sofia, 2016. – 66-72.)

Стоянов, Н. Метод за дефиниране на локални геоелектрични критерии за оценка на замърсяването на подземните води – БУЛАКВА, 2, 2004. – 21-27.(Stoyanov, N. Metod za definirane na lokalni geoelectrichni kriterii za otsenka na zamarsyavaneto na podzemnite vodi. – BULAKVA, 2, 2004. – 21-27.)

Ajdanlijsky, G., N. Stoyanov. Fluvial architecture of the sedimentary aquifer complex in the area of sanitary landfill Plovdiv. – Ann. UMG, Sofia, 46, I, 2003. – 1-6.

Daniels F., R. Alberty. Physical chemistry. John Wiley and Sons Inc., NY, 1966. – 674 p.

Keller, G., F. Frischknecht. Electrical methods in geophysical prospecting. Pergamon Press Inc., Oxford, 1981. – 535 p.

Stoyanov, N., G. Ajdanlijsky. Commrehensive approach for 3D simulation by mathematical modeling of groundwater contamination – Ann. UMG, Sofia, 45, I, 2002. – 105-108.

Stoyanov, N., P. Gerginov, E. Tarabees, A. Benderev, S. Dimovski. State of the art and the problems of interaction between groundwater and marine waters in the Nile delta – District Rashid, Egypt. – Proceed. 17th Intern. Multidiscipl. Scient. GeoConference SGEM, 2017. – 793-800. https://doi.org/10.5593/sgem2017/12.