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HYDROGEOLOGICAL MAPPING OF A MIOCENE AQUIFER BY TWO-DIMENSIONAL ELECTRICAL IMAGING

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Summary

Geoelectrical resistivity methods have been playing very important role in hydrogeological explorations for years, since they can provide information lithology porosity, permeability and water quality. But conventional resistivity methods, electrical sounding and electrical profiling, cannot satisfy demand for continuos coverage over an exploration area and for building of a detailed hydrogeological model, especially with complex geological models and 3-D structure shapes. Electrical sounding is based on a theoretical assumption of a horizontally stratified earth model, and electrical profiling maps only lateral resistivity changes at the same depth. Two-dimensional (2-D) electrical imaging (or 2-D electrical tomography), that has been introduced recently, can map the both vertical and lateral resistivity changes and provides for building three-dimensional (3-D) resistivity model of the underground.

Exploration has been carried out in the area of the Seona spring to investigate the possibility for pumping more water during dry season, from the well located near the spring. The water of the Seona spring emerges from Badenian carbonate aquifer, which shows irregular 3-D shape and heterogeneous lithologic composition. A network consisting of four electrical profiles has been established to acquire a 3-D resistivity model, which can be transformed in a 3-D hydrogeological model. Inverse resistivity model sections revealed high resistivity zone which has been correlated with Badenian limestone by means of existing outcrops. Low resistivity zones point to the marly layers. Exploratory borehole located on the basis of electrical data has confirmed derived hydrogeological model from the electrical imaging data. Heterogeneous limestone aquifer has been uncovered at depth 8.2 – 55 m. The aquifer is weathered and karstificated with two main cavern intervals.

Hydraulic connections between the caverns and the spring have been established during drilling, but also in a pump test by means of the airlift method.

The presented case demonstrates great possibilities of the electrical imaging method in mapping of irregularly shaped aquifers and building of a precise 3-D hydrogeological model.

Ključne riječi: metode otpornosti, dvodimenzionalna električna tomografija, hidrogeologija, miocenski vodonosnik

Sažetak

Geoelektrične metode otpornosti imaju važnu ulogu u hidrogeološkim istraživanjima već godinama, jer mogu dati litološke podatke i s tim povezane šupljikavost i propusnost, ali i podatke o mogućoj zaslanjenosti vode. Međutim klasične metode otpornosti, geoelektrično sondiranje i geoelektrično profiliranje, ne mogu udovoljiti zahtjevu za kontinuiranim pokrivanjem istražnog područja i za konstruiranjem preciznog hidrogeološkog modela, napose u složenim geološkim modelima i trodimenzionalnom obliku struktura. Geoelektrično sondiranje se osniva na pretpostavci horizontalno uslojenog modela podzemlja, a geoelektrično profiliranje može kartirati samo lateralne promjene otpornosti na istoj dubini. Dvodimenzionalno (2-D) električno mjerenje (ili 2-D-električna tomografija), koja se nedavno pojavila, može kartirati i okomite i uzdužne promjene otpornosti i tako omogućiti konstruiranje trodimenzionalnog modela otpornosti podzemlja.

Istraživanje je provedeno na području izvora Seona, kako bi se istražila mogućnost zahvata veće količine vode iz bušotine u okolici izvora, napose u sušnim razdobljima. Voda u izvoru Seona istječe iz badenskog karbonatnog vodonosnika koji je nepravilnog trodimenzionalnog oblika i heterogenog litološkog sastava. Postavljena je mreža od četiri profila kako bi se dobio trodimenzionalni model otpornosti, koji se može preoblikovati u trodimenzionalni hidrogeološki model. Interpretirani dvodimenzionalni modeli otpornosti su otkrili zone visokih otpornosti koje se mogu korelirati s badenskim vapnencima na izdancima. Zone niskih otpornosti ukazuju na laporovite slojeve. Istražna bušotina locirana na temelju geoelektričnih podataka potvrdila je hidrogeološki model načinjen na temelju podataka električne tomografije. Heterogeni vapnenjački vodonosnik otkriven je na dubinama 8.2-55 m. Vodonosnik je karstificiran i trošan, s dva glavna kavernozna intervala. Utvrđena je hidraulička veza između bušotine i izvora još tijekom bušenja, a napose pokusnim crpljenjem metodom "air-lifta".

Izloženi primjer pokazuje velike mogućnosti metode električne tomografije u kartiranju vodonosnika nepravilnih oblika i definiranju preciznog trodimenzionalnog hidrogeološkog modela

1. Introduction

Water explorations have become very important in the past decades due to growing demands for water supply. On the other hand the areas for hydrogeological mapping have been decreased because of urban and agricultural impacts, which have polluted many springs and regions. This implies that detailed geological model should be established in such an exploration to solve hydrogeological conditions, but also for the purpose of water protection.

Geophysical methods have been playing very important role in hydrogeological explorations for years. They can provide continious coverage over an exploration area and for building detailed hydrogeological model. A reduction of the total exploration costs is another very important reason to apply geophysical methods. Which geophysical methods would be applied depend on predicted geological and hydrogeological model. Geoelectrical methods affect the complete mass of a rock so that lithological (porosity, permeability) and water quality information can be attained. This implies that electrical resistivity methods are usually the main geophysical methods applied in hydrogeological explorations. But sometimes, for the reason of fast decrease of the resolution with the depth, other geophysical method should be applied, too. At greater targets depths the seismic methods can provide for better resolution and to discover some events which can not be resolved by resistivity methods (Šumanovac and Weisser, 2001).

Resistivity methods are based on determining a subsurface resistivity distribution from surface measurements of apparent resistivities. After data processing and interpretation, the information on geological and hydrogeological conditions can be acquired. The method of electrical sounding investigates vertical changes of resistivities or resistivity changes with depth, and the method of electrical profiling investigates lateral resistivity changes at the same depth. But these methods can not give satisfactory results in areas with complex subsurface geology. Electrical sounding gives information similar to borehole information and can not satisfy demand for continious coverage of an exploration area. The interpretation is based on a theoretical assumption of horizontally stratified earth model, which can be hardly expected in many geological models. On the other hand the electrical profiling maps lateral resistivity changes, but resistivity changes with depth are not seen. These problems have been recently solved by development of the electrical resistivity imaging (called also the surface electrical tomography). The method can map both the vertical and the lateral resistivity variations, which assures a continuous subsurface coverage can be attained.

This paper discusses the case of a hydrogeological mapping of a Miocene aquifer in Croatia by two-dimensional electrical imaging. Great potentials of the method to map complex geological areas have been confirmed by exploration borehole.

2. Two-dimensional electrical imaging

In recent years the electrical resistivity imaging has been developing rapidly. This method can give continious coverage of the underground as in two-dimensional (2-D) space so in three-dimensional (3-D) space. The use of two-dimensional electrical tomography has truly increased in hydrogeological, geotechnical and other shallow explorations in the last few years. The main advantage of this method is the possibility to map areas with complex subsurface geology (Griffiths and Barker, 1993), due to the presumption connected to 2-D resistivity earth model, meaning that the resistivities can vary in lateral and vertical directions. Development of this method started with the appearance of the multi-electrode systems (Griffiths and Turnbull, 1985; Griffiths et. al., 1990) with equally spaced electrodes and equally spaced pseudodepths. Computer-controlled data acquisition can be highly efficient and cost-effective field measurements. A somewhat different system for providing more measurements in shallow part, which has been applied for continuous vertical electrical sounding, was presented by van Overmeeren and Ritsema (1988). This system has enabled a roll-along mode of field measurements and it was later applied in 2-D electrical imaging by Dahlin (1996). Electrical imaging data can be interpreted by using appropriate inversion techniques.

Data acquisition geometry

In general, a measurement procedure consists of a set of profiling measurements for different depth levels. Field measurements are usually carried out by means of a multielectrode system. The electrodes are grounded at equally spaced distances along a profile, and connected with suitable cables and interface units to a resistivity meter. Computer-controlled systems use suitable software to carry out fully automatic data acquisition using selected measurement protocol. In this way a fieldwork can be carried out much faster by means of a smaller field crew than on a traditional profiling way. On the other side the equipment is more complex and thus much more expensive. In the last years a number of multielectrode acquisition systems have been introduced, actually all significant manufacturers of geophysical equipment offer one of their own. Those systems have been based on somewhat different electronic presumptions and construction design, but on very similar measurement geometry. The shallowest depth level is defined by the unit electrode distance, and the other are defined by a multiplication of it.

Any conventional electrode array can be applied in the system for data acquisition, but the most often the Wenner, the Wenner-Schlumberger, the dipole-dipole, and the pole-pole arrays have been used. The Schlumberger array is not used alone but in combination with the Wenner array, as with the shallowest depth level in a multielectrode system the Wenner array should be applied. For deeper depths of exploration the electrode spacing should be increased depending on applied electrode array. The Wenner array requires more open space to obtain certain horizontal subsurface coverage than the other arrays. The Schlumberger and especially the dipole-dipole and the pole-pole array can achieve better horizontal coverage for deeper targets and penetrate to greater depths with the same multielectrode system. Better horizontal resolution can be obtained by using the dipole-dipole and the Wenner-Schlumberger arrays due to smaller potential electrode distance than in the case of the Wenner array, which leads to a smoothing of the data, especially for deeper targets and greater electrode distances. On the other hand the main advantage of the Wenner array is the highest signal to noise ratio in comparison with other arrays. For the areas generating very noisy data sets, this array is the most reliable to be on the safe side. A resistivity inversion can be hardly carried out precisely if the data set is contaminated by high level of noises, becoming in some cases even unstable.

Data processing and interpretation

Two-dimensional measured resistivity data have been arranged and contoured in the form of a pseudosection. This section gives only a general overview of the subsurface resistivity distribution and the picture can be sometimes even unclear because of the influence of the electrode configuration on measured values. This means, different applied electrode arrays will give different pseudosection shapes for the same resistivity model. To obtain a more accurate resistivity distribution in the underground an inversion of the pseudosection should be carried out.

There are two approaches: one-dimensional inversion, and two-dimensional inversion. One-dimensional inversion is usually based on the Zohdy's automatic interpretation of vertical electrical sounding (Zohdy, 1989). The pseudosection is regarded as a series of closely spaced electrical soundings, which have been extracted one after another. After automatic interpretation of each sounding, the interpreted data is merged together to form a quasi 2-D section. This technique is useful in a stratified earth model, meaning basin conditions with slight or gradual lateral resistivity variations and gradual changes of layer thickness. But in complex environment this technique can only be used to acquire a general overview of the subsurface resistivity distribution. The second approach uses true 2-D inversion of the data. It seems the smoothness-constrained, least-squares inversion method that was presented by Loke and Barker (1995) has been very widely applied. The method is very suitable where strong lateral resistivity variations and depth changes (complex geological model) have occurred.

Geological setting

The main goal of exploration was to investigate the possibility for pumping the groundwater from the well located near the Seona spring, which would potentially increase the capacity during dry seasons. Investigated area lies at the northeastern side of Mt. Krndija, where various rocks of Precambrian, Palaeozoic and Neogene age are encountered (Fig. 1).

Palaeozoic units are known under the joint term of "Basement rocks". Hydrogeological map (Fig. 2) is drawn based on the Basic geological map, sheet Našice (Korolija and Jamičić, 1989). The explored aquifer is formed within the Middle Miocene carbonate sediments. In the elevated part of terrain, these rocks transgressivelly overlie the Palaeozoic metamorphics of the basement, while in the lower parts they are covered with the relatively impermeable Upper Miocene sediments.

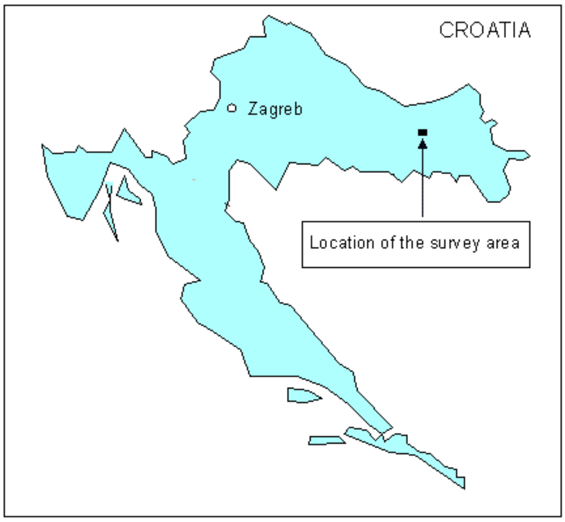


Figure. 1 Location map

Slika. 1 Položajna karta

Stratigraphy

Precambrian–Palaeozoic rocks (Basement rocks, Gsg), acording to Korolija and Jamičić (1989), are part of the metamorphic complex of Mts. Psunj and Krndija. In the study area, there are different varieties of gneiss containing amphibolite and granitoide lenses. They compose the biggest part of the studied area, mostly S and SW from the Seona spring. These gneiss varieties are differentiated by the levels of schistosity, folding, grain dimensions and by various proportions of petrogeneous minerals. They are mostly light to dark grey or greenish in colour and have a schistose structure. Principal mineral components of gneisses are quartz, acid plagioclase and biotite.

In a regional framework, these rocks are the basement of the Neogene sedimentary complex, and at the same time form the impermeable base of the Badenian aquifer with a transgressive and discordant contact between the two units. In discussing the hydrogeological conditions, it is notable that there are regions where the grusified and weathered zones are present at this palaeorelief surface.

Due to the possiblecirculation of the near-surface waters through these zones by means of gravitational flows towards the marginal or basal parts of the Badenian aquifer, there is potential for contribution to the recharge of the aquifer.

Badenian sediments (M_4^2) are composed of the conglomerates, limestones, sandstones and marls. They are found in the area S and SW from the Seona spring, where they transgressively and discordantly overlie the metamorphic complex described above.

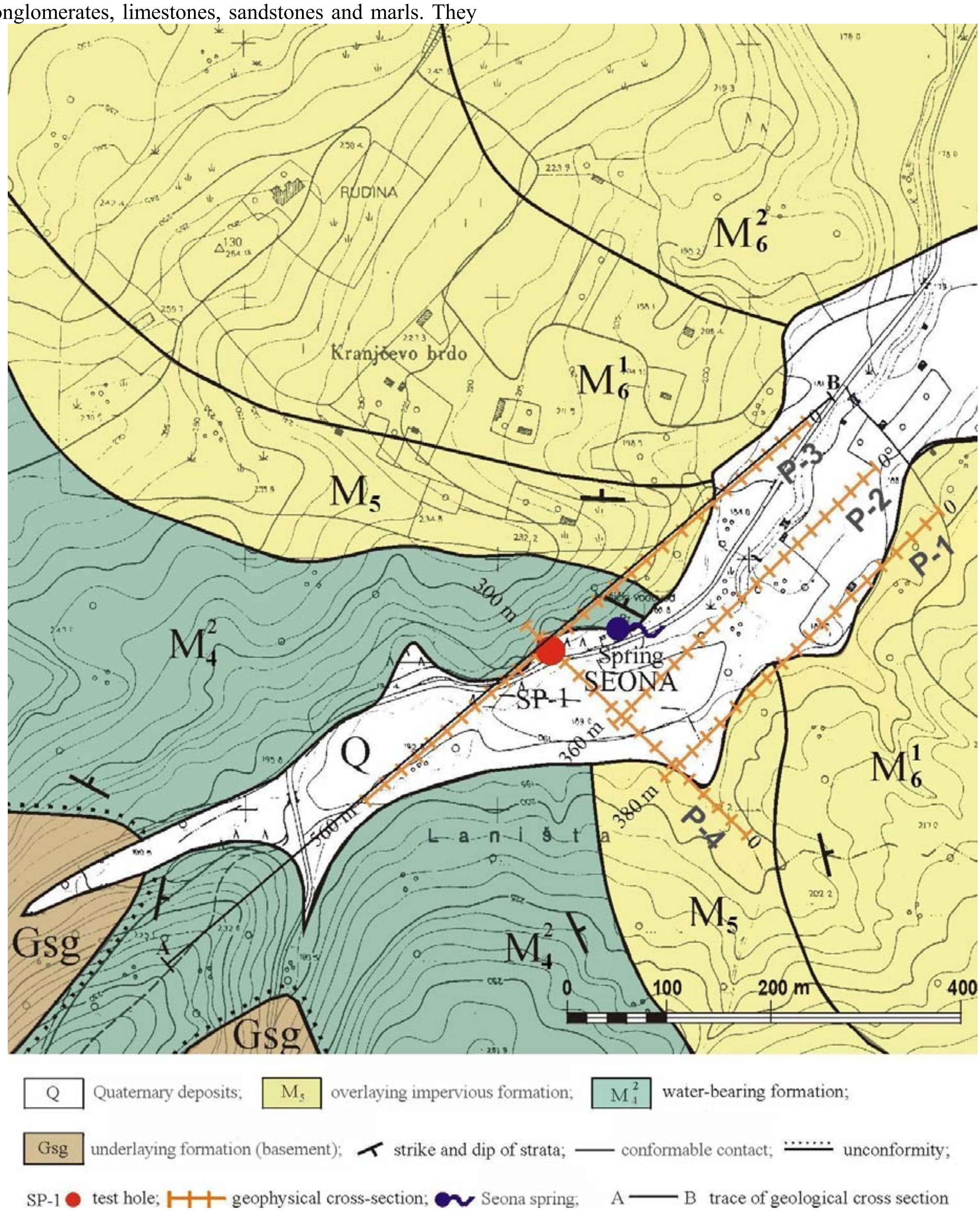


Figure 2. Hydrogeological map with traces of electrical imaging profiles

Slika 2. Hidrogeološka karta s položajima mjerenih tomografskih profila

The basal part of Badenian sediments is of polymictic conglomerates, occasionally brecciaconglomerates, with domination of the usually well-rounded pebbles of the schistose varieties of metamorphic rocks, frequently cemented with rich calcite cement or with fragmented biogene matrix (Korolija and Jamičić, 1989). Apart from the significant primary porosity, a secondary porosity is frequently encountered, which is interpreted as the result of both tectonics and dissolution processes, i.e. by dissolution of the carbonate cement. Dissolution is especially marked along the contact of the basal part of the aquifer with the grusified and frequently fragmented metamorphic basement.

Limestones, composing a large proportion of Badenian sediments, are mostly the fosiliferous bioclastic varieties interlayered with the calcareous sandstones. Small biolithite bodies are frequently encountered, too. The secondary porosity of limestones is especially developed by dissolution processes along numerous joints, while the primary porosity predominates in calcareous sandstones and especially in the framework of biolithite bodies. On the contact with Sarmatian sediments, layered sandy and calcareous marls prevail.

Badenian sediments of the investigated area are hydrogeologically important because they form a significant aquifer that is either naturally drained by numerous springs (Seona, Zmajevac, Stublić), or produced by means of the water wells (Gornja Motičina). Thickness of this unit in the studied area remains under 150 m.

Sarmatian sediments (M_5) are in the area of exploration composed of marls and marly limestones. As a rule, they are associated with the Badenian sediments, and there is a conformable contact between these two units (Korolija and Jamičić, 1989). Both the marls and marly limestones are layered and thickness of this unit is in the 20-40 m range. It is hydrogeologically important that these layers constitute the impermeable cover of Badenian aquifer.

As illustrated in the Basic geological map (Korolija and Jamičić, 1989), in the Miocene sedimentary succession, the Sarmatian layers are concordantly overlain by Lower Pannonian marly limestones and arenaceous marls (M_6^1). These sediments are pronouncedly layered and characterised by extensive spatial distribution. Thickness of this unit, as measured on outcrops, reaches 150 m. Impermeability is their major hydrogeological characteristic.

As a continuous succession of the Lower Pannonian layers, Upper Pannonian sediments (M_6^2) are represented by the light-coloured, almost white marls. These sediments are widely spread in the northern part of the studied area. Usually well layered, they are also impermeable. In the area of exploration the estimated thickness of this unit is in the 100-150 m range.

Quaternary sediments (Q_{al}) are found in the shape of lag laid down by the three watercourses – Našička rijeka, Vrela potok and Rijeka. These are mostly the lenses of sand and gravel incorporated in the sandy-clayey silt. Thickness of this unit in the study area doesn't exceed several meters.

Tectonics

The area of investigation lies in tectonic unit named the Krndija horst (Korolija and Jamičić, 1989). Two parts are differentiated within this unit, each with characteristically different palaeostructural evolution. The older part is composed of the crystalline rocks of Mt. Krndija, while the younger one belongs to the Neogene complex. The older part underwent severe restructuring through numerous orogenetic phases in the range from Baikalian to Alpian. Principal structure elements (foliations and axial plane cleavages) are presently striking east – west and have a southern vergence. The younger part was formed during the Neogene and Quaternary. Neogene sediments have a NW-SE strike and are mostly periclinally positioned in the study area, with layers gently dipping in direction of north. These layers are cut with several transverse faults whose traces coincide with the recent watercourses.

Data acquisition and processing

Survey design

The survey planning has been done on the basis of geologic data and predicted hydrogeological model, which has led to the conclusion that the most reliable geophysical method would be the electrical resistivity imaging. In respect to the expected irregular shape of the Miocene aquifers the method can provide for continuous lateral and vertical subsurface mapping. Impermeable rocks (marles and clays) and permeable rocks (limestones and sandstones) can be distinguished on the basis of their resistivities. Impermeable rocks have low resistivities, somewhere between 20 and 60 Ωm, while the permeable rocks have higher resistivities, more than 80 Ωm.

The exploration area was placed at the valley, with the captured spring placed at the northwestern border. The area was covered with four profiles, which are long between 300 m and 560 m, with total length of 1600 m. In the first phase three longitudinal profiles along the direction of the valley were placed (profiles P-1, P-2, and P-3). On the basis of the first results, in the second phase the profile P-3 was extended and one transversal profile (P-4) was also placed, Fig. 2. Profiles P-1, P-2 and the most part of P-4 laid on lowland part of the area with flat surface, while the profile P-3 and smaller part of the profile P-4 laid on the hillsides. Established net of the two-dimensional electrical profiles should provide for building at least quasi three-dimensional subsurface resistivity model and to enable three-dimensional hydrogeological mapping, but also to provide for reliable positioning of the exploratory borehole.

Field measurements and data processing

Electrical measurements were carried out by using our own electrode system. Wenner array was applied due to expected high electrical noises, as well as the ambient noises so called the geological noises. Unit electrode spacing of 20 m was applied with regard to the target depths between 10 and 100 m.

The measured data has been processed by means of the software applying Loke and Barker inversion method. The software employs a quasi-Newton technique to reduce the numerical calculations (Loke and Barker, 1996). It produces 2-D resistivity model satisfying measured data in the form of pseudosection. The goodness of fit is expressed in term of the RMS-error. A homogeneous resistivity model is used as the initial model, which is iteratively adjusted to fit the data. The software enables including of a terrain relief, and applying suitable topographic corrections. This is very important by reason of the deformations caused in a terrain with very high elevation variations.

Processed two-dimensional imaging profiles are shown in the Figs. 3-6. The measured apparent resistivities or the pseudosections are present in the upper parts of the figures, while 2-D interpreted resistivity models satisfying the measured data can be seen in the lower parts. On the basis of the RMS-error a degree of conformity between the measured and calculated pseudosection can be precisely evaluated. Lower RMS-error occurs at the profiles P-1 and P-2 (3.2 % and 2.0%), that point to the very good agreement. This means the explored geological structure can be approximated with real two-dimensional structures and low level of noises was present, as well. The profile P-3 has slightly higher RMS errors (3.7%), which point to the higher levels of electrical noises. The highest RMS-error on the profile P-3 can be also caused by the geological body with partially three-dimensional shape. This conclusion can also be derived on the basis of geological data and topographical position of the profile.

Geophysical interpretation

From the hydrogeological point of view areas with higher resistivities point to the permeable rocks and aquifers, in other words those are perspective areas. Interpreted inverse resistivities are in the range of 13-140 Ωm for all the profiles. The lowest resistivities are about 20 Ωm, which can be noticed at all profiles. The highest resistivities are noticed at the profiles P-3 and P-4, in general at the end of the profiles, but a bit lower resistivities are seen on the profiles P-1 and P-2. At the first look profiles P-1 and P-2 (Figs. 3 and 4), placed at lowlands, are very similar thus pointing to the conclusion on the same lithologic composition. In the beginning of the profiles lower resistivities are present, while the highest resistivities can be noticed at the ends of the profiles (about 100 Ωm). Strong resistivity changes, from lower to higher resistivities, can be noticed in general in the middle part of the profiles, thus pointing to a facies change or to a fault. In a hidrogeological sense the perspective area with permeable rocks is placed at the southwestern part of the area, and impermeable rocks (clays and marles) are present at the northeastern part of the area.

The profile P-3 (Fig. 5), partially placed on hillsides, looks quite different in comparison with the above mentioned profiles. Generally higher resistivities can be noticed on the profile, with low resistivities noticed only on a very small part at the beginning of the profile, placed actually in the lowland part. A few irregular bodies of high resistivities characterise this profile that point to a different lithology development in comparison with other profiles. In respect to the fact that the outcrop of the Miocene limestones is placed at the position 380 m conclusion can be drawn that the high resistivity bodies represent these limestones in a reefy development, which produced irregular bodies. The captured spring at the position 220 m and the small temporary spring at the position of 120 m also fall in the area of such high resistivity bodies, which means these bodies are probably main aquifers at the exploration area. In the middle part of the profile relatively wide zone of lower resistivities (approximately 50 Ωm) separates the high resistivity bodies. The geometrical elements should be also taken in consideration since they fall in a small valley in the terrain. This zone is probably caused by facies change and in general impermeable rocks, but it can also be a fault zone.

On the basis of considered 2-D electrical imaging data the conclusion can be drawn that the perspective area from hydrogeological viewpoint is placed in the southwestern part of the exploration area. The most promising area is on the profile P-3, in respect to established direct connection between the outcrop and the springs with the high resistivity bodies. The electrical imaging data together with geological data enabled determination of the position of the exploratory borehole.

Hydrogeological model and borehole results

The water of Seona spring emerges from the Badenian carbonate aquifer. Although this aquifer is of heterogeneous composition it generally constitutes a continuous belt along the rim of Mt. Krndija. The aquifer heterogenity results from the lateral and vertical succession of different lithotypes – organic limestones, conglomerates, sandstones and marls. Sandstones and marls are well layered, while the conglomerates are shaped in clinoform bodies, and organic limestones are in the form of small biolithite build-ups. Both types of

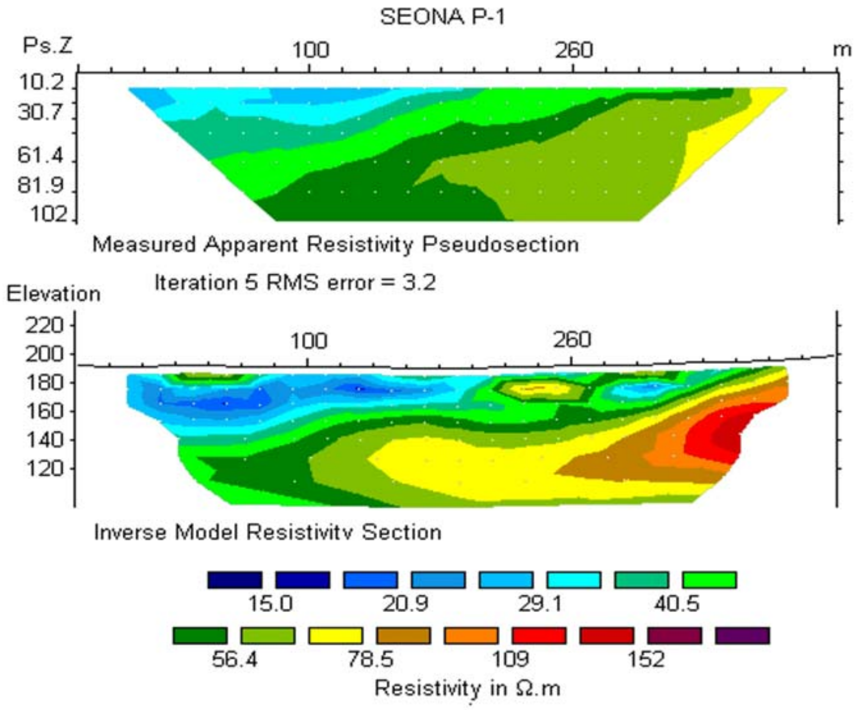


Figure 3. Two-dimensional electrical imaging profile P-1

Slika 3. Dvodimenzionalni profil električne tomografije P-1

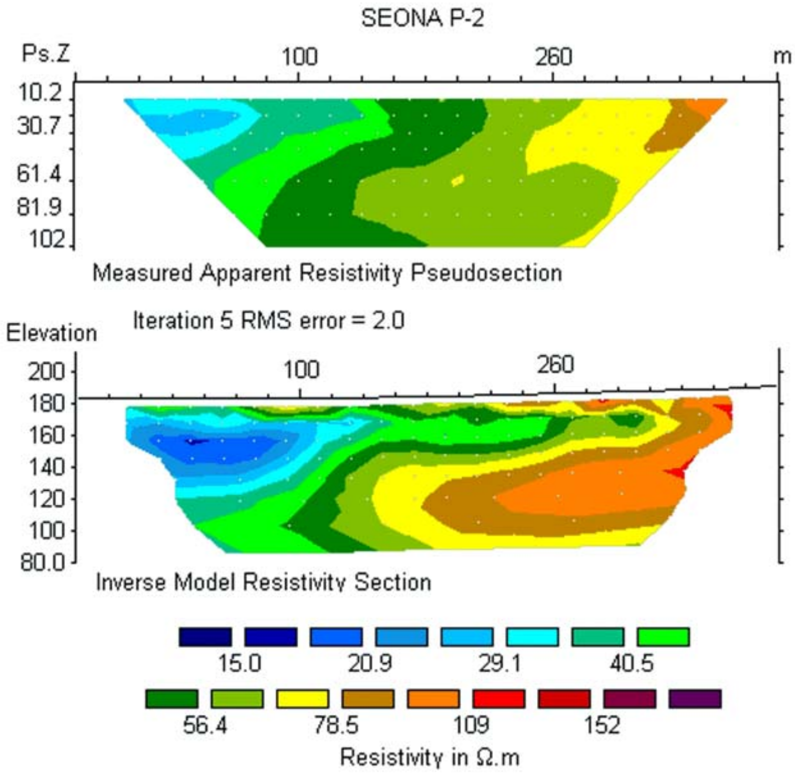
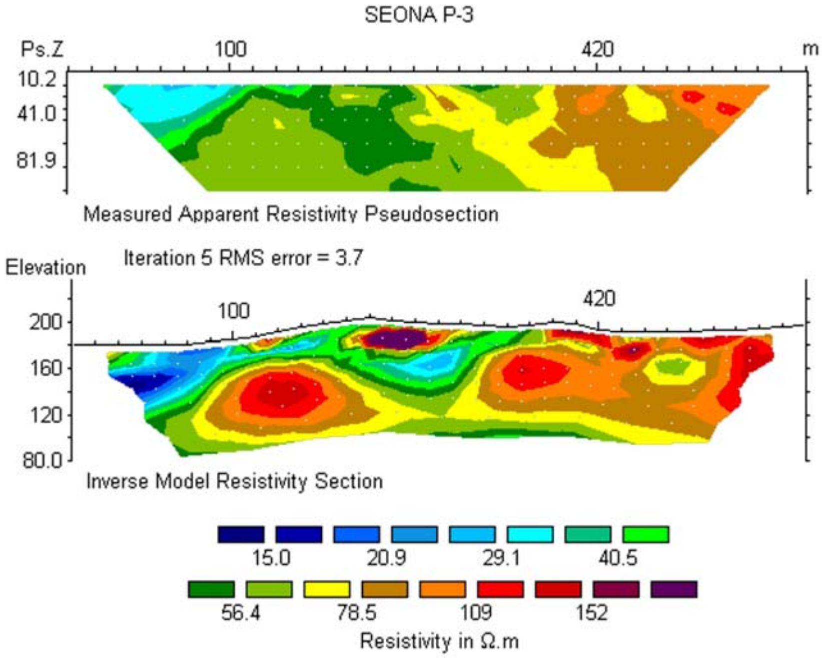


Figure 4. Two-dimensional electrical imaging profile P-2

Slika 4. Dvodimenzionalni profil električne tomografije P-2



Figur 5. Two-dimensional electrical imaging profile P-3

Slika 5. Dvodimenzionalni profil električne tomografije P-3

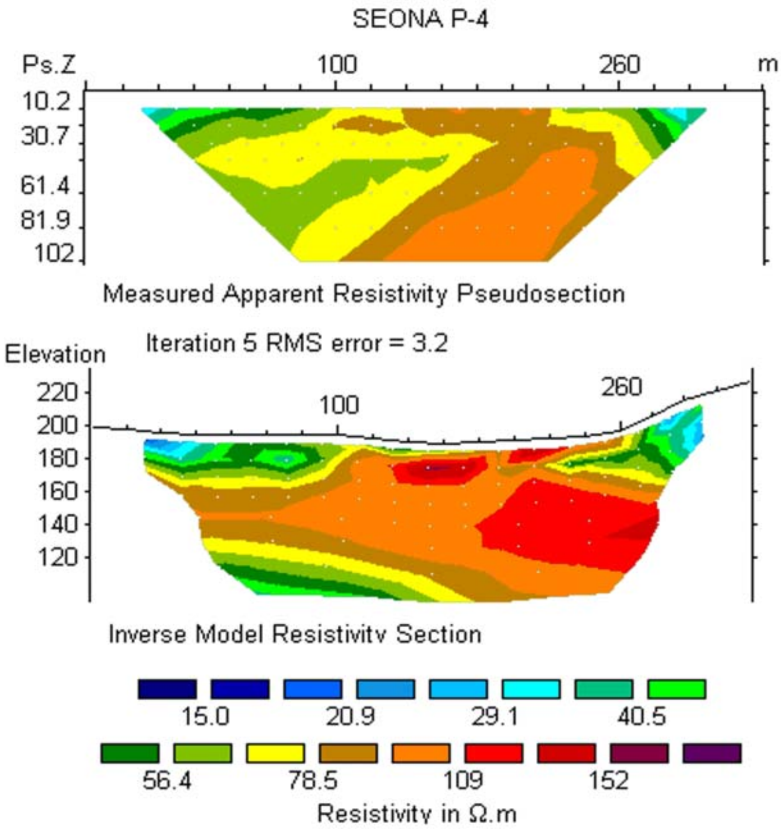


Figure 6. Two-dimensional electrical imaging profile P-4

Slika 6. Dvodimenzionalni profil električne tomografije P-4

porosity are significant for the groundwater accumulation. Primary porosity is mostly developed in the conglomerates, organic limestones and sandstones, while the secondary porosity results from dissolution of the carbonate cement of conglomerates and from karstification of limestones. Groundwater flows are exclusively concentrated in the significant fractures and caverns. The Seona spring is located in the marginal parts of the Badenian limestone sediments, in the area where they are covered with Quaternary lag. The spring regime has a markedly karst characteristics – the minimal discharge was measured at 3.6 l/s, while the maximal one was 39.6 l/s. Every higher significant increase in discharge is connected with pronounced turbidity, which confirms existence of the large concentrated flows through the system of caverns. Development of this system of caverns can be attributed to the transverse faulting, which is only mildly expressed at the surface due to the presence of the Quaternary stream sediments.

Interpretation of electrical measurements revealed the high resistivity zones that can be correlated with Badenian limestones and with contrasting contact of this unit with the marly layers characterised by a low resistivity. The main hydrogeological issue was – is there a direct connection of the interpreted geoelectric model withlithologic composition of water-bearing sediments and what is the depth of the privileged groundwater flows through the hydraulically continuous part of the cavern system. The exploration borehole SP-1 was located upstream from the Seona spring, close to the intersection of the profiles 3 and 4 (Fig. 2).

Three main sedimentary suites can be differentiated in the column of the SP-1 borehole (Fig. 7). The first one is from the terrain level to the depth of 8.2 m, the second lies in the 8.2-60.5 m interval, and the third one extends from the 60.5 m to the final depth of 100 m. The first sedimentary package is composed of the silty and clayey materials with occasional limestone fragments. It can be interpreted as the Quaternary sediments, covering the aquifer in the brook valley.

The heterogeneous limestone aquifer makes the second package of sediments. According to the borehole core determination, these sediments are in the 8.2-60.5 m interval, but the programme of well logs (N16" and N64" resistivity, gama-ray GR, and spontaneous potential SP) revealed the lower contact at 56 m. This unit is composed of the Badenian Lithotamnion limestone, with a gradual transition in the calcareous sandstones and conglomerates in the upper parts. The lower section contains interbeds of the breccia-like limestones and conglomerates. Looking at core material, the rocks are much fragmented and weathered till the depth of 55 m, and there are karstification traces in the 12-57 m interval. This means that weathered and karstified interval is positively defined by well logs. Various karstification traces exist. Sometimes these are the small cavities that can be observed on cores, or there are the small caverns, some of which are covered with amorphous calcite. The most significant caverns were registered by drop-down of drillings tools in the 19-19.8 m and 29-29.8 m intervals.

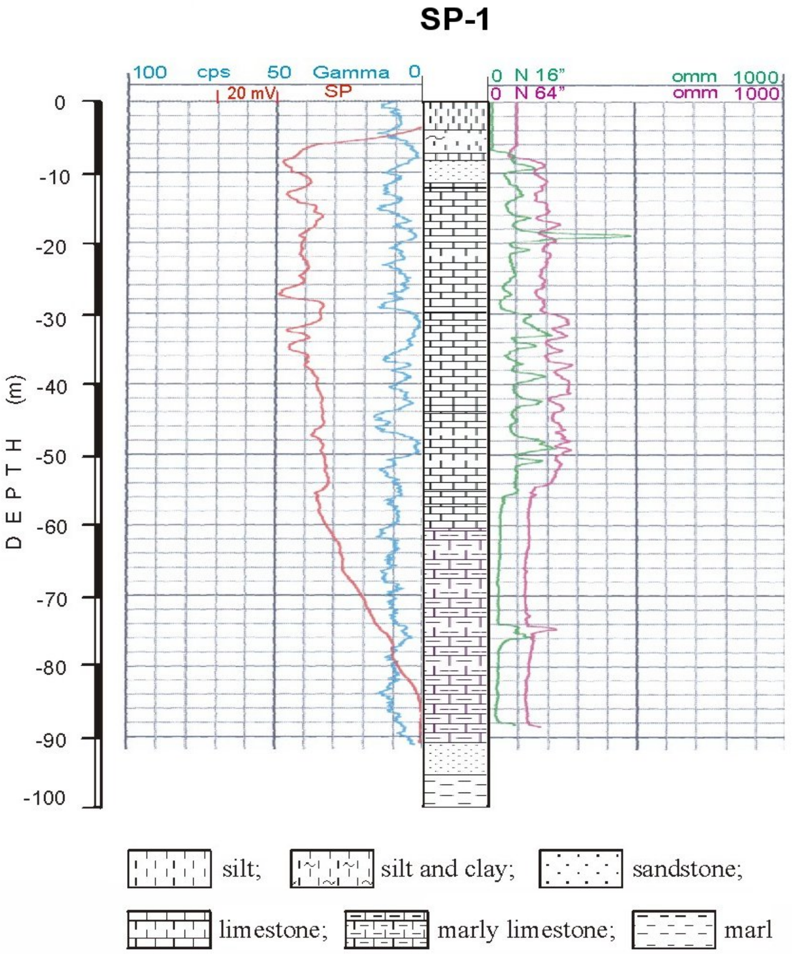


Figure 7. Gamma ray (GR), spontaneous potential (SP), resistivity (normal sonds N16" and N64"), and lithologic logs of the exploratory borehole SP-1

Slika 7. Karotaža prirodne radioaktivnosti (GR), spontanog potencijala (SP), otpornosti (normalna sonda N16" i N64") i litološki stup istražne bušotine SP-1

The third sedimentary package consists of marls, deeper than 60.5 m, which are positively defined as the regional basement of the aquifer.

A comparison between the interpreted resistivity model illustrated by the profile 3 (Fig. 5) and the lithologic column of the borehole (Fig. 7) results in conclusion that the high resistivity body as identified by the model can be correlated with the Badenian limestones. A high level of conformance between the interpreted 2-D electrical model and the actual lithology of sediments is achieved. The fact that the aquifer basement was drilled at somewhat shallower depth (55 m) than predicted, can be explained by differences between the actual local depth and spatial measurements that are reflected in 2-D model.

The hydraulic connections between the drilled caverns and the spring were already confirmed in the course of drilling, by the pronounced turbidity of the spring. Upon the completion of the borehole, a pump test was performed utilising an airlift. At the pumping rate of 8-10 l/s, the spring was completely drained-out, giving the final confirmation of the hydraulic connections between the caverns and the spring. Final geological and hydrogeological model was constructed on the basis of electrical and borehole data

. Representative geological cross section is shown in Fig. 8.

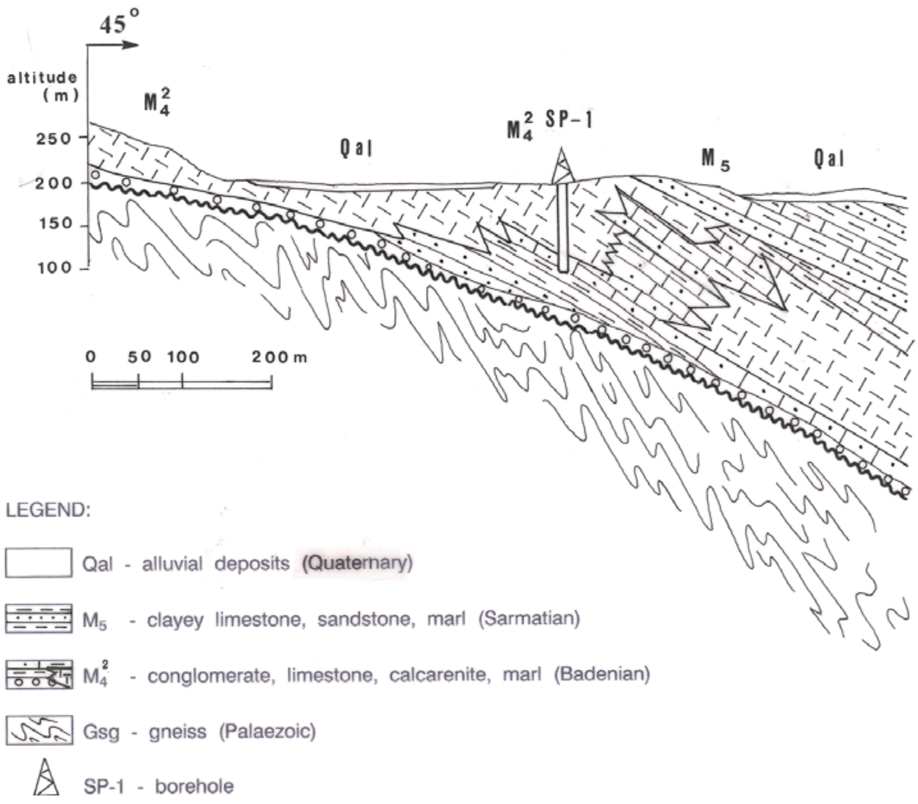


Figure 8. Geological cross section
Slika 8. Geološki presjek

Conclusions

Geophysical exploration was carried out by relatively new method of two-dimensional electrical imaging, which can provide continious lateral and vertical subsurface coverage. The net of the profiles has been established on the basis of geological data to enable a quasi three-dimensional hydrogeological mapping of the exploration area. Data processing has been performed by real two-dimensional inversion technique, published by Loke and Barker (1996). In respect to the low RMS-error noticed at the profiles P-1, P-2, and P-3 the conclusion on the real two-dimensional structures can be drawn. Higher RMS-error noticed on the profile P-3 points to the higher noise level and partially to three-dimensional structures.

In the northeastern part of the exploration area low resistivities can be noticed caused by the impermeable rocks such as clays and clayey sediments, thus making this part non-perspective from the hydrogeological point of view. Higher resistivities are seen in the southwestern part of the area pointing to the permeable rocks (limestones and sandstones) and possible aquifers. At the greater depths, around 100 m, the lower resistivities can be noticed again. The profiles P-1 and P-2 have very similar geoelectrical shapes, while the profile P-3 looks quite different in comparison with them, which indicates the differences in lithologic composition. The high resistivities, which are higher than at the other profiles, appear as a few separated bodies. These shapes are caused by the bodies of the Badenian limestones in a reefy development due to the fact that the limestone outcrop falls in such high resistivity body. In addition, the captured spring and small temporary spring can be also connected with the high resistivity bodies at the profile, which means they can be considered as a potential aquifer.

A high level of conformance between the interpreted 2-D electrical resistivity model and the actual lithologic column derived on the basis of borehole data is achieved. Although the aquifer basement was drilled at somewhat shallower depth (55 m) than predicted, the difference can be explained by the fact that lithologic column reflects the actual local relations while the model is an expression of the spatial measurements.

The presented case has demonstrated very great potentials of the two-dimensional electrical imaging in hydrogeological mapping of irregularly shaped aquifers. Conventional resistivity methods, the electrical sounding and the profiling can not provide the complete information in such conditions.

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