COBISS: 1.01

CHARACTERISATION OF KARST AREAS USING MULTIPLE GEO-SCIENCE TECHINQUES, A CASE STUDY FROM SW SLOVENIA

OPREDELITEV ZNAČILNOSTI KRAŠKIH OBMOČIJ S POMOČJO RAZLIČNIH RAZISKOVALNIH METOD, PRIMER IZ JZ SLOVENIJE

Nataša RAVBAR[1] & Gregor KOVAČIČ[2]

Abstract UDC 551.435.8(497.4-14)

Nataša Ravbar & Gregor Kovačič: Characterisation of karst areas using multiple geo-science techniques, a case study from SW Slovenia

This paper presents utilization of several different investigation techniques to better characterize karst environment. Geomorphological mapping, together with structural and lithological mapping, and electrical resistivity imaging have been carried out in a selected test site in order to evaluate intrinsic characteristics of a karst area. Identification, positioning and quantification of morphometrical properties of karst and other landforms have been determined. Tectonic deformations and lithological contacts of karst and non-karst rock have been precisely located. The extent and depth of the sediments have been examined. The results of mapping and electrical resistivity measurement have been arranged in comprehensive GIS database. The benefit of multiple investigation techniques application has been demonstrated. Employing a combination of methods revealed information on hydrogeologically most sensitive zones that were later used for comprehensive vulnerability and risk mapping, as well as groundwater tracing planning. Gained data provided new achievements in geophysical characterization of the studied area in the western outskirts of the Snežnik aquifer, in particular the Podstenjšek spring catchment. Findings can also be utilized to better understand relief evolution and can serve as a basis for various thematic and applied studies.

Keywords: karst surface, geomorphological mapping, structural and lithological mapping, electrical resistivity imaging, geographic information system.

Izvleček UDK 551.435.8(497.4-14)

Nataša Ravbar & Gregor Kovačič: Opredelitev značilnosti kraških območij s pomočjo različnih raziskovalnih metod, primer iz JZ Slovenije

Članek prikazuje uporabo več različnih raziskovalnih metod pri opredeljevanju značilnosti kraškega okolja. Z namenom vrednotenja fizično-geografskih lastnosti preučevanega območja smo izvedli geomorfološko in strukturno-litološko kartiranje, opravljeno je bilo merjenje električne upornosti tal. Identificirali in določili smo položaj ter morfometrične značilnosti kraških in drugih reliefnih oblik. Natančno smo določili potek tektonskih deformacij in litoloških stikov med kraškimi in nekraškimi kamninami. Proučili smo razširjenost in globino sedimentov. Rezultate kartiranja in merjenja električne upornosti smo uredili v obsežni GIS podatkovni bazi. Prikazane so prednosti uporabe več raziskovalnih tehnik. Združevanje raziskovalnih metod je prineslo informacije o hidrogeološko najbolj občutljivih območjih, ki so bile kasneje uporabljene v okviru obsežnega kartiranja občutljivosti kraške podtalnice in tveganja na onesnaženje. Rezultati so bili uporabljeni tudi pri načrtovanju sledilnih poizkusov. Pridobljeni podatki so podali nove dosežke pri opredelitvi fizičnih značilnosti zahodnih obronkov snežniškega vodonosnika, s poudarkom na hidrološkem zaledju izvira Podstenjšek. Ugotovitve predstavljajo osnovo za boljše razumevanje razvoja površja in lahko služijo kot podlaga za različne tematske in aplikativne študije obravnavanega območja.

Ključne besede: kraško površje, geomorfološko kartiranje, strukturno in litološko kartiranje, merjenje električne upornosti, geografski informacijski sistem.

[1] Karst Research Institute ZRC SAZU, Titov trg 2, SI-6230 Postojna, Slovenia, e-mail: natasa.ravbar@zrc-sazu.si
[2] University of Primorska, Faculty of Humanities, Koper, Titov trg 5, SI-6000 Koper, e-mail: gregor.kovacic@fhs.upr.si

Received/Prejeto: 28.11.2009

INTRODUCTION

Although carbonate rocks cover only about 12-15% of the world's surface, karst aquifers are increasingly becoming valuable drinking water resources (Salomon 2000; Forti 2002; Ford & Williams 2007). As the special character of karst makes water sources highly susceptible to human-induced and climate stresses, major recent concerns of scientists and practitioners relate to karst aquifer contamination and overexploitation (Drew & Hötzl 1999).

For successful protection and land use planning in karst, the concept of groundwater vulnerability mapping is often applied. Various approaches of groundwater vulnerability assessment were developed that base on different type of information about the soil and unsaturated zone, recharge conditions and other hydrological characteristics of the aquifer (Vrba & Zaporozec 1994; Zwahlen 2004; Ravbar 2007). Several direct and indirect methods are used for identifying, quantifying and mapping these factors. Most often, for proper protection several detail studies are required, among which geological and geomorphological characterisation, groundwater tracing, water balance estimation, spring hydrograph analyses and others remain as the primary tools.

Several authors have already emphasized that in order to identify hydrologically vulnerable areas, it is particularly difficult to determine epikarst characteristics and characteristics of layers overlying karst landscapes (e.g., Doerfliger & Zwahlen 1998*; Petrič & Šebela 2004). To date most effective methods are still geological and geomorphological mapping (Veni 1999). Currently available geophysical methods could additionally be applied for characterisation of subsurface properties (Bechtel *et al.* 2007).

Within a frame of a research focusing on the vulnerability mapping of the Podstenjšek catchment area in SW Slovenia, and providing improved source protection zones, geological and geomorphological properties of the area have been studied in detail. The aim of this paper is thus to demonstrate utilization of conventional methods, such as structural and lithological mapping, geomorphological mapping and electrical resistivity technique for comprehensive groundwater vulnerability and risk assessment purposes. More of local importance is the enhancement of geological and geomorphological characterization of the studied area for source protection efforts, for the further interpretation of the relief evolution or for other thematic and applied studies.

DESCRIPTION OF THE TEST SITE

The study focuses on the southwestern part of Slovenia, where western outskirts of the Snežnik massive (1,796 m) extend towards northwest into the Upper Pivka valley. Snežnik massive is one of the most valuable karst aquifers in the country holding important drinking water resources. Its western part drains several regionally and locally important water sources that are irreplaceable for more than 12,000 inhabitants of the Ilirska Bistrica municipality (Bistrica and Podstenjšek springs, boreholes near Knežak village and some other smaller springs; Fig. 1). During dry period the most important Bistrica water source also supplies villages in the neighbouring municipality and in the neighbouring country (Republic of Croatia).

The test site is the catchment of the Podstenjšek springs and its surroundings. It consists of Cretaceous to Palaeocene limestones and breccias thrusted over Eocene flysch (Šikić *et al.* 1972; Šikić & Pleničar 1975). Explicit thrusted structure is clearly expressed in a rocky escarpment that in some places reaches the heights between 200 and 400 m above the surrounding. Tectonic window near Knežak village also confirms the thrust structure (Pleničar 1959). Displacement of the upper thrust sheet over the lower-lying one (on the southwest) is estimated to be about seven kilometres towards the southwest; however intensity of thrusting is less distinctive northwest of the studied area (Placer 1981).

Due to the presence of the underlying flysch rocks a shallow karst aquifer is formed. The area is characterized by fast and strong groundwater table fluctuations. Groundwater level rise in response to abundant precipitation events and/or rapid snowmelt is manifested in intermittent lakes (Habič 1975). These commonly occur in the whole Upper Pivka valley (Fig. 1). In the test site two intermittent lakes (Šembijsko Jezero and Nariče) appear whenever groundwater level is sufficiently high. In the area of the intermittent lakes, alluvial deposits can be found, and in the uplifted Kamenščina dry valley at the outskirts of the studied catchment, there is periglacial material deposited in the dolines.

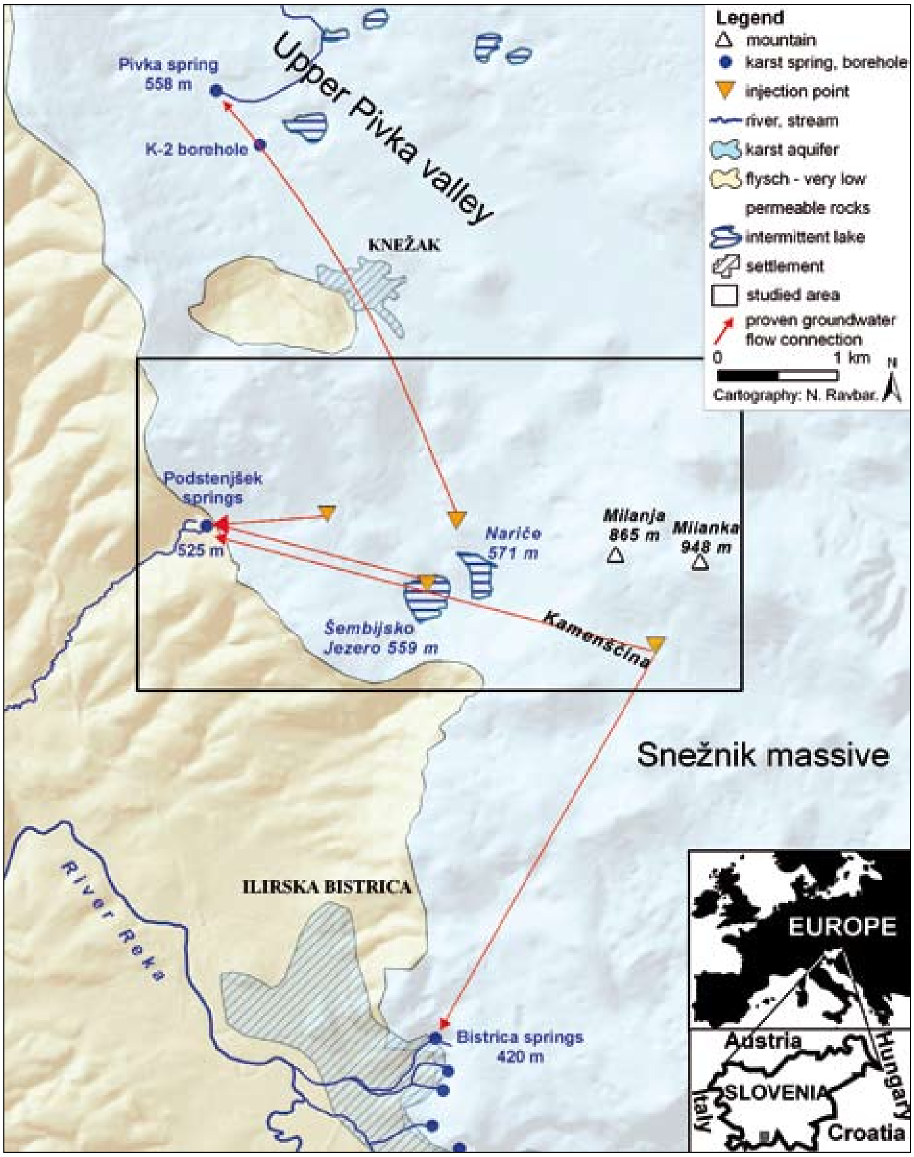

Fig. 1: Generalized hydrogeological map of the studied area and surroundings (Map based on DEM 12.5, Surveying and Mapping Authority of the Republic of Slovenia 2005; Šikić et al. 1972; modified after Ravbar & Goldscheider 2007).

The underlying flysch also causes an impermeable barrier for the groundwater that runs from the area of the Snežnik aquifer towards west and prevents water from draining towards the Reka river basin. Major quantities of groundwater, drained from the Snežnik massive, rebound from the flysch and thus flow northwards. Just locally the flysch barrier is interrupted and a smaller part of the underground water outflows as the Podstenjšek springs (Krivic *et al.* 1983).

MATERIALS AND METHODS

The geomorphological mapping was performed at the scale 1:5,000 by field examination in conjunction with the topographic maps, digital elevation model, digital orthographic photographs and the national cave database examination. Identification, positioning and quantification of surface landforms' morphometrical properties and endokarst features investigation were undertaken. Surface geomorphological features attributes have been processed and recorded using ArcGIS software package. The geomorphological map was elaborated using standardised karst and other geomorphological symbols (Veni 1999; Gustavsson *et al.* 2006; Häuselmann 2006).

After examination of the basic geological map of the area in scale 1:100,000 (Šikić *et al.* 1972) and other published sources (Buser 1976; Poljak 2000) quite some discrepancies and irregularities have been noted. With the aim to precisely locate and determine tectonic deformations and distinguish different lithological units, structural and lithological mapping was done after the method of Čar (1982) at a scale of 1:5,000. Method includes detection of lithological contacts and detection of different types of fractured zones in rock outcrops (crushed, broken and fissured zone). Mainly we focused on identification and location of the lithological juncture of carbonate rocks with flysch, periglacial or alluvium, as well as crushed and broken zones. Lithological characteristics and tectonic deformations were also mapped with the help of digital elevation model and digital orthographic photographs.

The extent and depth of soil and sediments has been examined using Super Sting R1/IP electrical resistivity imaging. Resistivity measurement is obtained by selecting four electrodes at a time (Fig. 6) and driving a known electrical current (I) between two electrodes. Two other electrodes are used to measure a voltage (V) or potential difference in the field. Electrodes are separated by constant spacing (a) and connected by cables to a computer controlled automated switching mechanism. Combined sounding and profiling using computer software provides a two dimensional data set of apparent resistivity (Loke 1999; Bechtel *et al.* 2007).

Five line profiles were performed for the indirect insight of the subsurface geological structure. Wenner array in all the profiles with a length of 100 m (5 m electrode spacing) was applied. The Wenner array is a relatively robust array, but is rather sensitive to vertical changes in the subsurface sensitivity and less sensitive to horizontal changes. Thus it is good in detecting horizontal structures and obtains greater depth penetration capacities. The resistivity of each medium is < 100 ohm m for clay and soil, between 100 and 800 ohm m for weathered rocks and/or sediments, and > 1,000 ohm m for limestone (Loke 1999; Gibson *et al.* 2004; Sauro *et al.* 2009).

RESULTS

GEOMORPHOLOGICAL MAPPING

The basic present relief characteristics of the studied area were shaped in the Pliocene fluvial and karst phases, and were more profoundly transformed by the Pleistocene processes (Kovačič 2006). In the Podstenjšek spring catchment karst relief forms prevail, however, also some fluvial forms and forms related to Pleistocene processes can be found (Fig. 2). In large parts of the area the karstified rocks are covered with very thin (~20-30 cm) soil cover. The most typical features are bowl shaped shallow dolines that intersect conical hills. Only in small patches there are outcrops of highly fractured limestone and individual karren. In the studied section 228 dolines have been observed. Their density reaches 38, and in some smaller parts even up to 60 dolines per km^2. Their bottoms are rather flat and covered by more than a meter thick soil. However dolines are scarce on the slopes.

Two larger karst depressions are associated with the intermittent lakes appearance. Their bottoms are covered with Quaternary coarse rubble (< 10 cm in diameter). On the east there is the noticeable Kamenščina hanging dry valley (Figs. 2 and 3). There are numerous smaller karst depressions on the bottom of the valley. In a few dolines well stratified clastic material can be found (Fig. 5). The sediments are composed of alteration of unconsolidated or partly consolidated layers of rubble less than 2 cm in diameter, layers of clay and layers of breccia. Mapping of geomorphological features has also identified numerous small dry stream channels generally running from the Kamenščina dry valley towards the intermittent lakes. The channels are very narrow and shallow with a rocky bottom.

The relief evolution of the Kamenščina dry valley has not been examined yet. For specific interpretation of landscape development detail studies are needed; however, some ideas can be inferred from the geomorphological mapping. On these bases, the authors deduce that the valley originates from the pre-karst phase of the Pliocene, was later subjected to Pliocene karstification, and profoundly altered by the Pleistocene periglacial processes. Several questions still remain open, but the interpretation of landscape evolution is not the scope of this study.

On the north, the undulating surface with alternating dolines and conical hills border the small inactive polje, which is the most south-eastern part of the Upper Pivka valley. It is assumed that the basic concave relief of this polje originates from Pliocene, and was later transformed by intensive erosional and accumulation Pleistocene processes. Geomorphological transformation during Pleistocene incised steep and narrow dry valley on the southeastern edge of the polje (upper right corner in Fig. 2).

There have been eleven caves registered in the studied area. All except three originate on the limestone-flysch contact and are situated on the thrust front. With

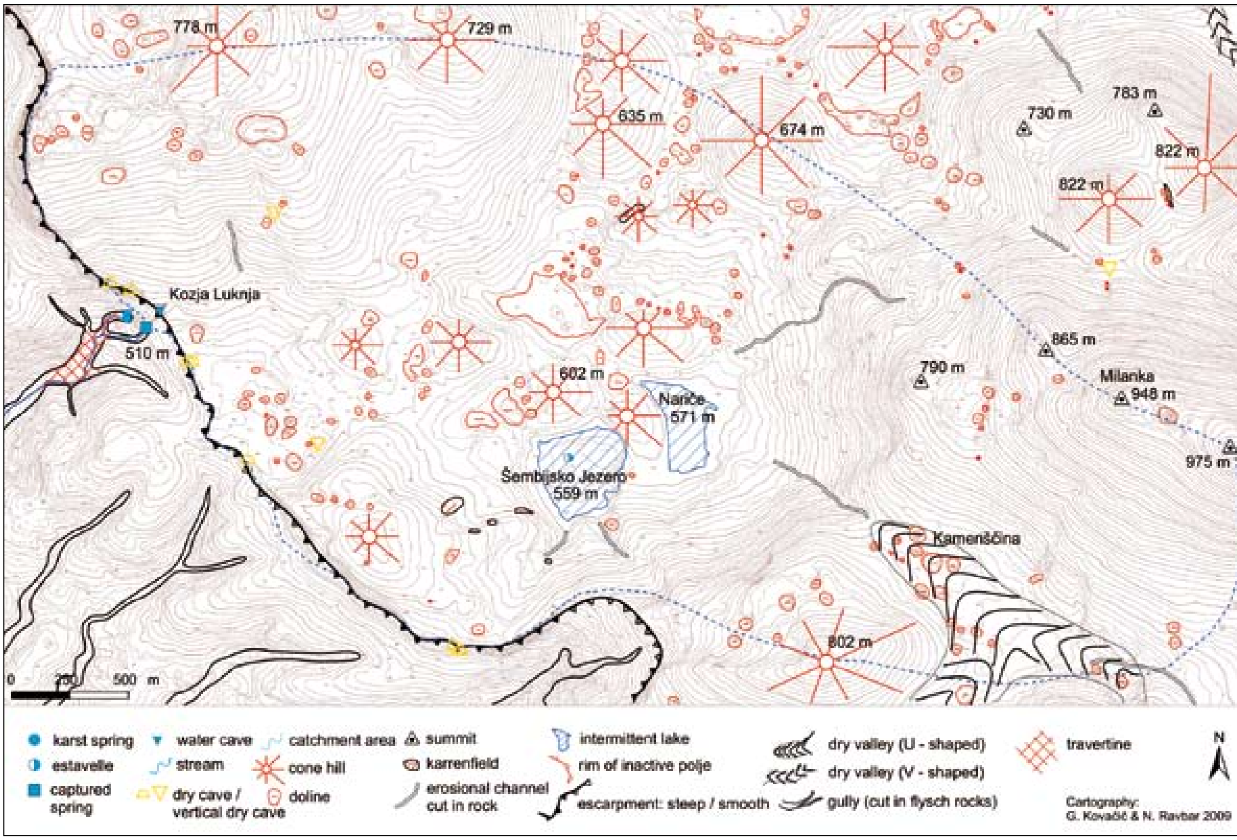

Fig. 2: Geomorphological map of the studied area (Map based on Topographical map 1:5,000, Surveying and Mapping Authority of the Republic of Slovenia; Register of caves 2009).

Fig. 3: Bottom of the Šembijsko Jezero and the Kamenščina dry valley at the back. Inset shows the sediments in the estavelle (Photos: N. Ravbar).

the exception of the Kozja Luknja cave, other caves are very short and dry. The Kozja Luknja is an intermittent spring cave where the underground water level with at least 20 m oscillation can be observed.

A thrust front at the southern and southwestern part of the investigated area forms the so-called karst edge, an escarpment between 200 and 400 m high. Below this escarpment small gullies deeply incised in mechanically less resistant flysch rocks prevail. At the bottom of the Podstenjšek pocket valley abundant travertine deposits can be found.

Fig. 4: Thrust contact of limestone over flysch forms the so-called karst edge (Photo: J. Logar).

LITHOLOGICAL AND STRUCTURAL CHARACTERIZATION

The performed lithological mapping revealed that the extent of the Quaternary alluvial deposits positioned and constructed by Šikić *et al.* (1972), and Šikić and Pleničar (1975) is excessive. Alluvial sediments were only observed in the bottom of the Šembijsko Jezero. Even though no sediments were observed on the bottom of Nariče, the measurements of electrical resistivity indicated that the sediments may appear to a smaller extent. Furthermore, the Kamenščina dry valley below the Milanka mountain is in places covered by thicker layers of periglacial material that has not been mapped before.

The five line profiles were carried out on the bottoms of Šembijsko Jezero and Nariče, and in the Kamenščina dry valley. The purposes of the investigation were merely to study the extent and depth of the sediments in the intermittent lakes and in the dry valley (Figs. 6 and 7, for locations see Fig. 8).

The profile (a) in the Šembijsko Jezero is orientated eastwards towards its bottom. The results indicate that the carbonate rocks are covered by lower resistivity layers. At the distance of 10 m from the beginning of the profile, lower resistivity layers cross the estavelle, which is covered by ~50 cm of sediment and a decimetre thick soil cover that has been also verified with the field observation (Fig. 3). According to the highly homogeneous results the depth of sediments and soils increases towards the centre of the depression, where these sediments reach a depth of more than

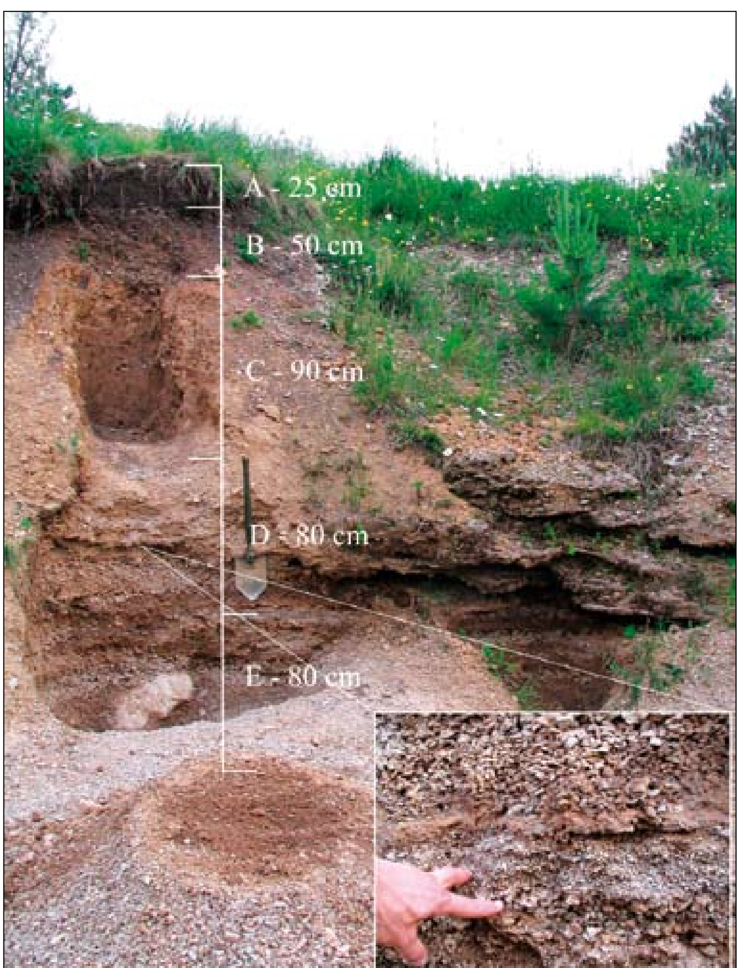

Fig. 5: Sediment profile in the excavated doline of the Kamenščina dry valley: A - soil, B - fine-grained rubble, C - clay, D - breccia, E - well stratified fine-grained rubble (Photos: G. Kovačič).

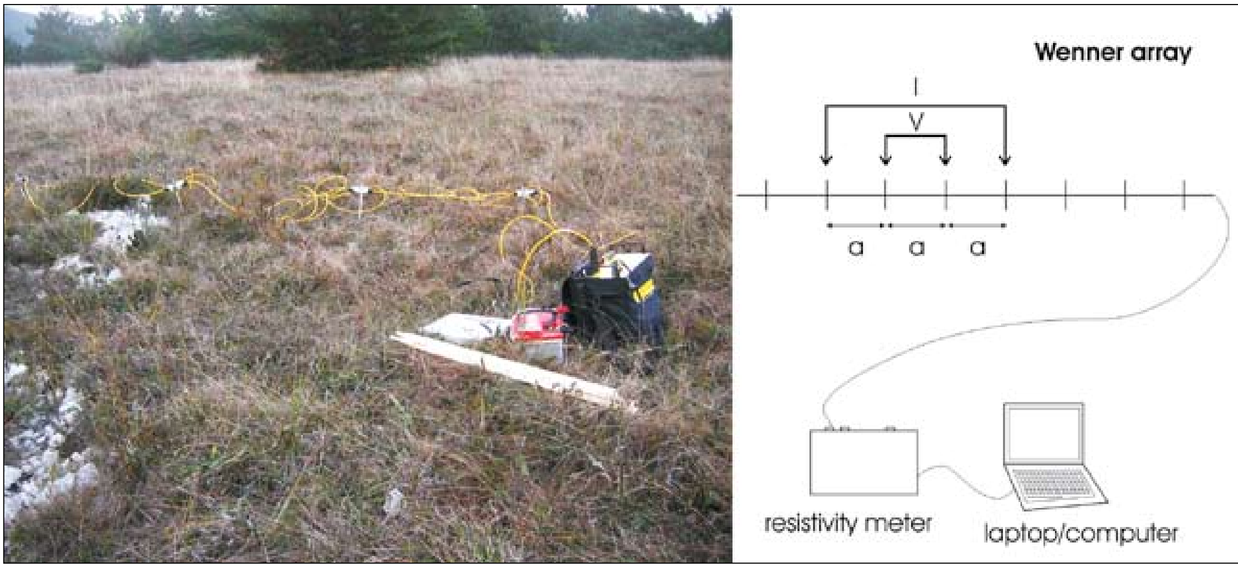

Fig. 6: The figure is showing the electrical resistivity measurement principle. The measurement technique comprises the resistivity meter and a number of electrodes sticked into the ground (Modified after Loke 1999; Bechtel et al. 2007; photo: N. Ravbar).

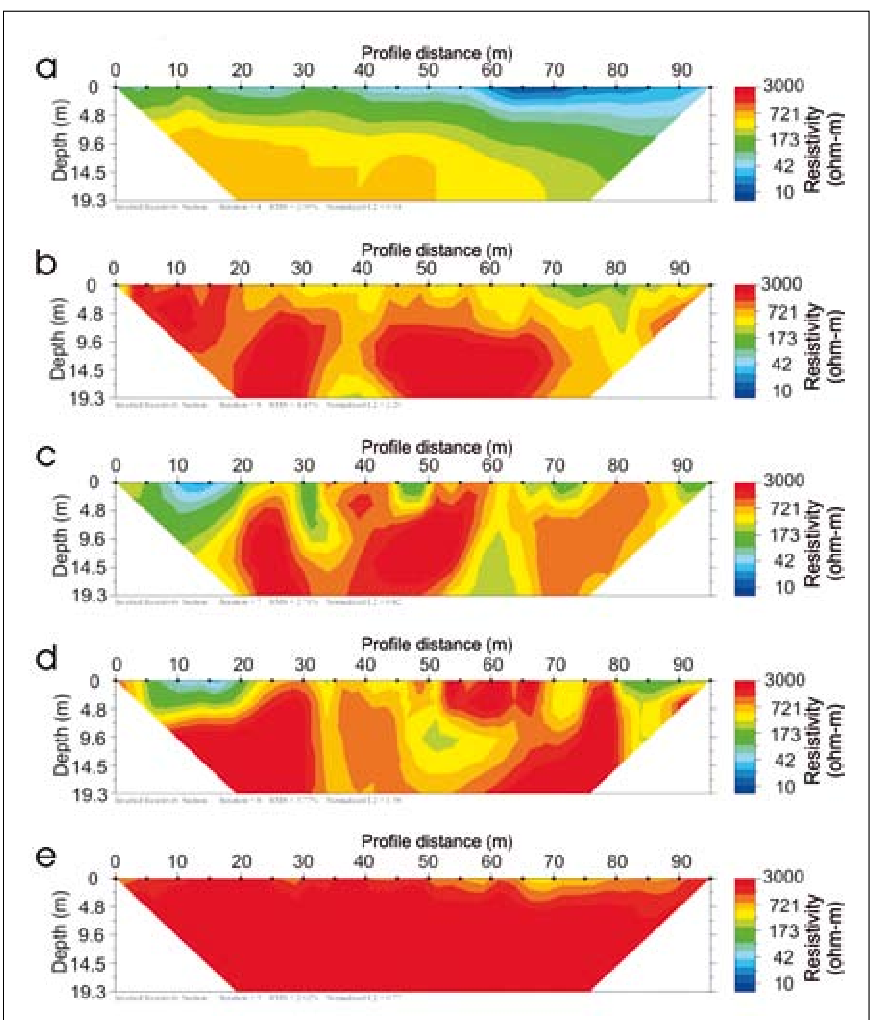

Fig. 7: Apparent resistivity pseudosections: Šembijsko Jezero (a), Nariče (b, c), Kamenščina (d, e). For exact location of the profiles see Fig. 8.

10 m with horizontally structured layers.

The profiles (b, c) at the Nariče were placed perpendicular to each other. The profile (b) is oriented eastwards and the profile (c) northwards. The results show large heterogeneity of the subsurface characteristics and its high fracturation. The fractured areas are forming pinnacle-cutter like features in the subsurface. The morphologically not distinctive patches of lower resistivity material that can reach depth up to 10 m or even more are possibly the infillings of detritius material.

The profiles (d, e) in the Kamenščina dry valley were performed perpendicular to the valley and orientated northeastwards. The (e) profile shows that the bottom of this part of the valley is not covered by soil and sediment layers of significant depth. Practically the entire profile crosses firm and homogeneous limestone rock basis that was also proved by field observation.

The heterogeneity of the profile (d), performed in the lower part of the dry valley, has been expected already from the geomorphological observations. It crosses two shallow dolines at both edges of the profile. There are several meters of low resistivity material filling the dolines. Hand auger drillings in the dolines of this area confirmed soil depth of more than one metre. In between the dolines there is a heterogeneous subsurface of pinnacle-like features, separated by zones of higher permeability and filled with low resistivity material.

Because of the explicit thrusted structure, tectonic deformation of the area is significant. Two thrust sheets are separated by the Snežnik thrust fault (Poljak 2000) that is clearly distinguishable as a rocky escarpment rising above the non-karst surrounding. On the south of the studied area (Fig. 8) the Snežnik thrust fault is displaced by the Šembije fault that converts into thrust fault towards the north (Šikić *et al.* 1972; Buser 1976).

During the mapping most significant tectonic deformations identified by Šikić and Pleničar (1975), Buser (1976) and Poljak (2000) have been recognized. Distinctive broken zones with fragments of crushed zones and presence of tectonic breccia have been distinguished and precisely positioned. At places also the dip orientation and dip angle of fissures has been measured. Dominant Dinaric orientation of fissures 70/70 (NW/SE) has been recognized (Fig. 8).

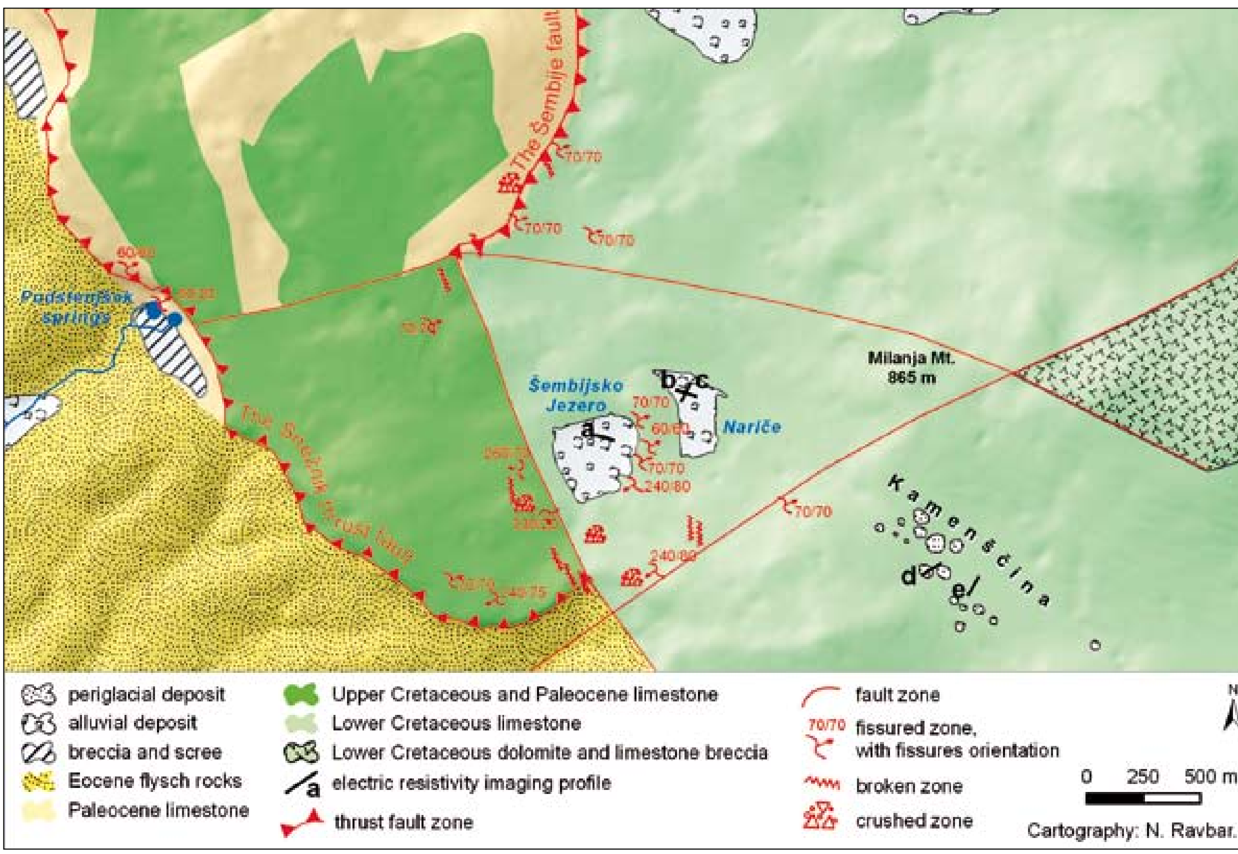

Fig. 8: Structural and lithological settings of the studied area with the locations of the electrical resistivity imaging profiles (Modified after Šikić et al. 1972; Šikić & Pleničar 1975; Buser 1976; Placer 1981; Poljak 2000).

DISCUSSION AND CONCLUSION

Karst aquifers are generally the most susceptible to contamination, and beyond among the most complex and least understood hydrological and geomorphological systems. To protect and cautiously manage karst groundwater resources profound studies are desired. For different purposes of engineering, spatial planning and protection in karst newly and quickly developing research methods and technological equipment is currently available that can be used as a stand-alone or in combination.

In the present study several different investigation techniques have been carried out to better characterize karst environment: geomorphological mapping, structural and lithological mapping, and electrical resistivity imaging. A large amount of resulting data has been arranged in comprehensive GIS database. Relatively simple and quick processing and recording has enabled management, editing and utilization of data. Employing a combination of methods in conjunction with precise examination of the results from the previous studies contributed to significant advances in characterisation of the selected karst area.

In the area of the utmost western foot of the Snežnik massive and the Upper Pivka valley in SW Slovenia despite strategic and economic importance of their groundwater resources, only a few general and detailed geological and hydrological researches have been conducted so far by Melik (1951), Habič (1984, 1989), Gospodarič (1989) and others. On the contrary, intermittent lakes appearance and groundwater connections in the Upper Pivka valley have attracted more hydrological interest (Habič 1968, 1975; Kranjc 1985; Ravbar & Šebela 2004; Kovačič & Habič 2005). With the increase of needs for supplementary drinking water sources additional hydrological investigations of the Upper Pivka valley have later been performed (Krivic *et al.* 1983, 1984).

The example of the nearby Bistrica karst spring illustrates some problems of water mismanagement, where sufficient protection zones have not yet been set up and water protection regulations have not been implemented properly (Kovačič & Ravbar 2005). Therefore additional studies and legal activities are still needed in order to ensure safe drinking water from springs under the Snežnik massive.

The presented fundamental research of the selected area demonstrated the benefit of multiple investigation techniques application. Gained results provided a comprehensive database of geological and geomorphological data that is supported with the completed technology of geographical information systems. On these bases, the recent comprehensive study of the Podstenjšek springs and their catchment has been done providing optimum water protection zones in Ravbar and Goldscheider (2007), which, unfortunately, have not been legalized. Estimations of certain feature's permeability has been conducted. The anticipated high permeability was translated into high source vulnerability or high risk to contamination respectively. Furthermore, the presented findings were later also used for tracing arrangement.

Resulting geomorphological, structural and lithological maps and electrical resistivity imaging results are not valuable only for protection purposes. They are useful for further exhaustive studies on the interpretation of landscape configuration and its development reconstruction, and for several specific thematic and technical applications as well (e.g., for karst hazards, planning and nature conservation, engineering purposes, etc.)

ACKNOWLEDGEMENTS

The study was founded by the Slovene Ministry of Higher Education, Science and Technology in the frame of the Young Researchers Programme, and is a contribution to the UNESCO/IUGS IGCP 513 Project "Global Study of Karst Aquifers and Water Resources". The authors acknowledge the help of Stanka Šebela (Postojna) and Nico Goldscheider (Neuchâtel) for their valuable contributions.

REFERENCES

Bechtel, T.D., Bosch, F.P. & M. Gurk, 2007: Geophysical methods.- In: Goldscheider, N. & D. Drew (eds.) *Methods in karst hydrogeology.* International Contributions to Hydrogeology. Taylor and Francis Group, pp. 171–199, London.

Buser, S., 1976: Geotektonska zgradba južnozahodne Slovenije.- In: Grad, K. (ed.) *Geotektonika, geofizika 3*. Osmi jugoslovanski geološki kongres, Bled, 1th–5th October 1976. Slovensko geološko društvo, 45–58, Ljubljana.

Čar, J., 1982: Geološka zgradba požiralnega obrobja Planinskega polja.- Acta carsologica, 10, 75–105.

Daly, D., Dassargues, A., Drew, D., Dunne, S., Goldscheider, N., Neale, S., Popescu, I.C. & F. Zwahlen, 2002: Main concepts of the »European approach« to karst-groundwater-vulnerability assessment and mapping.- Hydrogeology Journal, 10, 340–345.

Doerfliger, N. & F. Zwahlen, 1998: Practical Guide. *Groundwater Vulnerability Mapping in Karstic Regions (EPIK).*- Swiss Agency for the Environment, Forests and Landscape, pp. 56, Bern.

Drew, D. & H. Hötzl (eds.), 1999: *Karst Hydrology and Human Activities.*- International Contributions to

Hydrogeology. A. A. Balkema, International Association of Hydrologists, pp. 322, Rotterdam.

Ford, D.C. & P.W. Williams, 2007: *Karst hydrogeology and geomorphology.*- John Willey & Sons Ltd, pp. 562, London.

Forti, P., 2002: Speleology in the Third Millennium: Achievements and Challenges.- Theoretical and Applied Karstology, 15, 7–26.

Gibson, P.J., Lyle, P. & D.M. George, 2004: Application of resistivity and magnetometry geophysical techniques for near-surface investigations in karstic terranes in Ireland.- Journal of Cave and Karst Studies, 66, 2, 35–38.

Gospodarič, R., 1989: Prispevek k vodnogospodarskim osnovam Pivke.- Acta carsologica, 18, 21–38.

Gustavsson, M., Kolstrup, E. & A.C. Seijmonsbergen, 2006: A new symbol-and-GIS based detailed geomorphological mapping system: Renewal of a scientific discipline for understanding landscape development.- Geomorphology, 77, 90–111.

Habič, P., 1968: Javorniški tok in oskrba Postojne z vodo.- Naše jame, 10, 47–54.

Habič, P., 1975: Pivka in njena kraška jezera.- In: Fatur, S. (ed.) *Ljudje in kraji ob Pivki.* Kulturna skupnost Postojna, 41–54, Postojna.

Habič, P., 1984: Vodna gladina v Notranjskem in Primorskem krasu.- Acta carsologica, 13, 37–78.

Habič, P., 1989: Kraška bifurkacija Pivke na jadransko-črnomorskem razvodju.- Acta carsologica, 18, 223-264.

Häuselmann, P., 2006: Symbols for karst surfaces: The UIS list.- Z. Geomorph. N.F., 147, 3–7.

Kovačič, G. & Š. Habič, 2005: Karst periodical lakes of Pivka (SW Slovenia) during high waters in November 2000.- Acta carsologica, 34, 3, 619–649.

Kovačič, G. & N. Ravbar, 2005: A review of the potential and actual sources of pollution to groundwater in selected karst areas in Slovenia.- Natural Hazards and Earth Systems Science, 5, 2, 225–233.

Kovačič, G., 2006: Relief evolution in the hinterland of the Pivka river.- Acta geographica Slovenica, 46, 1, 33–55.

Kranjc, A., 1985: Poplavni svet na Pivki.- In: Gospodarič, R. (ed.) *Ljudje in kraji ob Pivki.* 2. knjiga. Kulturna skupnost Postojna, 155–172, Postojna.

Krivic, P., Drobne, F., Kokol, L., Bizjak, M., Juren, A., Marinko, M. & M. Paderčič, 1984: Hidrogeološke raziskave zaledja Zgornje Pivke, II. faza.- Geološki zavod Ljubljana, TOZD-I geologija, geotehnika, geofizika, pp. 14.

Krivic, P., Juren, A., Bizjak, M. & B. Ravnikar, 1983: Hidrogeološke raziskave zaledja Zgornje Pivke, I. faza.- Geološki zavod Ljubljana, TOZD-I geologija, geotehnika, geofizika, pp. 19.

Loke, M.H., 1999: Electrical imaging surveys for environmental and egineering studies: a practical guide to 2-D and 3-D surveys.- Report GeoTomo LLC, Penang, Malaysia.

Melik, A., 1951: Pliocenska Pivka.- Geografski vestnik, 23, 17–38.

Petrič, M. & Šebela, 2004: Vulnerability mapping in the recharge area of the korentan spring, Dlovenia.- Acta carsologica, 33, 2, 151–168.

Placer, L., 1981: Geološka zgradba jugozahodne Slovenije.- Geologija, 24, 1, 27–60.

Pleničar, M., 1959: Tektonski okni pri Knežaku.- Geologija, 5, 5–10.

Poljak, M., 2000: *Strukturno-tektonska karta Slovenije, izdelana po podatkih Osnovne geološke karte SFRJ, 1:100.000.*- Ljubljana.

Ravbar, N. & S. Šebela, 2004: The karst periodical lakes of Upper Pivka, Slovenia.- Acta carsologica, 33, 1, 159–173.

Ravbar, N., 2007: The protection of karst waters : a comprehensive Slovene approach to vulnerability and contamination risk mapping.- ZRC Publishing, pp. 254, Ljubljana, Postojna.

Ravbar, N. & N. Goldscheider, 2007: Proposed methodology of vulnerability and contamination risk mapping for the protection of karst aquifers in Slovenia.- Acta carsologica, 36, 3, 461–475.

Register of caves, 2009. Speleological association of Slovenia, Karst Research Institute ZRC SAZU (unpublished).

Salomon, J.N., 2000: Précis de karstologie.- Pessac Cedex, Presses Universitaires de Bordeaux, Collection Scieteren, pp. 249, Bordeaux.

Sauro, U., Ferrarese, F., Francese, R., Miola, M., Mozzi, P., Rondo, G.Q., Trombino, L. & G. Valentini, 2009: Doline fills - case study of the Faverghera plateau (Venetian Pre-Alps, Italy).- Acta carsologica, 38, 1, 51–63.

Šikić, D. & M. Pleničar, 1975: *Osnovna geološka karta Jugoslavije. Tolmač za list Ilirska Bistrica.*- Zvezni geološki zavod Beograd, pp. 51, Beograd.

Šikić, D., Pleničar, M. & M. Šparica, 1972: *Osnovna geološka karta SFRJ 1:100.000, list Ilirska Bistrica.*- Beograd.

Veni, G., 1999: A geomorphological strategy for conducting environmental impact assessments in karst areas.- Geomorphology, 31, 151-180.

Vrba, J. & A. Zaporozec (eds.), 1994: *Guidebook on mapping groundwater vulnerability.*- International association of hydrogeologists. Verlag Hienz Heise, 16, pp. 131, Hannover.

Zwahlen, F. (ed.), 2004: *Vulnerability and Risk Mapping for the Protection of Carbonate (Karstic) Aquifers. Final report COST action 620.*- European Commission, Directorate-General for Research, pp. 297, Brüssel, Luxemburg.