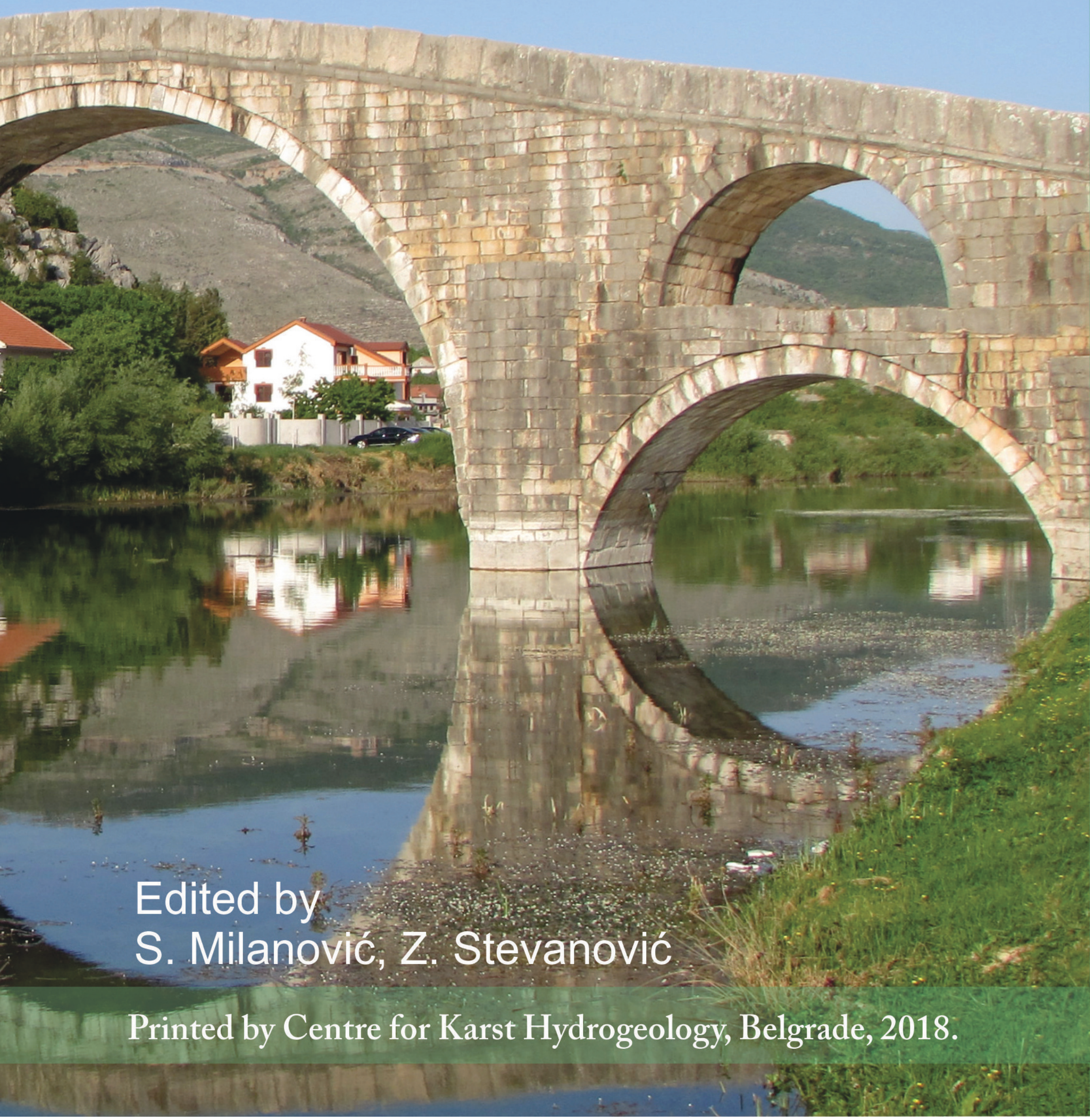
International Symposium

KARST 2018
Expect the Unexpected

PROCEEDINGS



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"Expect the Unexpected"

Editors:

Saša Milanović and Zoran Stevanović

Centre for Karst Hydrogeology
Hydro-Energy Power Plant "Dabar"

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Trebinje city, view from Leotar

View of Leotar from Trebinje city

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Proceedings of the Symposium KARST 2018 – "Expect the Unexpected"

Introduction

Karst and its waters are challenging the entire biodiversity, but above all the local population and engineers who are constantly trying to adapt karst behaviour to their needs. What is perceived as a challenge by local population is the limited water availability, uncertain crops and frequent flooding, while the engineers are struggling to define water storage and paths, control the flow, and protect the quality of water saving it from pollution. This is especially difficult in highly developed karst regions such as the "classic" Dinaric karst. The area between the Neretva and Skadar basins, shared by Bosnia & Herzegovina, Montenegro and Croatia - chosen as the venue of the symposium KARST 2018 - was declared by Jovan Cvijić, the founder of karstology, to be the "most completely developed karst anywhere". A large engineering project to control the biggest European sinking stream Trebišnjica and utilise its energy potential was implemented in Trebinje and its vicinity, laden with large karst poljes. More than half a century had passed since this project began, and four decades later we can say that most of it was completed quite successfully. The project's experiences and achievements are still intriguing to both professionals and students, and the conference KARST 2018 can serve as an opportunity to reminisce and share knowledge and information about its operation.

It has also been four decades since A. Soderberg wrote the article evaluating the design and construction of the two dams in Ordovician limestones in Tennessee, "Expect the Unexpected". We are using this slogan, frequently cited by those working in karst, as a subtitle of our symposium. One of the experts that liked this slogan very much due to his vast experience, and who spent most of his career in Trebinje working on the "Trebišnjica" project, is Petar Milanović. This entire event is dedicated to the 80th anniversary of his birth. His work and many books and papers reflect great effort and enthusiasm he had invested in this karst water regulation project.

The symposium is attended by more than one hundred specialists from around the world. Many of them are coming from "karst countries", where they are facing problems concerning water control and environment protection in their everyday professional lives. The Proceedings consists of 56 contributions, written by 150 authors. The five keynote papers discuss various aspects of karstology and karst hydrogeology, from historical to actual geo-environmental prospects. Presentations are divided into three main groups: 1) Geological and Hydrotechnical Engineering in Karst, 2) Karst Geomorphology, Speleology and Speleogenesis and 3) Management and Sustainable Use of Karstic Water Resources.

Providing an opportunity for the exchange of experiences and new ideas, this three-day long Symposium, as well as the field trip, should help this and future generations of practitioners and end-users in their attempt to better understand karst and its wild nature and minimize the negative effects of "unexpected" results.

Zoran Stevanović
Chair of the Scientific Committee

Saša Milanović
Chair of the Organizing Committee

Key Note Contributions

THE EVOLUTION OF KARSTOLOGY

Derek Ford[1]

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Abstract: Modern karst studies began in the Dinaric karst region, stimulated by pioneer works of the Serbian geographer, Jovan Cvijić. Since his death in 1926, new generations of geographers, geologists, physicists, chemists, civil and hydraulic engineers, bio-scientists with widely different interests, social scientists, resource managers and conservationists have converged to create a new inter-disciplinary field - 'karstology'.
At the core of karst studies is rational understanding of the 'triple porosity' (matrix, fracture and conduit flow) nature of the karstified aquifer. The controls of solution conduit evolution are quite well understood: conduit distribution is deterministic but complicated by many different factors. Investigation of conditions in the matrix, fractures and inaccessibly small conduits demands multiple approaches both in the field and in modern computer modelling. Rarely is it fully successful – "Expect the unexpected"!

Key words – Dalmation karst; Jovan Cvijić; triple porosity aquifers; conduit flow.

The evolution of karstology.

Dr Petar Milanovic and I are of similar age. He grew up in the Dinaric region, the cradle of karst studies, trained in civil engineering, and has become a foremost authority in dealing with the many engineering problems that arise in management, economic development and conservation in karst areas. I grew up in the southwest of England, fell in love with climbing mountains and exploring caves, and studied physical geography in order to understand them better. Over our professional lifetimes, it is true to write that Petar and I have witnessed the convergence of our interests into the new, distinctive scientific sub-field of "karstology". This is recognised and emphasised in the opening chapter of Petar's latest book (Milanovic, in press), by the recent formation of a Karst Section within the Geological Society of America that has separated from the older Geomorphology/Quaternary and Hydrogeology sections, and by the scope and contents of many current international conferences.

In pre-historic Europe and elsewhere karst springs or defensible caves formed the cores of many of the earliest towns (e.g. Athens, Jerusalem; Shaw 1992). The natural water flows were often modified for agricultural or urban distribution; for example, in Roman times an artesian hydraulic head in the Ras-el-Ain spring cluster in Mesopotamia was engineered to elevate water above a plain and discharge it to otherwise arid lands (Burdon and Safadi 1963). Similar works continued sporadically until the Enlightment and there were many observant reports and speculations by travellers in karst lands, those of Valvasor (1689, cited in Shaw 1992), around what is now Postojna being outstanding examples. However, there was more emphasis on fantastical writings about caves as portals to the Underworld. It was not until the 19th Century that most substantive scientific investigations began (Ford 2015). Writers in Belgium, Britain, France, Italy, etc. made significant contributions but the foremost regional focus was in the Dalmatian karstlands.

It was in 1893 that the Serbian geographer, Jovan Cvijić, published his University of Vienna doctoral thesis 'Das Karstphänomen'. Sweeting (1962) describes it as "….. the beginning of karst studies proper." Cvijić was a geographer of his period, a field man whose wide interests also included glacial geomorphology and regional ethnography, and who possessed an enviable capacity for rapid sketches of features of interest (Figure 1). Das Karstphänomen works systematically through the typology of surface karst landforms from smallest to largest – karren (*skrape* or *skripovi*), dolines ("the diagnostic landform" and lengthiest part of the book, including pioneer applications of quantitative geomorphology), dry valleys and gorges, and concludes with the great Dinaric poljes. In the following years two other Dalmatian researchers presented sharply contrasting views of the organisation of the aquifer draining these landforms. Alfred Grund (1903) presented what today would be categorised as an 'equivalent porous medium (EPM)' model, while Friedrich Katzer (1909) drew a picture of disorganised solutional conduits guiding the groundwater flow (Figure 2A, B). Cvijić responded with what is, to my eye, an altogether superior interpretation (Cvijić 1918; Fig. 2C), showing distinct vadose and phreatic zones with an 'epiphreatic' (seasonally inundated) zone between them and a lithologically determined base of karstification; I would modify this model today only by inserting an 'epikarst' fringe of dense solutional features on the top of it. Cvijić also contributed a model for a geographical cycle of erosion/solution in karst landforms (Sanders 1921) that was a marked improvement on predecessors because it recognized some of the realities introduced by the varying lithology and geologic structure in the rocks.

After Cvijić' death in 1926 other lines of karst research developed that, amongst geomorphologists, were somewhat misdirected into overemphasis on the importance of climate differences in the creation of the surface landforms (e.g. Lehmann 1936, 1954) at the expense of more thorough studies of the effects of varying lithology, purity, structure, structural deformation, etc. in the carbonate rocks, on development of the landforms and aquifers. After 1945 sedimentologists and petroleum geologists made major advances in our understanding of carbonate deposition and the causes of its facies variations.

The frequent occurrence of paleokarst horizons of different kinds and, hence, differing petroleum storage, drew them into karstology; e.g. publication of an influential genetic debate in North America (James and Choquette 1987) and a Eurocentric world review by Bosak et al. (1989). During the first half of the 20th Century worldwide experience with dams and reservoirs on limestone that either leaked disastrously or failed to hold any water at all led to major increases in interest in karst by practicing engineers, as exemplified by Professor Milanović' well-received textbooks (Milanović1981, 2004) and others. Economic costs, pollution control and environmental protection have re-focused the interests of karst enthusiasts with a very wide range of professional training, producing major texts and geomatics programs in China, Europe, North America and elsewhere (e.g. Zwahlen 2005, van Beynen 2011). In the organic world, biologists, micro-biologists, biochemists, medical researchers and entrepreneurs, now study the nature and evolution of lifeforms at all scales in the distinctive, restricted environments that prevail in karst caves and aquifers, in searches for new species and adaptations (Culver 2012).

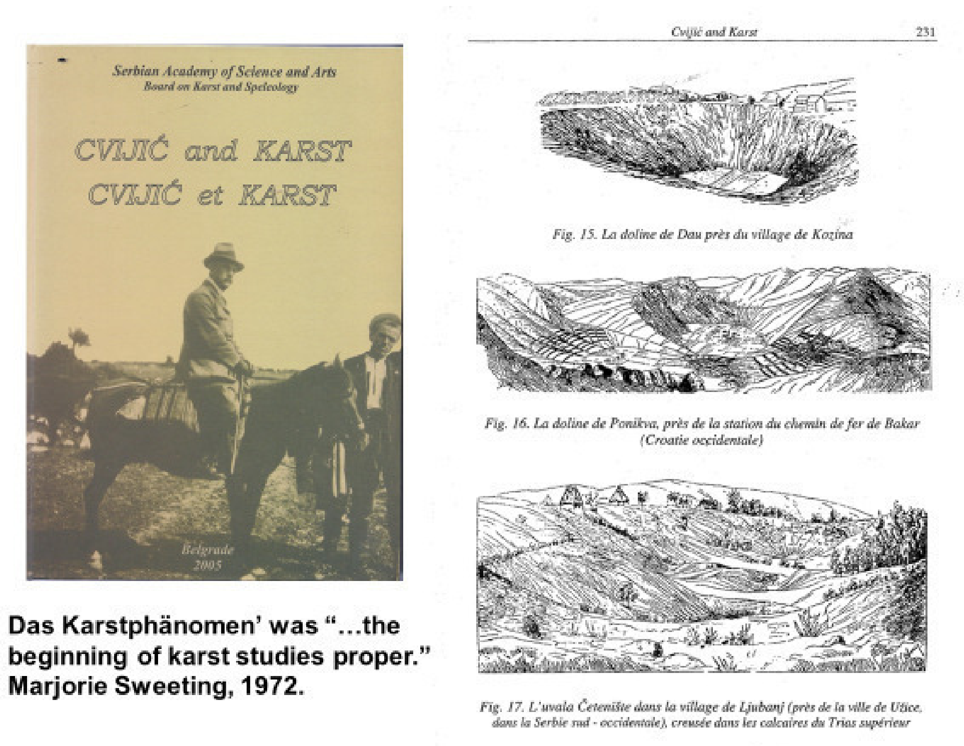

Figure 1. Jovan Cvijić (cover of Stevanović and Mijatović (eds.) 2005. Cvijić and Karst.) Three of Cvijić' field sketches of dolines and uvalas.

Rock control: the complexity of karst aquifers in limestone and dolomite.

For rational development, management and conservation in karst terrains it is essential to understand conditions in the local rocks as fully as possible (Milanović, in press). There is said to be a greater variety of 'facies' (differing kinds of deposits) in the carbonate rocks than in all other categories of sedimentary rocks combined (e.g. James and Jones 2016). In addition, there may be more soluble anhydrite, gypsum and salt interbeds in the precipitates, and/or insoluble clastic layers (clay, silt, sand, etc., ranging from paper-thin layers to thick aquitard beds): these all interrupt steady carbonate deposition, causing more potential complexity. This initial variety is succeeded by the very wide range of conditions that may be experienced during the compaction and cementation (the 'diagenesis') of the sediment pile as it accumulates over millions of years, and then by its structural deformation by tectonic processes that uplift it into the meteoric groundwater and erosion ('telogenetic') realm (Figure 2).

Karst groundwater systems can develop in and be restricted to single limestone beds or extend throughout carbonate sequences as much as five thousand metres in thickness. It is generally recognised that thick to massive formations, as in much of Dalmatia, are best suited to karstification, but the world's longest mapped cave (Mammoth Cave, Kentucky, >600 km) is contained within a mere 50-60m of regular platformal limestone beds, while arguably the most intriguing caves discovered during our professional lifetimes (Lechugilla Caverns, New Mexico) straddle a mixture of reef, backreef and detrital facies.

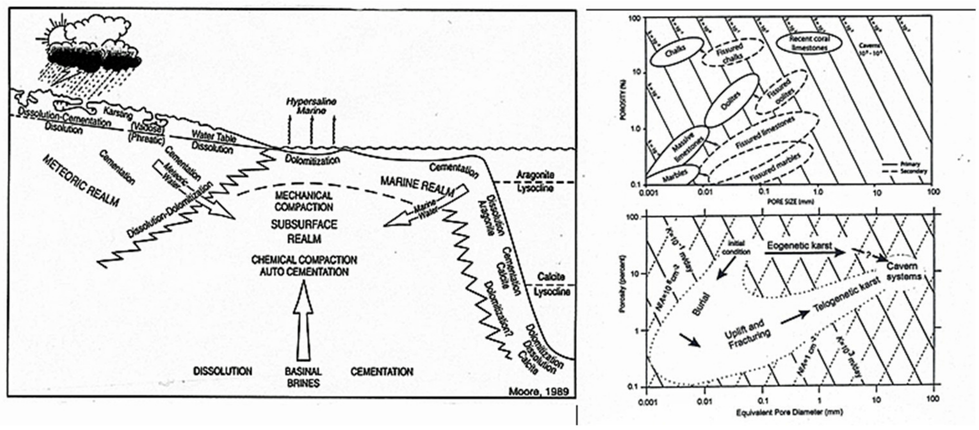

Figure 2. Models of carbonate rock deposition and diagenesis from Moore (1989), Mylroie and Carew (1995).

By definition, a carbonate karst aquifer is one that is drained by one or more channels that have been enlarged by aqueous solution to dimensions big enough to permit turbulent flow (and, thus, accelerated carbonate dissolution) where there is sufficient hydraulic head, = 'conduit flow'. A diameter or width of no more than one-two cm is normally adequate, implying that the aquifers can function karstically where the conduits are much too small for human entry. In fact, turbulent flow probably prevails for most of the time in most such conduits. It is generally accepted that the majority of karst aquifers will exhibit 'triple porosity', however – tiny inter-crystalline, fossil and vuggy voids in the *matrix* of the rock plus narrow planar openings in a proportion of the *fractures* (bedding planes, joints) and faults that are penetrable by water) where flow will be laminar, draining to the *conduits* with their turbulent flow. 'Double porosity' conditions (*matrix plus conduit*) are observed occasionally where the limestone is diagenetically immature and has few fractures because it escaped significant deformation during uplift; e.g. some of the chalk in southeast England and northwest France (Rodet 2010). *Fracture plus conduit* double porosity is quite common in carbonates subject to high metamorphosis that eliminated any water exchange and flow in the matrix. In highly metamorphosed limestones it is sometimes proper to envision a condition of 'conduit-dominant double porosity' – 90%+ of the porosity is within the solution channel itself, the storage (effective porosity) in the fracture that guided being very small, and that in the matrix non-existent; e.g. Lauritzen (2010) in some examples of Norwegian caves in marble and mica-schist.

(i) Cavernous aquifers. The origin and development of accessible solution caves in meteoric aquifers has been studied quite intensively for 150 years and is reasonably well understood. In a single generation the conduits tend to develop branch-work plan patterns (L x W) that focus the flow from sinkholes, fractures and matrix upon a single spring or narrow cluster of springs (see Ford & Williams 2007; Worthington and Ford 2009). Greater, often confusing, complexity in the appearance on the map is usually due to development of later generations of caverns beneath the first ones as results of external valley entrenchment lowering the spring lines. Locally, floodwater mazes may add to the visual confusion. In their long sections (L x D) caves may exhibit one of four relationships with the water-table, as shown in the righthand frame of Figure 3; they may loop deeply below it, fix its elevation at the upper apices of multiple loops, develop entirely along it, or be a mixture of looping and water-table elements. Deeper looping is favoured by more massive beds, steeper stratal dips and/or lack of opportunity to discharge along the strike of the rocks (see Ford & Williams 2007). Audra (1994) challenges the existence of deep loop conduit systems but modern cave diving to -250m or more is finding them often. Seasonal overflow to higher springs (usually, a previous generation that is in process of being abandoned) is common in mountainous regions with snowmelt or monsoon climatic regimes; this creates an *epiphreatic zone*, as Cvijić recognized (Figure 3). At the top of the vadose zone above it, today we should recognize the more widespread and important occurrence of a subcutaneous zone of intense dissolution, the *epikarst,* because it has very important short-term storage capacity. Examples of deep looping, multiple looping, and epikarst behaviour will be presented in the author's conference lecture.

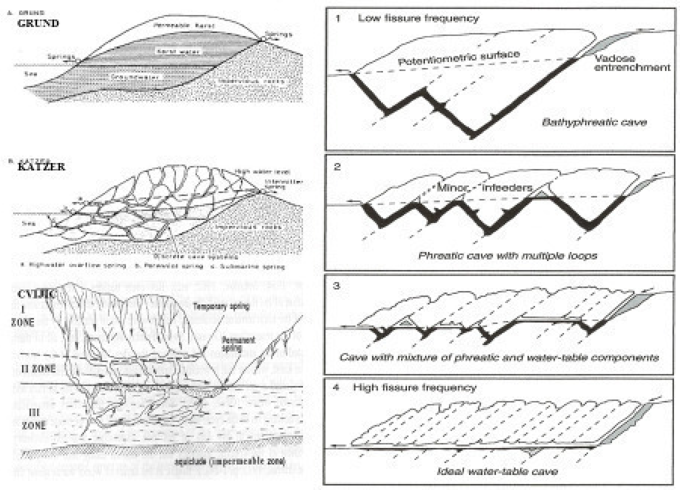

Figure 3. Left – the karst aquifer models of Grund (1903), Katzer (1909) and Cvijić (1918). Right- the 'Four State' model of the relationships between the watertable and karst solution conduits (see Ford & Williams 2007).

(ii) Inaccessible aquifers. Only a small proportion of any cavernous aquifer is directly accessible to cavers, and the majority of aquifers are wholly inaccessible. They are explored by other means. Milanović (in press) stresses that it is essential to make as detailed a geological map as possible of any site that is to be managed or developed. I concur and would add that, if it can be done, determining the location of any springs and groundwater sinks in the area, then installing discharge, temperature and EC monitors and designing and carrying out a dye trace programme, should be the next steps. Surface geophysical surveys are always undertaken at a site – seismic, gravimetric, electrical resistivity, induce polarity, etc. All have substantial limitations, their accuracy is highly variable and rarely to be trusted to depths of more than a few tens of metres; the case of the search for "Canada's greatest undiscovered cave" (using resistivity) will be presented as an example. Boreholes, with coring, piezometry, standard downhole recording (including realtime video) are expensive but essential: inter-hole dye tracing is proving to be a helpful addition to standard pumping and Lugeon testing.

In conclusion, it has become standard practice to attempt to model all of the flow in an aquifer by computer. There are a wide range of programs available (e.g. Lancia et al. 2018) but, in the English-speaking world, variations of MODFLOW public domain software (Langevin et al. 2017) are the most widely used. Kresić and Mikszewski (2012) provide a comprehensive review of adaptations for conduit flow. I would stress that the modeller should attempt to use all of the types of field data noted above that are available. This has often been neglected by practitioners not trained in karst, sometimes resulting in drastic errors of understanding and forecasting; two examples from the Niagaran dolomite karst of Ontario (Canada) will be presented in my lecture. "Expect the unexpected"!

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WHEN RESEARCH AND PRACTICE INVOLVES KARST: EXPECT THE UNEXPECTED

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Abstract The 2018 Trebinje karst conference title alerts all who might live or work in carbonate, marble, gypsum or halite terrains. Experienced geologists and engineers should take special note when first assigned to new karst projects or intend to investigate karst features, processes and events in unfamiliar karst settings. My learning curve has been varied despite professional years mainly focused on Appalachian karst. Few unexpected examples will illustrate: Identification of numerous natural and man-related factors alone and in various combinations that account for porosity and conductivity distribution, with soluble rocks, atmospheric deposition resulting in acidic and nonacidic streams, gasoline spill in cavernous limestone leading to an exploding water well, constraining rates of halite dissolution and breccia pipes for US DOE's TRU-waste bedded-salt repository (WIPP), New Mexico, pressurized brine pockets resulting in flowing wells, heat-induced fluid inclusion migration, importance of Devils Hole climate record to Yucca Mountain total system performance assessment and regional arid hydrogeologic setting.

Keywords: Multiple conductivity controls, acid deposition, breccia pipes (halite) Devils Hole, Nuclear Waste Isolation

Introduction

Welcome to Trebinje, the Trebišnjica, diverted above to a coastal power plant, crossed via the ancient Arslanagić Turkish bridge and consumed within Popovo Polje, returning again to nourish Ombla and other springs. Thank you for sharing your research findings, desire to learn, renew friendships, network and strengthen claims to your research niche. The 2018 Karst Expect the Unexpected organizing committee appreciates your contribution to this conference, one of more than twenty–three cave and karst conferences scheduled for 2018-2021. We share common purposes, an attraction to the many aspects and engineering challenges posed by karst and to honor Petar Milanović for his many academic, scientific and engineering contributions greatly expanding knowledge of karst. We recognize his wife, Tihana, who tirelessly maintained their inviting home, resembling at time more a field and research office and raised two outstanding children while Pero tirelessly explored caves, ponars or was abroad. Tina and Saša are now distinguished for their scientific and engineering contributions.

My wife, Estelle, children Katarin, George, Evelyne and Byron, first met the Milanović family attending the Karst Water Resources U.S.-Yugoslavian Symposium, Dubrovnik, June 2-7, 1975. Our first trip, with Katarin as an infant, (1966) was by train, Belgrade to Athens via scenic gorges, blue-green rivers, smoke filled tunnels, Skopje's earthquake rubble and more. This is our eighth visit to the challenging Dinaric karst, its > 1,000 islands, bays, 6100 km coastline, often difficult to access interior, rivers that come and go, poljes, picturesque villages and stoic habitants, reflecting a long and complex political history and demanding physical environment. Who can forget sunrises and sunsets at Split; Kotor Bay; Korčula's Burna Bay; Posip wines, Slivovitz Domestica; hospitality and stimulating conversations.

As a student and early faculty member, few karst-related papers, let alone dedicated sessions were included in scientific conferences, i.e., GSA, AAAS, AGU and others. Karst research was not part of One's day job. Advances were made by adventurists exploring and mapping caves, conducting tracer tests, "witching" for groundwater, pursuing archaeological and ecological interests or expanding tourism while over time expanding knowledge of karst phenomena not regarded by some as important science. Engineering practice progressed by trial and often costly error e.g., foundation and impoundment failures, leaky and failed dams, random groundwater exploration and unsuccessful wells, sometimes polluted waters, hard to trace and capture pollutants, flooded mines and quarries.

Petar Milanović and associates continue to enrich and broaden my understanding of karst features, processes and events in various karstic terrains together with useful methods of investigation for which I am grateful. I benefited from early edits of his widely distributed books, field trips and discussions including insights gained during his family's extensive travels and studies while at numerous U.S. centers of active karst research. Lessons learned were shared with my >100 graduate advisees and >5,000 students who attended classes, colleagues and clients. Many of you have had similar experiences and we look forward to your contributions to this 2018 Trebinje karst conference.

Expect the unexpected is sage advice for all engaged in research and practice in areas that contain some or are dominated by soluble rocks: limestone, dolostone, marble, gypsum/anhydrite and rock salt. New unexpected occurrences are inevitable especially if you begin work in new terrains. Only brief examples are permitted here.

Simplicity v Complexity

Janet Aitken, my undergraduate structural and economic geology instructor said, "simple explanations are best". Darcy's law is elegant but limited when working at extreme ends of the hydraulic conductivity scale now spanning 19 orders of magnitude! Quantifying flow in conduits and lava tubes stands in stark contrast to rocks where only diffusion is possible. Regarding strata as "impermeable" maybe acceptable for some geotechnical projects but not others, e.g., isolation of nuclear and hazardous wastes.

My list stands at 36 and counting: natural and man-related variables taken alone and in various combinations that contribute to spatial distribution of porosity, hydraulic conductivity and other engineering properties (Parizek, 2002). The task is to narrow the list of most probable variables for a given Karstic setting in order to plan and execute cost-effective site characterization efforts required of critical geotechnical projects and when confirming or advancing understanding of karst features, processes and events. Once significance and magnitude of each contributing factor has been determined using one or another one-off-analysis procedure, these can be overlain on geologic and hydrologic maps to improve conceptual models useful in refining numerical groundwater and management models. This attribute-overlay methodology applies to all geologic settings. Early benefits may be noted when comparing success exploring for groundwater using earlier more random v the attribute-driven procedure. Well-yield data were obtained for the Penn State University, University Park campus and Borough of State College, PA, USA, both located in Ridge and Valley province of the Appalachian Mountains. The region is underlain by nearly 2743 meters (9,000 feet) of folded and faulted limestone and dolostone, Late Cambrian to Devonian in age. Wells with a yield of 9.46 l/s preferably in excess of 15.7 l/s were regarded as successful given large municipal demands.

The well success rate for earlier more random methods was 36 and 23 percent for Penn State and the Borough respectively and then increased to 80 to 95 percent using the overlay method. Given a more regional search opportunity where other favorable attributes could be combined to identify "sweet spots", resulted in 2 for 2, 2 for 3, and 4 for 4 successes with yields ranging from 44 to 189 l/s., development of site-scale, predictive groundwater flow and transport and basin-wide flow models for fracture-flow dominated carbonate aquifers.

Although all carbonate strata included in this well study appear to contain similar fractures, joints, faults and apparent petrographic properties, porosity and hydraulic conductivity differ widely among stratigraphic units. Improvements are needed, estimating aquifer potential, using first principles when mapping carbonate rocks and studying them in the laboratory. It would be more cost-effective to use field testing methods for confirmation rather than as the starting point when conducting hydrogeologic and geotechnical investigations.

Geologic Map and Trout Atmospheric acid deposition has eliminated sustaining populations of Brook Trout within preexisting cold water fisheries along Laurel Ridge in southwestern PA and elsewhere. Laurel Ridge is an anticlinal mountain that contains the sandy Loyalhanna Limestone (Carboniferous) with different exposure configurations within tributaries eroded along its flanks, some alkaline, others not. Many springs within valley fill sediments and near valley walls located below limestone outcrops are acidic and contain Al concentrations lethal to Brook Trout. Anticipating a creel limit with geologic map in hand but lacking spring and stream chemistry for both base-flow and storm-flow conditions will require stop at a fish market. Unraveling groundwater flow within the 21 m thick fractured Loyalhanna and colluvial-alluvial ravine deposits is elusive despite what might appear as favorable distributions and exposures of limestone.

Craters During a June 12, 1970 thunderstorm, a 24 m deep well hand dug in Ordovician limestone exploded. It demolished a concrete well pit and excavated a crater 7.6 m across with a 0.6 to 0.9 m rim-crest diameter and apparent depth of 3.6 m. Soil and rock deformation revealed both lateral compression and vertical bedrock uplift had occurred. A dry cave 4.5 to 6.0 m high was reported at about 12 m “large enough in which to turn a team of horses”. Using graphs developed for analyzing explosive craters, density and volume and mass of ejected debris (≈ 8.4368 x 104 kgm) energy required of 4 x 1015 ergs were obtained equivalent to 90.7 kgm TNT (Gold, et al, 1970). Because gasoline was detected in a well drilled inside the original hand dug well, energy contained in gasoline and methane that was required were computed: as little as 9.46 l and between 6.1 to 19.8 m^3 of methane were adequate. The property owner discovered that from 757 to 946 l of gasoline were unaccounted for from their storage tank 46.7 m away. The 1.4 and 7.8 volume percent mix of oxygen and gasoline vapor was possible given dimensions of the hand-dug well and cavern. A spark from an electric motor that powered the piston pump from within the well pit triggered the explosion in full view of the housewife while she was washing dishes. Had she looked to heaven in thankful prayer, it would have been visible through holes in the roof and ceiling!

In contrast, a gasoline spill near Mechanicsburg, PA, USA, spread over nearly 0.77km2 with a product thickness of 2.1 m within dense but weathered Ordovician limestone. The gasoline pool was encountered by a contractor while drilling illegal drainage wells. This individual did not report “his treasure” because undercover, he was able to fuel business vehicles at no cost. A 231.9 mm rain event occurred late July 1969 raising the floating gasoline into basements and fumes where basements were higher than the water table. Explosions occurred in two cellars and again at a later date. Seventeen fracture-trace extraction wells were drilled, and more than 1.43845 x 106 l of gasoline were recovered. A single well yielded 2.897 x 105 l during March 1969 (Rhindress, 1971) in contrast with as little as 9.46 l of gasoline required to create the crater reported above.

Fuel spills and vapor releases are not uncommon in karst terranes. Vapors may escape from sanitary landfills, originate from buried organic-rich soil horizons, leaky pump-storage gas fields, conventional and nonconventional oil and gas development projects, improperly plugged and unplugged abandoned wells. Pennsylvania has estimated tens of thousands of unplugged legacies oil and gas wells, possibly some brine wells that predate the 1856 Drake Well. Fortunately, shallow occurrences of freshwater and marine limestones are somewhat limited in distribution where the majority of legacy wells are expected.

Breccia Pipes More often than not near surface and shallow dissolution features and processes receive attention at geotechnical project sites rather than concerns for deep dissolution. The U.S. Department of Energy selected and characterized a site in Permian salt within the Delaware Basin of New Mexico and west Texas, USA, in which to isolate transuranic, or TRU Wastes, primarily alpha emitters, produced for the nation's defense program. A small percentage of TRU wastes emits beta and gamma radiation. Ninety-seven percent of wastes being emplaced at the Waste Isolation Pilot Plant (WIPP) is contact-handle waste and the remainder is remote-handled shielded waste.

Permian Ochoan Series salts of the Salado Formation were selected for the repository horizon at a depth of 655.3 m. Considerable effort was spent quantifying the rate of salt dissolution from above, within, in between and below two Rustler Dolomite formations located above the Salado salt and within interbedded anhydrite beds above and below the repository horizon together with their exposed western outcrops. Deep dissolution of salt was revealed by structural disturbances of Castile Formation marker beds located below the Salado. Some structural lows underlay topographic depressions in the overlying desert suggesting a reliable dissolution predictive relationship. More intensely disturbed zones were discovered near the buried margin of the hydrologically conductive Capitan Reef. Further to the west and south, younger cover salts and sediments were eroded exposing the reef containing Carlsbad and other caverns.

Miners at the Mississippi Chemical Mine, USA, encountered steeping downward dips in a potash ore horizon until at a point underlying a hill in the desert above. Their mining machine encountered ring fractures, angular blocks of anhydrite and halite having collapsed from overlying beds and traces of petroleum. The hill above is Hill C, a circular body of breccia continuous from mine working to the surface. This dome-shaped feature has relief of about 30 m, eroded near its center forming a topographic basin breached at places. It is flanked by Mescalero Calcite which engulfs the Gatura Formation and brecciated Triassic rocks with angular blocks of conglomeratic sandstone 3 or more m across (Sayder et al, 1982). The Mescalero Calcite is an arid soil dating from ca 500,000 years. The area surrounding Hill C subsided as a result of regional near surface salt dissolution. Ring-like elevated portions of dipping caliche outline the breccia pipe supported by more resistant sandstone breccia. Elevation difference between caliche anchor points and desert surface nearby were used to constrain regional salt dissolution rates averaged over 500,000 years. Persistence of an adequate roof thickness of Salado salt was assured.

Hill A is exposed as a low, circular breached hill resembling a topographic basin with relief of about 12-15 m and about 370 m diameter. The rim of the hill is capped by Mescalero caliche similar to Hill C with rather uniform dips away from the rim of about 15°. Within its topographic basin, brecciated debris composed of angular blocks of Triassic claystone, sandstone and conglomerates are confined within a circular area about 245 m in diameter. Hills A, B and C are believed to have formed by a brine-density flow dissolution process concentrated near the base of salt. Anhydrite beds most likely provided roof support for growing voids until these cantilevers failed resulting in rapid brittle failure of overlying salt. By one mechanism, collapse may have involved slow letdown and stopping of overlying rocks as suggested for some Redwall Limestone breccia pipes near Grand Canyon, Arizona, USA (Wenrich, 1985; Wenrich and Sutphin, 1989).

The age and hydrologic significance of known breccia pipes and possibly for new abrupt failures were WIPP safety concerns. The abrupt collapse of two Wink Sinks above the El Capitan Reef where it is also buried to the south and east of WIPP near Wink and Kermit, Texas supported the abrupt collapse hypothesis. These circular voids surrounded by ring faults and surface depressions were 110 m and 137 m in diameter immediately after collapse and may extend to reef rock below. Some believe Wink 1 might have been the site of an improperly cased injection well responsible for cavity development that led to abrupt roof collapse. Over time, collapsed debris within these circular pools would have to become cemented with salt to resemble Hills A, B and C.

The first waste packages were received at WIPP, April 28, 1999, with thousands now stored in rooms excavated in salt with more to come. Final sealing of all man-made penetrations surrounding and leading to the repository to preclude possible solution pathways is mandated.

Breccia chimneys have been described in the northern part of the Michigan salt basin, USA, Crater Lake, in Saskatchewan, Canada, in Keuper gypsum near Hanover, Germany and elsewhere. The presence of contact and non-contact radioactive wastes stored in the leaky, unstable Asse II Mine within a Lower Saxony-German salt dome, comes to mind (Wikipedia). Design adequate for mining salt proved to be inadequate to meet requirements for a mined geologic repository intended fort long term isolation of nuclear waste. Collapse and flooding of a Louisiana salt dome mineral extraction site is another case in point.

Pressurized pockets of brine encountered below the Salado also were regarded as unexpected to those who have not worked in the Delaware Basin. At least 10 out of 63 oil and gas wells and one dedicated WIPP site characterization well penetrated brine pockets with initial pressurized surface discharges rate that ranged from 137.4 to 3785 m^3/day. Nor is it our experience to expect fluid inclusions to migrate toward a heat source crossing salt crystal interfaces toward nuclear waste packages. More recently, Abelson, et al, 2018, attributed human-induced desiccation of the Dead Sea as the cause of more than 6,000 collapsed sinkholes and severe property damage along its western coast through solution of a 10-to 70-m deep salt layer. The authors have recorded nanoseismic events indicative of subsurface instabilities several years before sinkhole collapse. Desiccation has allowed intrusion of fresh groundwater from the Judean Mountains to the west to dissolve previously stable salt. Dead Sea sinkholes are shallow by contrast to Delaware Basin breccia pipes, Wink Sinks and breccia pipes reported near the Grand Canyon. Of interest is the rate at which karst processes can change when subjected to new boundary conditions such as at Wink and Kermit.

Milankovitch and Yucca Mountain Yucca Mountain is located in southwestern Nevada in the U.S. Basin and Range province. It has been extensively investigated for use by the US DOE as a mined geological repository for isolating up to 70 metric tons of nuclear waste from commercial reactors, spent nuclear fuel from non-DOE research reactors and other sources. Although not licensed to allow construction, waste would be stored in tunnels excavated in volcanic tuff elevated above the water table. Both independent engineered and natural geologic barriers would be relied upon to ensure nuclide isolation with a high degree of confidence in an existing arid environment. Welded and non-welded ash flow tuffs were deposited on thick Paleozoic sequences of carbonate and other younger rocks subjected to compression and then extension that produced the Basin and Range hydrogeologic setting. Active faults, and younger volcanic deposits exist in the region. These were dated and analyzed for probabilistic reoccurrence given consequences should one intrude the repository.

Yucca Mountain is located within the Death Valley regional groundwater basin (≈ 100,000 km^2) where discharge occurs along springs, seeps and in the Death Valley salt pan. Other localized discharges occur elsewhere within this regional flow system adding to the challenge defining pathways, flow rates and barriers to present and future groundwater flow and transport. The regional water table at Yucca Mountain stands in volcanic tuffs and valley fill sediments above more permeable Paleozoic carbonates. This is important in the total systems performance forecasts of nuclide fate and transport when eventually they leach from placement drifts, travel through unsaturated and saturated tuff and then alluvium to the accessible environment. Travel times to the 10km compliance boundary would be reduced significantly if tuff were to become dewatered and allow nuclides to enter carbonate aquifers. This might occur given extensive future groundwater withdrawals, prolonged desiccation from the last pluvial and/or increased hydraulic conductivity within impeding layers located along existing flow routes to Death Valley due to tectonic extension.

Funeral Mountain is an imposing topographic and structural feature located between the proposed repository and Death Valley. If it is an effective hydraulic barrier, groundwater must follow a long flow path around the mountain before entering Death Valley. Faults within Funeral Mountain, however, incorporated masses and wedges of limestone likely to provide shortcuts for concentrated flow leading to Death Valley. Flow volumes of Death Valley springs immediately southwest of Funeral Mountain exceed estimated recharge rates for tributary basins located along the southwestern face of the mountain thus, requires an additional source of water, yet another karst hydrogeologic, drilling and geophysics project awaiting clarification.

Debate persisted regarding the origin of isolated deposits observed in Amagosa Valley south of Yucca Mountain. Are they remnants of playa lake deposits or paleodischarge deposits? The correct paleo-discharge interpretation provided evidence of high stage of the paleowater table during pluvial and evidence for likely shorten future nuclide travel distances to the accessible environment. Constraints on timing and duration of climate states and water budget estimates are vital elements in total system performance assessments. Data available for this analysis included study of packrat middens, playa-lake cores obtained from Owens Lake, CA, Searles Lake, CA, Death Valley, CA, Lake Bailkal, Siberia, vein calcite obtained from Devils Hole and compared with Vostok ice-core and ocean-basin core analyses.

The Yucca Mt project has a connection to Belgrade University and Serbian astrophysicist Milutin Milankovitch (1879-1958) and his theory of orbital variations: consequences of wobble, tilt and obliquity that predate high speed computers. As a graduate student (1956-1961) and even later, debate raged among notable glacial geologist about which drift deposits should be assigned to the Kansan, Nebraskan, Illinoisan, and/or Wisconsian glacial stages and their sub-stages; how many and how far did each ice sheet extend; how to resolve disagreements at state boarders, etc. C14 dating techniques had to be in error, considered useless when in conflict with well-established stratigraphic dogma. More than four or five major glaciations were impossible despite emerging, later compelling evidence contained in deep sea cores that extended the temperature record back 480,000 yrs. (Hayes et al, 1976).

The Devil Hole climate record extended to >5000,000 yrs. It provided the longest, continuous land-based record through analysis of >30 cm thick layers of dense mammillary calcite that precipitated continuously from calcite supersaturated groundwater within a 91 m deep tectonic fracture and collapsed void, not a plannar conduit formed by dissolution (Winograd et al 1992; Riggs et al, 1994). Winograd et al found a record that closely mimics all major features in the Vostok (Antartica) paleotemperature and marine oxygen-isotope ice-volume record but found differences in timing of termination (glacial) among the Devils Hole, Vostok and SPECMAP record inconsistent with Milankovitch theory for the origin of Pleistocene glacial cycles. Winograd et al concluded that Devils Hole cycles originated from internal nonlinear feedbacks within the atmosphere-ice sheet-ocean cycles.

A 500,000-yr. climate record has emerged that combines the past climate record obtained from Devils Hole and orbital parameters that now projects 500,000 yrs. into the future. It sheds light on ecological conditions within existing selected geographic climatic settings that can serve as an analog for estimating past and future ecological conditions (Sharpe, 2004), along with many other scientific applications.

Professor L. Hinnov, from George Mason University and others are extending astrogeodynamics to earlier stratigraphic records with the expectation of deciphering orbital controls on sediment records beyond 50 ma. Astrogeodynamical forces recorded in carbonate stratigraphy in time may assist in correlation and detailed hydrological characterization of soluble rocks. Milankovitch never doubted his work and soldiered on despite doubters, criticism and theory largely ignored for about 50 yrs. (Graham, 2000). The

Hayes et al deep-sea core sediment paper showed that they were all able to extract the temperature record back 450,000 yrs. as predicted by Milankovitch's theory 18 yrs. after his death and far longer following earliest publications of his theory.

Final Word

We, by contrast, are all fortunate that the work of Petar Milanovic´ is celebrated, has been accepted, publications widely distributed, and his talents remain in demand. Tina and Saša, through the encouragement of your mother and father, it is not surprising that you are both driven by such a legacy.

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KARST WATER RESOURCES OF AUSTRIA, HYDROGEOLOGICAL ASPECTS AND PROBLEMS

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Abstract: Karst water is in Austria an important water resource for supplying the public with drinking water of acceptable or excellent water quality. About 50 % of the inhabitants of Austria are supplied with karst water. Karst water will be used mainly from springs in the Northern Calcareous Alps, with significant examples of the Viennese Mountain Water Supply, and also of the cities of Graz and Innsbruck. To ensure high quality and quantity different protection measures such as protection zones are applied. Problems of quantity for water supply are usually not encountered and problems with water in construction work can be minimized by a thorough hydrogeological investigation, efforts for a sustainable water management are still necessary.

Key words: Karst water, hydrogeology, water protection

Significance of karst water in Austria

Karst water in Austria is one of the most important drinking water resource. From a total area of 83879 km^2, about 22 % (18453 km^2) comprises karst formations, and 80 % of these formations are located in the Northern Calcareous Alps. From 8.77 million inhabitants of Austria (reported by Statistics Austria as of 2017/01/01) about 50% of inhabitants are supplied by karst water. Karst water supplies (at least to a greater extent) are for the cities of Vienna, Graz, Salzburg and Innsbruck, where 28% of all inhabitants of Austria are living. 32% are living in smaller towns or villages around the bigger karst massifs. The individual figures show therefore an important national significance of the karst water resource. Water from other aquifers (porous or fractured) is used also for drinking water, in particular in the eastern and southern part of Austria with smaller towns and villages and in rural areas. Water from surface water reservoirs can be neglected, and also water from cisterns, which is used only in very remote dry regions or for mountain huts.

Water balance and hydrogeological setting

The mean annual precipitation in alpine regions of Austria is about 1476 mm. This is higher than the average of 1170 mm for the total area of Austria as shown below (Figure 1). The recharge varies between 218 and 834 mm/y, whereas the average is 560 mm/y. This accounts for 38% of the total and is equivalent to 25 x billion m^3/a, from which 12.5 billion m^3/y is usable. In total 4.7 billion m^3/y are ecologically usable. Ecological usability means in this paper, that the minimum daily mean in a long-term time-series of spring discharge is the lower limit to which an aquifer can be exploited (Harum et al., 2001). The karst phenomenon in Austria is concentrated in the Northern Calcareous Alps (mainly Triassic to Jurassic limestones and dolomites) as mentioned above (Figure 2).

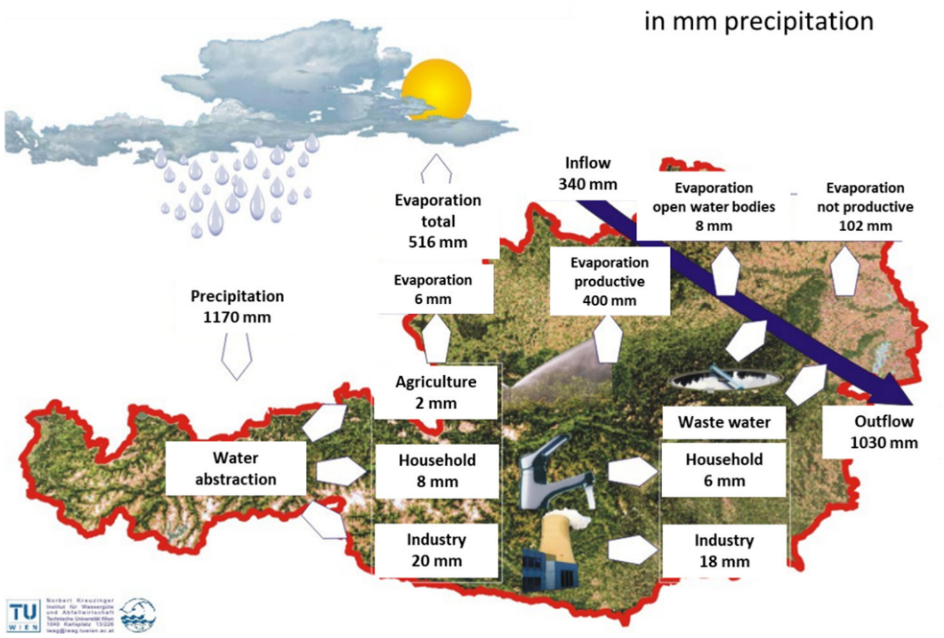

Fig. 1. General water balance of Austria and water demand of main consumers.

Large quantities of karst water are available in this part of Austria, lesser quantities in the southern part and in the mid-section of Austria (mainly in Paleozoic formations).

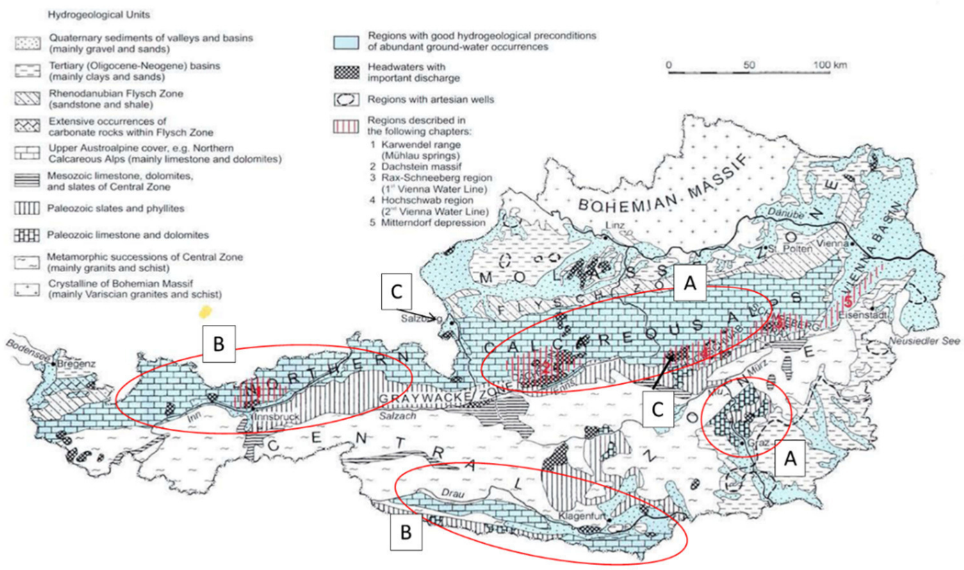

Fig. 2: Types of karst water resources in Austria (red encircled). A: Water resources from platform karst massifs, B: Water resources from karstic mountain chains, C: Water resources from porous groundwater fed from karst massifs (modified from Schubert, 2000).

Examples of water supplies from karst massifs in Austria

The most prominent example of a water supply from a platform karst massif (Figure 2, type A) is the 1st and 2nd Viennese Mountain Spring Supply in the eastern part (Hochschwab and Schneeberg area) of the Northern Calcareous Alps (Figure 3). Luckily it is possible to transport the water in a 90 km (1st) and in a 180 km (2nd) long pipeline mostly without pumping to the reservoirs of the city. Moreover, the water quality is high enough, so that there is no treatment necessary at the capture and in the pipelines. Only in the reservoirs a slight chlorination is applied to ensure microbial safety before introducing the water into the public supply line.

An example for a water supply from a karstic mountain chain (Figure 2, type B) is the main water supply of Innsbruck in the western part of Austria (Figure 4). This water supply (Muehlau springs) is located in the mountain chain of Nordkette, which forms the northern margin of the Inn valley. The water supply is situated in a partly karstic and prominently fractured aquifer of Triassic limestones and dolomites. The water – formerly a free outflow of springs – is captured within a tunnel system and therefore well protected against pollution.

Fig. 3: Left: Kaiserbrunn (main spring of 1st Viennese Water Supply; Mean: 0.7 $m^3.s^{-1}$, Minimum: 0.16 $m^3.s^{-1}$), Right: Kläffer Spring (main spring of 2nd Viennese Water Supply; Mean: 5.4 $m^3.s^{-1}$, Minimum: 0.5 $m^3.s^{-1}$) under flood conditions. (Photo left: C. Houdek, ©MA31-Vienna Water).

An example for a water supply from a porous (granular) aquifer fed additionally by karst water (Fig. 2, type C) is the water supply of the city of Graz (southern Austria; Figure 5). One third of the total water demand is provided from an aquifer at the southern margin of Northern Calcareous Alps (adjacent to southern Hochschwab area). The quality of the water is excellent, so that the karst water (together with pumped groundwater) is introduced into the supply line without any treatment and people can drink the water directly from the tap.

Fig. 4: Impressions from the interior of the Muehlau spring tunnel system. The capture gallery has been set within the saturated zone. The water enters from numerous open fractures and is collected in a rectangular channel and transported outwards (Photos: R. Benischke, G. Winkler).

At the maximum 200 L/s will be pumped and transported via a 76 km long pipeline to Graz. A second part of the water supply is the use of a karst spring from the nearby Schöckel mountain (Paleozoic limestone) at the northern edge of Graz. These waters will be recharged artificially into the porous groundwater aquifer and will then be pumped out at a rate of about 100 to 150 L/s. When the artificially recharged the water will be cleaned through a sand filter to avoid turbidity and other pollutants. Parallel a dense control program ensures the water quality.

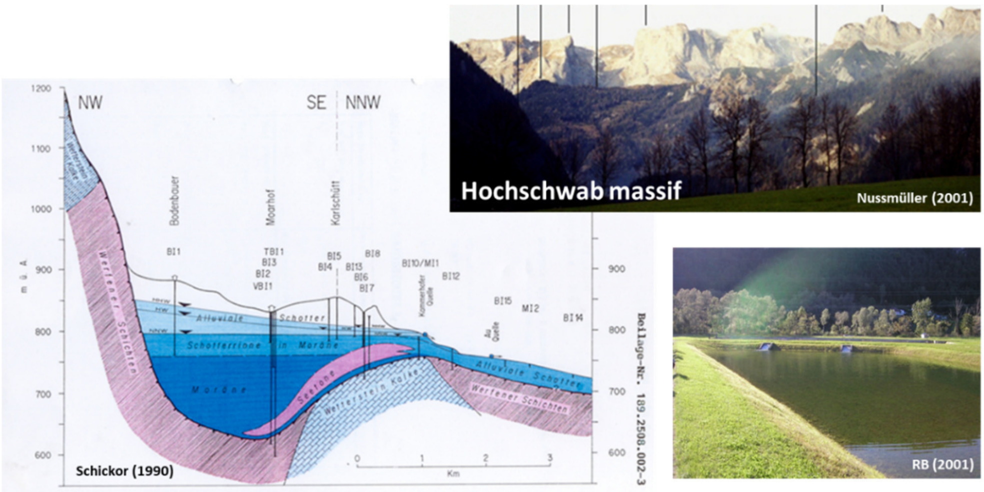

Fig. 5: Left: Geological section of the water supply from the karst area. Upper right: Southern flank of the Hochschwab. Dark blue: Water fed from the karst aquifer is pumped out of the sedimentary glacial filling of the valley. Lower right: Artificial recharge into a sand filter basin to clean up water from turbidity (Photos: R. Benischke, C. Nussmüller).

Problems of water quality and problems with water in construction work

If problems encountered with the karst water quality then all usual measures are taken to overcome or to avoid such problems. Although the karst water quality is acceptable or excellent for the intended use, there are sometimes problems arising e.g. from turbidity or microbiology. In such cases water will be treated preventively, e.g. by UV-irradiation, chlorination, ozonisation, ultra-filtration or in case of turbidity it will be discharged. To ensure a maximum protection against unwanted environmental or anthropogenic influences protection zones are established.

Problems with water in construction work occur during construction of dams and reservoirs or tunnels. Usually it is a sudden unexpected water intrusion into a tunnel or water loss of a reservoir. A thorough hydrogeological field-work can help to avoid in advance such problems. Nice examples (Figure 6) were the construction of reservoirs for electric power-plants in the Northern Calcareous

Alps, such as Salza Barrage in the Dachstein Massif or Diessbach Reservoir in the Steinernes Meer/Salzburg.

Fig. 6: Left: Diessbach Reservoir (Steinernes Meer/Salzburg) (www.salzburg-ag.at/erzeugung/unsere-kraftwerke/wasserkraftwerk-diebach-2588/). Right: aerial view of Salza Barrage (Dachstein Massif/Styria) (www.ennstalwiki.at/wiki/index.php/Datei:Salza_Stausee.jpg)

Both reservoirs are situated in a strongly karstified area but below the drainable zone. In these cases, the karstification did not reach the upper level of water in the reservoir, therefore the reservoirs are tight and show no water losses.

Protection of water quality and quantity

To protect the water, protection zones of different sizes are intended. In Austria usually, different protection zones have to be distinguished: a protection zone I (protection of the capture building, which covers in general only a small area), a zone II (extended protection zone), and sometimes also a zone III or a wider conservation area. In special cases a kind of framework regulations will be set under supervision of the ministry for land and forestry, environment and water management, if for example different federal provinces are concerned. Transboundary aquifers usually handled by a mixed commission of the concerned states and are based on a state treaty.

In Austria there is partly a different usage of protective zoning. In every case the border of such a zone must be unique, but not necessarily along the borders of individual plots. Usually there are interdictions, commandments and reporting obligations to the state authorities.

Main goal of all protective measures is to assure high quality water in sufficient quantity for drinking purposes, but also an acceptable quality and quantity for industrial and commercial use. The position of water authorities and potential consumers of Austria is that the water should be - wherever it is possible - native and untreated.

Standard analytics comprises hydro-chemical and microbiological analytics but have to be extended to specific isotope systems and inorganic and organic trace substances from urban and rural activities, as well as from industry.

Efforts for a sustainable water management are still necessary and we can be sure that the work of hydro(geo)logists will not be reduced, as the responsibilities of scientists and public stakeholders grow more and more under the observed continuous or sudden changing climatic, environmental and even political conditions.

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DIKTAS: INTERNATIONAL GROUNDWATERS OF DINARIDES

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Abstract: Protection and Sustainable Use of the Dinaric Karst Aquifer System (DIKTAS) project addressed these important issues, brought various specialists and stakeholders together and evidently contributed to collaboration and awareness in the region. The project overview below (modified from the final DIKTAS brochure) is meant also as a reminder and introduction for the project next phase that starts this year.

Project Identity

The DIKTAS Project (the first phase 2010 - 2016) has been a collaborative effort to facilitate the equitable, sustainable management of the Dinaric Karst Aquifer System's transboundary water resources and protect the unique dependent ecosystems from natural and man-made hazards including climate change. It was initiated by the aquifer-sharing states, Albania, Bosnia & Herzegovina, Croatia, and Montenegro, with the support of the Global Environment Facility (GEF). It is funded by GEF with substantial co-financing by the participating countries and other partners.

DIKTAS is a GEF regional project, implemented by the United Nations Development Programme (UNDP) and executed by the International Hydrological Programme of the UN Educational, Scientific and Cultural Organization (UNESCO IHP). The core DIKTAS project partners are the Dinaric Region's four fund-recipient countries: Albania, Bosnia & Herzegovina, Croatia and Montenegro. Non-fund recipient countries participating in the project are Italy, Slovenia, Greece, and France.

Methodology

The DIKTAS Project followed a methodology common to GEF projects, based on conducting a Transboundary Diagnostic Analysis (TDA) and preparing a Strategic Action Programme (SAP). The TDA, a substantial scientific and technical assessment, was used to enhance the understanding of the groundwater resources' environmental status, in order to identify, quantify, and set priorities for the transboundary environmental concerns, as well as identify their root causes as means to specify practices and locations from which environmental degradation derives. Building upon the TDA factual basis, a Strategic Action Programme embodying specific policy, legal, institutional or investment actions will be nationally adopted within a harmonized multi-country context. Actions included in the SAP will address the top priority transboundary concerns to restore or protect the transboundary water resources and ecosystems. Adopted and implemented by partner countries at the highest government level, the SAP aims to provide a regional vision for the sustainable management of the Dinaric Karst Aquifer System and propose the means to achieve this.

Outcomes

1. Scientific knowledge for the Dinaric Karst Aquifer System was enhanced and harmonized.

A large amount of data and information was collected through the TDA to analyse and assess the Karst groundwater management status and framework. This process focused on the hydrogeological characterization, the environmental and socio-economic assessment, the assessment of legal and institutional frameworks and policies, and the stakeholder analysis. The TDA covered Albania, Montenegro, Bosnia & Herzegovina and Croatia, assessing and harmonizing hydrogeological data, as well as data on natural and anthropogenic conditions. The knowledge produced can be used by partner countries to take informed decisions about the karst aquifer management. Experts updated the existing GIS databases for all partner countries with the features included in the DIKTAS hydrogeological map.

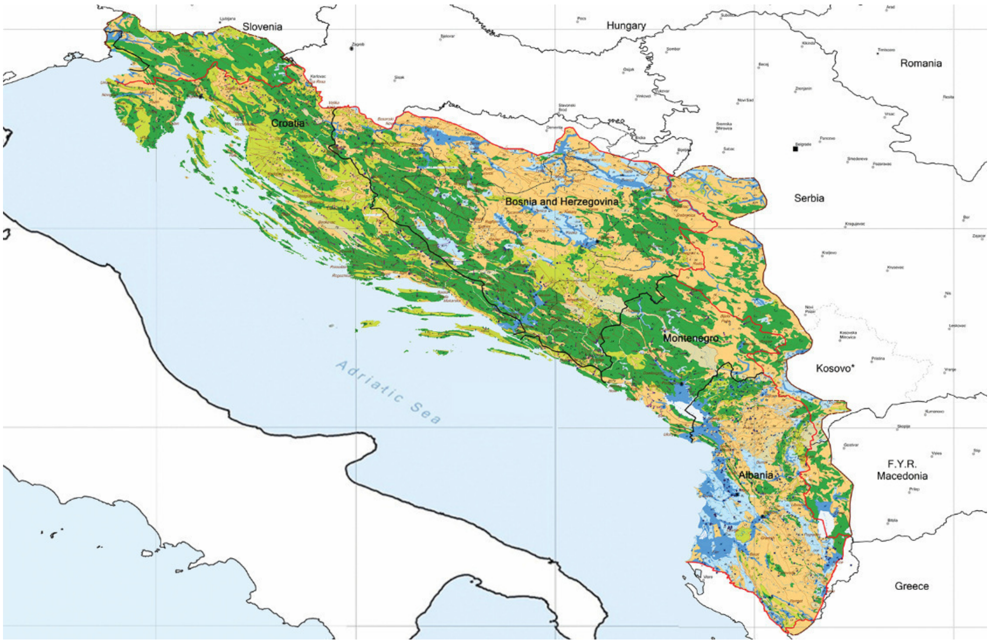

Fig. 1 Hydrogeological Map of Dinaric Karst

2. The main transboundary challenges and their root causes were identified.

An in-depth analysis of eight selected Transboundary Aquifers allowed the identification of the most important transboundary issues of concern along with their causes. A Root Cause Analysis was used to identify, and later, address the core of the problems; not just their "symptoms".

The main challenges in groundwater management include cross-sectoral coordination, lack of implementation of IWRM principles in groundwater governance, as well as lack of public administration capacity and public participation in decision-making

procedures. The inappropriate disposal of solid waste and wastewater was recognized as the most important threat to groundwater. Karst groundwater pollution is also owed to agricultural and industrial activities. Infrastructure for hydropower production, a significant part of energy production in all DIKTAS countries, has negative impacts. The lack of financial means, the unregulated market economy and the weak environmental values have an overall negative impact on the management of the karst water resources. Due to lack of monitoring at local and regional level
there is limited assessment of the status quo and future trends with regards to karst groundwater quality and quantity.

3. Discrepancies in laws and policies of partner countries were identified to enable collective action to address the identified issues.

The Project assisted partner countries to create the conditions to apply common principles and work towards an agreement on the implementation of common measures at transboundary level. A SWOT analysis was performed to map the strengths, weaknesses, opportunities and threats the karst management is currently faced with, by collecting information on the legal, institutional and policy setting in the region. Common approaches and principles as well as areas of concern shared among partner countries were identified, along with contradicting national strategies and gaps in national legislations that may have an adverse effect on decision making related to the water resources management framework.

4. The widest possible consensus among stakeholders was secured and awareness was raised, to facilitate a behavioral change regarding karst management, as the basis for sustainable results.

The stakeholder engagement activities, based on the DIKTAS Stakeholders & Public Participation Strategy, succeeded to raise awareness among stakeholders about the value of the water resources and the need to manage these in a sustainable way. Moreover, it facilitated the long-term commitment of aquifer sharing countries to sustaining the Project results through the strengthened sense of ownership by politicians, decision makers, users and other stakeholders.
A Stakeholder Analysis was used to identify the characteristics and understand the opinions and perceptions of the stakeholders regarding the management of the water resources. A number of stakeholder groups including water management competent ministries, regional authorities, research institutions, tourism organizations, NGOs working on nature and ecosystems, as well as private sector industries and hydropower units, were consulted for the preparation of the TDA and the SAP through focus group meetings, roundtables and internet based tools.

5. Coordinated action was initiated at both the national and transboundary levels.

The National Inter-Ministerial Committees allowed the engagement and contribution of all related sectors in each partner country, for the identification of the priority issues and solutions under the five Water Resources and Ecosystem Quality Objectives included in the SAP. This ensured cross-sectoral work at national level, including the sectors of water resources, land use planning, forestry, finance and energy.

The Regional Consultation and Information Exchange Body, composed of partner countries' senior government officials is the first step to their systematic commitment to transboundary cooperation, as it forms the key technical-political interface of the Project discussing, commenting and approving the project outputs, such the TDA and the SAP. Regional management actions for reaching each objective include measures regarding policy and legislation, monitoring and data management, training and awareness-raising, as well as investments.

<u>Way Forward: Strategic Action Programme</u>

The five objectives identified for the Strategic Action Programme:

- Ensure sufficient groundwater availability in dry periods, to support water supply and environmental flow.
- Maintain and improve (where required) karst groundwater quality.
- Ensure protection of Groundwater Dependent Ecosystems, specific features and their ecosystem services for the future.
- Support equitable use of groundwater resources.
- Raise awareness and build capacities related to karst water and dependent ecosystems management.

Suggested priority actions include:

- The establishment of a common groundwater monitoring program followed by intense capacity building in the public sector.
- The harmonization of criteria for the delineation of source protection zones, aimed at a harmonized policy/regulatory framework.
- The establishment of a legal framework in transboundary sanitary protection zones.

A proposed shared vision is *to achieve joint sustainable and equitable use and protection of the Dinaric Karst Aquifer System* as the outcome of consultations among countries and stakeholders. Upon adoption of the SAP by the aquifer sharing countries, it will guide action in the years to come.

THE GEO-ENVIRONMENTAL PROBLEMS IN KARST REGIONS OF CHINA

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Abstract: The karst is widely developed both in South China and in North China. Many geo-environmental problems have been caused by the constructions over these areas. This paper, firstly, is to introduce some wider conservancy and water power stations with larger scale and the main geo-environmental problems, such as leakage and collapse as well as the other geo-hazards which includes landslides and debris flow etc. and related treatments are introduced. Secondly, the main karst geo-hazards caused by high-speed railway and subsurface ways in urbans are discussed. The rocky desertification in karst regions of China as the important problems for development in mountain regions have been paid more attention to research. Indeed, the rocky desertification as the one of the karst environmental phenomena is appearing by the natural karstification, particularly, by the unseasonal development to enhance the soil lost in the less covers over karstified mountain regions. This paper is emphasizing that the protection and reconstruction of eco-systems in karst regions are the first purpose in studying karst regions, so that it is needed to take comprehensive researches together with karst developmental rules and the changing evolution over eco-geoenvironment by the developmental and engineering impacts. The better eco-geoenvironment, the more beautiful karst landscapes.

Key words: karst, geological hazards, geo-environment, protection, reconstruction

Geological and Hydrotechnical Engineering in Karst

IMPACT OF KARST FEATURES ON WATER INFLOW INTO TUNNEL- CASE STUDY: ZAGROS TUNNEL-IRAN

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Abstract
In hard-rock tunnels, most of the inflow comes from a small portion of the tunnel length, some of the inflow comes from a large portion of the tunnel, and much of the tunnel is dry. The total inflow accumulates as the sum of all the inflows. Zagros tunnel passes through different formation and in a part of its route cuts the limestones with the karstic potential. In this paper based on the geological investigation, observed and measurement water seepage into tunnel in recorded sections using the numerical modeling, (The Universal Distinct Element Code (UDEC)), the water ingress into tunnel has been estimated. Results show that the large portion of water inflow is from the fault zones and karstic zones. From the amount of groundwater inflow point of view, the results show that amount of 50% of tunnel length can be classified as a low risk and around of other 50% has a high risk and critical conditions.

Key words: Karst, Zagros tunnel, seepage hazard

Introduction

The hydrogeological features in a karstic environment need special attention as there is an increased risk for water inflows and for environmental problems. Tunneling in limestone may thus be a challenge for both geologists and engineers owing to: high coefficient of infiltration from meteoric water, very high permeability; often nonlinear underground flow, preservation of high values of permeability at greater depths, potential of development of large hydrogeological basins, which may extend far beyond the boundaries of the corresponding geographic hydrological basins of the considered area, involving, thus, greater quantities of groundwater, development of a non-uniform and heterogeneous pattern of flow paths. Depending on the post-tectonic and paleogeographic evolution of the area, preferential flow conduits and karstic tubes could be developed with a capacity to transmit water at large discharge rates. These conduits drain the surrounding jointed or finely fractured rock mass of low or medium permeability, groundwater flow in a flooding manner throughout the transfer (“unsaturated”) zone and -potential crossing of large underground cavities filled eventually with earth materials with the possibility also to carry a column of perched ground water.

One of the major practical difficulties often associated with tunnel construction is related to groundwater. In fact, some of the most disastrous experiences in tunneling have been the result of interception of large flows of water from highly fractured water-saturated rocks (Freeze and Cherry 1979). Estimating groundwater inflow into tunnels is a difficult art, even if done carefully. There are several analytical expressions in the literature to calculate discharges into tunnels (Goodman et al. 1965; Zhang and Franklin 1993; Heuer 1995; Lei 1999; Karlsrud 2001; Raymer 2003; El Tani 2003).

The main purpose of this paper is to classify the tunnel based on the amount of water inflow and combination between results and actual geological features.

Zagros tunnel

Zagros tunnel with about 48.7 km length is being constructed in Kermanshah province of Iran. This tunnel consists of 4 parts being excavated separately. The execution of the last part of the tunnel is drilled by two TBMs from the Leileh River to Kordi Ghaseman River.

Geology

The geological structures of the western part of Iran are under the influence of the general trend of the Zagros Mountain Zimkan Anticline which the lowest part is located at el.730 m a.s.l. and the Zimkan River flows with an angle proportionate to the Range in this area. This trend is in NW-SE direction observed along the folds cropping out (anticline, syncline). The axis of Zimkan with the least overburden (113 -m thick) lies in this section. There are syncline structures on both sides of Zimkan anticline whose most heights are about 1682 and 1384 m a.s.l. in the north and south of Zimkan area respectively. The tunnel is located at el. 612 m a.s.l. of Zimkan.

Karst in Zagros Tunnel

The type of karstic zones in Zagros tunnel is recognized as a fluvio karst type. Fluvio karst or evidence of tributary surface stream that lead to stream beds underground when the drainage occurs.

In the area where the tunnel is located, there are many arid valleys at high altitudes. The paths of these valleys are often not regular. Some of them, like the valley of the village of Seyed Nabporab, are perpendicular to the tunnel.

In fact, there are currently no waters on the surface of valley, but the evidence of exploratory boreholes drilled near the Zimkan valley in the vicinity of this site clearly shows the level of the upper surface of the karst region (Figure 2). This set of porous rocks is seen at a certain level in all boreholes.

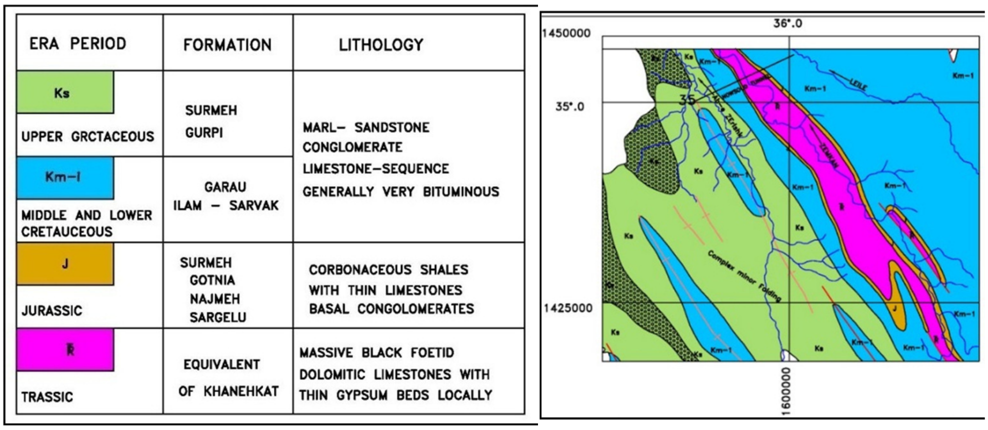

Fig. 1. Geological map of Zagros Tunnel

It seems that this level has been the area of fluctuation of underground water in the past, but at the time of this study the surface of the water was far below this level due to the dry period of recent years. The existence of several faults, sometimes with a length of more than 30 kilometers normal to the tunnel pathway, initially forms water passageways. Then during the time, water penetration in limestone and dolomite rocks extends the karstic aquifer region. Some of the dry valleys show a general agreement with large and local faults. The expansion of underground flows along the Zimkan Highlands with the same mechanism. The currents are the same water bearing zones as observed in tunnel.

Fig. 2. S4 borehole in the Zimkan area from depths of 125-132 meters - porous rocks

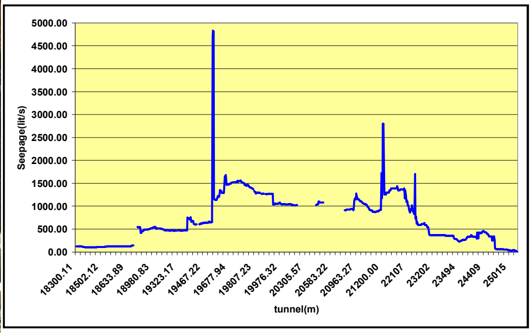

Fig. 3. Seepage(lit/s) Vs Tunnel chainage(m)

Given that along the faults and crushed areas, karsticity occurs more quickly, therefore the phenomenon of karsticity in this range follows the lines of faults, and any tectonic factors. The presence of Zimkan reverse fault in the anticline axis leads to the creation of a crushed zone along the Zimkan valley, the effects of which are found in the cores of the exploration borehole. Due to the existence of this fault zone along the valley, it seems that a deep stream under the Zimkan River can be existed and thus transfer and channeling of groundwater along these zones has occurred. Considering the general morphology of the region and the flow of streams along the surface, general flow of groundwater is predicted to follow the northwest direction. Due to the extent of Zimkhan anticline with a length of more than 30 km and the existence of extensive fault systems and limestone rocks, water is driven along it and thus large karstic conditions and aquifers are predicted to be extended in this area.

The most important lithostratigraphic units of the region that enjoy the potential karsticity are the Jurassic and Triassic calcareous and dolomitic units. Among Jurassic dolomitic limestone units there are interlayers and sometimes lenses of evaporative units (gypsum and anhydrite). The evaporative zones in the lower parts are often dissolved and the empty spaces that are often filled with sediments seen as an influx of materials during the tunnel drilling.

Nowadays, the drilling of the tunnel is completed and the results of the water leakage in the tunnel have been measured so far. In Fig. 3, the water leakage values of the tunnel are given, measured up to the end of the tunnel construction.

The 19632 chainage of tunnel is one of the most important areas of water leakage. In this place, about a discharge of 4 cubic meters per second along with an influx of materials were encountered that stopped the tunnel drilling operations. This was again encountered in the chainage of 19672, as seen in Figures 17 and 16.

In fact, this range is the distance between the F16 and F17-1 faults, which is well illustrated in the geophysical results.

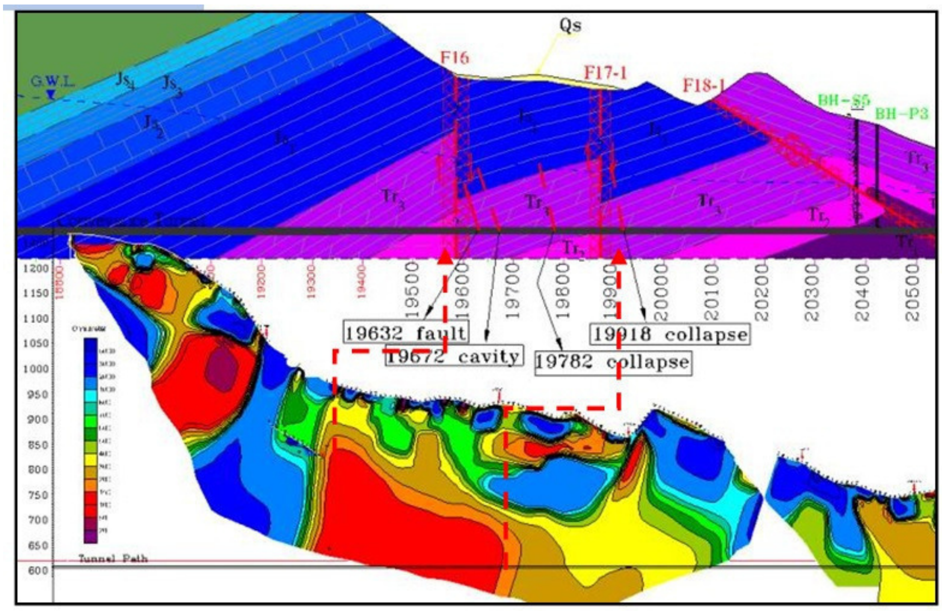

Fig. 4. Combination of geophysical results and geological sections

Another area of water leakage is chainage 21611. According to the geological section, it is related to the Homajge fault. The length of this fault is at least 15 kilometers. Along the tunnel, on the surface of the earth, alternate loose and dry valleys are observed. The volume of water flowing at depths of more than 430 meters is significant.

Fig. 5. Right-F16 Fault Area 19632 - Left Hollow Area 19672- Empty Space behind Segment- Stone: Brecciated Dolomite

Another very high water leakage observed in chainage of 22950. According to the geological section, it is related to the F14 fault. The fault F14 interrupts the lower Cretaceous-Jurassic and Triassic strata. This is a fault is dextral strikeslipe fault. Displacement of the horizons in this fault is over 140 meters. This movement is documented in visual observations in field observations. (Fig. 6)

Numerical methods

Defining the boundary conditions, material properties, rock mass and joints characteristics are the most parameters to generate the numerical model. Based on the geological investigations, the DEM model has been generated and the seepage rate into the different sections of the tunnel have been calculated. It is obvious that the accuracy of calculations by software is totally depends on the accuracy of input parameters [13]. Figures 7 to 8 are show the generated model for tunnel.

Faults and major joints have the significant roles in water flow. Therefore, the fault zones have been modeled separately using the FEM software. Figure 9 to 10 shows the generated model for Fault zone.

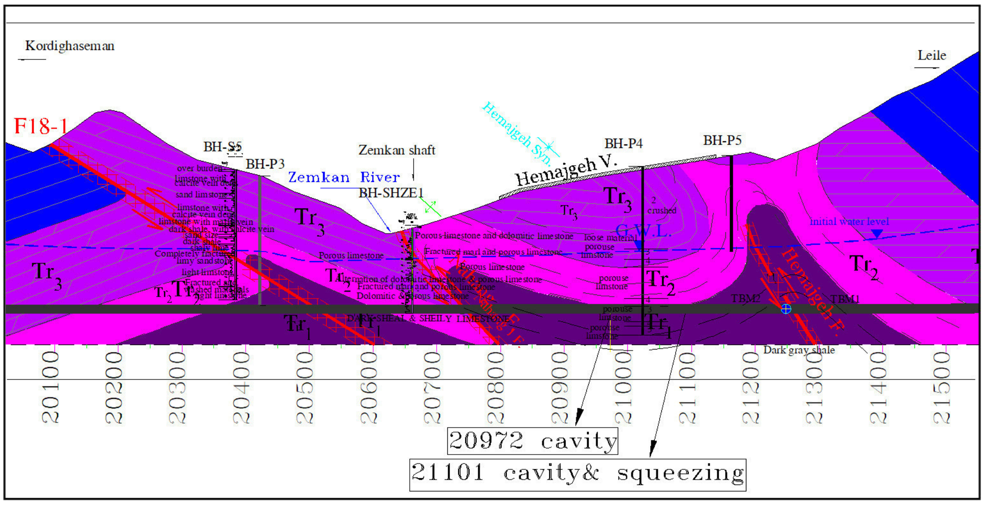

Fig. 6. Engineering geology section of tunnel from 20100 to 21500

Fig. 7. Satellite image of the F14 fault and displacement of Jurassic and Cretaceous


Fig. 8. The fault in the 21611 tunnel and at a depth of 433 meters of ground surface

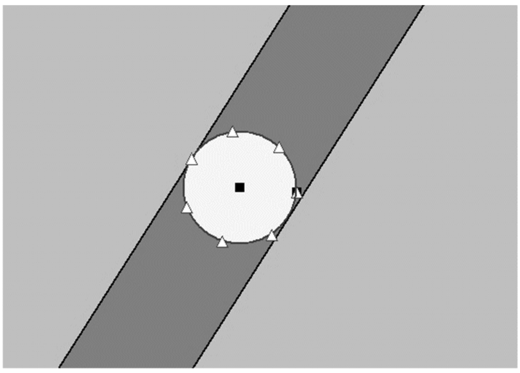
Fig. 9. Generated model for the fault with 5 m crashed zone width

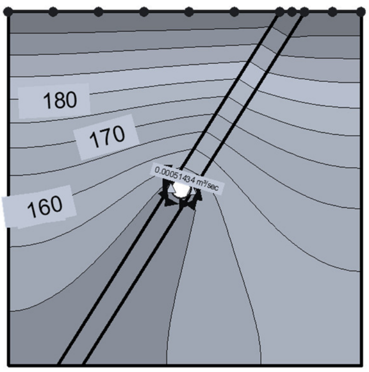

Fig. 10. Distribution of water head above tunnel in fault zone

Results of numerical method are show in the Figure 11.

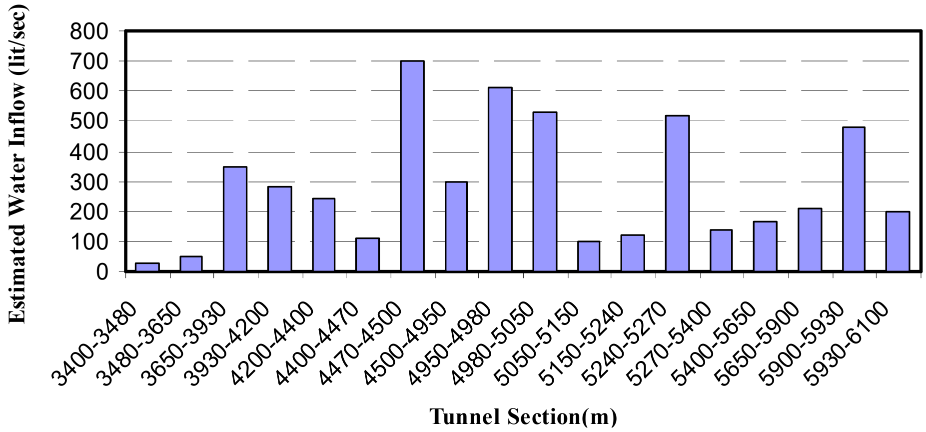

Fig. 11. DEM modeling results

Observed water flow into tunnel

The actual water inflow into tunnel has been measurement for each section of tunnel. Table 1 shows the amount of cumulative water observed in tunnel.

Table 1. Amount of water flow measurements

Estimated Cumulative Water Inflow (lit/sec)	Equivalent Length(m)	Chainage(km)
938	80	3400-3480
1092	170	3480-3650
1366	280	3650-3930
1700	270	3930-4200

Comparing between observed water flows into tunnel and estimated using analytical equations have been shown in figure 12&13.

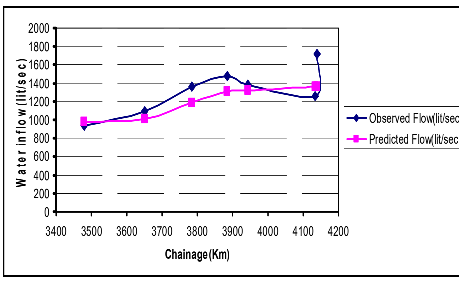

Fig. 12. Comparison between observed and estimated water flow.

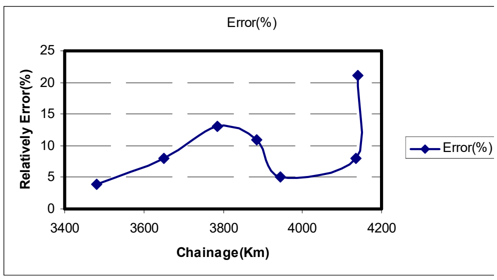

Fig. 13. Relative Error

Base on Fig. 12. The actual water inflows into the tunnel are in good agreement with the estimated groundwater inflow into tunnel. In addition, distinct geological features (i.e. shear, fault or crashed zones) which might not be intersected by conventional packer intervals have been considered in the method.

Conclusion

Groundwater inflow assessment is essential for the design of tunnel drainage systems, as well as for assessment of the environmental impact of the associated drainage. Analytical and empirical methods used in the conventional engineering practice does not adequately account for the effect of the jointed-rock-mass anisotropy and heterogeneity. In this study, based on the geological investigations such as water head above Zagros tunnel, rock mass permeability, the groundwater inflow into tunnel has been estimated. It is showed that the calculated flow values are in a good agreement with the observed and measurement ones. Considering the hazard of ground water ingress, the results show that about 50% of tunnel length can be classified as a low risk and around of other 50% has a high risk and critical conditions. Applying these results provides the designers with a more reliable data to design of the convenient drainage system, drilling method, and tunnel support.

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KARST AND HYDRAULIC CONSTRUCTION IN BULGARIA

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Abstract: Hydraulic construction is of significant importance for the economics and the population of Bulgaria. The geological environment has basic importance for designing, constructing and exploiting of this type of facilities. The karst phenomenon impacting approximately ¼ of the Bulgarian territory is one of the critically risk factors for them. As a consequence of the preliminary performed geological and hydrogeological studies on karst terrains, a number of variants for hydraulic facilities were rejected in spite of their suitability by other reasons. Nevertheless, 320 dams and hydraulic systems were built in areas related directly or indirectly to carbonate rocks, creating favorable conditions for karst formation. The present study discusses some of more expressive examples. The overview of these cases shall improve the quality of the future designing of hydraulic constructions in karst terrains.

Key words: karstic waters, karst, hydraulic construction, Bulgaria

Introduction

The geological conditions have a dominant importance for constructing and exploiting of hydraulic facilities. The presence of karst is one of the riskiest factors in this aspect. The worldwide practice shows a number of cases of impounded reservoirs and the related systems in regions with karst, as well as the change of the hydrogeological conditions of the surrounding areas (Milanović, 2005, 2015). The aim of the present study is to present one overview for the hydraulic facilities on the territory of Bulgaria built inside areas with karstified rocks, or directly impacting the existing karst and related karst waters.

Characteristics of the karst in Bulgaria

Karstified rocks are outcropping on about 23% of the territory of Bulgaria – limestones, dolomites and marbles, containing more than 6000 caves inside.

Besides, because the platform type of structure of North Bulgaria, a wide presence exists of typical karsric aquifers often recovered by other type of rocks. The carbonate rocks in South Bulgaria and in Balkan Mountain form separated basins, mostly with mountain karst, due to the complicated tectonics. The surface and underground karst formations are widely presented.

Hydraulic facilities in Bulgaria

Several thousand dams have been built on the territory of Bulgaria barraging lakes of total exploitable volume of approximately 6,8 billion m^3. The dams are of different types and dimensions, consequently barraging different water volumes. The micro-storage reservoirs of earth-fill embankment dams have the widest presence. They are used for irrigations, aquacultures and drinking of animals. Only 48 dam-reservoirs are of significant volumes, and they barrage 5628 million m^3 of water, or this is 82,8% from the total storage volume of the all dam likes. These dams have been built for barraging more important rivers, and they are of gravity rock-fill or concrete type, some of them being of considerable high (the highest dam is the dam "Vacha" - 144,5 m). Their waters are used for electric power generation, for supplying drinking and industrial water, for irrigation. A part of the storage reservoirs in Rila Mountain and especially in the Rhodope Mountain are interconnected by derivation canals and in this way cascades of number of reservoirs were created. The water from artificial lakes in different river valleys is redistributed by tunnel derivations. Waters from the collector canals of mountain streams and rivers are directed towards some of the dam reservoirs. Some typically earth-fill embankment tailing dams barraging river beds, as well as the large number of recently constructed barrages for micro-power plants must be considered as hydraulic facilities in Bulgaria.

Hydraulic constructions and karst – examples

More than 320 dams and other types of hydraulic constructions in Bulgaria are directly or indirectly related to carbonate rocks with conditions for karst formation (Fig.1.). The performed preliminary studies on karst terrains have shown the technically difficult and economically unprofitable realization of such type of facilities. The designed sites were completely rejected or alternative variants were chosen in some of the cases. As an example, the dam construction on the bed of Vit River was declined in spate of the morphologically suitable narrow valley near the village of Sadovets (Ivanov et al., 1960). The performed drilling had shown the existence of large open karst caverns approximately at the level of the river and at the upper part of the water saturated zone of the Senonian limestones forming the river valley escarpment. The ground waters in the karst have a good connection with the river. The probable barraging with a dam will result as an important impact on the big karst springs situated downstream from the designed dam. Another interesting example is the refuse to realize the storage reservoir "Maragidic" situated at the highest altitudes in Central Balkan Mountain (Grancharov, 1959; Chanov et al., 1986). The dam and the reservoir were designed entirely on granites, but the karst was the dominant factor for stopping the project realization. A particularly interesting phenomenon is presented in this area – an existence of pseudo-karst forms (sinkholes) in the granites. They were formed by infusion of river water in the intensively fractured and altered allochthone granites, overthrusting the highly karstified Senonian limestones. The fractures impact the whole thickness of the granites and the penetrating river water creates conditions for pulling out by suffusion of the grus sand from the granites downwards in the karst caverns in the limestones. The creation of water reservoir will accelerate the processes of suffusion, will activate the karst processes and will provoke a serious loss of reservoir waters. A number of designed dams and reservoirs in Bulgaria were never built because the proved risks due to the high level of karstification and the significant potential for losses of waters.

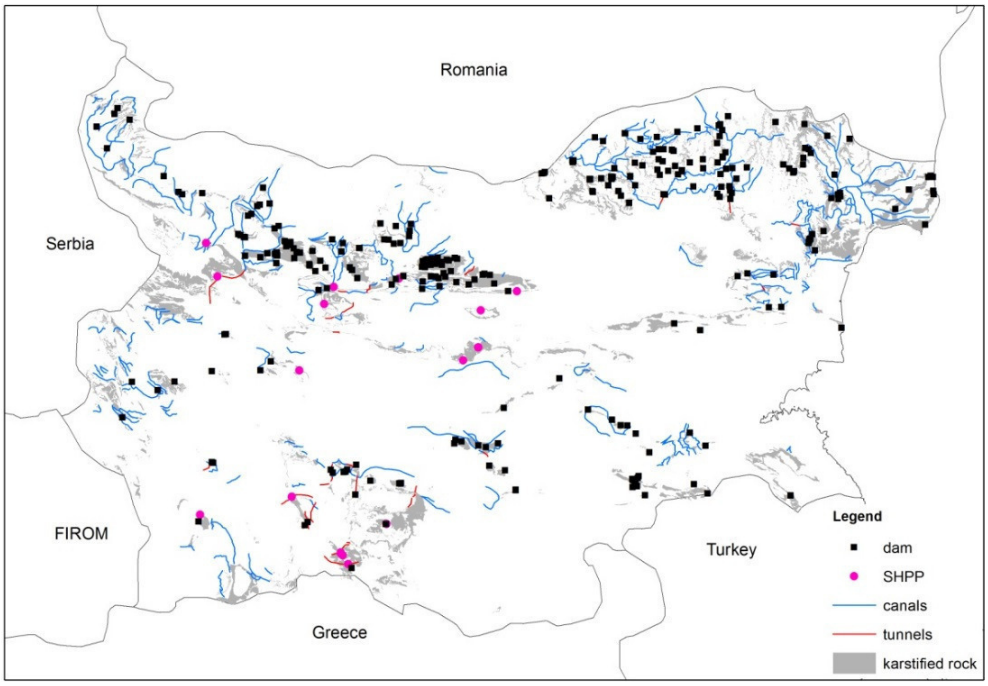

Fig. 1. Outcrops of the karstified rocks in Bulgaria and hydraulic constructions

Nevertheless, that the karst exists in some of the regions, after performing the necessary geological and hydrogeological investigations proving the technical feasibility and the economical expediency, many dams were done. The dam and the lake of one of the first artificial reservoirs created in Bulgaria on Zlatna Panega River near the town of Lukovit (the years 1925-1936) have been situated entirely on Maastichian limestones. But no problems were detected concerning the filtration. Even the existing karst spring at the foot of the dam has never changed its discharge regime, despite the water level of the lake.

But a few cases exists, when the raising of the ground waters level and an overflow of karst springs appeared. The last big dam "Tsankov Kamak" built in Bulgaria during the period 2004-2009 in Central Rhodopes on Vacha River and its tributary Gashnia River, has recently problems with the karst. The dam of type concrete-double arch is 130,5 m high. The problems have appeared because the significant permeability of the fractured and karstified marbles outcropping along the bed of Gashnia River (Schröttner, 2005). For the protection against potential losses of water through the karstified and fractured zones in the marbles a cover of geo-membrane is made, as well as concrete fillings of some areas of flooding (Fig.2.). The level of the ground waters in the region has been changed after the execution of the insulation, due to the decreased feeding from the rivers or because the impossibility for direct draining towards the bed of Gashnia River. The regular inspection of the facilities in July 2017 discovered fracturing of the insulation along the bed and the banks of Gashnia River. The lake was completely discharged from water and a repair is now running.

Fig. 2. Insulation of the bed of Gashnia River

The most serious problem in Bulgaria, related to the hydraulic construction on karst terrain, is the dam of the impounded reservoir "Ogosta" (Benderev et al., 2006) on Ogosta River at the nearest vicinity of the city of Montana. The main karst spring is at about 400 m north-eastwards from the dam. It is draining the karst basin in Upper Jurassic and Lower Cretaceous rocks outcropping along the western bank of the lake (Fig.3.). The preliminary performed tracing investigations have proved the connection of the waters from Ogosta River and the spring, the underground velocity being of 25-30 m/h. After the barraging by the dam and the beginning of impounding of the reservoir, the discharge of the spring began to increase sharply. The gryphon of the spring and the canal trough the city was not able to outfall the water quantities. New outlets of ground waters appeared westwards from the spring. It was recorded a rising of the ground water level in the city. A tunnel of lengths of about 300 m has been excavated for connecting the karst gallery discovered by skin divers, and for reducing the water quantity directed towards the city. The spring discharge raised more than 10 times (from 80-100 l/s to more than 2 m³/s) due to the impounding of the dam lake during the years 1987-1988.

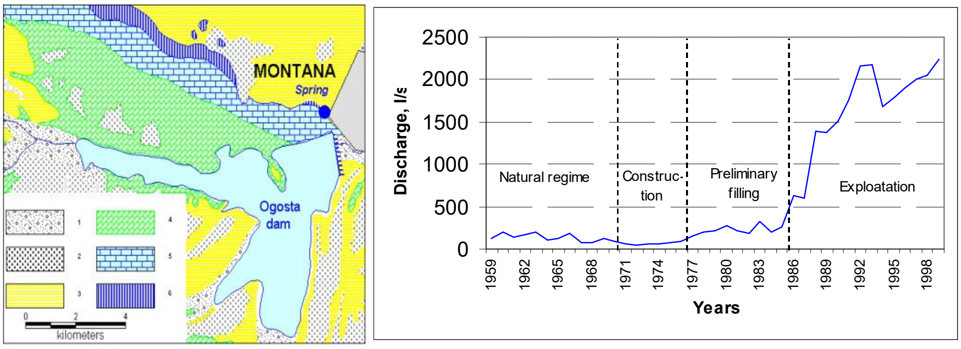

Fig. 3. Geological map in the Ogosta dam vicinity and alternation of the spring flow rate`(Benderev et al.,2006): 1 –fans and alluvial deposits; 2 – eluvial materials; 3 – Neogene formations (clay, sands, sandstones, marls, limestones); 4 – Cretaceous formations (marls, sandstones, aleurites, argillites and limestones); 5 – Low Cretaceous – Upper Jurassic formations (limestones); 6 – Middle– Low Jurassic formations (sandstones, gravelites and conglomerates)

Similar example is the dam of the tailings pond near the town of Laki, built in the years 60-70 of the past century. In reality it represents storage reservoir on Ugovska River on the area of outcrop of highly karstified pre-Paleozoic marbles (Naidenov, 1973). At the vicinity of the barraging dam 3 intercalations of gneiss-schists have been detected, having important impact on the karst processes. The grouting of number of springs of significant discharge was executed in the constructional excavations and the lake basin. During the filling of the tailing pond it was established a water loss by karstic canals, and the discharge of two springs raised 2-3 l/sec to 500-600 l/s and from 10-15 l/s to 300 l/s. It was determined also the presence of tailing waste in 4 other springs. The velocity of the karst waters was between 700 and 1000 m/d. Injections were made in the caverns for stopping the leakage.

Karst terrains are also crossed by some of derivation tunnels of the hydrotechnical cascades, mainly in the Rhodope Mountain. A part of these tunnels is inside the zone of aeration, but during the tunneling of some others (from HPP "Teshel" to HPP "Nastan" of cascade "Gorna Vacha") an influx of karst waters appeared (Ivanov et al., 1960). The most abundant influx of karst waters was recorded at the access window I of the water race canal of HPP "Batak" (more than 500 l/s). It decreased lately in the time.

Direct impact on the karst waters has the collecting canal "Petrohan", deriving the waters towards HPP "Barzia", besides its position on non-karstified rocks. The canal is covered, but the open collectors are situated at altitudes from 1400 to 1450 m, and they redirect significant quantity of waters from the rivers running southwards the main mountain ridge of Balkan Mountain (Stara Planina Mountain). The principal problem is that these rivers at lower altitudes rich the highly karstified Triassic limestones and dolomites where they loss totally their waters inside the well expressed blind valleys. The consequence is the decreasing of the feeding of the karst springs, especially for the karst spring of Iskrets. Its discharge has dropped down from 5% during high water seasons to about 40% during the dry summer months (Benderev et al., 2006).

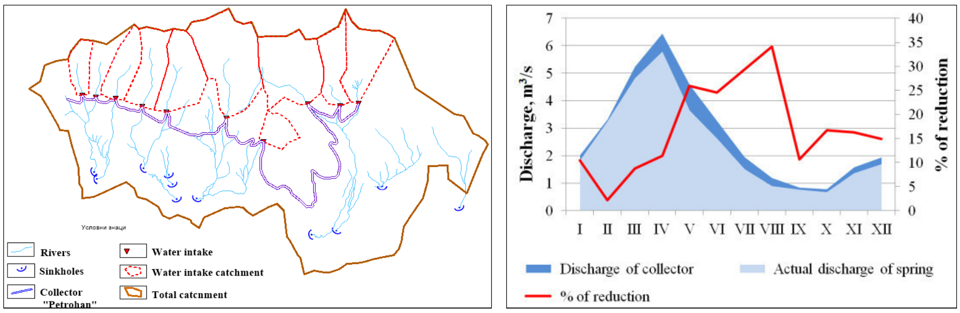

Fig. 4. Map of the water collections and the out flowing and the taken away waters of Iskrets Spring.

During the last years an intensive implantation of small HPP and the related barraging dams and canals is going on. From the existing 318 small HPP only 18 are in areas impacted by the karst. But taking into account their relatively inexpensive and faster realization, very often the sites of their dams are not designed on appropriated places. As an example, one of the most inappropriate sites chosen for implantation of small HPP was in the area of the rail-way station of Cherepish (Western Balkan Mountain). On the territory of only 3 km^2 more than 180 caves exist. The performed geological, structural, karstological, speleological and geophysical studies have proved that the intensive karst manifestation is presented on the site of the barragind dam, as well as on the entire territory of the future reservoir. The only way for stopping the underground filtration is the total cementation of the reservoir bed.

Conclusion

The performed till now studies, constructions and exploitations of hydraulic constructions on karst terrains in Bulgaria have given a serious positive, as well a negative experience. This experience could be applied for the future similar activities. At this way the benefit is the increasing of the knowledge for the karst from practical, theoretical, methodological and regional aspects.

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INSTALLATION OF GROUND- AND WATER-SOURCE HEAT PUMPS IN KARST TERRAINS (CASE STUDIES FROM CROATIA)

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Abstract
Hydrogeological and thermogeological properties of the shallow subsurface in the Dinaric karst area of Croatia were investigated in the context of its utilization for ground- and water-source heat pumps (GSHPs and WSHPs). It was determined that rock thermal conductivities are favorable for GSHP utilization and that wells with high enough yield and stabile seawater or groundwater temperatures for WSHP utilization can be designed in appropriate structural settings. Advantages and disadvantages of the utilized methodology have been pointed out, as well as methods which should prove useful in the future. Hydrogeological, geotechnical and thermal risks expected during the drilling, installation and operational phases have also been identified. Presented case studies have given the insight into the heat pump installation options and conditions in Croatian part of the Dinarides, but can be useful to other researchers and engineers both in the Dinarides and in similar karst regions.

Key words: Dinaric karst, rock thermal properties, hydrogeological properties, heat pumps, Croatia

Introduction

Fig. 1 Locations of presented boreholes

Ground- and water-source heat pumps with high seasonal performance factors are considered as renewable resource heating and cooling devices by the EU (Directive 2009/28/EC) and their application is steadily increasing. An EU funded GeoMapping project was conducted in 2013-2015 at eight geologically diverse locations throughout Croatia (Fig. 1) in order to determine the geological conditions for their utilization (Borović et al., 2015).

Four of the studied locations were situated in karst terrains (two near the Adriatic coast and two in the hinterland). 100 m deep boreholes were drilled and double U-pipe heat exchangers were installed. Borehole core examinations and sampling were conducted, and thermal parameters, which are crucial in determining systems' efficiency, were measured both in natural scale (Thermal response test - TRT and Distributed TRT - DTRT - using advanced distributed temperature sensing by fibre optic cables installed inside the U-pipe) and in laboratory scale (direct measurement on core samples using ISOMET 2114 equipment by AppliedPrecision). In another project wells were drilled on the site of a future hotel in order to ensure supply of seawater for a heat pump system. Due to limited land area owned by the investor, the research aimed at finding significant fracture systems which can support the required production and reinjection rates.
A variety of natural and engineering conditions were encountered during the course of these projects, the experiences from which can be useful to shallow geothermal project development in similar karst environments known for heterogeneity and anisotropy of engineering, hydrogeological and thermal parameters.

Closed loop / ground-source heat pump cases

Heat pumps coupled to closed-loop borehole heat exchangers have been widely utilized and investigated both theoretically and experimentally in the past few decades. Theoretical models following Fourier's law of heat conduction are based on the assumption of a homogeneous and isotropic ground (e.g. Ingersoll and Plass, 1948; Carslaw and Jaeger, 1959), which generally does not correspond to reality, especially in karstified subsurface. Long-term (years and decades) performance of GSHP system is highly dependent on the balance between heat extraction during the heating period and heat injection into the surrounding ground during the cooling period. This balance depends on the climate of the region, ground thermal properties and heat advection by groundwater flow, which is why it was necessary to investigate the potential corresponding to local conditions. To this aim, four boreholes have been drilled in the Dinaric part of Croatia and different conditions have been encountered. While the boreholes in Poreč, Gospić and Zadar were drilled in carbonate rocks (limestones), in Knin mostly evaporitic rocks were present (gypsum and anhydrite in different proportions). In such environments thermal properties of the subsurface were correspondingly disparate (Tab. 1). It is known that the matrix porosity in carbonate and evaporitic rocks is very low, i.e. negligible in an engineering sense. Therefore, their thermal properties are mostly dictated by the thermal properties of minerals constituting the rock matrix, the fracture and/or karst porosity and the fluid which fills in fractures and caverns. In such medium it is very significant which fluid fills in the voids, because air has roughly 30 times lower thermal conductivity than water, which in turn has tenfold lower thermal conductivity than rock forming minerals, e.g. λ_{air}≈0,02 W/(m*K), λ_{water}≈0,6 W/(m*K), $\lambda_{minerals}$≈1 - 7 W/(m*K).

*Tab. 1 Average thermal conductivities of rock samples in W/(m*K)*

	Gospić	Knin	Poreč	Zadar	AVERAGE
foraminiferal limestone				2,73 (8)	2,73
Cretaceous limestone			2,18 (4)	3,28 (4)	2,73
Jelar breccia	2,95 (6)				2,90
gypsum / anhydrite		3,01 (17)			3,01

Ten measurements per sample were conducted (number of samples in parentheses).

It is visible that different rocks of carbonate (calcite) composition have quite similar thermal conductivities in laboratory scale (Tab. 1). Also, rock thermal conductivity is lower than that of pure mineral calcite. Unlike rock (and especially rock mass) thermal conductivities, those of pure minerals have been precisely determined. At standard temperature, for calcite it is in the range of 3.3 - 3.6 W/(m*K) (Robertson, 1988) or 3.3 - 3.8 W/(m*K) (Momenzadeh et al., 2018), depending on the orientation of crystals in relation to heat flow.

Fig. 2 Evaporite rocks in Knin borehole

The evaporite rock mass consisting of gypsum and anhydrite is very interesting, because according to Robertson (1988) thermal conductivity of gypsum is 1.2 W/(m*K) and of anhydrite 6.0 W/(m*K). Although it was not possible to determine the proportions of gypsum and anhydrite in the rock by standard optical methods, different proportions could be assumed on the basis of very variable thermal conductivities. E.g. the evaporites were present in a 60 m sequence (Fig. 2). Out of that, 17 rock samples were collected and thermal conductivities were measured in a range of 1.63-5.16 W/(m*K)

In an environment with significant freshwater flow from the hinterland its impact cannot be overstated, which was specifically proven by thermal recovery measurements after distributed thermal response testing in Zadar. It is clear that in such places thermal recovery is rapid in comparison to other areas where groundwater flow is lower, which is visible from much higher thermal conductivity measured by DTRT in comparison to laboratory measurements on samples (Tab. 2). In this case a combination of karst environment and strong groundwater flow through the karst conduits or preferential flow paths eventually caused significant drilling equipment drop-downs and blockades, which resulted in abandonment of the borehole and its relocation nearby.

*Tab. 2 Results of subsurface thermal conductivity determination in W/(m*K) along the borehole length*

	Measurement technique		Discrepancy (%)
	LAB	DTRT	LAB-DTRT
Gospić	2,92	2,73	6,96
Knin	2,58	2,08	24,04
Poreč	2,19	2,05	6,83
Zadar	2,86	3,21	-10,9

In Fig. 3 it is important to notice that caverns are present (which, depending on the groundwater levels can be filled by water or air - causing different heat transfer environments), as well as *terra rossa* and rock fragments with *terra rossa* causing lower thermal conductivity, since thermal conductivity of such mixtures was determined at different localities to be around only 1 W/(m*K).

Fig. 3. Different materials in the rock mass of Zadar borehole: (1) terra rossa; (2) cavern; (3) rock fragments and terra rossa – partially solidified; (4) fractured rock.

In Gospić the situation was much simpler, since out of the 100 m which were core-drilled, 97 m were, in engineering sense, uniform *Jelar breccia* (clast-supported, unsorted, mostly monomictic limestone breccia with miciritic, mostly reddish matrix), intersected by a few more significant fractures (possibly faults) (Fig. 4). In such an environment (similar to the Poreč borehole), when the fractures are minor and the limestones are generally undisturbed, thermal properties are more consistent and depend on the thermal properties of rock forming mineral.

Fig. 4 Compact Jelar breccia (left) and a fracture with striations (right)

Open loop / water-source heat pump case

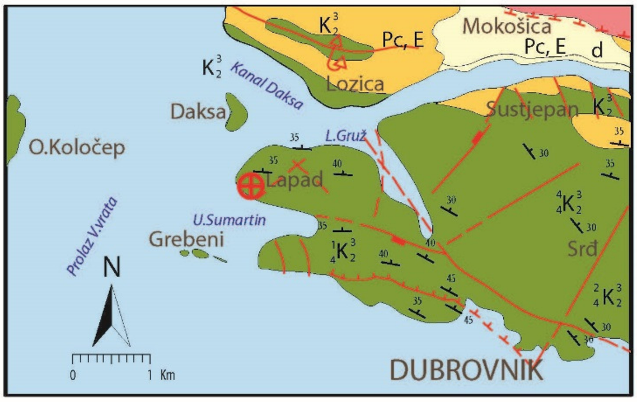

Fig. 5 Locations of boreholes in Dubrovnik (red circle) on the geological map according to Marković (1966)

WSHPs are thermodynamically more efficient than GSHPs, which is a consequence of more efficient heat transfer by advection, in comparison to conduction. At the location of a future hotel in Dubrovnik (Fig. 1), boreholes were favoured to surface intake due to aesthetic requirements, but also as a solution which offers higher energy efficiency. Predicted drilling area for the boreholes was only 400 m^2 (2 piezometers, 2 production and 2 reinjection wells). The goal was to identify preferential flow paths in tectonically disturbed Cretaceous carbonate rock mass (Fig. 5). The initial hydrogeological prospection was conducted by mapping the structural elements and determining the positions of tension and dissolution fractures in the rock mass, which were considered to be the most promising structural element, able to ensure hydraulic properties which will enable high enough yield and good reinjection properties of the future wells (Urumović et al., 2016). Abstraction wells are 30 and 40 m deep and both reinjection wells are 25 m deep. The depths of abstraction wells were increased in comparison to initial plan, in order to minimize the temperature variations of seawater. This approach resulted in a very favourable regime between two production and two reinjection wells. The required seawater intake for the system was 50 L/s. According to well parameter calculations (Rorabough, 1953) from pumping test, over 500 L/s were secured. Pumping test was conducted with Q_{max}=50 L/s and drawdowns in the abstraction wells were negligible (10 - 22 cm), varying in concordance with tidal cycle. Owing to an excellent yield of the abstraction wells and total reinjection, heating and cooling for both buildings of the establishment are now supplied by the system originally planned for only one (smaller) building. Although seawater temperature will certainly experience some seasonal variations, it will be far less pronounced than it would be the case using direct intake from the sea. The boreholes further from the shoreline are used for abstraction to minimize seasonal temperature variation caused by insolation. Such layout will increase the seasonal performance factor of entire heat pump system throughout its operational lifetime.

Conclusions and lessons learned

Shallow subsurface of the Dinaric karst area, which makes up roughly a half of Croatian territory, was investigated for GSHP and WSHP utilization, and the results were encouraging for both type systems' deployment. Collected data show that laboratory measurements systematically overestimated ground thermal conductivity in karst terrains in general, but underestimated it in the areas of high groundwater flow from the hinterland through karst conduits, i.e. the properties of rock mass do not correspond well to thermal properties of carbonate rock as a monolith. DTRT has proven to be an excellent indicator of natural scale thermal properties of karstified rock mass and, additionally, of karst phenomena such as highly karstified fault and fracture zones – preferential paths of groundwater flow where heat is transferred by advection, not only by conduction in the solid matter (Soldo et al., 2016). Also, the unpredictability of drilling and heat exchanger installation in karst terrain was confirmed and attributed to subsurface geological properties.

There are risks involved both during drilling and operational phases. During the drilling, tools blockade and/or drop-down in the borehole have to be foreseen. Strong groundwater flows can amplify these problems. For practical purposes most of such boreholes will be drilled without coring, which would diminish related karst problems. If more boreholes or wells were planned, seismic refraction profiling would be advisable before the drilling, in order to reduce the drilling risks. Electrical resistivity tomography should be conducted to identify preferential groundwater flow paths or seawater intrusion paths in the case of drilling for WSHPs.

Risks present in the operational phase can be divided into hydrogeological risk (water contamination by refrigerants and carrier fluids in an environment of negligible autopurification capacity), geotechnical risk (destruction of installed borehole equipment during storm events; evaporite rock swelling) and thermogeological risk (excessive cooling or heating of the subsurface if heat extraction/injection imbalance cannot be dissipated due to low heat and groundwater flow; thermal short-circuiting).

Since only a limited number of possible research locations were available, no dolomite or flysch rock masses were tested in the Dinaric karst area. This should be a topic of future investigations due to their widespread distribution throughout the Dinaric karst region.

Acknowledgement

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HYDROGEOLOGICAL RISK FACTORS OF DAM AND RESERVOIR CONSTRUCTION IN KARST TERRAINS – "THREE DAMS IN THREE GORGES" IN SERBIA

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Abstract: A brief analysis of construction risks is presented for three artificial reservoirs in Serbia: 1 / "Bogovina", 2/ "Stubo-Rovni", and 3/ "Arilje-Svračkovo", planned in terrains mainly composed of karstified limestone. Each of the cases features specific geological and hydrogeological properties of the terrain, and, therefore, specific mechanisms of (potential) water losses under conditions of significantly altered hydraulic properties of karst aquifers. Presented examples confirm that the construction of dams and reservoirs in karst terrains carries potentially high risks of water losses, and that detailed hydrogeological research should be carried out in the early stages of project preparation. Special attention should be paid to: 1/karst aquifer contact zones with impermeable rock formations, which may act as complete or partial hydrogeological barriers to underground flows (losses) from the planned reservoir, 2/underground hydraulic connections of flooded karst, with permanent and occasional karst springs outside the reservoir topographic catchment.

Key words: lake-reservoir, karst aquifer, water losses, hydrogeological research

Introduction

Construction of dams and lake-reservoirs generally carries a construction risk, while the implementation of such projects in karst terrains significantly increases the risk and requires additional funds and time dedicated to detailed hydrogeological and engineering-geological research. The risk of construction in karst may be divided into two categories: 1/ site selection risk, and 2/ risk in the exploitation phase [1].

Site selection risk can be reduced to an acceptable level by well-conceived hydrogeological and engineering geological research: detailed mapping of terrain, hydrometry, geophysical survey, exploratory drilling, speleological research, tracing tests, packer tests, pumping tests, etc. Based on obtained results, an estimate of water losses is carried out, followed by recommendations for sealing works that will reduce the losses to an acceptable level.

The risks in the exploitation phase are [1]: 1/time (aging) factor - degradation of natural deposits or sealing masses in cracks and cavities 2/induced seismic activity,3/breaks (collapses) that may be activated under the weight of artificially increased water level, most often at the bottom of the river valley where the karst forms might be covered by alluvial deposits, 4/submerged karst springs or swallow holes (ponors) as potential pathways for underground outflows (losses) of accumulated waters.

Since the 1970s [2] and concluding with the current planning documents [3,4], the water management strategy of the Republic of Serbia has been based on the construction of a number of dams and reservoirs with relating regional water supply systems (RWS). The paper presents a brief analysis of the construction risks for three planned reservoirs: 1/ "Bogovina", 2/ "Stubo-Rovni", and 3/ "Arilje-Svračkovo" (Fig.1), in terrains mainly composed of karstified limestone. Out of several construction risks, only water loss potential is discussed. Other relevant risks – geotectonic predisposition and seismicity of the area, stability of the lake bed and sides in altered hydrological (hydraulic) conditions, intensity of erosion processes in the basin, possible geochemical and anthropogenic water quality degradation, impact on existing resources for water supply, ecological and social impacts in artificially altered environment and similar –were not considered in this article.

Fig. 1. Geographical positions of the reservoirs (A – finished, B – under construction, C – planned)

The "Bogovina" Case Example

The dam and reservoir were designed in the 1980s on the Crni Timok River in eastern Serbia (Fig. 1), on the terrain consisting mostly of karstified Lower Cretaceous limestone (Fig.2) with a maximum water level at 275 m.a.s.l., for the purpose of supplying water to several settlements in the Timok region. However, due to a successfully completed project of karst aquifer regulation (Stevanović, 2010), works on the dam construction were postponed for an infinite period of time. The water supply of the targeted settlements was based, starting from 2001, on the "transitional solution"–groundwater tapping using four pumping wells located in the drainage zone of the karst spring Mrljiš, which is the main and lowest drainage point of the karst aquifer.

Hydrogeological research has been carried out to assess the risk of water losses from the planned reservoir under modified hydraulic conditions in the karst aquifer [6,7]. The key results of the conducted research are (Fig 2):

1/The Bogovina cave (266 m.a.s.l.) is a sort of „hub" of the hydraulic mechanism of the karst aquifer.Tracing tests showed that, during low-middle water levels, groundwater flows from the Bogovina cave to the Mrljiš spring (which is flooded by the reservoir) and the abandoned coal minelocated within a heavily fractured Oligocene marlstone. In periods of high waters, groundwater flows to the periodical karst spring Fundonj (263 m.a.s.l). The Bogovina cave is also a periodical karst spring which forms the Bogovinska River, a downstream (in regard to the dam profile) tributary of Crni Timok.

2/Several pumping tests carried out in the Mrljiš drainge zone caused the lowering of groundwater levels in the Bogovina cave zone. It is important to point out that the maximum flow rate of the Mrljiš spring (before regulation) was over 2 m^3/s, which indicates high permeability of the karst channels and cavities in the Bogovina cave-Mrljiš directions.

3/ Several boreholes in the area have shown that karstification is intensively developed at the depth of app. 80-90 m.

The results indicate potentially significant water losses from the reservoir, whereas non-karstic rock formations (b1-Cretaceous sandstone and b2-Oligocene marlstone, Fig. 2) represent only fractional groundwater barriers. Under the conditions of artificially elevated hydrostatic pressures, water infiltration will intensify through the bottom of the reservoir in the Mrljiš drainage zone, and there will be flushing and removal of deposits from the karst channels and caverns. Masked karstic forms (by alluvial deposit) could cause further collapses. It has been assumed that after the reservoir fills up to the level of app. 263 m.a.s.l, infiltrated waters may form reverse underground flow to the

Bogovina cave, as well as further, towards the Fundonj spring and the abandoned coal mine. If the lake reaches the level of 266m.a.s.l, the losses will be increased by the outflow from the Bogovina cave. In addition, it is possible that some of the accumulated water would also be lost through the right bank of the reservoir, due to the assumed partial character of the barrier (b1) and the hypsometric relation of the karst-nonkarst (b3), and flow to the Arnauta River (Fig. 2) as well as further, downstream of the reservoir.

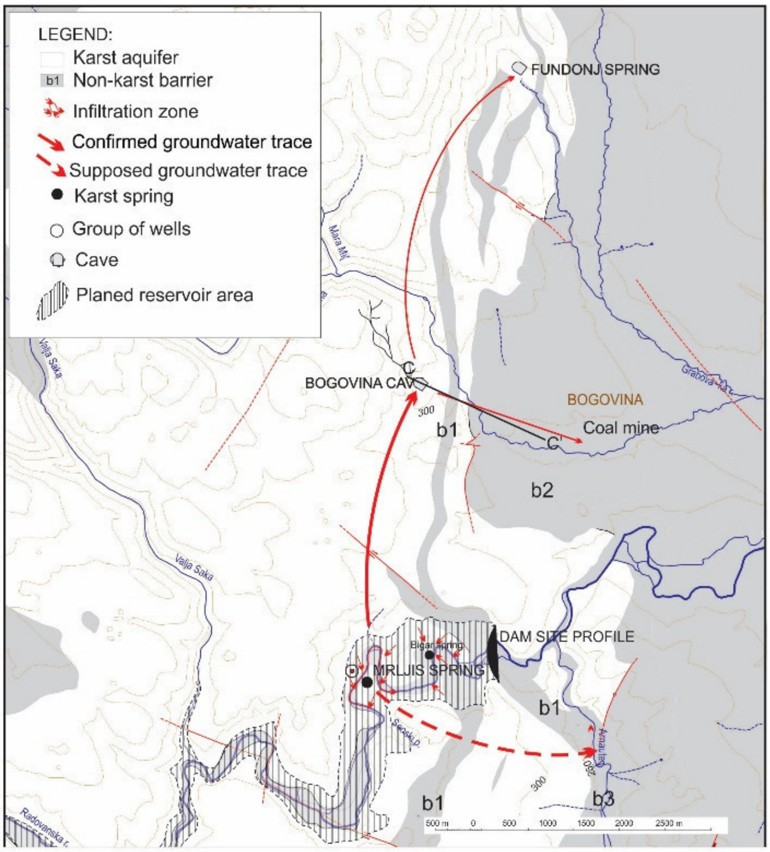

Fig. 2. Hydrogeological scheme of the "Bogovina" reservoir wider area

The "Stubo-Rovni" Case Example

The "Stubo-Rovni" dam (western Serbia) was completed in 2010. It is planned for it to form a lake of 50 million m^3in the valley of the Jablanica River and its tributary Sušica (Fig.3), with the maximum water level of 360 m.a.s.l and the minimum of 310 m.a.s.l[8]. The primary purpose of the dam is the municipal and technical water supply of the Kolubara District.

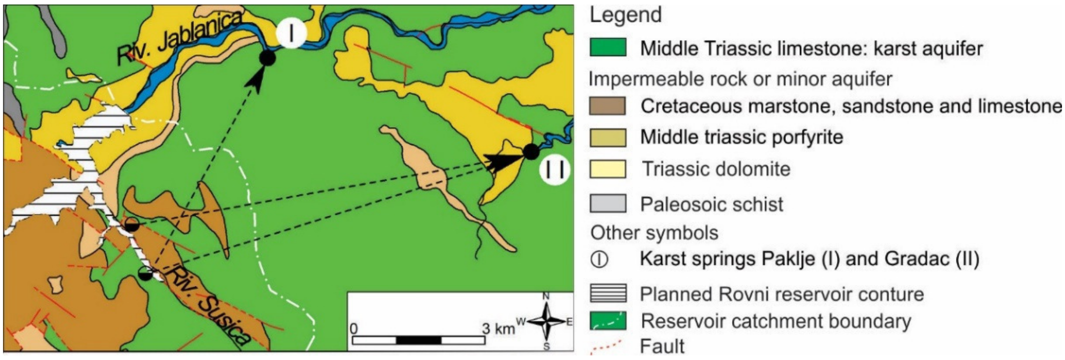

Fig. 3. Hydrogeological scheme of the "Stubo Rovni" area [9-modified]

The reservoir is positioned at the western rim of the "Lelić karst" area, and it is planned to flood the Sušica valley (canyon), formed in highly karstified Triassic limestone (Fig. 3). The average flow rate of the Sušica River is very low, and the riverbed frequently dries out during the summer seasons. Several characteristic karst features (ponors, periodical and permanent karst springs) have been observed in the Sušica valley. Tracing tests have proven that Cretaceous flysch does not create a complete barrier to groundwater outflow to the Paklje and Gradac springs [10], outside the lake catchment (Fig.3). These two springs are the major drainage points of the Lelić karst aquifer. The higher lake level in the Sušica valley will intensify the underground outflow. According to the dimensions of ponors, the swallow capacity is estimated at hundreds of litres/second, while the average river flow of Jablanica (1967-2007) at the dam profile is 1.37 m^3/s [8]. The lowest boundary between impermeable Cretaceous flysch and Triassic karstified limestone (Fig. 3), in the Sušica valley,is at the altitude of 330 m.a.s.l. Therefore, a recommended solution is that the highest lake level does not exceed 330 m.a.s.l.

The "Arilje-Svračkovo" Case Example

The "Arilje" dam will be built at the profile "Svračkovo" of the river Veliki Rzav (western Serbia). It is planned to form a lake of 20 million m^3, with a maximum water level of 420 m.a.s.l [11].
The terrain of the wider zone is composed mostly of Middle Triassic karstified limestone (Fig.4).

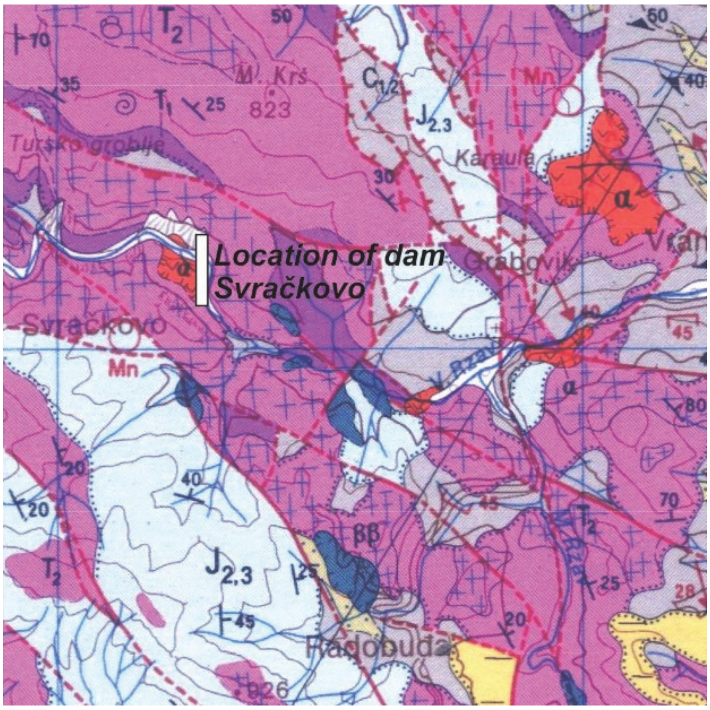

Fig. 4. (Hydro)geological map of the wider zone of Arilje dam
Legend: Water permeable rock/deposit: T_2 – Middle Triassic karstified limestone; al, s: Quarternary deposits: alluvial; Impermeable rock or minor aquifer: $J_{2,3}$-Jurassic diabase-cherts formation; ββ-Jurassic diabase α-Middle Triassic porphyrite; T_1-Lower Triassic sandstone, marlstone and limestone; $C_{1,2}$-Carbon metamorphized sandstone and conglomerate

At the dam section, the bottom and the sides of the Veliki Rzav valley are built of the Lower Triassic karstified limestone and, in the higher parts, of (relatively) impermeable riolites of the Middle Triassic and (relatively) impermeable rocks of the Lower Triassic and Carboniferous (Fig.5).Numerous open and filled (with clay material) caverns were identified by drilling holes along the dam section up to the depth of about 100 m. Several packer tests have shown that the permeability of karstified limestone is large to very large. Upstream of the dam profile, the majority of the karst springs are registered on the left side of the Veliki Rzav valley, at the altitudes above 420 m.a.s.l., outside the hydraulic influence of the planned reservoir. The construction of the dam would commence assuming that most of the water losses at the dam section can be prevented and reduced to a minimum with adequate sealing works, and that there is no risk of outflow from the catchment through the reservoir bottom and banks.
It is certain that there will be no significant groundwater outflows through the left bank of the reservoir, due to the Lower Triassic groundwater barrier (Fig. 4), and that is why most of the karst springs are registered at higher altitudes.

However, given the continuity of karstified limestone spreading along the right valley side (Fig. 4), the risk of underground losses through the bottom and the right bank of the future lake should not be excluded. Currently, there is insufficient data for a more detailed assessment of this risk. Simultaneous hydrometry of the Veliki Rzav streamflow in successive sections upstream and downstream of the dam profile, as well as observation of discharges of registered karst springs downstream the dam site, are recommended before any further construction work takes place.

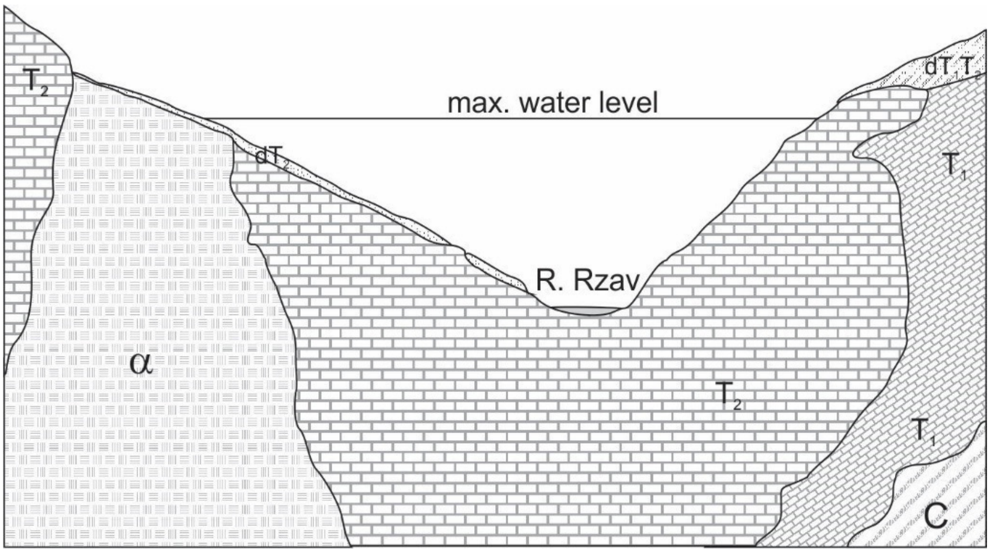

Fig. 5. Schematised geological profile of the dam site
Legend: Water permeable rock/deposit: T_2 – Middle Triassic karstified limestone (karst aquifer); Impermeable rock or minor aquifer: α-Middle Triassic porphyrite; T_1-Lower Triassic sandstone, marlstone and limestone; C-Carbon methamorphised sandstone and conglomerate; Max. water level in planned reservoir

Conclusions

A brief analysis of the construction risks for three planned or partially completed lake-reservoirs confirms the complexity of building such reservoirs in highly permeable karstic terrains. Each of the cases features specific geological and hydrogeological properties of the terrain, and, therefore, specific mechanisms of (potential) water losses under conditions of significantly altered hydraulic properties of karst aquifers. Evaluated case examples certainly confirm that the construction of dams and reservoirs should be adapted to local hydrogeological circumstances, for instance by decreasing the height of the dam and by reducing the reservoir size. Potentially high risks of water losses could also be reduced by performing adetailed hydrogeological research in the early stages of the project preparation,in order to timely take into account all the aspects of the site selection risk and the risks in the exploitation phase.

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TIME SERIES FOR IMPACT ANALYSIS OF GROUT CURTAIN ON HYDRAULIC BEHAVIOR IN KARST

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Abstract: The construction of grout curtain in the karst is a very common procedure to reduce water losses from a reservoir. Based on long-term monitoring, and by application of nonparametric correlation and rescaled partial sums - RAPS, water table fluctuations were analyzed to obtain general trend and relation between piezometer at the immediate zone of grout curtain. Short-term, but very frequent monitoring of water table in the reservoir (SWT) and in seven piezometers, provides considerably better insight into hydraulic behavior in karstic media. By separating the rising limb from the recession limb on hydrographs and presenting on correlograms of adjacent piezometers (in front and behind of the grout curtain), hysteresis loops were analyzed. A different shape of hysteresis can be used for interpretation of hydraulic behavior in karst media and functioning of the barrier. Application of this procedure was applied on case example of Prevoj (Lazići) dam at the grout curtain located on the left bank.

Key words: Long and short-term time series, grout curtain, hysteresis, hydraulic behavior in karst

Introduction

A grout curtain should be sufficiently impermeable and possible a rise of the gradient of leaking water through the grout curtain, increases the possibility of its failure (Milanovic 2004). Analysis of the hydraulic behavior in karst and functioning of grout curtain presents an important task for every dam and surface reservoir constructed in karstified rock. Monitoring of water losses based on long-term as well as on short-term monitored data, represents an important part of controlling seepage through grout curtain. By characterizing of hydraulic mechanism and focusing to the specific zone of a hydraulic barrier, issuing the underlying support for timely reaction and cost-effective sealing measures.

Study area

By the construction of embankment dam at the riverbed of Beli Rzav, of low hydropower potential, formed surface water reservoir Lazići, for reversible hydro-power plant (RHPP). This is accomplished by pumping water from Drina River to the Lazići reservoir, upward more than 600 m. Total reservoir volume is 170x10^6 m^3, and minimal and maximal operation levels are 815 and 881.5 masl. consequently. Embankment dam is 130 m high (881 masl) from Beli Rzav river bed and consists of two rockfill dams with impermeable core – Prevoj (316 m long) and Kanjon (218 m long) with emergency spillway in between built in rock mass, 400 m long. To reduce uplift forces in dam foundation and in the body of the dam, two drainage galleries were constructed. Grout curtain below the Prevoj dam is about 30 m deep, and water leaking is very noticeable on the left bank of Prevoj dam. Therefore 109 m long grout curtain was additionally built through the gallery (at the 883.2 masl) inside in the rock mass, from 843.20 masl to 803.8 masl. Initially, well grouting space was every 2 m, but supplementary density increased to 0.5 m in some part. At the present condition, water leakage reaches the amount of 200 l.s^{-1}, at the maximum operating level of water in the reservoir. On the left bank of the Prevoj dam, in Cretaceous limestone and marly limestone, six piezometers were constructed in the narrow zone of the grout curtain, and one piezometer is located on the side of reservoir about 100 m away, and about 300 m in front of the grout curtain, to represent state of groundwater (period of recession). In addition to the above, two drainage galleries (G1 and G2) were also included in the program of monitoring (Fig. 1). Since that this reservoir was built for RHPP, fluctuations of the water table in the reservoir are very pronounced, and not necessarily related to the water-season. Therefore, short-term but frequent monitoring is very instructive.

On the basis of preliminary hydrochemical analyses, the TDS (total dissolved solids) values ranged from 250 to 586 mg.l^{-1} for selected piezometers and water from the reservoir. The lowest value comes from the reservoir water and was used as starting point for comparison with other samples. Ca-HCO_3 was the dominant water type, showing the strong influence of carbonate rock, with an exception for Na-HCO_3 observed in piezometer P-2, indicating the different conditions of groundwater circulation.

Long-term time series analysis

According to the long-term measurements of the water table, with an irregular interval from 2005-2015., Spearman rank order correlations were used to explore interrelation of surface water table (SWT), selected pairs of piezometers (P-1 to P-4) and two drainage galleries (G-1and G-2). Piezometers P-5 and P-6 were constructed recently, in 2015.

Correlation analysis shows a very strong connection between SWT and galleries, as well as piezometers at the dam side (Tab. 1). Adjacent piezometers P-3 and P-4 show very strong correlation indicating a possible hydraulic connection. But correlation solely is not a regnant factor for estimating certain connection. This could be a case where the degree of sealing in the vertical sense is not the same, so we could have unsealed gaps, and correlation coefficient will not be so highly significant.

Fig. 1. Detail map of the left bank of Prevoj dam; P-1 to P-6 monitoring wells inside the gallery, inclined 12º in front and back of the Lazići reservoir

Tab. 1. Spearman rank order correlations; marked are significant at p<0.05

	P-1	P-2	P-3	P-4	G-1	G-2	P [mm]
SWT	0.666	0.380	0.691	0.545	0.932	0.946	-0.064
P-1		0.453	0.750	0.676	0.573	0.607	-0.114
P-2			0.548	0.568	0.351	0.344	0.009
P-3				0.836	0.672	0.634	-0.113
P-4					0.504	0.492	-0.115
G-1						0.925	-0.086
G-2							-0.048

Long-term time series analysis provides possibility to quantify trends and fluctuation records. Rescaled adjustment partial sums (RAPS) represents a suitable method for determination changes, whether they are natural or artificial (Bonacci 2007). Analysis of adjacent piezometers in the zone of grout curtain shows a different behavior. SWT in the reservoir is characterized by the same sub-horizontal trend as observed in P-2 (behind of the grout curtain) and P-3 (in the front of the grout curtain), while the trendline for piezometers P-1 and P-4 shows a trend of rising water level. This can be interpreted as a gradual loss of function of hydraulic barrier in the zone representing by piezometers P-3 and P-4 (Fig. 2). The upward trend in P-2 can be interpreted as impulse response from the different zone (eg. P-3 and P-4).

Short-term time series analysis

To inspect hydraulic functioning of grout curtain in detail, frequent monitoring was performed from 5th August 2015 to 27th October, at the level of every five minutes. During this period about 24000 logs were collected. Monitoring program included SWT in the reservoir and seven piezometers: three sets of piezometers in the narrow zone of grout curtain (P-1 to P-6) and additional one, situated on the side of the reservoir (P-7). This piezometer was used as representative observation point for state of groundwater, showing period of recession and low influence of SWT in the reservoir.

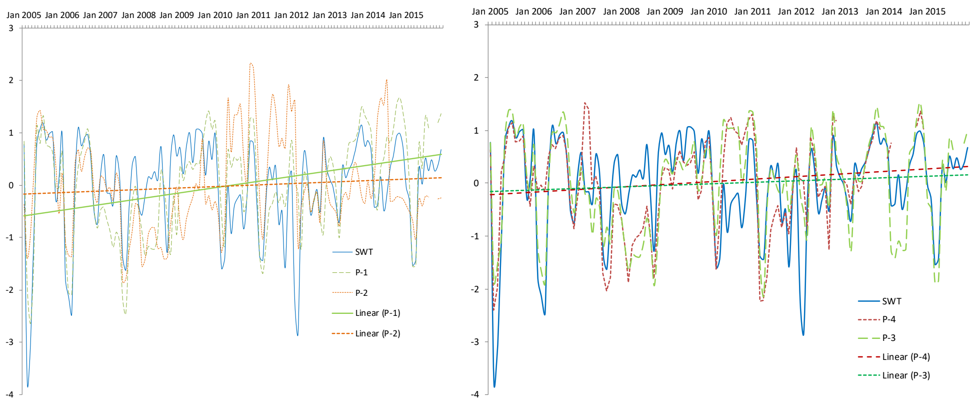

Fig. 2. RAPS analysis of mean monthly SWT in reservoir and adjacent piezometers P-1, P-2 (left); P-3, P-4 (right) in the zone of the grout curtain

The hydrograph for most of the piezometers was below the SWT and ranged of about 12 m (for P-1) to 23 m (for P-2), except for P-6, only during the short period of low level in the reservoir, and for P-5 which was constantly above the SWT (Fig. 3). Both (P-5 and P-6), were located deeply in the rock mass, at the end of the gallery. By comparing on the rescaled hydrograph of piezometers P-7 and P-5, it is clearly noticeable recession period of natural state of the groundwater on P-7. The recession of natural state of the groundwater also has influence at the piezometer P-5 in front of grout curtain (Fig. 4, on the left). By comparing the piezometers P-5 and P-6 on the rescaled histogram, peak delay on P-5 relative to P-6 suggest that leakage from reservoir probably does not come from this zone and presents an impulse response of leakage from neighboring zone (P-3 and P-4) (Fig. 4, on the right).

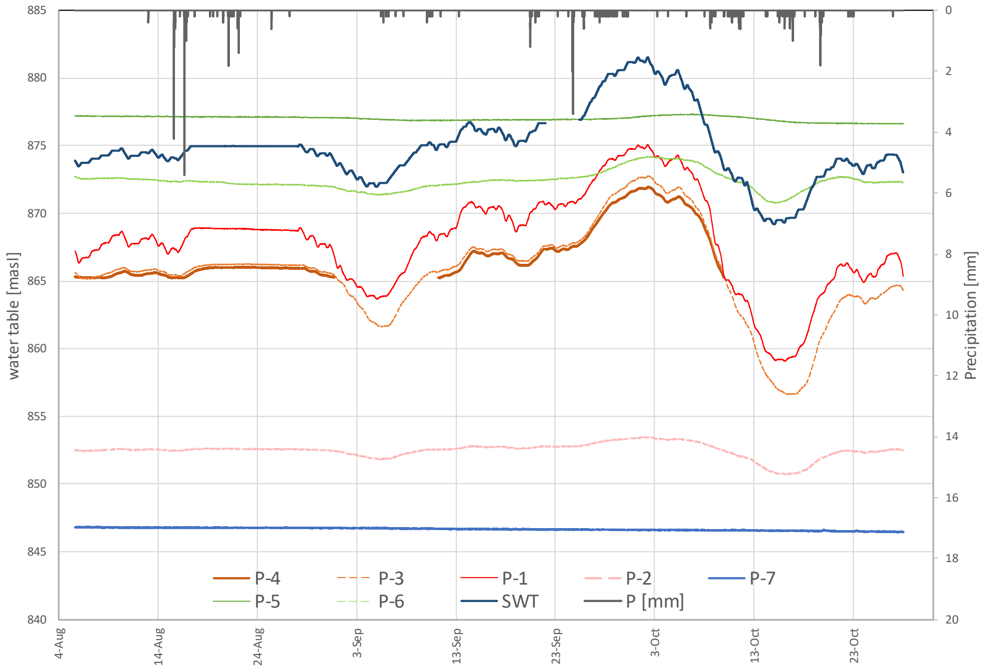

Fig. 3. Hydrographs of surface water table in reservoir (SWT) and analyzed piezometers P-1 to P-7

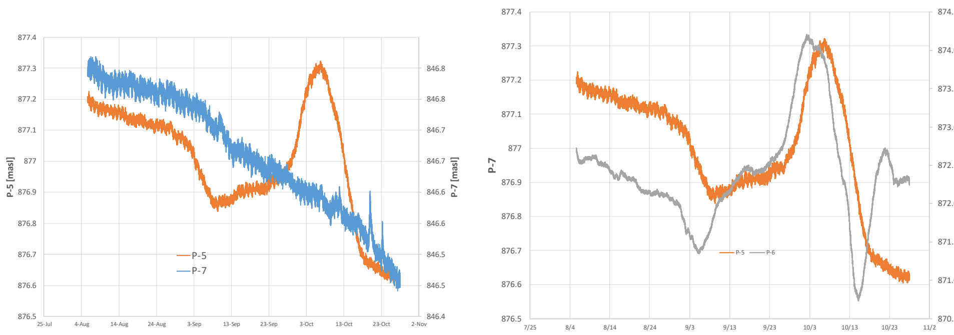

Fig. 4. Hydrographs of observed pairs of piezometers P-7 and P-5 (on the left), P-5 and P-6 (on the right) presented on different vertical axis

The correlograms of the adjacent of piezometers (in front vs. behind grout curtain) and SWT vs. piezometers on the side of the reservoir, shows nonlinearity. Based on the loop of the hysteresis, it is possible to analyze the hydraulic behavior of adjacent piezometers and estimate condition of the hydraulic barrier. Similarly, when it comes to Lugeon test (Houlsby 1976), according to the shape of the loop it is possible to define the type of flow regime. Consequently, in the grout curtain like in rock masses, the hydraulic conductivity (leaking) depends on apertures and infilling characteristics (Goodman 1980). By separating of the rising limb (marked as – *up* on graphs) from the recession limb (marked as – *down* on graphs) hysteresis loops are formed. The obtained scatterplots indicate significant differences in the hydraulic behavior between adjacent piezometers in the narrow zone of the grout curtain (Fig. 5, on the left). Hysteresis phenomenon is more obvious with the distance from the reservoir, deeply in the rock mass, as the consequences of the complexity of flow process in karstic media as well as the existence of two interrelated flow regimes (from the reservoir water and from groundwater – Fig. 5, on the right):

- The correlogram P-1 vs. P-2 (A), shows not so intense relation as observed from the relation SWT vs. P-1 (B), but it follows the same shape. This relation (B) showing laminar to transitional turbulent regime with pressure increment, so that the upper parts of the rock mass are more karstified. Considering that, it can be concluded that hydraulic barrier is fully functional, with possible seepage below the barrier. Prelaminar chemical analyses from the P-2, also confirm this case.
- Scatterplot of water table P-3 vs. P-4 (C) showed as straight line, representing a consequence of seepage through the barrier with the strictly laminar flow. This hydraulic behavior leads to gradual flushing grouting material, already indicated based on long-term time series. The correlation of the SWT vs. P-3 (D) shows more complex relation as consequence of less karstified marly limestones, and the possible existence of joints with infillings of low permeable materials.
- The correlogram of water table for pair P-5 vs. P-6, located deeply in the rock mass, expresses the all complexity of interrelation of groundwater and reservoir water (E). The complexity of mechanism of matrix flow and channel flow is presented in relation SWT vs. P-5.

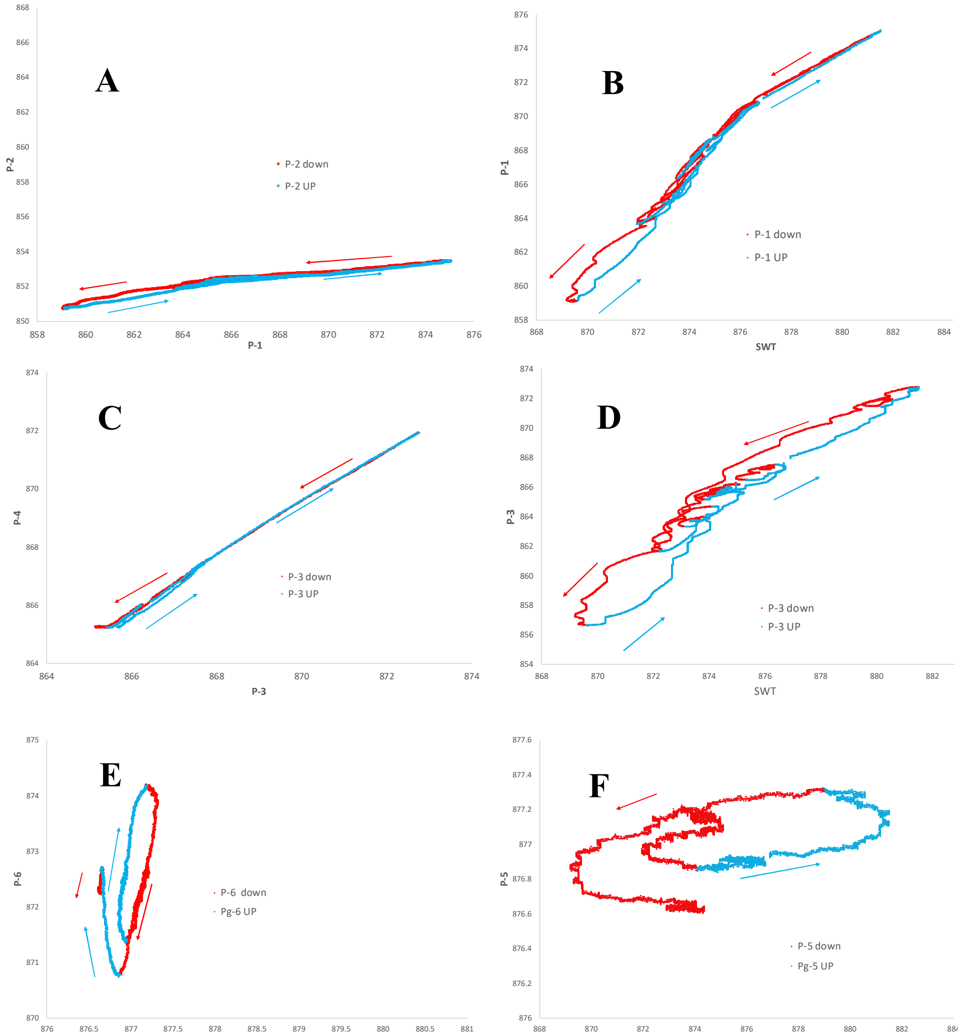

Fig. 5. Hysteresis of the simultaneous 5min values of water table in adjacent piezometers P-1 to P-6 (on the left), and SWT vs. piezometers, on the side of the reservoir (on the right)

Conclusion

The role of the grout curtain in karst aquifer hydraulic behavior presents a very important task in the dam stability and leaking process. Monitoring program, based on long-term and short-term but frequent observations, provides a quality basis for characterization of leaking process. Moreover, the applied analysis of the time series provides the possibility of focusing on the specific zone within the grout curtain.

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THE EXPERIENCE OF THE DAM CONSTRUCTION ON GYPSUM-BEARING ROCKS (IN THE TERRITORY OF THE FORMER USSR)

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Abstract: The article is devoted to the experience of dam construction, at the base of which there are gypsum-bearing rocks. In the world there are about 70 similar dams, of which about 15 - on the territory of the former USSR. The description of the Kama hydroelectric power station (HPP), the Mingechaur HPP, the Yerevan HPP, the Baypazinsk HPP are given.

Key words: gypsum karst, dam, the Kama HPP, the Mingechaur HPP, the Yerevan HPP, the Baypazinsk HPP

The presence of soluble rocks, such as gypsum and rock-salt, in the foundations of hydraulic structures cause engineering geological conditions that are difficult and unfavorable for safe construction (Cooper, 2013; Ford, 1989).
On the globe, karstic rocks are widely developed and occupy a tenth of the land area (51 million km^2).

In the former USSR, the total area of gypsum-bearing rock extends to about 5 million km^2 (Gorbunova, 1977). Hydrotechnical construction in such soluble rock regions can create conditions of enhanced dissolution and karst development that can threaten the structures. Throughout the world there are examples where the dissolution of gypsum in dam foundations have resulted in tragic consequences. The failure of the St. Francis dam in California, USA, is one catastrophic example where 400 people perished as a result. Numerous problems are associated with dams on gypsum, these include settlement, cracking and seepage with the constant threat of failure or expensive remediation. For example, in the vicinity of Basel, on the Birs River, the dissolution of gypsum beds in the dam foundation caused settlement and cracking. Settlement was also observed on the San Fernando, Olive Hills, and Rattlesnake dams in California. Loss of water from reservoirs on gypsiferous rocks is common and seepages through the dam foundations were recorded on the Osa River (Angara basin), in Oklahoma and New Mexico (USA). Seepage and gypsum dissolution causes cavities to form and these features have been found in the foundations of the Hondo, Maximilian, and Red Rock dams, along with a dam in the Caverly valley, Oklahoma. Gypsum also occurs in the foundations of the San Loran dam in Catalonia, Poecos dam in Peru, and a number of dams in Iraq (James 1978; James, 1980).

In a number of cases, the presence of gypsiferous rocks resulted in the rejection of the dam site for construction, an example being the Saint Baume dam in Provence, which was found to be on gypsiferous marls. Surveys for the Rian dam in the vicinity of Alter Stolberg, south of Harz, stopped after gypsum was discovered in the foundation zone. Gypsum has been proved in the foundations of more than 50 dams and rock salt, which is more soluble, has been found in the foundations of others including the Rogunsk and Nureksk dams on the Vahsh River in Tajikistan (Maximovich, 2006; Milanovic. 2000; Molokov, 1981).

In the world, there are about 70 (operating, unfinished, destroyed) dams on gypsum-bearing rocks, of which 15 – on the territory of Russia and the former CIS countries (Table 1). In the territory under consideration, the Cambrian and Lower Permian gypsum-bearing formations occupy the largest area.

***Table** 1 – Dams on gypsum-bearing grounds in the territory of Russia and the former CIS countries*

The name of the dam	Country	Operate (+)/ doesn't operate
The Kama dam	Russia	+
The Mingechaur dam	Azerbaijan	+
The Erevan dam	Armenia	+
The Tbilisi dam	Georgia	+
The Baipazinsk dam	Tajikistan	+
The Nureksk dam	Tajikistan	+
The Sangtuda dam	Tajikistan	
The Farhad dam	Uzbekistan	+
The Bratsk dam	Russia	+
The dam on the Osa River	Russia	+
The Rogunsk dam	Tajikistan	the construction is underway
The Irganay dam	Russia	not completed
The Lower-Kafirnigan dam	Tajikistan	not built
The dam on the Iren' river	Russia	not built
The Cheboksary dam	Russia	not built

Consider the experience of building some of them and the methods used to protect them from destruction.

The Kama hydroelectric power station (HPP) on the Kama River (Russia). The karstic gypsum-anhydrite and limestone-dolomite rocks include in the zone of influence of the structure. The karst processes were activated after the creation of the reservoir (fig. 1) (Maximovich, 2006; 2009).

The rocks of the base of the HPP have an uneven vertical plastering. In the sulfate-carbonate stratum, as a whole, an increase in the content of calcium sulphate down the section is observed (Kuznetsov, 1947). The rocks in the section of the dam section are characterized by heterogeneous fracturing.

In the design of the Kama HPP as a protection of gypsum-bearing rocks from dissolution, it was expedient to create a waterproof canopy in the upper pool with a length of 110 m, a cementing curtain at the beginning of the draining and vertical deep drainage in its middle, but in the process of work the created curtain could not provide the design value of the head, defined in 27%. With time, the veil lost its effectiveness.

To compact the cement slurry, a gel-forming oxaloaluminosilicate solution was proposed. The use of a silicate solution for tamponizing fractured soils at the base of the dam in domestic practice was carried out for the first time (Buchatsky, 1976, Voronkevich, 1976). Tamponage effect of this solution is achieved due to the formation of a gel from a colloidal solution after its introduction into the array by injection.

The densification, begun in the end of 1974, underwent a channel part of the cement mill with a length of 465 m. Two side curtains with the length of 100 m each were created. Thus, the curtain has a U-shape. As a result, the magnitude of the pressure drops on the veil in the Shemsha and Upper Solikamsk aquifers increased significantly. This led to a decrease in the filtration pressure on the base of the hydraulic structure and, correspondingly, an increase in the stability factor of the dam on the shear (Maksimovich, 1983).

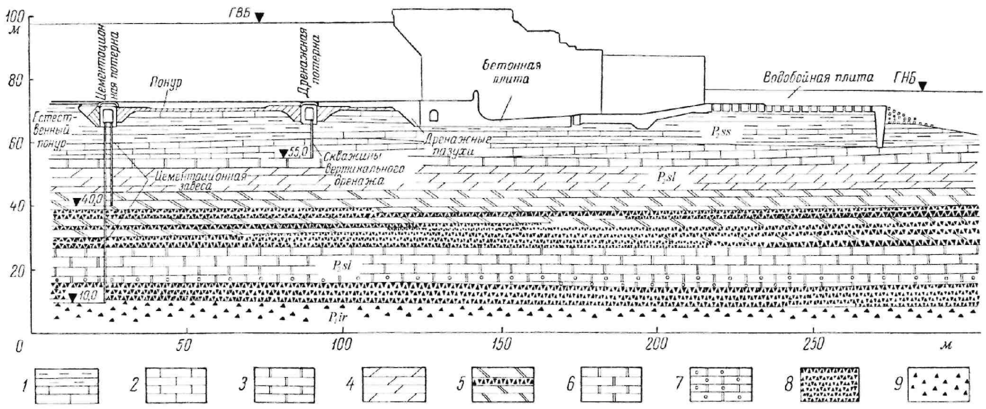

Figure 1 - Geological section of the base of the Kama HPP (Maximovich, 2006). P_2ss Sheshminsky horizon: 1 mudstone, siltstone with interbeds of limestone; P_2sol Solikamsky horizon: 2 limestones, 3 dolomites, 4 marls, 5 marls and dolomites with interlayers and gypsum lenses, 6 dolomites, 7 dolomites clay; Pir irenskiy horizon: 8 gypsum, 9 anhydrite

Thus, the example of the Kama HPP shows that careful geological studies, regime observations and a complex of engineering and geological measures to increase the rock stability allow successfully operating pressure hydraulic structures in the areas of distribution of sulfate rocks for a long time (Maksimovich & Meshcheryakova, 2017).

The Mingechaur HPP on the Kura River (Azerbaijan) (fig. 2) (Geology…, 1959). The valley of the Kura River is embedded in the deposits of the Apsheron stage, characterized by the development of weathering cracks, mainly uncovered, including crystals and veins of secondary gypsum.

In order to increase the stability of the slope, it was drained by a number of almost horizontal wells drilled from the excavation to the clay layer, and also to prevent the waterlogging of sandstones, they were shielded on both sides by a special cementing curtain on the drained area.

Fears of the possibility of development in the rocks of the base of processes of dissolution and suffusion determined the design of the anti-filtration curtain. Due to the high aggressiveness of groundwater in relation to cement, prevailing in the thickness of closed cracks, and among open - filled with loose material, a bitumen emulsion was used to install the veil. In order to prevent the latter being washed out on separate sections, the bitumen curtain is supplemented with cementitious curtain.

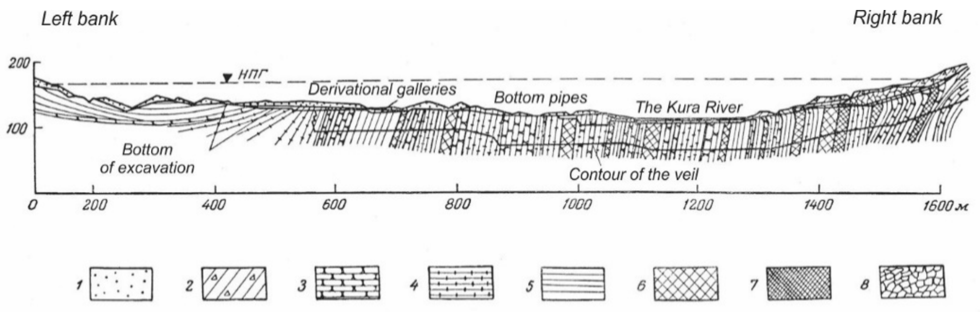

Figure 2 - Geological section along the axis of the Mingechaur HPP (Geology…, 1959) Quaternary deposits: 1 - alluvial loams, gravel pebbles and sand, deluvial and proluvial-deluvial loams; 2 - fragments of bedrock with loamy aggregate (landslide soils). Absheron deposits: 3 - silty sandstone; 4 - sandstone-clayey silt; 5 - silty clay; 6 - intermittency of powerful words of sandstones, clays, aleurites; 7 - intermittency of low-power layers of sandstones, clays, silts; 8 - tectonic breccia

The Yerevan HPP on the Hrazdan River (Armenia) with gypsum-bearing clays at the base (fig. 3). In deeper horizons there are gypsum strata with a thickness of up to 10-15 m. The total thickness of the gypsum-bearing strata is 300 m. On the site of the dam, the upper layers of the gypsum-bearing strata lie directly in the riverbed.

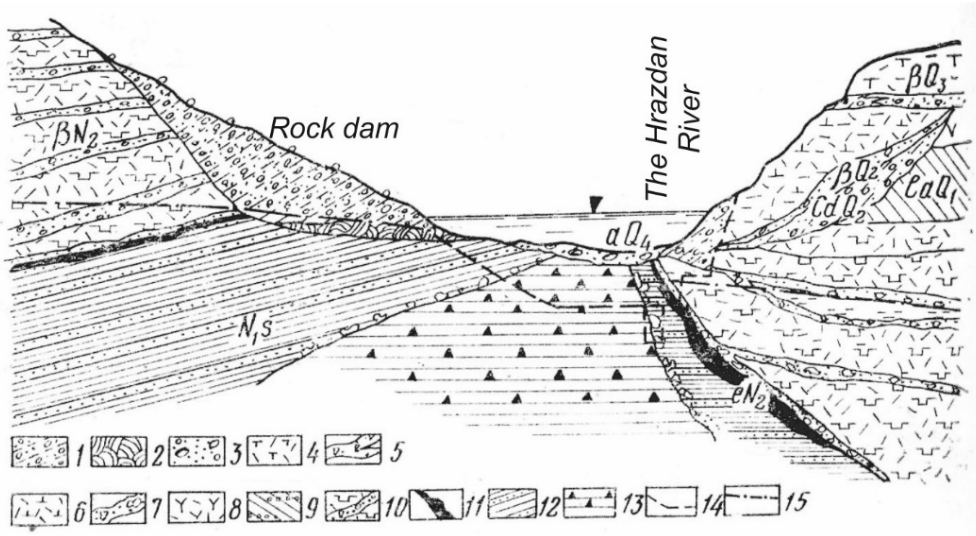

Figure 3 - Geological section of the Yerevan Dam section (Lykoshin, 1992)
1 - fragments of basalts with loam and sandy loam; 2 ancient landslide formations; 3 - boulder-pebble deposits of the riverbed. Hrazdan; 4, 6, 8, 10 - basalts; 5- boulder-pebble deposits with fragments of basalts; 7 - basalt slags; 9 - lacustrine-alluvial deposits; 11 - clays red-brown; 12 - clays calcareous, partially gypsum; 13 - clays calcareous, strongly plastered; 14 - sole of a concrete pile tooth; 15 - groundwater level before the construction of a hydroelectric power station

As protective measures, a curtain at the base of the dam is arranged by the shock-mechanical method (the Ikos-Feder method). At the base of the dam, a deep borobeton tooth is created, mating with the frontal and airborne cement curtains in the fissile basalts of the right bank. Within the layer of gypsum slabs, which in the underworld of the valley has a thickness of 6 m and steeply falls deep into the right bank, the concrete-pile tooth reached a depth of 30-40 m. After 40 years of operation, no deformations of the dam and associated structures were recorded (Geology…, 1959; Lykoshin, 1992).

The Baypazinsk HPP on the Vakhsh River (Tajikistan). The geological structure, in which the Cretaceous, Paleogene and Quaternary deposits take part, is characterized by a significant karst of carbonate rocks and the presence of gypsum under pressure structures (fig. 4). The thickness of individual gypsum interlayers varies from a few cm to 2-3 m (Lykoshin, 1992).

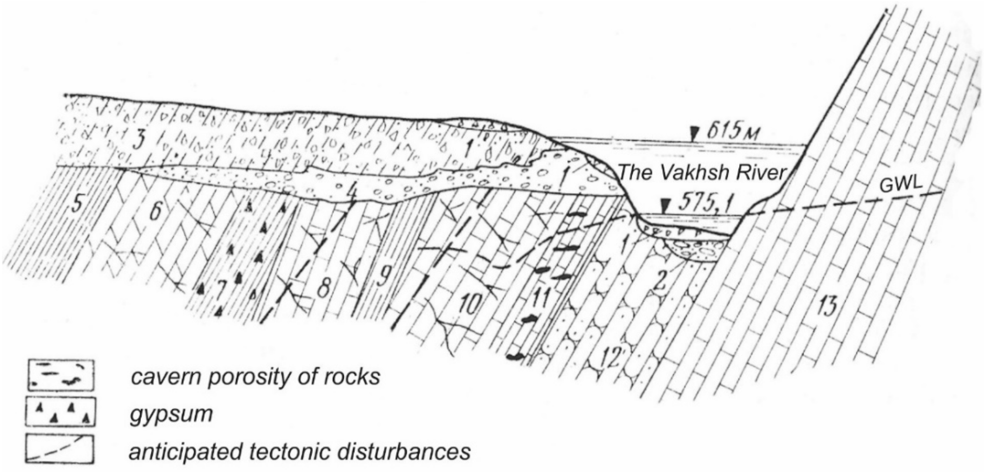

Figure 4 - Geological and lithological section of the Baipazinsk hydroelectric station (Lykoshin, 1992)
1 - bulk ground; 2 - alluvium; 3 - deluvial-proluvial deposits; 4 - proluvial-deluvial deposits; 5 - Turkestan clays; 6 - Upper Alayan; 7 - Middle Alayan; 8 - Lower Alayan; 9 - Suzak clays, Bukhara limestones: 10 - upper pack, 11 - lower pack; 12 - Adzhar sandstones; 13 - Maastricht limestones

From the side of the upper slope of the dam and in the channel of the river there is an anti-filtration screen and a drain. The same screen is made on the slopes of the left and right banks, on the section between the dam and the tunnel in order to reduce the filtration in the body, the base and bypassing the dam, as well as the proper coupling of the dam to the banks. The anti-filtration spillway devices are implemented in the form of a concrete drain before the weir, an anti-filtration curtain under the concrete threshold of the weir and mating walls, anti-filtration spurs in the areas of shore adjacencies, drainage under the drains and drainage in the rapid flow zone. Observations have shown that, due to the adopted design and silting of the reservoir, the hydrounit for filtration and deformation of structures is in favorable conditions.

The above examples show that the presence of soluble rocks and the development of karst processes in the area of pressure hydraulic structures creates serious problems in their operation, significantly increases the cost of construction and repair, and in some cases can lead to accidents and destruction of the dam, which is accompanied by human casualties. Practice shows that the cost of repair works related to the development of karst processes can be comparable with the cost of the structure (Maksimovich et al, 2017).

Note that the obvious mistakes in the exploration, design, operation and organization of observations are repeated year after year for a long time. This is largely due to the fact that by now the experience of dam construction on soluble rocks has not been generalized, there are no clear methodological approaches to the quantitative assessment of karst processes in the dam impact zone.

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EVALUATION OF EVAPORITE KARSTIC CHALLENGE IN GOTVAND DAM RESERVOIR

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Abstract

Upper Gotvand Dam &Hydropower plant is located near to the city of Gotvand in Khuzestan Province of Iran. This dam is the most downstream reservoir dam with total volume of 5 billion cubic meters constructed on the Karun River. The main objectives of this dam are to generate hydroelectric energy, control flood and supply of drinking, agricultural and industrial water. 4.5 km apart from the dam axis on the left bank, there is a formation so called Gachsaran that contains thick and karstified sequences of evaporative formation. Given that a significant portion of this mass was going to be submerged being below the normal water level of the dam following the impounding, many studies were conducted on the dissolution, water escape and the change in reservoir upcoming water quality. The studies began with geological and water quality disciplines and continued with physical and numerical modeling of the dam reservoir. Accordingly, the impounding and then powerplant operation have been planned and carried out so that quality of water of the reservoir and downstream is acceptable. Thereafter, the water quality has been monitored in regular intervals both in the reservoir and the downstream discharge. The results show that the operational scenarios have been successful.

Key words: Gachsaran formation, dissolution, dam reservoir, water quality

1 - Introduction

The presence of soluble formations such as gypsum and salt in the dams' reservoir can cause several impacts among which the change in the water quality is the most important one. Resevoir water tightening can be severely vulnerable because of dissolution and the creation of a karstic environment. Addressing such a serious problem is very difficult because similar cases have been either rarely reported or have had disappointing results.

Upper Gotvand Dam is a tangible and successful case, which, despite the big problem of soluble formations including salt in its reservoir, was constructed and impounded. This paper aims to describe all measures such as technical studies and remedials, taken to minimize any negative influence on the water quality.

2 – Technical Studies

Geographical Location and Weather

Upper Gotvand Dam is located in the north of Khuzestan province of Iran and near Gotvand city. With a height of 185 m, this dam is the highest earth fill dam in the Middle East. It was constructed on the Karun River which is the largest river of Iran with an average annual discharge of 12 billion cubic meters. This dam is the most downstream reservoir dam constructed on the Karun River. The study area is located at the beginning of the mountainous area of Khuzestan province. The lowest and highest temperatures in summer and winter are 50°C and-1°C respectively. The average precipitation in the Karun basin is about 750 mm per annum.

Geology

Gotvand Dam reservoir is located in folded zone of Zagros range which is elongated located from the southwest of Iran to the north with a width of 150 to 250 km. It has an almost northwest - southeast trend, in which the Paleozoic, Mesozoic and Tertiary sediments over laid with the same dip. In the early Permian, Zagros was covered with continental evaporative deposits, followed by limy sediments associated with shallow seabed together with shale and logon to middle Triassic facies.

The geological formations existing in Gotvand reservoir, ordered from the old to the recent ages, are Gachsaran-Mishan, Aghajari and Bakhtiari. Gachsaran Formation, well known due to Gachsaran Oil Field, has rarely been studied on account of its gypsum-salt nature created as a result of the high deformation and high inter-strata movement of anhydrite and salts. Aghajari Formation in terms of lithology is composed of brown to gypsum limy sandstone, veins of gypsum of reddish marlstone and siltstone. Grayish marlstone and limestone of Mishan Formation are located in the lower contact of Aghajari Formation with gradual conformable boundary. Unconformable Bakhtiari Formation is observed in the upper contact of Aghajari Formation. Bakhtiyari Formation comprises limy conglomerate containing chert with sandstone existing alternately between them (see Fig. 1).

Anbal salt area is a part of the Gachsaran Formation located 4.5 km in the upstream direction of the dam axis. It is bounded by the Karun River in the north and west and by the valleys in the south and east. There are two salt mines within this area. This area is surrounded by Mishan Formation. Mishan Formation consists of colored marlstone and limestone. This area has more than hundreds of sinkholes some of which with over 50 m in diameter and over 80 m in depth (Fig. 2)

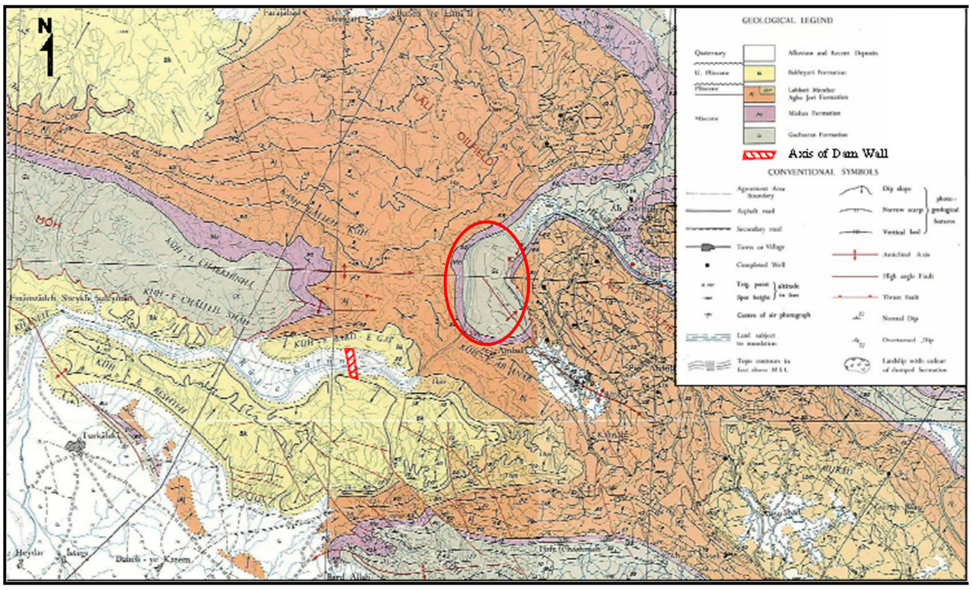

Fig. 1. Geological map of study area

There have been performed geotechnical studies, exploratory borehole drilling, field and laboratory tests as well as landslide studies on this area. Besides, geophysical investigations have been carried out using geo-electric, seismic reflection, GPR, and micro-gravimetric methods.
In addition, water quality tests and salt dissolution rate assessment have widely been carried out applying different methods.

Fig. 2. L: Halite strata near Karun river; R: Sinkhole in Anbal area

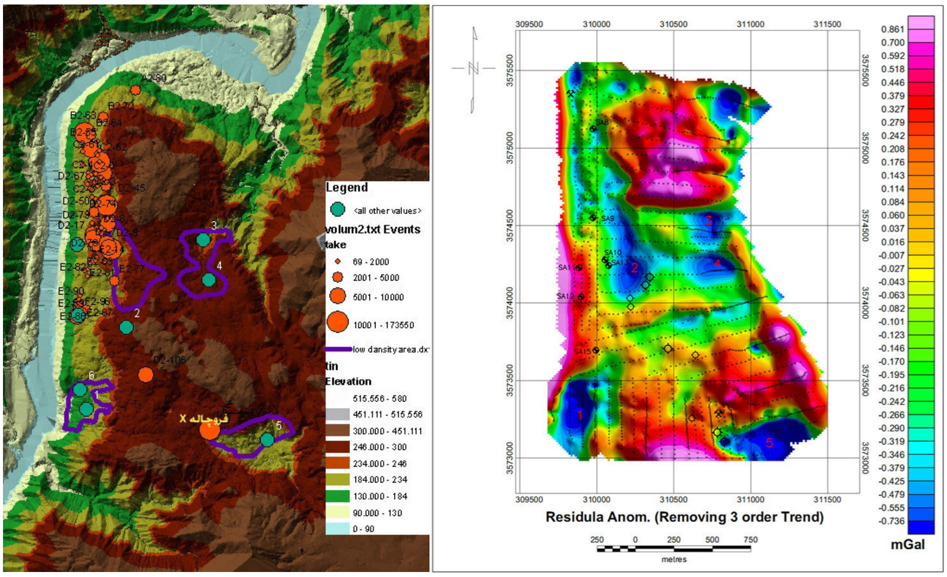

Fig. 3. L: The elevation model of the area on which the results of filling the sinkholes are drawn; R: The geophysical results applying microgravity method -The blue parts show the low-density areas, and the reddish colors are the highest in the order of magnitude, respectively. Low-density areas can be related to karstic spaces,

Salt Volume

One of the most effective factor on our studies was estimation of the salt volume. To this end, the salt outcrops that had been observable from the north to the south in the different elevations from 110 and to 200 m a.s.l. with a slope ranging between 40 to 50 degrees toward the abutment, were accurately mapped on the 1/2000 topographical drawings and then they were integrated with the results of exploratory boreholes and the salt Percentage existing therein. A maximum of 17% of the entire area has been considered as salt. Lastly the salt volume was modified using Petrel and Arc GIS software and estimated about 61 million cubic meters.

Chemical analyses and calculation of dissolution rate

The water samples were taken from the boreholes, river and other water sources such as springs and streams of the area and chemically analyzed. A model was used so as to calculate the amount of ion introduced through the Gachsaran Formation to the reservoir applying Phreeqc software. Unfortunately, due to the wide range of ions concentration in the boreholes' water, the accurate results were not possible to obtain. In order to estimate the salt dissolution rate, different laboratorial models were applied (see Table 1).

Table (1): Methods and results of various tests of dissolution rate

Specifications Method	Dissolution rate (cm / h)	Remarks
Full dissolution	1.25	Assuming complete dissolution of the materials involved with slipping
Indices tests	1	Assuming the samples are open on the flank
Flow circulation	0.85	Assuming velocities of about cm / 1
Model 1: 200	3	By installing appropriate indicators in the model
Dissolution of hidden salts in the karstic cavities	0.25	Using the flow circulation method with zero velocity - using special tests for dissolution cavities

Study and modeling the reservoir water quality

At Firstly, the water quality was analyzed along the river at different sections. Then, the reservoir quality modeling was performed using two software programs of C-Equal-W and Mike11 software. These numerical studies were carried out for several scenarios consisting of different rates of dissolution, different reservoir impoundment conditions and water velocities, and the various combinations of the discharge gates of powerhouse, spillway or bottom outlet.

The final results of all models can be summarized as follow.
-The prediction of water salinity in the case of no remedial action can be hazardous and critical during the first year.
- An oversaturated layer will be formed in the bottom of the reservoir.
- Dissolution rate is the most impressive agent on the water condition.
- If the dissolution rate increases, the first year of impoundment will be more critical.

Therefore, it was decided the remedial measures to be taken to reduce the dissolution rate.

3 .Constructional remedies

Construction remedies were defined in a package including: a) Modification and covering the slopes along the river. - Different materials such as geomembranes, nano, water tightening oil derivatives and clay have been considered to cover the slopes and efficiency of each one was examined in the reservoir physical model (on the scale of 1:200) that was constructed at the job site. Finally, a clay cover with average thickness of 25 meters and a riprap protection layer were selected and implemented.

b) Filling the sinkholes- About 123 sinkholes existing on surface of the area were filled with the mixture of clay slurry and water (totally 555,000 cubic meters), (Fig. 3L).
c) Adding a shaft gate on the bottom outlet tunnel and a discharge pipe in the bottom of the reservoir to prepare sufficient flexibility for dam operation considering the reservoir stratification (Fig. 4)

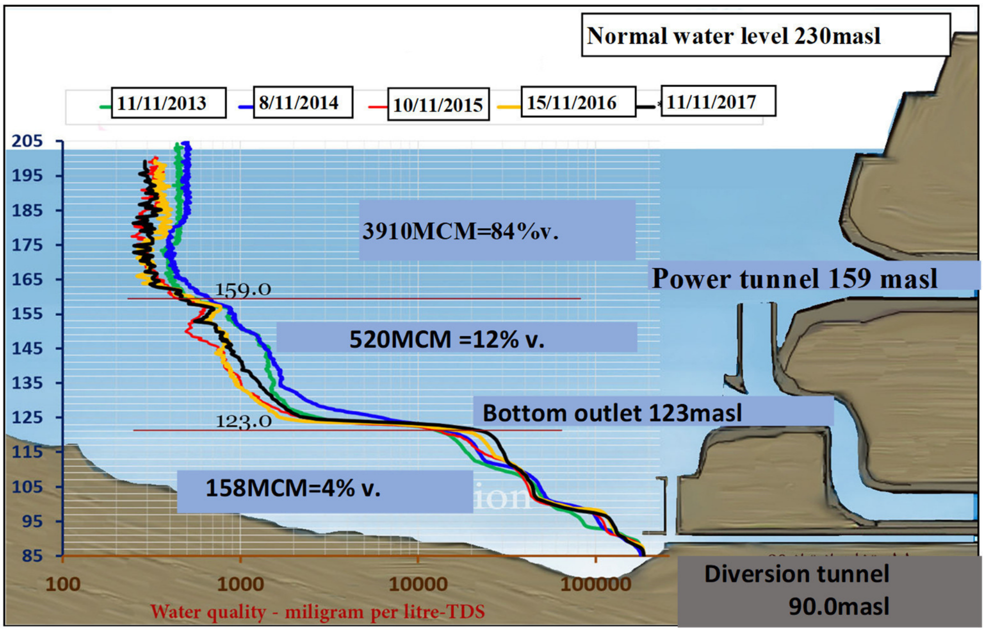

Fig. 4. The salinity variations of the reservoir relative to the depth in different years, Different levels of access to reservoir water.

4. Results of water quality and current condition of Gotvand Dam reservoir

Gotvand dam was impounded in 2012. The reservoir has daily been monitored since the beginning of the impounding till now using an automatic profiling data logger buoy. This instrument records the parameters of depth, salinity, temperature, oxygen, turbidity, and gives online reports. According to these results, operational scenarios have been applied taking water with particular discharge from each dam outlet such as the powerhouse, bottom outlet tunnel and bottom pipe so that the overall quality of the dam out flow is always kept in a admissible range.
Figure 4 shows the salinity variations of the reservoir relative to the depth in different years. As seen in this figure, the reservoir stratification has clearly been formed and the reservoir water quality has been improved in the recent year.

With regard to the solutions and predictions made during the years after the impoundment, the river water quality has had no meaningful change at the downstream area (Fig 5).

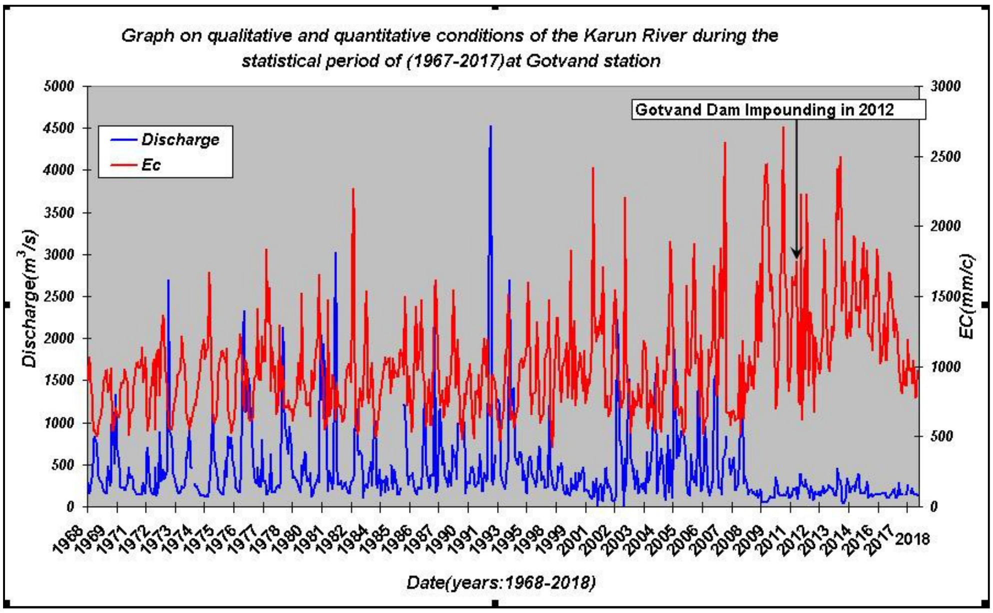

Fig. 5. Water quality and quantity at the downstream (Gotvand station) during statistical period (1967-2017)

5. Landslide

There has been reportedly no massive landslide in the area till now. Furthermore, reservoir hydrography was done twice in 2014 and 2018. Results of 2014 depicted gradual settlements in this formation. Nevertheless, no serious landslide was observed. New results are going to be available in the new future.

6. Conclusion

The salinity problem was thoroughly investigated. The relevant solutions have been successful and quality conditions of outflow have been acceptable. The salts dissolved from Gachsaran Formation have been accumulated at the bottom of the Reservoir. Under different situations such as earthquake, climate change and long term presence of the high saturated water trapped in the bottom of the reservoir, behavior of the dam and other structures should be investigated in the future and the risk management program should be updated accordingly.

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HYDROGEOLOGICAL CHARACTERISTICS OF KARST AQUIFER UNDER THE CONDITIONS OF RESERVOIR AND DAM UTILIZATION - EXAMPLE OF BILECKA RESERVOIR (TREBINJE, BOSNIA AND HERZEGOVINA)

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Abstract The results of multiannual observation of groundwater fluctuations of a wider area of Bilecka reservoir (Trebinje, B&H) indicate that there is a good hydraulic connection of the reservoir and a part of the karst aquifer of the reservoir right side. In some further parts of the right side of the aquifer, due to complex lithostratigraphic features and tectonic composition, the influence of the reservoir is changeable, so hydrogeological and hydrodynamic characteristics of how this aquifer part functions, have not been clearly studied up to now. On the basis of some earlier data, when the reservoir level is lower than 360 metres of altitude, there can be a change of the natural condition in that aquifer part as well. Because of this, as well as due to the fact that the theory on the circulation of water from the Orah zone (the right bank of the accumulation) to the identified karst springs on lower positions has not been either dismissed or approved, one should bear in mind the possibility of occasional local change of hydrodynamic conditions when the water levels in the reservoir are different. The studies presented in this work have been conducted with the aim of providing additional and clearer explanations of how the karst aquifer functions under different conditions determined by the levels of the surface waters of the reservoir and the levels of groundwaters of the examined karst aquifer.

Key words: karst, reservoir, tracert test, GWL

Introduction

Even though there have been some complex and expensive researches in karstic areas (carried out for the sake of building a dam and reservoirs) which have been executed for a number of years, all with a view to sustainable use of the water potential of karstic areas, it is often possible that some amounts of water get lost through the sides of the accumulation or under the body of the dam, which means that the purpose of the project is called into question along with the sustainable use of these waters (Therond, 1972; Zogovic, 1980; Milanovic P, 2000; Bruce, 2003; Turkmen, 2003; Ford and Williams 2007; Fazeli, 2007; Bonacci 2008, Milanovic S., 2015). These are the exact issues which have accentuated the need for constant monitoring of the groundwaters of a karst aquifer in the conditions of the regular reservoir function as well as taking precautions regarding potential occurrences of the water loss.

In the course of the last sixty years, some of the most comprehensive and most complex researches have been executed for the sake of the sustainable use of the waters of karst areas (both ground and surface waters) within the project of Trebišnjica Hydrosystem which is situated in the very heart of the typical karst Dinaric Alps of eastern Herzegovina. Numerous problems and even some failures when realizing similar projects all over the world have indicated the complexity and risk involved in undertaking The Trebišnjica Hydrosystem project in the area which is well-known as the world's most distinguished and famous karst phenomenon (Milanovic, P. 2006). Alongside the constant maintenance and examination of the functionality of the already built facilities (dams, reservoirs, tunnels, etc.), today the works on constructing the final part of this huge system, that is The Upper Horizons, are also under way.

This paper also shows a part of the research which refers to defining the possible water losses out of the right side of the Bilecka reservoir along with the hydrodynamic characteristics of groundwater and the influence of the surface waters on the karts aquifer. A special attention is paid to the site of Orah where the only collapses within the reservoir space have been registered which automatically means potential spots of the water loss from the reservoir banks. Likewise, the new research (partially presented in this work) also needed to confirm and prove the role of the dolomite anticline as well as regional hydrogeological barriers and the effect it has on the water-bearing qualities of the right side of the Bilecka reservoir. Although the positive influence and function of Lastva anticline has been confirmed in course of a long research period and the process of exploiting the Bilecka reservoir, the karstic springs such as Mlinica and many others (hypsometrically lower by 100 metres than the maximum reservoir level) have never been thoroughly studied before as the zones of potential water drainage which leak out of the Bilecka reservoir nor the collapse zones at the site of Orah and their possible connection.

Geology of the study area and the causes of the problem

The study area is situated in eastern Herzegovina in the very heart of the karstic Dinaric Alps and it occupies the area in between the two reservoirs. The smaller reservoir Gorica was formed by constructing the Gorica dam, whereas the biggest reservoir in the region of Bilecka was formed by constructing the Grancarevo dam. Constructing the Grancarevo dam, the reservoir basin "Bileca" was formed and it is 18 km long while its total volume is 1,277 billion m^3 (Milanovic P., 2006). The position and geological features of the left side of the Bilecka reservoir rule out the danger of losing any water through some rock masses which build up this area unlike the right side which is placed in between the two afore mentioned reservoirs. The terrain where the „Bileca" reservoir was formed consists of the upper-triassic dolomites, limestone and dolomites of all the jurassic sections as well as the limestone and dolomites of the upper-cretaceous period (Natevic, Petrovic, 1964/65) (Figure 1.).

Materials and methods

In order to determine the hydrogeological function of the aquifer of the studied right side of the Bilecka reservoir, that is the karstic springs as potential drainage zones on lower positions as well as their connection with the sinking or collapse zones in Orah, it was necessary to perform a range of specific hydrogeological researches whose goal had been to obtain high-quality data for the sake of defining hydrodynamic behavior of the karst aquifer and the role played by the Lastva dolomite anticline.

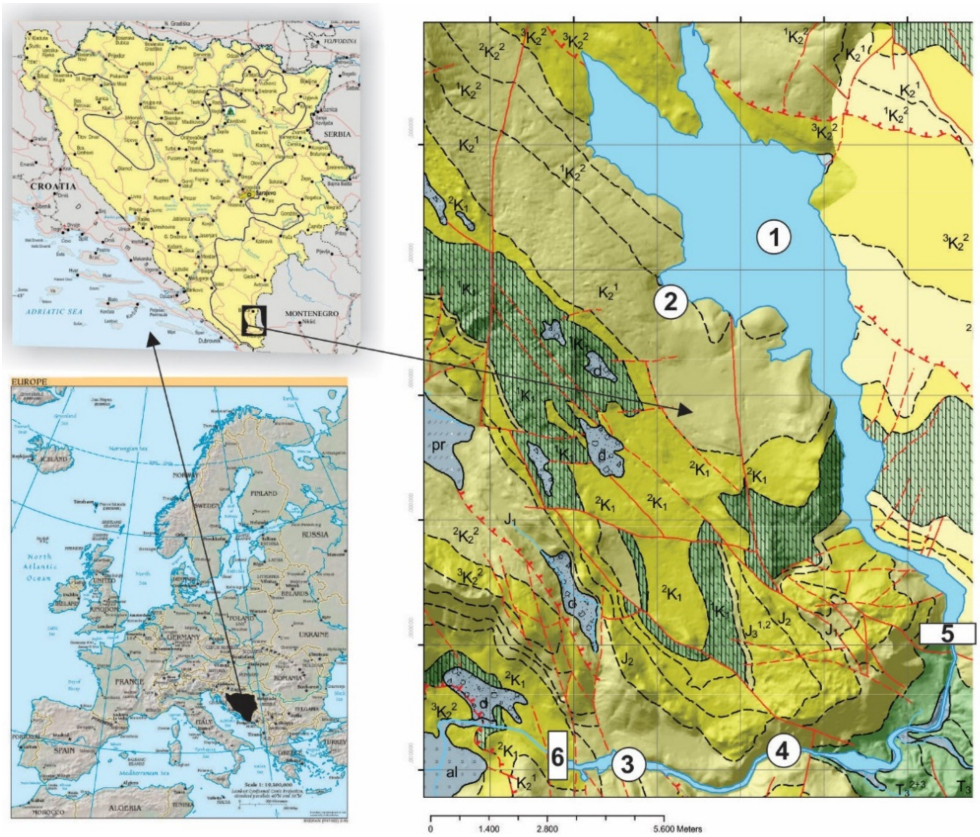

Fig. 1. Geographical position and hydrogeological map (yellow polygons – karst aquifer, green polygons fisured aquifer; 1 – Bileca reservoir, 2 – Orah area, 3 – Gorica reservoir, 4 – Karst spring Mlinica, 5 – Grancarevo dam, 6 – Gorica dam)

The approach to the problem took place through the following three parallel directions:

- Theoretical approach which implied the following: synthesis, classification and analysis of the available fund documents in relation to possible water leaking through the right side of the Bilecka reservoir from the zone of Orah to the spring of Mlinice; synthesis, classification and analysis of the results of monitoring the levels of groundwater in a wider study area as well as the analysis of the influence of the water level of the Bilecka reservoir on the groundwater oscillations; and a design of the 3D model of the groundwater circulation in the study area.
- Detailed and complex terrain researches such as the following: videoendoscopic logging of all the piezometers in the reservoir zone on the right bank side and of all the typical piezometers in the immediate vicinity of the reservoir HPP Gorica as the lowest hypsometric point of all the executed researches; thorough geodetic survey of the study area and a detailed geological and hydrogeological mapping of the terrain; sampling the water from the typical piezometers and springs for providing chemical analyses and isotope analysis; performing comprehensive morphometric, speleological and cave diving researches in the entire study area; monitoring groundwater in the drainage zones by establishing hydrometric profiles as well as monitoring the levels of groundwater on the 12-hour basis; running the tracing test by the application of Na-fluorescein for the sake of defining the groundwater direction within the selected piezometers and collapses in the zone of Orah; formation of a comprehensive monitoring network of the groundwater of a wider area of the Bilecka reservoir and its integration into a regional spatial 3D model of the karst aquifer's.
- Final study phase was reflected in the design of the hydrogeological 3D-oriented model (Milanovic, 2010) on the basis of all the above mentioned studies with the spatial analysis of the karst aquifer’s functioning in different hydrogeological and hydrological situations.

Results and discussion

After gathering and analyzing the existing documentation, a hydrogeological model was formed as a foundation for all the future researches. The monitoring data and database were integrated into this model along with the logging data of 13 piezometers, 6 speleological objects, 3 karstic springs, 14 collapses and all the remaining relevant information gathered in the course of hydrogeological mapping. Into the same model other things were also integrated and these are the data of the time series of monitoring groundwater levels of the selected piezometers as well as the data of the groundwater tracing test, and the data on the oscillations of the water in the Bilecka and Gorica reservoirs.

In terms of their location, all the researches have been split up into three zones: the collapse zone of Orah, the zone in between Orah and the karstic spring of Mlinice, and all the springs on a hypsometrically lower zone.

The zone of Orah, a potential water loss site from the reservoir with the total of 14 registered collapses (Figure 2), was the subject of detailed both morphological and hydro-geological researches and the tracer test with a view to defining a possible connection between the collapse and karstic aquifer on the right side of the reservoir. Altogether, 8 potential collapses were traced in the process of which 8 kilograms of Na-fluorescein were spent. Into each collapse where the tracer was inserted, something in between 20 and 80 m^3 of water was injected (depending on the size of the collapse itself and the quantity of the tracer injected). After infilitrating the tracer, its possible reappearance was monitored in both the reservoir whose level was 277 m a.s.l. due to a drought period and in the nearest piezometers, as well. The result of this test was the following: the tracer reappeared in the reservoir space at a few sites, whereas the tracer was not registered in any of the monitored piezometers. Therefore, one may conclude that under such hydrological conditions (drought period and a low ground level of the water in the reservoir), the hydraulic connection between the zone of Orah and the karstic aquifer of the reservoir right side cannot be realized. Part of the results of this tracer test are shown in Figure 2.

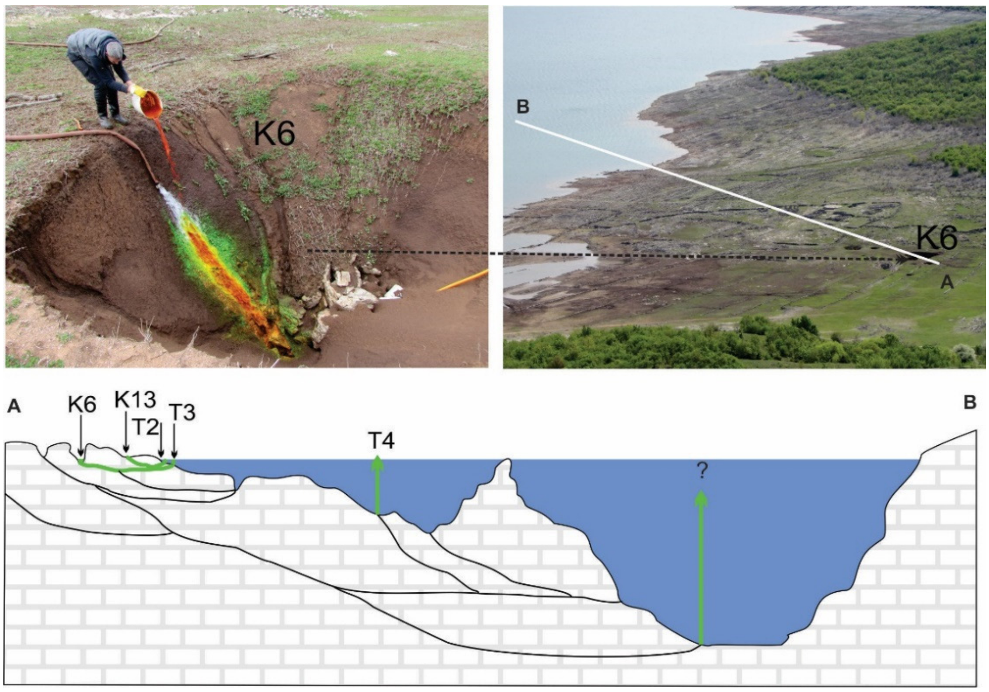

Fig. 2. Results of tracer tests in Orah zone with schematic cross sections

Defining the hydrogeological and hydrodynamic characteristics along the direction from the zone of Orah to the lowest drainage point of this karst aquifer, Mlinica spring, took place in a few phases as it was earlier shown. In the course of mapping, a few speleological objects were identified and examined, as well as the execution of cave diving research of the Mlinica spring, all of which provided an insight into the development and spatial distribution of karst channel of the study area. Over 200 metres of karst channel were examined. In order to define the functioning of the karst aquifer and the hydraulic connection wih the reservoir and downstream drainage zones, a continual monitoring of ground waters in the selected piezometers and in the karstic spring of Mlinica was performed. The monitoring data of groundwater levels and their relation with the precipitation and with water level change in the reservoir and the discharge yield of the Mlinica karstic spring are shown in Figure 3.

As one may see from the presented charts, it can be clearly observed that apart from the GWL in piezometer B-3 and piezometer B-9, all the other piezometers have an expressed dependence on the yield of Mlinica spring, oscillations of the water in the reservoir and precipitation. The increase in the groundwater level in piezometers is almost simultaneously accompanied by the increase of Mlinica spring discharge. Likewise, apart from the above mentioned piezometers, there is an almost complete dependence of the water level change in the accumulation on the change of the GWL of the karst aquifer. Piezometer M-4 completely reflects the oscillations of the reservoir water.

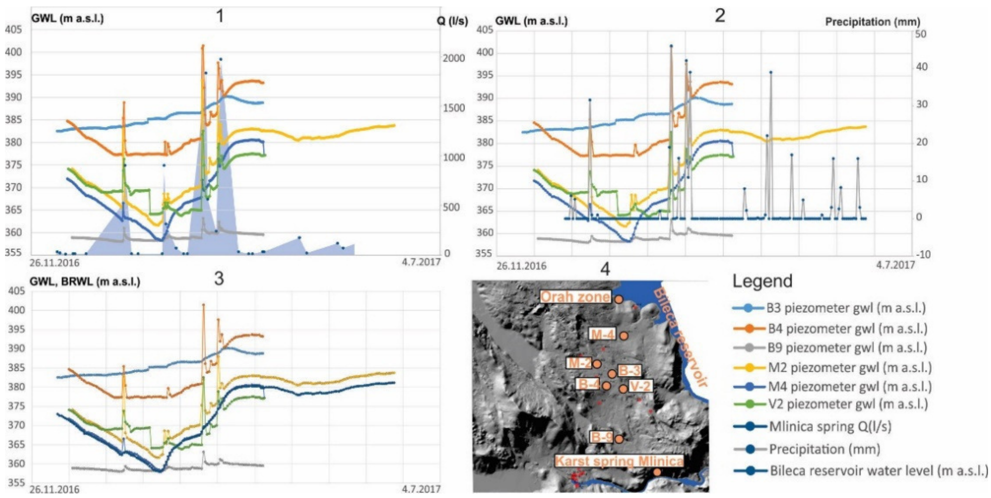

Fig. 3. Comparative diagrams of: 1 – GWL (ground water level) and spring Mlinica discharge, 2 – GWL and precipitation, 3 – GWL and BRWL (Bileca reservoir water level), 4 – Monitoring points

The tracer test for the purpose of defining the movement direction of groundwater of the karst aquifer of the right reservoir side was performed in piezometer B-3 which is the most representative piezometer from the stance of its hydrogeological characteristics and its spatial position. Before the tracer was inserted, the terrain was visited, and zero samples were taken at the sites envisaged in advance, that is at the potential sites of future reappearance of the dye and also the discharge yield at the monitoring spots were measured. The discharged of the most important monitoring spot of Mlinica spring was about 35 l/s at the time of inserting the tracer and from the distance of 7km from the place of inserting the tracer according to the calculations on the basis of certain equations, it was enough to use between 0,5 and 1,2 kg of Na-fluorescein to perform the tracer test. Still, since at the time of performing this tracer test, there were the conditions of recession period and since this was the tracer test performed in a piezometer without a clear finding about the existence of some stronger underground flow, it was decided to carry out the test with 4 kg of Na-fluorescein. After inserting the tracer via a previously set up system, 600 l of water were injected into the piezoemeter together with tracer. Monitoring the appearance of a tracer was done at all the sites of its potential reappearance which were previously determined. Monitoring sites at which the samples were captured for the sake of detecting the tracer are the following: B-4, B-9, M-2, V-2, V-1 as well as at Mlinica spring. In the text down below, there is a figure and diagram of the appearance of tracer concentration at the monitored sites (Figure 4). Apart from the piezometers, the samples were taken at the Mlinica spring where the marker appeared 7 days later in the concentration of 0.72*10-9 mg/l.

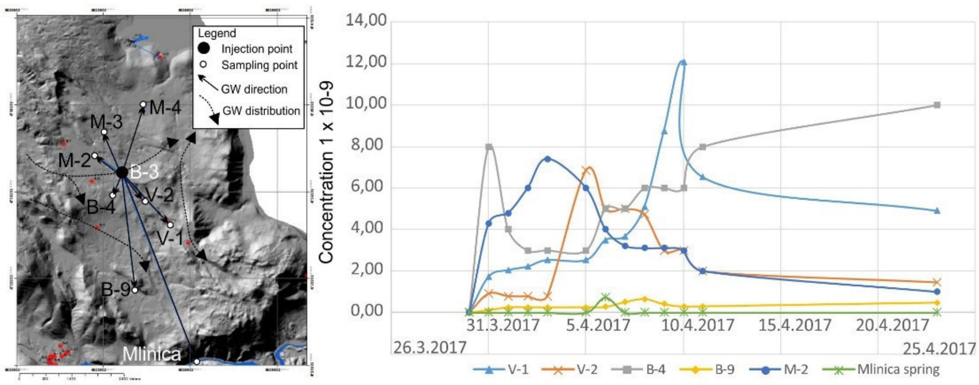

Fig. 4. Groundwater direction and distribution established by tracer tests

Conclusions

The results of the tracer test as well as the results of monitoring both surface and groundwater shown in the previous text clearly indicate the existence of redistribution of the groundwater inside the karst aquifer of the right side of the reservoir. To put it more precisely, they indicate that there is a clear hydraulic connection starting from the zone of Orah to the spring of Mlinica. However, due to complex hydrodynamic conditions of the study area, there can hardly be a case in which the water from the reservoir would firstly recharge the karst aquifer and then circulate towards the lower drainage zones.

On the basis of all the collected and analyzed data and the making of the 3D spatial model as well as the previously examined hydrodynamics of the karst groundwater, what was obtained is a complete spatial model of how the karst aquifer functions under the conditions defined by low and high groundwater levels and low and high levels of the reservoir. Exactly, integrating all the data into a 3D spatial model and their processing, led to obtaining the results according to different types of hydrodynamic conditions which may be found in the karst aquifer and are related to the influence of high or low water of the reservoir. For such a model formation, as the etalon model we used the model of realistic conditions formed in the course of the study, that is from November, 2016 to June, 2017. This one and other similar models of how the karst aquifer functions according to the water level in the reservoir and the groundwater level of the karst aquifer, and for the sake of defining potential water losses from the reservoir, are shown through the following 4 models:

- Model 1 – low levels in the reservoir and low GWL (etalon model-defined during these studies),
- Model 2 – low and medium water levels in the reservoir during the submergence that is high GWL,
- Model 3 – high GWL and maximum water levels in the reservoir,
- Model 4 – high water levels in the reservoir in course of recession period and low GWL, theoretically possible only under specific conditions of the work of the hydro system, reservoir and tunnels of The Upper Horizons (artificial conditions).

The main conclusion which needs to be drawn by a longer range of measuring all the piezometers and the yield of the Mlinica spring on a daily basis is that under normal hydrogeological conditions there is no significant water loss from the reservoir, whereas on the other hand, the aquifer formed in the right side of the reservoir from Orah to Mlinica is in its major part drained at the Mlinica spring and with its smaller part into the Bilecka reservoir.

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OPEN QUESTIONS ON THE IMPLEMENTATION OF ENGINEERING GEOLOGY TECHNIQUES AND METHODS IN KARST

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Abstract: The article deals with some questions remained open as concerns the implementation of techniques and methods of engineering geology to the karst environment. Karst, a fragile environment characterized by significant peculiarities, must be carefully studied and analyzed before applying approaches which, even though valid in other settings, might potentially produce severe problems to the karst landscape and the natural resources therein contained, including the high-quality karst groundwater.

Key words: karst, engineering geology, hazard, groundwater, management

Introduction

Karst is a peculiar environment, different from any other setting on Earth as concerns geology and morphology, and the hydrological and hydrogeological behavior. This is at the origin of the beauty of its surface and underground karst landscapes, but, at the same time, results in extreme fragility, and high vulnerability to pollution. Human activities may have significant effects in karst, producing irreversible changes, eventually causing severe contamination or deterioration and destruction of the natural resources.

Many contrasting forces act in karst. The presence of great quantity of high quality water resources has since a long time attracted man, to exploit groundwater as source of potable water, and for many other purposes, including production of hydro-electric energy. However, when planned without taking into the due account the peculiarity and fragility of karst, engineering works may cause serious negative effects to the environment. This paper summarizes some of the questions still open to engineering geology as concerns the implementation of techniques and methods typically applied in other environments but which have many difficulties in being successfully used in karst terrains.

Living in karst, and engineering geology issues

Many ancient civilizations settled in karst territories, a choice which, beside other logistic considerations, was often dictated by the availability of high quality water, that is, an essential element to found a town. Several examples of important towns supplied by karst springs, or by aqueducts transporting waters tapped at the springs of carbonate mountains, are worldwide known. The importance of water availability and the need to preserve its quality are at the origin of the realization of ancient hydraulic structures underground. Following the lessons learned from very ancient techniques used to build *qanat* in arid and semi-arid lands (English 1968; Lightfoot 1996; Al-Taiee 2012), the Romans were able to realize tens of km-long underground aqueducts, where the choice to keep the hydraulic channels below the ground was dictated by the need: i) to conceal and to protect them from enemies; ii) to protect them from erosion and deterioration; and iii) to be less disruptive to life above ground (Parise et al. 2015a).

Since long times, therefore, in karst contrasting forces are acting: the need to exploit natural resources, and the delicate balance and fragility of the environment. Karst hydrological systems are particularly susceptible to suffer negative effects from human activities and are highly vulnerable to pollution and land-use changes (White 2002). Design and development of engineering projects in karst environments require specific approaches aimed at minimizing the detrimental effects of hazardous processes and environmental problems (Parise et al. 2015b). Professionals and practitioners often simply transfer to karst environments methods and techniques that were thought and initially adopted in other natural settings; in this way, without taking into the due account the peculiarity of karst, many problems may be encountered. Some of these, and the related questions still opened, are dealt with in this article.

On the use of geomechanical classifications of rock masses

Rock masses are anisotropic and discontinuous, due to presence of discontinuity families of different origin: from sin-sedimentary features as bedding planes, to post-depositional joints and faults. When compared to soil mechanics, therefore, a greater complexity of the simulation models for rock masses derives. To this, several other factors must be added, as the landscape changes produced by natural processes, anthropogenic activities, or by a combination of the twos. In consequence of these changes, sensible variations in the rock mass properties and performances might be registered. Complexity of the issue is further increased when dealing with carbonate rock masses, since, beside the aforementioned types of discontinuity, other features are produced by karst processes. Soluble rocks (carbonates, evaporites, etc.), through the action of infiltrating water, and the solution processes acting in the rock mass, are characterized by complex networks of voids and conduits, and by passages of variable size, which may reach dimensions enterable by man (Ford & Williams 2007; Palmer 2007). These features represent definitely the larger discontinuity family within the rock mass, in terms of size, frequency, and pervasiveness, significantly controlling the flow of water, especially during flood periods.

Fragility of karst and high vulnerability of the natural resources therein contained represents a peculiar characteristic that is worth to be faced by means of approaches specifically dedicated to karst, which have necessarily to take into account the presence of typical landforms (voids, conduit/caves of variable size, swallow holes, etc.), and their variable functionality as well (Fookes & Hawkins 1988; Waltham & Fookes 2003; Andriani & Parise 2017). Ignoring karst features in the analysis and characterization of carbonate rock masses, any approach followed, or model implemented, will inevitably result in too great uncertainties (if not errors), and in incorrect information to the engineers. The first question to answer is therefore: given the high complexity of carbonate rock masses, and the difficulties in representing the karst voids, how should we proceed to fully characterize karstified carbonate rock masses?

In practice, what happens is that at the preliminary design stage of engineering works the practical way to analyze rock masses and estimate their strength and deformability is to apply the available rock mass classification systems. Despite the widespread and quite successful use of these classifications for rock support system design for tunnels, dams and other rock works, doubts and/or practical difficulties of application still remain for soluble rock masses interested by karst (Andriani & Parise 2015, 2017). In detail, the role of conduits and caves in diminishing the strength of carbonate rock mass is an issue which has never been taken into account in the available classifications. However, the presence, size and features of karst conduits may play a significant role in influencing the overall behavior of the carbonate rock mass, locally causing a dramatic reduction of the strength, or becoming preferential pathways for the flow of water. It is not easy to include such effects, which analysis ideally requires a thorough knowledge of the geometry, the spatial development and the frequency of the voids. Starting from analogs with cave systems actually surveyed by speleologists might represent a first step in the attempt to characterize the effects of karst conduits.

Problems are not limited, however, to inclusion of karst features in the analysis. Another very important question arises when considering which model to consider in rock mechanics for carbonates: continuous media, equivalent continuous, or discontinuous media? In the continuous model, the rock mass is considered homogeneous and isotropous, practically without any discontinuity. In the equivalent continuous model, the discontinuous medium is assimilated to a continuous medium where the discontinuities control the behavior of the whole rock volume. In the discontinuous model, discontinuities are a crucial part of the geometrical model, and must be taken into account in the analysis for which geological structures control the anisotropy in terms of strength and deformability of the rock masses. Typically, the equivalent continuum approach may be followed for highly degraded, crushed and strongly tectonized carbonate rock masses; in these cases, hypothesis of homogeneity and isotropy in terms of strength and deformability properties could be invoked.

At the same time, the variability in some of the joint features (pervasiveness, aperture, infillings) might cause significant variations in the overall behavior. Even presence of resistant sectors in the rock mass, such as rock bridges, could change the strength and deformability features of the intact rock. Apart from all these theoretical considerations, in the real world, with particular regard to high complexity of karst environments, the presence of cavities, residual deposits, and redeposited calcite partly or totally filling the discontinuities, make extremely difficult the choice to select the most proper approach to be used, and, in turn, the numerical methods most respondent to the physical reality.

Hydrogeology, and aquifer vulnerability maps in karst

The many difficulties any hydrogeologist has to face in karst are summarized by the saying "Expect the unexpected", motto of this congress, which well transfers the unpredictability of many situations in karst terrains. At the same time, the great variety of involved parameters, and heterogeneity of properties, does not mean the impossibility to characterize and model. Nevertheless, dedicated efforts are required in order to increase as much as possible our knowledge. We must be open and flexible to change plans, designs, ideas when new data come out, documenting unpredicted situations.

The high vulnerability of karst aquifers to pollution derives from the direct connection existing in karst between the surface and the subsurface drainage. Any action carried out at the surface may rapidly reach the underground water flow through the networks of interconnected conduits. The high rapidity of transport, combined with the turbulent flow regime, result in poor natural depuration capability, greatly facilitating the fast dispersal of pollutants in the aquifers. Further heterogeneity of karst aquifers is expressed by different behavior in different conditions, with the possibility to move rapidly from laminar to turbulent flow, this latter characterizing the flood periods.

In karst the groundwater level may experience dramatic rise in a short-time lapse in response to recharge events like a rainstorm. When the surface and the underground hydrology have been in some ways altered because of engineering projects and/or urban development, the rise may also appear as unexpected, since it was never registered before at that site. In such situations, the potential risks posed to infrastructures, engineering works, and, in general, to the built up environment, are very difficult to anticipate and manage (Lopez-Chicano et al. 2002; Parise 2003; Bonacci et al. 2006; Bailly-Comte et al. 2008). In the attempt to evaluate these features, a variety of important components for hydrogeological studies must be carried out: mapping structural and stratigraphic units; multi-temporal interpretation of air photos and differential interferograms; geophysical surveys, performed through a combination of different techniques; understanding of the main groundwater characteristics (direction of movement, recharge, discharge, etc.); one-year (at least) monitoring of water-levels; etc.

Excavations, tunneling, mining

Even simply works as excavations in karst may have very dramatic consequences: the reduction in overburden above caves, for instance, might be at the origin of a reduction in the strength of cavity roofs, triggering underground failures which propagation upward might eventually produce a true sinkhole (Waltham et al. 2005; Parise & Gunn 2007). At the surface, the topographic depression created by the excavation may act as a site of infiltration and attract the concentration of runoff during heavy rainstorms.

Among the most common situations, the decline of water table related to groundwater over-exploitation or dewatering for tunneling and mining may enhance the sinkhole hazard, or result in variations in the drainage systems, up to drying out of springs. Encountering unpredicted features as breccia pipes, or water-filled conduits during underground excavations will result in water inrushes and instabilities (Milanovic 2000; Bonetto et al. 2008; Lucha et al. 2008; Zhou & Beck 2011; Palma et al. 2012; Ciantia et al. 2015). The possibility of such situations must be reduced to a minimum through a careful analysis of the characteristics of the carbonate rock mass, with particular regard to the discontinuity systems and their infillings. At this aim, the combination of data from speleological surveys and explorations in the same rock type, and from geophysical surveys, performed whenever possible with combined techniques, may provide useful information to reach a sufficient amount of information for a preliminary characterization of the specific rock mass object of the study. This goal must be pursued in the early stage of the project, to be prepared to any possible circumstance during the later stages.

Modelling often does not take into any account the peculiarity of karst, and the use of models and programs developed for settings highly different from karst is a quite common practice. This represents too much an assumption in karst: models used just for the sake of showing some numerical data and outcomes, besides being not useful, might be very dangerous, too, inducing non technicians (including land managers and decision makers) to take wrong decisions, based upon the fake conviction that we do have a sufficient knowledge of the karst systems. Which, actually, is typically not the case.

Management of karst lands

The direct interaction between surface and subsurface environments in karst is frequently disregarded in land-use planning and development, and result in severe problems with high economic impacts. Karst environments require specific investigation methods to proper manage and safeguard the sensitive geo-ecosystems and natural resources associated with them (Parise et al. 2015b). Management of water resources in karst is problematic due to the great variations in the water reserves and the minimal flow during recession periods (Goldscheider 2005). Waterworks relying on karst waters must therefore face these problems, which are particularly exacerbated in arid or semi-arid climates, characterized by low precipitation and huge evaporation; in these situations, the possibility of aquifer over-exploitation and depletion of non-renewable groundwater resources might be very common. Without specific plans to manage the irrigation, even decisions by individual farmers may lead to severe problems for water reserves. This, for instance, is occurring in several countries, due to massive abstraction of non-renewable fossil groundwater (Stevanovic 2013).

Long return period of extreme events may lead to wrong decision in terms of land management and planning. Any engineering works producing variations in the natural topography and hydraulic pattern, or clogging natural ways of water infiltration in the underground, might radically change the response of the land to heavy rainstorms, resulting in unexpected areas of impoundments and in flooded territories. At the same time, damaging sinkholes are often induced by anthropogenic changes in the karst system (Newton 1987; Beck 2005; Parise 2012, 2015; Song et al. 2012), caused by engineering projects which result in having impacts that were unpredicted, or not evaluated, in the early stages of its design. A checklist of the potential human activities that may accelerate or trigger the formation of sinkholes is presented by Gutierrez et al. (2014).

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ALTERNATIVE SOLUTIONS FOR THE CLOSING OF PONORS IN SLANO RESERVOIR IN THE NIKŠIĆ POLJE

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Abstract: The idea to prevent or reduce seepage from the Slano Reservoir in Nikšićko Polje the exremely karstified and porous zone, the Barovića ponor zone, has to be waterproof by construction of alternative remedial measures instead of grouting technology. Results of grouting technology alone, conventionaly applied, are questionable, better say in so karstified rocks can ending in failure. Based on the newly collected data, long time monitoring and detail analysis the surface waterproofing technology is suggested as the most promissing. Commonly used surface waterproofing includes compacted natural soil, clay layer(s), geomembranes, geosynthetic clay liners, asphaltic screens, shotcrete, reinforced shotcrete, reinforced concrete slabs, different kinds of geotextiles, and grouting carpets. Surface solutions require less financial resources and are the more promising solution. By application some of listed technologies possibility to prevent losses of approximately 0.5 m^3/s from the Slano Reservoir in dry period of year are real. At head of 534 m it is significant increase of power production and benefit for the ''Perućica'' HPP.

Key words: karst, reservoir, ponors, surface remediation, reduction of losses

Previous experiences in the closing of the ponors on the Slano Reservoir

In the Nikšić Polje, large-scale injection works were undertaken in order to create surface reservoir in the classical holokarst environment. In period from 1961 to 1981, the largest grout curtain in Dinarides, (7 km long and max. depth 120 m) was made in order to form the Slano Reservoir ($112x10^6$ m^3). On the Krupac Reservoir, small size grouting works were performed. All of them were successful, and in the Hydro Power System (HPS) of ''Perućica'' HPP since 1960 has significant amount of water for its operation throughout the year. The most important feature of the system is that water from the river and reservoirs in the Nikšićko Polje are used at a head of 545 m. In addition to the two reservoirs, there is the Vrtac retention, which are temporary storage for the waters of the Zeta River. In spite of application of various technologies this storage space has not been achieved to be watertight to until present days.

During the long-term existence of the grout curtain under the dam and along the southern perimeter of the Slano reservoir, they were locally exposed to hydraulic pressures, from both, upstream and downstream direction.

So far, the additional works to improve the Slano grout curtain, in 1988 and in 2010/11, didn't show satisfactory results in some zones, despite of a huge quantitiy of injection material have been used.

Hydrogeological characteristics along the route Orlina - Široka ulica

Previous experiences in remediation of the Slano Reservoir show that the area of the Barovića ponors is a "black hole" and applied grouting does not achieve satisfactory results.

That is why more and more, alternative solutions and procedures for surface remediation are being considered, not only of the Barovića ponors but also for the nearby ponor zones. The idea becomes more realistic because on the route of the Orlina - Široka ulica the injection sections VII/2 and VIII in the length of 300 has never been done. An analysis of the available data and experiences on similar structures in the world shows that surface treatment are economically more acceptable than the re-grouting of the existing grout curtain.

Before taking into consideration the new procedure, a detailed description of the ponors zones will be presented. The following are distinguished: Barovića ponors, Pejovića ponors, Baletića ponors and still not discovered sinking zones.

In the long period of the Slano Reservoir operation the Barovića ponors (Fig. 1) were neglected, although in 1965 measured seepage was Qg=1.90 m^3/s. Only in 1998, the registered and documented losses were Qg=0.3-0.7 m^3/s (Vlahović M, 2003). By constant monitoring it was determined that regime of this zone is sinking only as it is case of the most of the seepage areas along the southern perimeter of the reservoir. The length of the ponor zone is approximately 200 m.

Figure 1. Barovića ponors. Left and middle - Ponor in limestone crack and at contact clay/limestone (Vlahović M, 2003), Right - Sink into one of Pejovića ponors (Energoprojekt-Beograd, 1955)

The Barovića ponor zone should be considered broader, up to the right dam heel. The nearby grout curtain sections over the past 60 years have never been re-grouted. In the west, the Barovića sinking zone is connected to the Pejovića ponors.

Pejović ponors, unlike of Barovića ponors, show some elements of estavelle, as illustrated by the analysis of the Pejovića sinking zone (1983) designer of the grout curtain ''Slano'', Vlahović, V. concluded that *"these ponors have regime of estavelle".*

Possibility of application surface waterproof structures in the Slano Reservoir

Based on field reconnaissance and analysis of the available data, the idea arose that the infiltration zone of Barović and the surrounding ponors can be closed by sealing alluvial ponors and ponors in limestone by surface remedial structures.

Construction of surface waterproofing structures along the route Orlina - Široka ulica (Fig. 2 & 3). On the indicated route, 4 locations of the ponors with typical profiles can be distinguished. These are, from east to west (Fig. 2 & 3) the following locations:

> I - Barovića ponors; II - Pejovića ponors; III - Baletića ponors (The half of grout curtain section VII - is never performed); IV - Ponor-unclear (Injection section VIII - never finalzed as part of the original grout curtain).

Schematic presentation of conceptual model to be applied for surface seepage prevention of Barovića and Pejovića ponors is shown on a typical cross-section through the Barovića ponors (Fig. 4).

For analysis of possible surface technologies for remediation of the ponor zones on the Orlina - Široka ulica route, a brief description of the regime of groundwater outflow at these locations is given:

I. Barovića ponors (606.2-608.8 m above sea level) - Hydrogeological characteristics show that there is no groundwater outflow during the flood water events so the Barovića ponors es are not estavelle. Accordingly, in this zone the surface sealing technology is suggested as promising. This data should be taken into the account during design and construction of technical solution to prevent seepage from the Slano Reservoir.

II. Pejovića ponors (about 602 m above sea level) - According available data there are no indications for discharge, so far. If the idea become acceptable for construction the watertight blanket over the critical zone the hidrogeological character of the Pejovića ponors would be directly determined only when the reservoir is empty. If according an earlier opinion (before grout curtain construction) the Pejovića ponors at extreme hydrologic cases has regime of estavelle, most probably existing grout curtain change its regime. Grout curtain prevents the flow of groundwaters from the south towards them, and today we only have the overflowing and floods in the Pejovića depression.

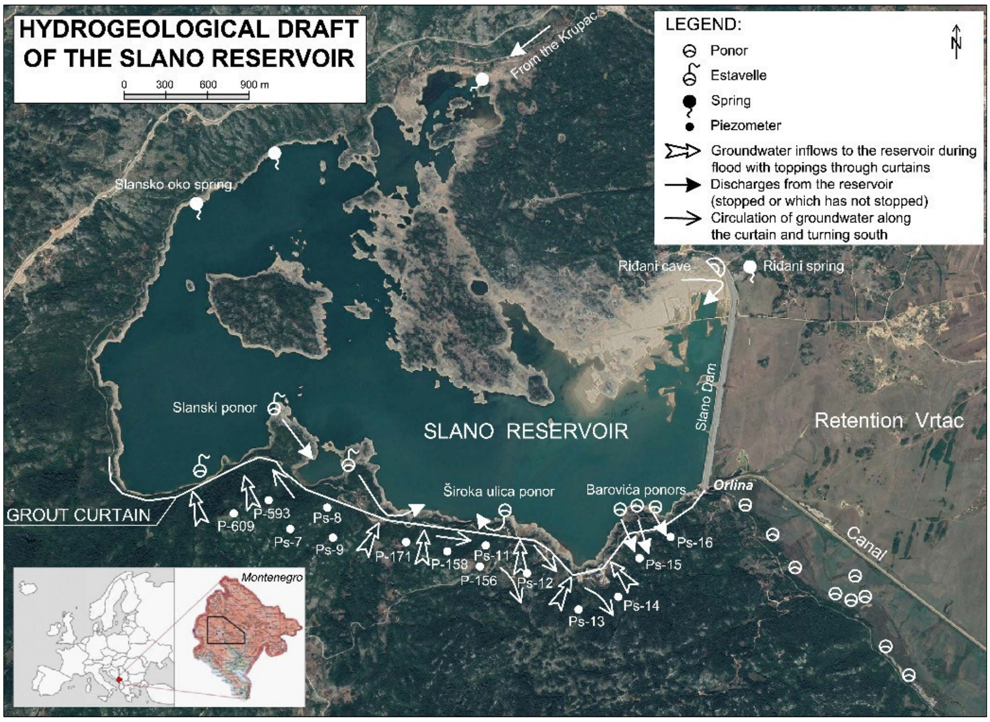

Fig. 2. Hydrogeological draft with directions of groundwater movement after the grout curtain "South perimeter'' on the Slano Reservoir (Vlahović M, et al, 2014 and supplemented)

III. Baletića ponors (612,7-613,6m above sea level) - The small capacity sinking zone is found in cracked and cavernous limestone. The shotcrete is suggested to be applied as remedial measure.

IV. Profile through grout curtain section VIII-This section has never been executed, and on the basis of the karstification limestone and according verbal information by locals, seepage in this zone is probable. In this case the shotcrete technology should be efficient measure on the sides of the reservoir.

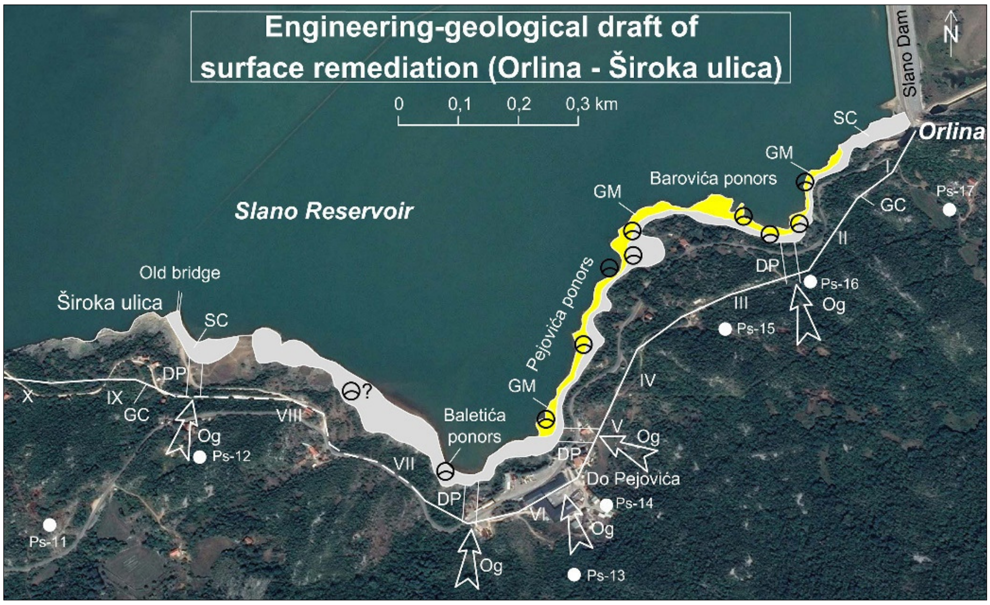

Fig. 3. Engineering-geological draft of the Slano Reservoir with a route for suggested waterproofing works. Legend: See Figures 2 and 4

The optimum condition for the application of different kind of waterproofing blankets is absence of significant groundwater uplift, since the space in the rock massif for the collection of atmospheric and other waters is protected with an existing ground curtain and a surface watertight blanket. Destruction influence of local groundwater and possible uplift pressure will be mitigated or eliminated by construction of efficient drainage system (Fig. 4).

On the basis of the detailed investigation program, a preliminary remediation procedure will be organised.The route in which this procedure would be applied would start from the west towards the east along the following zones: Estavella E ''Široka ulica'' (Old bridge) -Baletića ponor - pending section VII and section VIII - Pejovića ponors - Barovića ponors - Right abutment of the dam Slano in length of approximately 2 km (Fig. 4).

Depending on the geotechnical and hydrogeological characteristics of the storage of Slano reservoir, it is possible to apply surface treatment technologies.

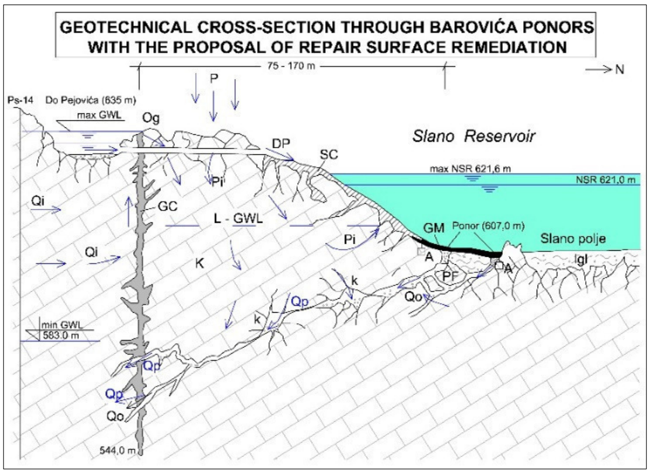

Fig. 4. Typical geotechnical cross-section with possible repair procedure at the location of Barovića ponors.

Legend: Lgl-Limnoglacial clays; K-Cretaceous limestone; k-karst canals; Ps-14-Piezometer; min.GWL-Min. groundwater level; max.GWL-Max. groundwater level; Qi- Inflow to reservoir; Qo- Outflow from reservoir; Og-Overflow groundwater through the grout curtain; P-Precipitation; Pi-Groundwater from precipitation infiltration; L-GWL-Local groundwater level; Qi- Outflow water from precipitation infiltration; NSR 621m-Normal slow of reservoir; max.NSR-max. the achieved level of reservoir; GC-544m-The lowest bottom of grout curtain; SC-Shotcrete; GM-Geosynthetics (geomembrane); PF-Ponor filled with compacted clay; A-Anchors; DP-drainage pipes

In order to design an efficient reservoir waterproofing solution in karstified roks the key requirement is to prevent any hydraulic contact between reservoir water and the karstified limestone at the reservoir banks or at the bedrock contact underneath any alluvial deposits. According experience at number of reservoirs in karst, among the number of waterproofing technologies, the successful surface prevention measures are: shotcrete, different kind of clay blankets, different kind of geomembranas and combination of clay and geomembranas. Of course, large ponors usually situated along the reservoir perimeter needs special treatment before final blanket has to be constructed. General properties of these technologies are presented at a few sentences.

<u>*Shotcrete (SC)*</u> - The most efficient technology to achieve the required level of watertightnes and way to close the permeability zones in karstified reservoir banks is shotcrete. It is applied under pressure to penetrates in fractures, carrens, and cavities. In particular cases it can be used also for dental sealing. In the case of reservoirs with maximum head 10 - 15 m the shotcrete thickness varies between 5 and 12 cm. To prevent the micro-cracks, steel reinforcement meshes (Ø 3 mm) or different fibers are used (Milanović, P. 1999).

The important characteristics of shotcrete in these works are: toughness, tensile strength and low water permeability. The disadvantages of shotcrete occur when cracks and cavities are filled with clay, when the rock is wet and mudy, and when plants and roots are present. Therefore, the rock surfaces are washed with pressurized water, and plants has to be completely removed.

Resistance on strong uplift is low. At sections with strong uplift is necessary to install drainage system including pipes Ø 200 - 500 mm to reduce the uplift pressure.

Compacted clay blanket (CC)- The clayey blankets usually consists of one or two compacted clay layers with a drainage system beneath the blanket. In the case of Slano Reservoir the compacted clayey blanket should be applied locally as part of ponor zones blanketing (together with geomembrane) and ponor plugging as final layer, also, together with geomembrane.

The individual alluvial ponors at Barović area are situated along the reservoir perimeter at a length of about 200 m. Alluvial ponors occur in alluvial sediments deposited above the karstified limestone. As a rule, the bottom of channel in the clayey/sandy sediments is connected with karst channels in the rock (Fig 1). After dental filling, there and the surrounding terrain are protected with compacted clay material. The procedure is performed on alluvial ponors around limestone humps not far from the reservoir perimeter.

The funnel like alluvial ponors should be filled by the principle of "reverse filter". At the bottom, the layers of broken stone, whose fraction decreases to the surface. The final layer of thickness 0.5 m is made of compacted clay. At some case local grouting of alluvial channel bottom can be required.

Geomembrane (GM) - Geomembranes are very useful covers, frequently applied for waterproofing reservoirs and the bottoms of tailings ponds. In order to completely prevent the loss of water into the sinking areas, geomembranes in combination with compacted clay in many karst reservoirs have fully met the project requirements. Most types of geomembranes are efficient to the pressures of 10 bars in reservoirs, or more. If they have to span gaps (wide open cracks or circular openings such as ponors), then their tensile strength and puncture resistance must be supported by different type of geotextile to reinforce the resistance of the waterproof layer.

Geomembranes are products manufactured with rigid quality control and are easy and quick to use during construction and, also easy for remediation during reservoir operation. If this kind of blanket protection is applied for large diameter ponors specific treatment of ponor down to the karst channel in rock mass is required (Fig. 3 & 4).

In karstified rock this kind of prevention generally requires additional special structures (different kinds of sub-membrane drainage and aeration installations). If it is under strong pressure from above or is exposed to any strong upward pressure from below, a geomembrane alone will not be sufficient to resist these forces.

In relation to grouting works, the surface solutions are cheaper, easier for construction and required remediation during operation of the reservoir is simpl. It is important to note that these works are always more efficient and cheaper, in continuity, when are performed without interruption.

Similar procedures can also be applied on the northern edge and along the left abutment along the route: Slano Dam (Riđani cave - the Riđani ponor in the length of 430 m) and along the abutments of Krupac Dam.

Conclusion

After a long time, it is important to note that some of the ponor zones on the reservoirs of Nikšić Polje (Slano and Krupac) can be remediate by surface treatment stead of construct hew or to re-grout existing grout curtains.

Previous experiences and new materials used for surface waterproofing treatment have proved to be very effective on a large number of similar structures in the karst. Experience with application of surface watertightness solution for Slano Reservoir will be very important to apply same technology to decrease or eliminate massive seepage from the Vrtac retention.

The presented procedure would enable the capture of new quantities of water of at least 0.5 m^3/s during low levels of the Slano reservoir, and at a natural head of 534 m of water per turbine HPP "Perućica" would be a significant benefit.

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Karst Geomorphology, Speleology and Speleogenesis

OPEN QUESTIONS IN KARST GEOMORPHOLOGY: DISCUSSIONS ON KARSTIC UVALAS

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Abstract: The most characteristic features of karstic landscapes are closed depressions of various sizes and origin. Within the group of these depressions, dolines and poljes clearly stand out as the most typical. There is a considerable number of references which include uvalas as well, but the offered definitions are often unsatisfactory (e.g. referring only to the size of the form). Several issues related to the position of uvalas in the system of karst closed depressions are discussed in this contribution: terminological problems, genetic issues, relation to other geomorphological processes (fluvial and glacial), etc. Among the genetic issues, the doline-coalescence interpretation of uvala formation is most frequently mentioned, but it has many shortcomings which are usually overlooked. Furthermore, we must keep in mind that the present state of surface morphology is not necessarily what it had been in previous morphostratigraphical phases of relief evolution.

Key words: karst morphology, karst depressions, uvala, Jovan Cvijić

SOME ASPECTS OF KARST DEVELOPMENT IN CARBONATE SEDIMENTS OF THE SHAN-PLATEAU IN MYANMAR (BURMA)

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Abstract: The Shan-Plateau is located in Central-Eastern Myanmar, to the east of the city of Mandalay. It is built-up by a sequence of dolomites, limestones and shales, referred to as the Plateau Limestone Group or the Shan Dolomite Group. This sequence, having a thickness of more than 3000 m, is deeply intersected by the valley of the Myitnge River. The relief of the valley shows some distinctive geomorphological features, which reflect the geological situation and the effects of erosion. The massy and approximately 300 m thick dolomitic limestone, which presents the uppermost strata of the Shan-Plateau, is characterised by widespread Karst dissolution phenomena. This situation is widely known by professionals and attributed to the entire Plateau Limestone Group. Reconnaissance investigations by the author along five cross sections from the plateau rim down to the valley bottom revealed however, that the similarly massy dolomite sequence underneath is not affected by Karst dissolutions. This paper describes the findings and discusses the reasons for it.

Key words: Karst Development, Dolomitic Limestones, Dolomite, Shan-Plateau, Myanmar

1. INTRODUCTION

The Shan-Plateau in central eastern Myanmar is well known for its very thick carbonate platform sediments and widespread karst development. The various rivers, all contributors to the majestic Irrawaddy River, are deeply eroded into the plateau.

In January 2015, the author undertook a geological reconnaissance tour to investigate the general geological conditions along a 50 km long stretch of the Myitnge River for a planned infrastructure project. Five walk-over traverses from the plateau rim down to the river have been undertaken to become familiar with the stratigraphic succession, structural and tectonic features, as well as to study the effect of karst features. The study area, discussed in this paper, is located between 90 and 100 km to the east and north-east of the city of Mandalay in Central Myanmar (Fig. 1).

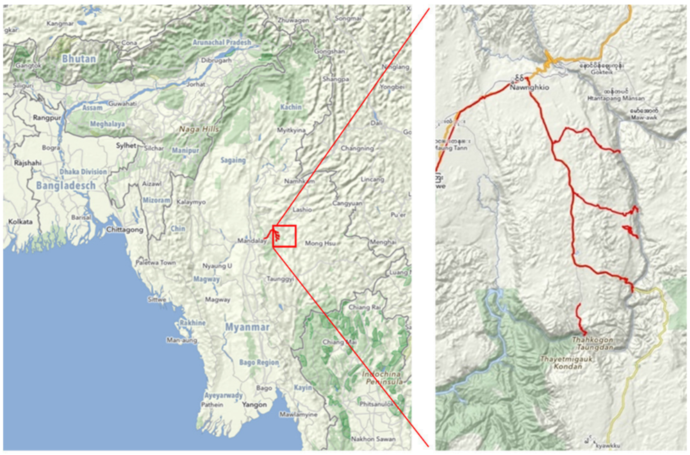

Fig. 1. Location of investigation area in central eastern Myanmar with GPS-tracks of reconnaissance tours.

2. GENERAL SITUATION

Lithostratigraphically, the Shan Plateau is built up of a sequence of dolomites, limestones, and some shales, referred to as Plateau Limestones (Group) or the Shan Dolomite Group (Bender 1983 and Report on Regional Geology, 2010) The sequence has a thickness of more than 3,000 m. The age of these sedimentary bedrock units ranges from Devonian (approximately 410 million years old) to Middle Triassic (approximately 230 million years old). Some authors divide this thick sequence into Lower and Upper Plateau Limestones with a sedimentary hiatus between them (Explanatory Notes to Geological Map, 1977 and Report on Regional Geology, 2010).

Fig. 2. Extract from Geological Map scale 1:2,000,000 (1977) with indication of investigated area.

The relief of the Myitnge River valley shows some distinctive geomorphological features, which reflects the geological situation and the effects of erosion. The

River has intersected and eroded the Shan-Plateau in different phases, which can easily be recognised in the middle section of the right river bank (Fig. 3):

- The rim of the highest plateau level is clearly marked in the central part to the west (right bank) of the river, but far away from the current river path (red line).
- Below this uppermost plateau level a smaller intermediate plateau level with a less pronounced rim can be observed (blue line).
- The third level is marked with a wide plateau ending in a rim to the narrow, deep and V-shaped gorge of the current river flow path (green).

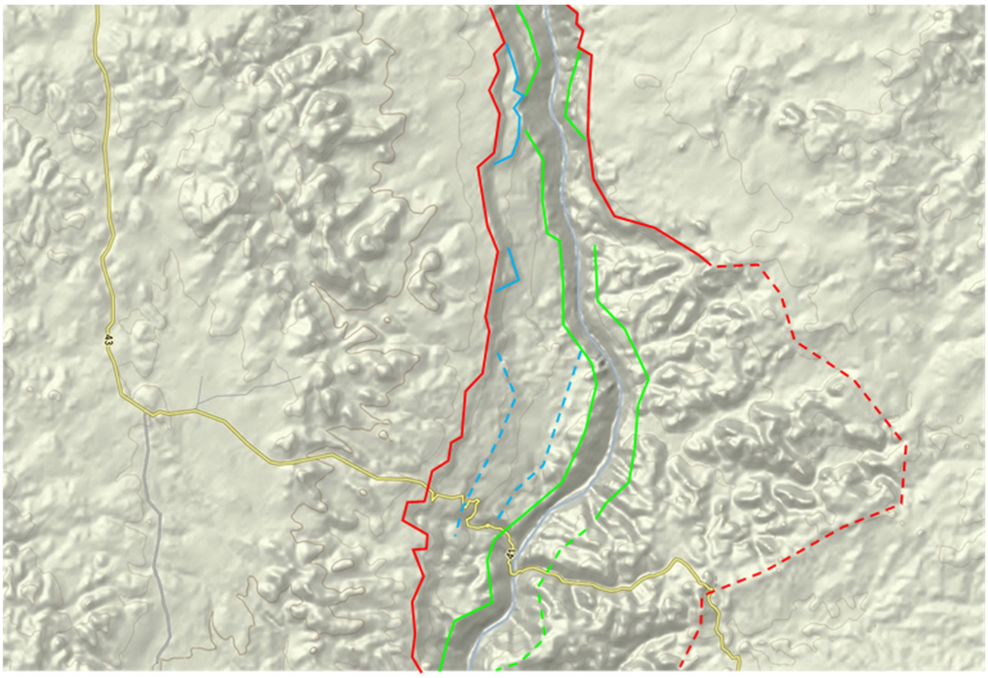

Fig. 3. Main geomorphological features in the investigated area; for details see text above.

3. FINDINGS FROM THE FIELD TRAVERSES

During the site visit along the five different sections, four main geological units of main interest could be distinguished: two bedrock types and two sub-recent to recent surface deposits. Beside these, the usual scree material and alluvial deposits (mainly boulders, cobbles, gravel and sand, only few fines) are present. From plateau top to river bottom, the four main geological units can be briefly described as follows:

- Dolomitic Limestone (Fig. 4, left): A bedrock with varying shades of grey and texture. The limestone is partly dolomitised and brecciated with a heterogeneous distribution and has widely spread cavities of several metres in size. This unit, which is several tens of metres in thickness, forms the uppermost cliff and rim of the geomorphology (red line in Fig. 3). Its base is probably extensively brecciated and easily erodible and forms the intermediate level of the middle platform and less prominent rim (blue line in Fig. 3).

- Red Residual Soil: It covers the surface of the dolomitic limestone except on steep cliffs. This clayey material derives from tropical weathering of the bedrock and its thickness varies widely.

Fig. 4. Left: Dolomitic limestone with Karst cavities. Right: Massive dolomite without Karst cavities (below green line). The red and green line correspond with the colored lines in Fig. 3.

- Dolomite (Fig. 4, right): Very thick (>100 m), mainly massy, partly moderately bedded bedrock of varying shades of grey and heterogeneously affected by tectonic impact. It can be jointed to a moderate to dense level, with the joints being tight or healed by white thin calcite. As is the case with the dolomitic limestone, the dolomite is also partly heterogeneously brecciated and thus partly weakened from its usually high strength. Such zones or pots of a few centimetres to few metres in size are easily eroded by flowing (river) water and can form caves. All high cliffs and the V-shaped river valley below the green line in Fig. 3 are formed by this limestone.
- Calcite Tufa (or travertine, Fig. 5): This material can cover the three geological units described above from below the top cliff (the red line in Fig. 3) down to the Myitnge River. When ground water, oversaturated with dissolved calcite, dissipates or flows out of the bedrock, pressure and temperature conditions suddenly change and calcite precipitates at the surface, either on rock or on the vegetation, and forms the typical appearance of tufa sediments, which are varying considerably. These tufa deposits can be observed either (i) along small creeks from the elevations of dolomitic limestone down to the river, or (ii) as widespread areal deposits. Deposited on bare bedrock surfaces, or even upon red residual soils, the tufa appears very compact and hard and can hardly be

destroyed by firm hammer blows. This material is classified as relatively old. If the water runs over the vegetation and the calcite is precipitated on the plants, a very soft and porous (due to rotten organic material) tufa is present (recently precipitated material).

Fig. 5. Left: large calcite tufa deposits near right river bank. Right: compact calcite tufa deposits over dolomite near right river bank.

In the following the most important observations regarding karst in this area are described and discussed in more detail.

- On the uppermost plateau, limited by the red line in Fig. 3, no single karst-feature was observed. This is due to the thick cover by residual soils and agricultural land.
- In the cliffs of the dolomitic limestone below the red line (see Fig. 3) widespread caves of a few centimetres to several metres in width and depth are observable (see Fig. 4, left). These caves are formed from the karst dissolution of limestone.
- The occurrence of old and recent tufa is an evident sign of active karst in the area. However, its distribution mainly along small river creeks shows that the karst springs are located at higher levels in the area of the dolomitic limestone. The various springs observed at the level of the Myitnge River are not to be categorised as karst springs out of the dolomite. Their source is surface water from higher levels running along the surface of the insoluble dolomite and through the porous tufa (see Fig. 5, left and Fig. 6).
- The caves observed within the dolomite (below the green line in Fig. 3) are solely a result of mechanical erosion of heavily brecciated areas by river water. In some areas, the surface of the dolomite shows small karrens of only a few millimetres to a few centimetres in depth. These morphological features are visible in two forms: (i) joints in the dolomite, healed with pure white calcite, which is highly prone to karst dissolution and (ii) mechanical erosion and polishing by the sediment load (sand, gravel, cobbles) in the river.
- On the widely outcropping dolomite area along the Myitnge River valley numerous vertical holes in the dolomite are present. They have a

diameter and depth of several tens of centimetres, up to around one metre. These features are not of karst origin, but of mechanical erosion by cobbles and small boulders due to turbulent water flow (pot holes).

Fig. 6. Various locations on dolomite surface with tufa deposits deriving from surface water running from the top-level (dolomitic limestone) to the Myitnge River. Left: surface water dissipates into huge porous tufa deposit and appears again as a spring at the lower boundary to the dolomite (see also Fig. 7).

The conclusion from oral information provided by the villagers on top of the plateau is that there are two different (and probably independent) groundwater levels in the Shan-Plateau (see Fig. 7). For water supply, they use collected rainwater from the roofs, ground water from classic shallow wells, or pumped from deep boreholes.

The shallow wells are only a few metres deep and end in the red residual soil. Some interconnected channels with gravelly material might collect rainwater penetrating the ground and feed the wells with recent groundwater. During the rainy season, the groundwater level is reported to be higher than during dry season, but there is generally only a small fluctuation.

An example of a second type of well, where water is pumped up through a deep borehole, could unfortunately not be visited. It was reported that one well is approximately 50 m deep. It is assumed that this borehole ends in the dolomitic limestone underneath the residual soil and that the water represents the karst groundwater in this rock unit (meaning that the depth/base of the active karst zone is within this dolomitic limestone at the top level).

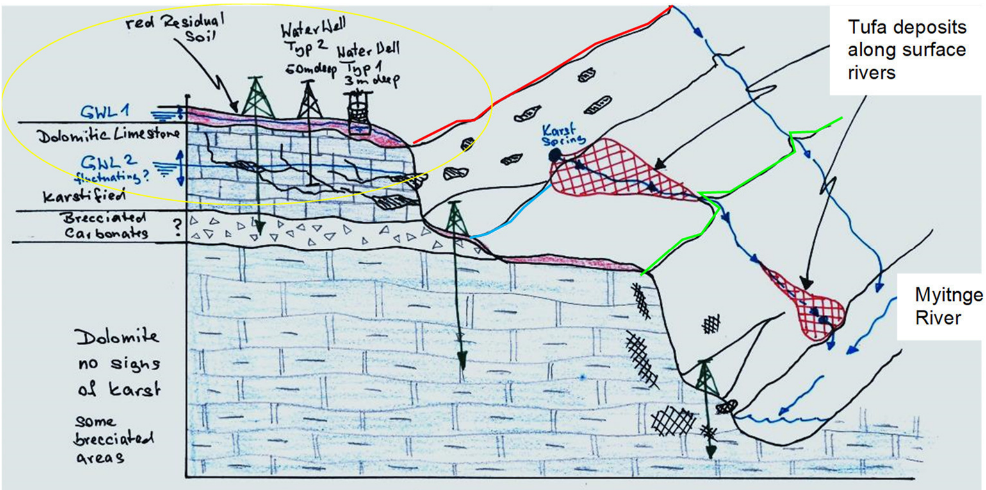

Fig. 7. Sketch of the most important findings in the investigated area; for details read text above. The red, blue and green lines correspond to the colored lines in Fig. 3. Three drilling locations for additional investigations are indicated.

4. INTERPRETATION OF THE KARST SITUATION

The summarised findings from the site visit can be interpreted as follows:

- There exist two, probably independent, groundwater levels. The lower one (GWL2) is at a relatively high level within the Shan Plateau and within the dolomitic limestone.
- Running rivers with tufa deposits are observable from elevations at the level of the dolomitic limestone and thus most probably deriving from karst springs within the dolomitic limestone.
- The main volume of bedrock eroded by the Myitnge River consists of dolomite, not showing typical karst phenomena (except for some very superficial and small karrens due to thin joints healed with calcite). The only weak areas within this very strong bedrock are brecciated zones, prone to mechanical erosion by flowing river water.
- Extent and role of the brecciated layer between the dolomitic limestone and the dolomite are yet not clear and understood. What is the geometry and what is its impact on the karstification process? How far is it present? Is it a horizon prone to karstification or is it a barrier for karstification?
- The current depth/base of karstification seems to be located somewhere inside the dolomitic limestone or eventually directly above the upper limit of the dolomite.
- The dolomite seems not to be affected by the karstification process.

Additional and very important arguments for the fact that only the top layer of dolomitic limestone is karstified and that the dolomite in the valley bottom is not, could be derived during detailed discussions between Petar Milanovic and the author of this paper:

- The karstification process requires much more time than the normal river erosion.
- In the middle section of the project area, the Myitnge River formed at the higher levels (dolomitic limestones, and probably brecciated layer, see Fig. 3) quite large intermediate plateaus, reducing the speed of vertical erosion to depth. The base of karstification could follow more or less the base of river erosion.
- Later, in the dolomite, the Myitnge River could more quickly erode into the dolomite, forming the narrow V-shaped gorge and the karstification process could no longer follow the river erosion. A reason for this change of type of erosion could be a fast tectonic up-lift of the area, forming the present Shan-Plateau.

The current knowledge and interpretation of the situation has to be deepened and confirmed with further thorough site investigations, e.g. with investigation boreholes, as indicated in Fig. 7 and hydrogeological tracer tests.

Acknowledgment: The author would like to thank Petar Milanovic for the interesting and highly valuable discussions during this project.

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INVESTIGATION OF THE LOCAL VARIATION OF PHYSICAL AND MECHANICAL PROPERTIES OF THE COVERING DEPOSITS IN ORDER TO HAZARD ASSESSMENT OF KARST (ON THE EXAMPLE OF SULFATE-CARBONATE KARST OF PERMSKY KRAY, RUSSIA)

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Abstract: We present the technique of karst hazard assessment used on the territory of Ust-Kishert village. We analyse the factors of the research area natural structure which is characterized by the abundance of carbonate-sulphate karst. The condition and the strength properties of the overburden sediments can serve as indicators of weakening of the rock mass. We used this idea for the integral analysis of physical and mechanical properties to construct the cartographic model of karst hazard assessment. We then compare this model to the one proposed earlier.

Key words: physical and mechanical properties, overburden sediments, karst hazard, weakened rock mass elements.

Introduction

The purpose of this study is to identify the areas of local changes of overburden physical and mechanical properties relative to the background level. We consider such areas as the sites of the most probable location of the weakened zones in karstic rocks. The working hypothesis of the investigation is as follows: the physical and mechanical properties of the overburden vary over the-weakened zones in the karstic rocks. These local changes depend on the degree of hydrogeological activity of the karst cavity and on its vertical dimensions.
In this study, we associate karst cavities and crushed zones with weakened elements and consider them as the areas of disintegration of karstic sediments, characterized by increased fracturing and weathering, often to a state of rock flour. The development of cavities in the formation affects its natural stress field, thus initiating such deformations as protrusions towards the empty space or collapse of the arch of the cavity with possible creation of the hole on the surface.

Short characteristics of the research area

The investigated rock mass is situated in predominantly gypsum and carbonate-gypsum karst area (Gorbunova *et al*, 1992) of the Kishert district in

Perm region, Russia. In terms of the tectonic structure, the area is located in the northern part of the Ufimian arch within the eastern margin of the East European Platform, and in the Sylvian Basin within the Cis-Uralian foredeep. The broad distribution of the tectonic faults, which is clearly traced in aerial and satellite imagery, indicates the high tectonic activity of the research area. Geological structure of the area is represented by 1) the Artinian and Kungurian carbonate and sulphate-carbonate-clay deposits of the Permian period Cisuralian series, 2) Neogene-Quaternary karst-slumping deposits, 3) Quaternary fluvial and alluvial formations — sandy loam, clays and loams with debris and rubbles of bedrock.

Most of the karst cavities (22 pcs, 39.3 %) were drilled in the areas with Quaternary deposits of 15–20 m in thickness. The maximum number of karst sinkholes (30 pcs, 30 %) is confined to the areas with a similar thickness of the Quaternary sediments (15–20 m). Underground and surface karst forms are found within the areas of the Quaternary sediments thickness of 10–25 m. 55 funnels were encountered on the surface and 20 karst cavities were found by drilling (Shilova, Kovaleva,2015).

Research methodology

The idea of using the anomalous values of overburden physical and mechanical properties as the indicators of the weakened rock mass elements location is implemented in this work. The intervals of the overburden anomalous strength parameters are determined by performing one-dimensional statistical analysis.

Only the Quaternary clayey subsoils were analysed in this work, because of the sufficient number of laboratory measurements of the strength properties for statistical analysis. Clayey subsoils used for analysis were of plastic to solid consistency. Subsoils with very high plasticity were not involved because of the sharp variation in strength parameters after water saturation of clay.

In addition, the interest to the properties of clayey subsoils is drawn by earlier researches carried out by the authors. Based on these researches, it was concluded that the most karst hazardous areas are those where loams with the thickness of 10–25 m are predominant. The largest number of karst cavities is found in the areas where loams have a thickness of 15–20 m (17 pcs, 48.6 %) and 25–30 m (11 pcs, 31.4 %). The areas composed of loams have the highest karst sinkholes occurrence (56 pcs, 72.8 %).

All the values of physical and mechanical properties of clays and loams retrieved from the wells were taken to perform a one-dimensional statistical analysis for obtaining the distribution curves of measured parameters. The most suitable theoretical distribution curves are applied to the empirical ones based on the corresponding distribution law (normal or lognormal).

In addition, we performed a one-dimensional statistical analysis only for the samples taken from wells in close proximity to those ones which revealed weakened rock mass elements.

The lack of data on the size of karst cavities and crushed zones, together with the absence of precise methodological recommendations on calculating the horizontal morphometric parameters of weakened rock mass elements from vertical ones, make it difficult to determine the maximum permissible distance for assigning a subsoil sample to the category of samples taken near the karst cavities. However, S.V. Shcherbakov and V.N. Kataev (Shcherbakov, Kataev, 2013) found the relation between vertical and horizontal morphometric parameters of surface karst formations when studying the large volume of karst forms morphometry data. Using this relation and the maximum vertical thickness of the weakened rock mass elements of the study area, we can now determine their horizontal size. The sample taken within the distance of this size is now in the immediate vicinity of the weakened rock mass elements, in this case — 50–60 m.

The distribution curves of strength properties as a function of the presence of karst cavities were constructed after the one-dimensional statistical analysis. The differential curves that reflect the distribution of the physical and mechanical properties in the study area have the peaks that correspond to the average values of the investigated parameter that are the most common for the areas of the weakened rock mass elements. The range of mean values for the area is determined based on the mean *M* and the standard deviation σ from the mean and is equal to $M_i \pm \sigma$.

Using the integral distribution curves of the strength properties of subsoils throughout the territory and on the sites, close to the weakened rock mass elements we can find a certain coefficient *k* (1) which would represent the difference of the investigated parameters values (Fig. 1):

$$k = \frac{X^A_{P_{0.1}}}{X^B_{P_{0.1}}}, (1)$$

where $X^A_{P_{0.1}}$ *is the investigated parameter value near the weakened rock mass elements with probability of 0.1,* $X^B_{P_{0.1}}$ *is the investigated parameter value on the entire study area with probability of 0.1.*

Considering the values of investigated parameters for several probabilities (e.g. 0.1, 0.4, 0.7) we can find the average value of *k*, which can then be applied for similar by the natural structure territories on the basis of laboratory measurements of the overburden subsoil samples. In other words, it is possible to find areas of possible appearance of weakened rock mass elements calculating the strength properties by their distribution on the whole territory. Apart from evaluating the strength properties of the overburden, we propose the obtaining an integral index of the overburden condition using the laboratory subsoil samples data — subsoil density ρ, subsoil void ratio *e*, specific adhesion *c*, and internal friction angle φ.

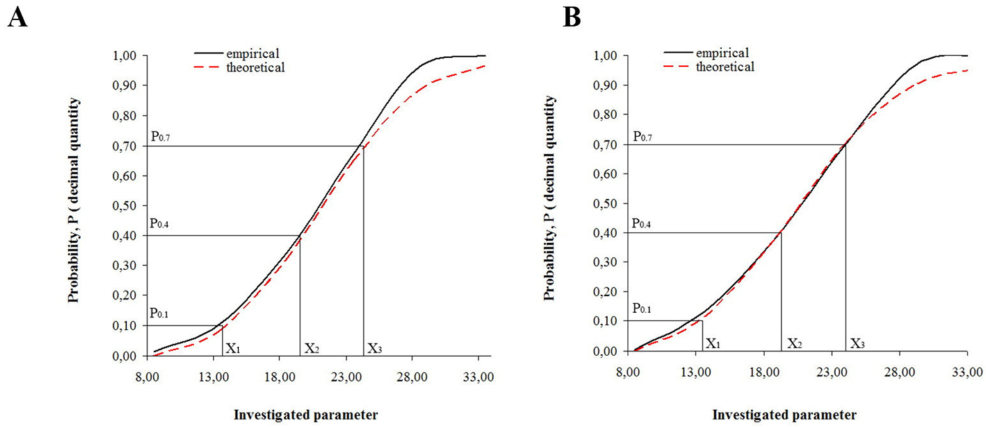


Fig. 1. Integral distribution curves of the investigated parameter values. A — near the weakened rock mass elements, B — for the whole research area

We performed the local analysis using statistical methods and computer modelling. According to the laboratory data, the order statistic is constructed for each factor. Then, the descriptive statistic was obtained — *AF* is the average factor value in the study area, and σ is the standard deviation. Further, the empirical and theoretical distribution curves were plotted in accordance with the law of random variable distribution determined earlier. The theoretical distribution curves indicate the intervals of background and anomalous values: Ca ≥ *AF* ± σ — for angle of internal friction and porosity coefficient, Ca ≤ *AF* ± σ — for subsoil density and specific adhesion.

The physical and mechanical parameters of samples were ranged by the intervals on the distribution curves and mapped using the sampling locations. The obtained maps then were graded by the level of karst hazard with the maximum of (3) assigned for anomalous parameter values and the minimum of (1) for background values. To detect the weakened karstic rock masses these maps were overlapped with each other. The result of the overlapping is an integrated cartographic model which has zones of the maximum total score

values corresponding to the areas with the highest probability of karst cavities and crushed zones appearance.
Validation of the research was accomplished by a spatial analysis of the karst cavities locations proved by drilling in the study area. The results are presented in a form of a table and the number of underground karst forms spatially related to the categories of the integral model is noted.

Research results

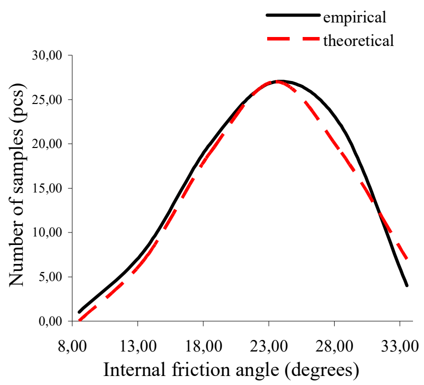
The distribution curves of the overburden clayey subsoils strength properties are gained as the result of one-dimensional statistical analysis (Fig. 2). Using these integral curves, it is possible to find the average coefficients of transition from the background strength properties values (Fig. 2-b) to anomalous (Fig. 2-a). For the angle of internal friction φ and the specific adhesion *c*, these coefficients are as follows:
1) $k_{\varphi 0.1}$=1.07, $k_{\varphi 0.4}$=1.05, $k_{\varphi 0.1}$=1.03, $k_{\varphi\ average}$=1.05,
2) $k_{c0.1}$=1.03; $k_{\varphi 0,4}$=1.02; $k_{\varphi 0.1}$=1,03; $k_{\varphi\ average}$ =1.03.

The analysis of physical and mechanical properties of the overburden resulted in an integral karstological model of the study area. The model was graded into three categories with different total scores (Fig. 3). The territory with the average total score values has the greatest number of crushed zones and karst cavities. However, the highest density of karst forms is confined to the areas with the maximum total score values which corresponds to the joint locations of the zones of abnormally low or high values (Table 1).

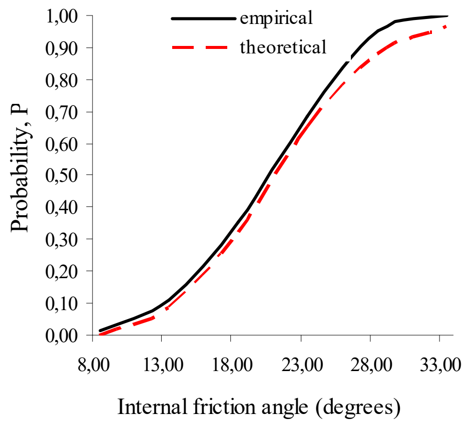
Table 1. Quantitative assessment of karst hazard according to selected categories

Hazard category	Integral parameter, points range	Area of the category (km^2)	Num. of karst forms		Density of karst forms (pcs/km^2)	
			crushed zones	cavities	crushed zones	cavities
1	< 5	2.30	4	10	1.7	4.4
2	5-8	2.40	14	34	5.8	14.1
3	>8	0.70	6	16	8.5	22.7

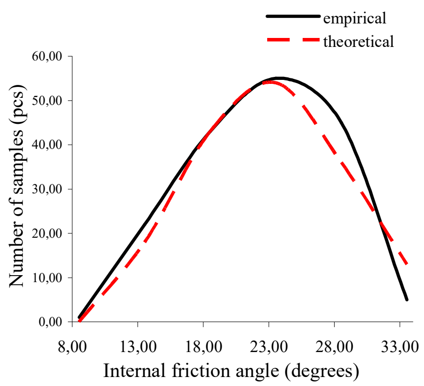
A (82 samples)



Mean, M	21,0	
Standart devistion, σ	5,9	
Distribution	Normal	
Value range (M ± σ)	15,1	26,9



B (171 samples)



Mean, M	20,3	
Standart devistion, σ	6,1	
Distribution	Normal	
Value range (M ± σ)	14,2	26,4

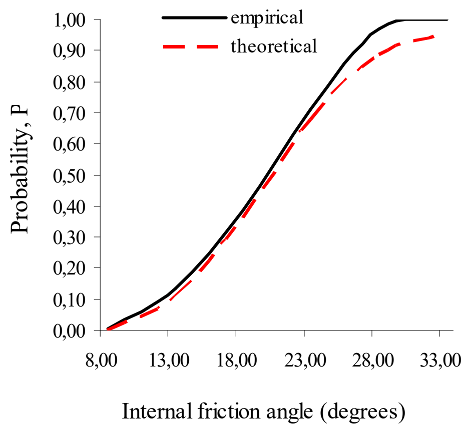


Fig. 2. Differential (left) and integral (right) distribution curves for internal friction angle. A — near the weakened rock mass elements, B — for the whole research area

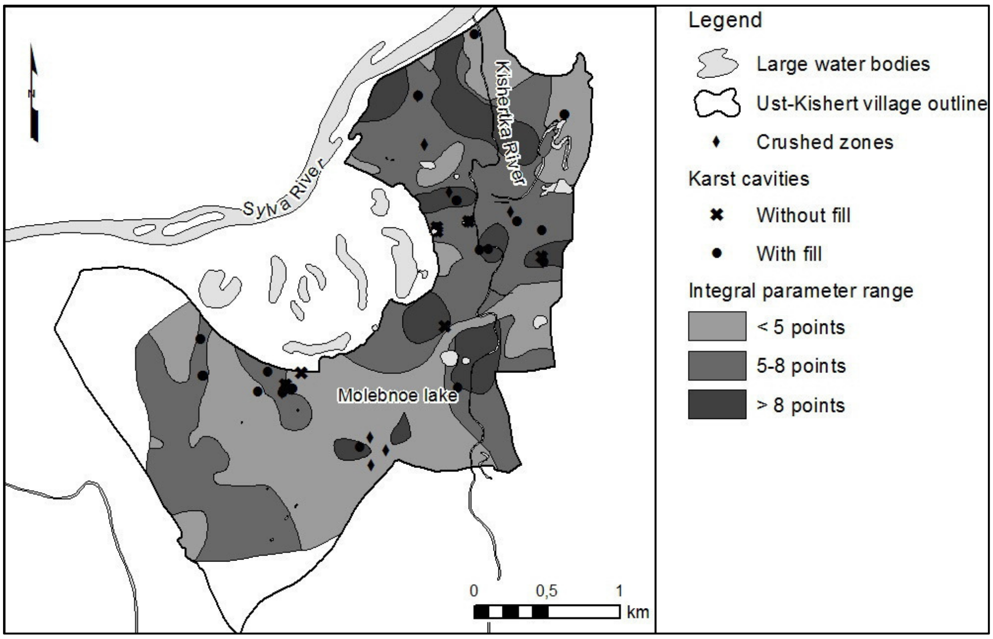


Fig. 3. A map of the integral parameter for the overburden condition (Drobinina, 2016)

T.G. Kovaleva earlier assessed the karst hazard of the Ust-Kishert village territory analysing how the geological and hydrogeological parameters of karstic rock mass influence the surface and underground karst forms distribution. Using the qualitative and quantitative data from 100 karstological wells and the surface and underground karst forms abundance data she determined the most and the least karst hazardous intervals of indicators values and built a cartographic model of karst hazard assessment (Kovaleva, 2015).

When comparing the two cartographic models we can determine the spatial match of the hazardous categories. Both models have the central part of the investigated territory as the most dangerous. The southern part, on the contrary, is characterized by a lesser danger.

Conclusions

The obtained coefficients of $k_{\varphi \text{ average}}$ and $k_{c \text{ average}}$ can be applied for similar territories to determine the strength properties and approximate the abundance limits of the areas of possible location of weakened rock mass elements.

The proposed technique of karst hazard assessment is based on the determination of the integral indicator of the overburden condition and has a local use and certain limitations. It makes possible to contour the possible areas of weakened rock mass, but not to specify the exact locations of karst cavities. However, through this analysis one can outline the direction of further detailed study.

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ESTIMATIVE KARST INTERPRETATION OF SATELLITE IMAGES OF THE SOUTH – SOUTH-EASTERN DISTRICTS OF PERM REGION

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Abstract: This publication is dedicated to the methodology of karst areas interpretation in the Southern and South-Eastern districts of Perm Region by using large-scale high resolution satellite images. This paper describes methodical approaches for identification of karst forms on the day surface by various terrain conditions: forest coverage, illumination, building density and seasons. Approaches for determination of karst diameters depending on their geometry and on the density of vegetation are recommended. Maps of karst landforms have been created.

Key words: karst forms, funnels, diameter, cosmic images, interpretation

Introduction

Estimative karst interpretation is performed within the frame of solving applied research tasks, such as: identification of on the day surface visually detectable karst forms, including karst hole genesis, local ground depression and their concentration, in karstological literature called «karst fields». In addition to the location of surface deformations, their geometrization is preformed and the following data are defined: area, perimeter, diameter, karst forms concentration. The interpretation was accompanied by the standard procedure of factual data gathering and systematization, the building of karst areas database and the preparation of geological information for following analysis. As a result of the interpretation and analytical actions, influence patterns of various geological and hydrogeological factors on the positional relation, the intensity of formation and parameters of fixed karst forms were determined.

Research area

Studies have been conducted on the karst developing areas, which in the scheme of karst zonation of the Perm region [1] conform structural-tectonically to the Eastern edge of the East European Plain and the adjacent part of the Ural Foredeep, such as: Nizhnesilvenskiy, Ilinskiy, Kishertskiy areas of gypsum and carbonate-gypsum karst developing, Osintsevskiy area of the closed salt and gypsum karst and the area of carbonate karst of Ufimskiy swell. On the specified areas sulfate (gypsum, anhydrite) deposits of the Irene horizon of the

Kungurian stage are mainly karsting and carbonate (limestone, dolomite) rocks of the Filippovsky horizon of the Kungurian and Artinskian stages of the Cisuralian Epoch of the Perm System are karsting in a lesser extent. Geological-structural conditions – platform, karsting – conform to the bald, covered with turf, on large areas to under-eluvial, in the river valleys to under-alluvial and to the under non-karst rocks closed type of the Solikamsk Horizon of the Ufa Stage of the Cisuralian Epoch of the Permian System. Karst forms are very diverse: funnel, sinkholes, swallow holes, caves, karst ravine, sinks, etc. On the earth's surface the most common karst forms are funnels including dolines. The total area of interpretation is 9558.2 km^2.

Expert method

This study is technically based on the high resolution satellite images (CFS) provided by Google Maps, Bing Maps, Geo Hab, ESRI, Yandex. The view and justification of using images from the public package of satellite images concerning their quality and resolution, as well as analysis of present karsting areas to identify surface karst forms, were carried out using the program SAS Planet.

Viewing, analysis, and vectorization of the CFS, which meet the requirements of the tasks according to their content, quality and resolution, were carried out in the Next GIS (nextgis.com). The analyzed KFS were used as the background without downloading. Settings of the working draft are following: WGS 1984 UTM Zone 40N projection Mercatora / WGS84. As karst interpretation was based on the large-scale CFS, the resolution of images has become the determining choice factor of the suitable images for karst forms diameter calculating with a required accuracy. The parameters and scale of KFS were estimated in the program SAS Planet. Based on the resolution of the images, the working scale (level) of the images and the calculated theoretical error of the cross-section of the karst forms were determined. The parameters for displaying CFS in SAS Planet and Next Gis in the raster format with JPG extension are shown in the table. 1.

Table 1. Parameters of CFS in the raster format with JPG extension

Level CFS	Scale	Resolution m/Pix	Size jpg in pixels	Jpg size in inches	Mp jpg	DPI jpg
z19	1:1000-	0,32 м/pixel	256*256	(3,56*3,56//)	0,1	72
z18	1:1870-	0,64 м/ pixel	256*256	(3,56*3,56//)	0,1	72
z17	1:3750-	1,29 м/ pixel	256*256	(3,56*3,56//)	0,1	72

The digitization of karst forms was carried out on the operational scale 1:500 - 1:1000-1:2000 (z18-z19), by increasing the scale to more than 1:500, the

boundaries of forms were blurred and lost their clarity, so the evaluation of the cross bars of karst forms became meaningless.
The main interpreting features on the CFS are the karst phenomena themselves (the number and the pattern of their spread over the area), easily recognizable geometric parameters (usually a rounded, symmetrical form), which are visually easy to determine in large-scale images (Fig. 1).

Color CFS of high resolution Google, Bing Maps, Yandex, etc.are well-read photographs, on which the elements of the terrain, hydrographic networks, vegetation, buildings and structures are clearly and definite reflected. Deciphering features are usually well expressed, and the shape and the color of the objects allow to identify karst forms (mainly funnels) in the open area with a sufficient degree of reliability.

All the above has determined the choice of the research area. The Southern and South-Eastern parts of the Perm region are of unique landscape – Kungur forest-steppe, which is characterized by a predominance of steppe areas with alternating small forest areas. Favorable natural and geological environments – a significant intensively developed karst areas, free from forests, have provided optimal conditions for the interpretation and for the receiving of standard source material [2].

Fig. 1 Karst field in 2.3 km from the village Upper Kungur.

The undoubted advantage of the methodological approach is the unified method to identify karst forms on the terrain and to evaluate their parameters with the specified accuracy (error) by the actual resolution of the FSC. Karst forms are a characteristic feature of the landscape of Kungur, Orda, Kishert, Suksun and other districts. Funnels are easily recognizable and stand out in the pictures because of their shape (round, oval, elongated), as well as of the nature of their location in large or small groups (fields), usually chaotically and randomly. However, there are a few funnels or an ordered set in the form of a chain along splits or groups of linear grikes. In time, the shapes of funnels on the Earth surface do not change, but the shapes of their transverse profiles change because of gentling their boards. The craters are overgrowing with thick grass, shrubs and trees. Vegetation is also an important indicator of surface karst forms deciphering.

The funnels are the point elements of collection of melt and rainwater and thus create conditions for active development of grassy and woody vegetation within their limits. On some areas there are funnels with varying degrees of grass, shrub, trees, which indirectly indicates the order of collapse and allows to estimate the size of the forms depending on their relative age [2].

For the present CFS (72 DPI) by the maximum allowable scales of 1:500 – 1:1000 decryption, when 1 mm on the map corresponds to a distance of 0.5-1.0 m, areal visualization of forms up to 1 m is meaningless, because the error of 1 mm may exceed the actual size of a karst funnel. The geometrization of forms up 1 m by scale 1:500 is more balanced, so 4 mm on the map will correspond to a funnel with the diameter of 2 m. For this reason, all forms smaller than 1 m weren`t geometrized.

The transverse dimensions of karst forms identified by the classification were compared with their dimensions during the field verification work in Orda and Kungur districts. The control check was selective, there were measured more than 30 craters with lateral sizes from 5 to 40 m. The results of the research have estimated the following: the dimensions of the forms (from 5 to 30 m), calculated remotely, on average, were smaller than the actual dimensions (measured by tape) for 1-1,5 m. The remote calculated diameters of 30 m and more - for 1.0-2.0 m exceeded the actual dimensions. In this case, the measurement error could be made during both measurements: during tape measurement - because of the rugged relief, and during the karst forms visualization.

During the identification and the subsequent vectorization karst forms were divided into two groups (SHP-files): areal and pointlike. In the first group are those karst forms which diameters were established easily. As the "nominal diameter" of a karst form the biggest or the external, visually discernible diameter (the circle) of a funnel was taken; at the same time, the actual material obtained from karst fields verification surveys showed that in most cases, for bushy or treed funnels, it is possible to determine the diameter accurately enough, as the edge of vegetation is usually limited by shape, or slightly goes beyond it. For Kungur and Orda districts, fields verification surveys have confirmed this assumption. In some areas the process of karst forms overgrowing was observed; at the same time there were funnels (identical by the form in the picture and the size) completely open, partly overgrown and completely closed by vegetation; that allowed for overgrown forms to substantiate the diameter dimension by analogy with open funnels (Fig. 2).

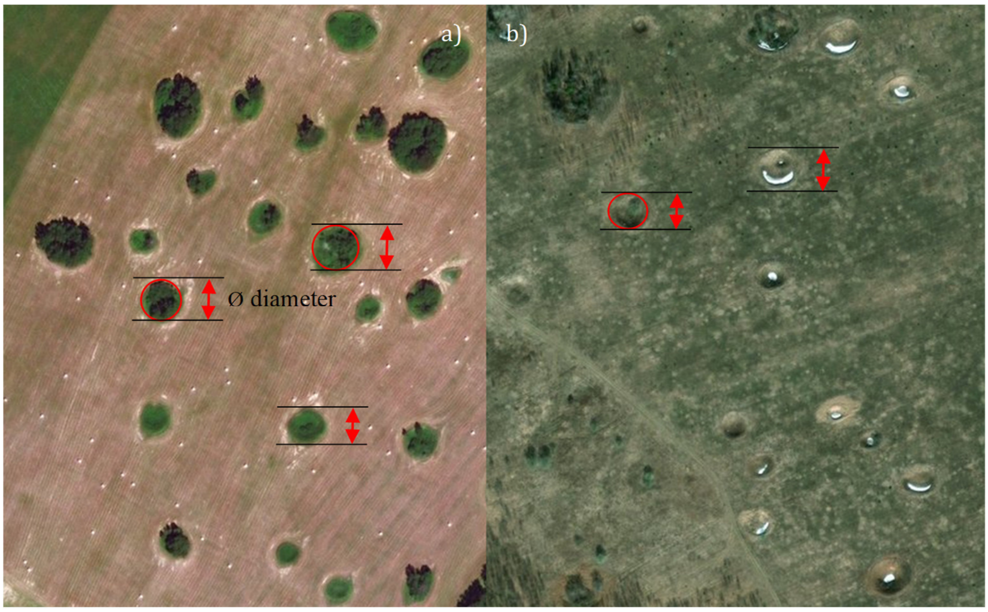

Fig 2. Methodical approach to the geometrization of karst forms: a) The district is 1.5 km from the village Klyuchi b) The district is 0.6 km from the village Kiselevo

To the same group was subsumed the part of the forms, which etiology was doubtful because of the strong population, the layout of the relief, the location in the forest or in a shade of another object, etc. [2].

Large clusters of sinkholes in areas, where the karsting rock comes up to the day surface, were detailed analysed and visualized as point objects; on the karst density map such areas are specified as the areas with the highest karst density, up to 600 pieces/km^2.

Research results

The volume actual material characterizing the karst landscape of Southern and South-Eastern districts of Perm region was obtained as a result of conducted research. The verification field work has confirmed the objectivity of the work performed. Statistical parameters of karst interpretation are presented in the table 2. The empirical distribution of the diameters of the polygonal karst forms corresponds to the lognormal law (Fig. 3), the average diameter reaches 18.5 m. The character of the development of karst forms on the daily surface is illustrated on the density map (Fig. 4).

Table 2. General statistical indicators of interpretation of the territory

Karst area	The number of forms, pieces	Point feature, pieces	Polygon features, pieces	The area of the region, km²	The area forms, km²	Karst, %	Conditional density, pieces / km²
Kishertsky	1954	648	1306	306,33	0,81	0,26	6,38
Irene	39016	21973	17043	3380,71	6,38	0,19	11,54
Nizhnesaldinsk	22704	7830	14874	2132,7	5,37	0,25	10,65
The Ufa	4484	3232	1252	2703,63	0,27	0,01	1,66
Osintsevsky	297	150	147	861,04	0,058	0,01	0,34
Total:	68455	33833	34622				

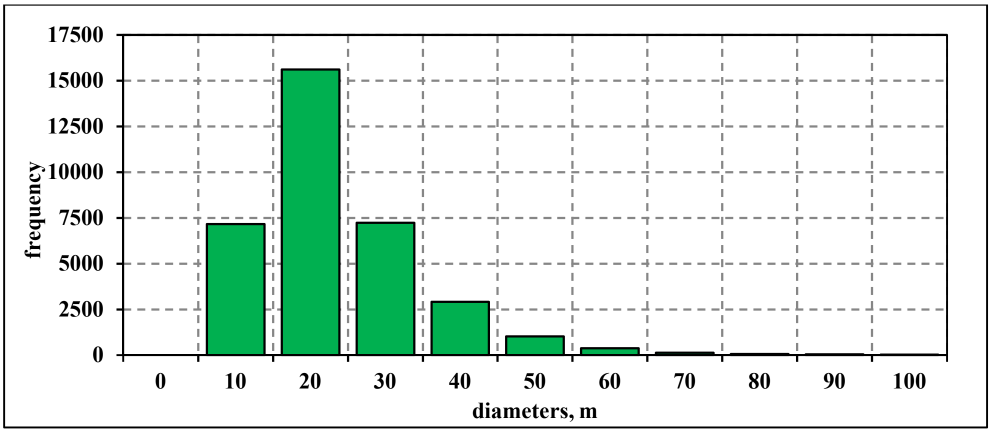

Fig 3. A graph of the diameter distribution of karst forms

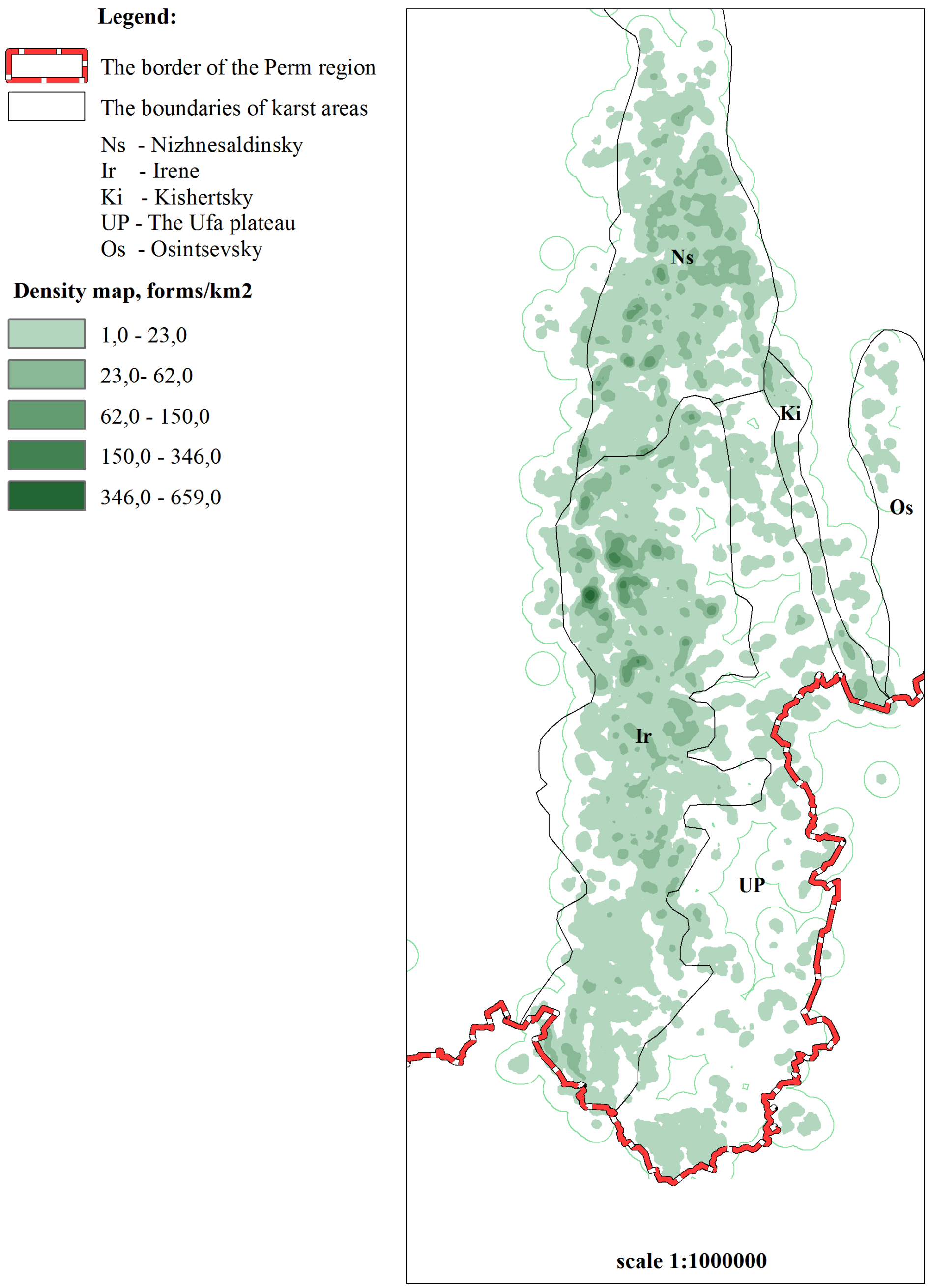

Fig 4. Map of the density of surface karst forms

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SPECIFIC FEATURES OF THE KARST SPRING PALILULA IN NORTHWEST BULGARIA

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Abstract: The studied karst spring Palilula from Northwest Bulgaria is characterized by fast reaction to rainfall events and water temperature about 14°C. Based on field explorations of the area, most possible location of inflow of surface waters from the Lipenska River is identified. Obviously, the spring receives water from the neighbor rivers – most possibly the Lipenska River south from the spring issue. This karst aquifer presents a complex system where a mixture of warm groundwater and surface waters occurs.

Key words: groundwater, karst spring, regime, Palilula, Montana, Northwest Bulgaria

Introduction

The aim of the study is to detect specific features of the karst spring Palilula in Northwest Bulgaria, based on field studies and analysis of different time-series (for spring discharge, temperature and chemical content of its waters, as well as the regime of precipitation and water stage in neighbor river). The geological structure and palaeo-geographical evolution of this territory are considered as well.

Physico-geographical description

The study area is located in Northwest Bulgaria within the Ogosta River basin, 13 km east from the town of Montana (Fig. 1).
The studied karst spring issue appears at elevation 104 m asl in the village of Palilula northeast from the hill Pastrina. The hill is characterized by several peaks with the highest one at 563.7 m asl. Due to high level of biodiversity, large part of the hill (35.5 km^2) was designated as protected zone “Pastrina”. Other land use in the area is agricultural (forest, grassland).
The main river course in the area is the Ogosta River with its tributaries the Botunya River flowing northeast from the hill, and the Shugavitsa River draining the southwestern and western parts of the hill.

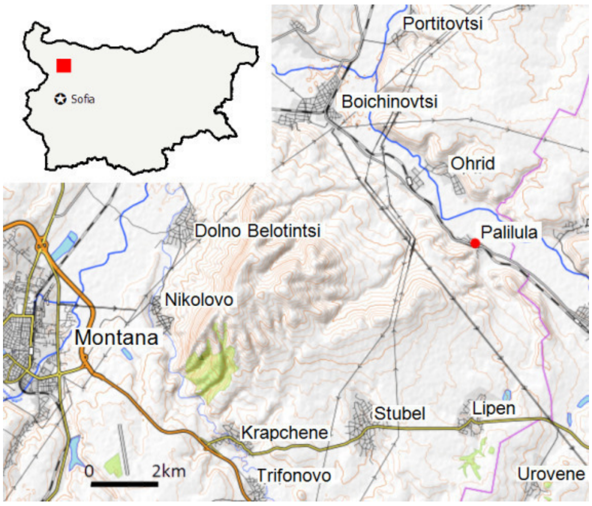

Fig. 1. Location of the karst spring Palilula (red circle)

The climate of the area is moderate continental with hot summers and cold winters. The mean annual temperature is about 11°C and the mean annual precipitation sum is 627 mm for station Montana (160 m a.s.l.).

The palaeo-geographical evolution of this territory shows continental conditions during Palaeogene, with deep incision in Early Miocene of the palaeo-rivers flowing northwest to the remote Dacian see (Spiridonov and Jelev, 2013). Later in Middle Miocene ingression of the sea waters occurred that filled these erosion valleys of the palaeo-rivers with clayey and marly deposits of the Badenian age. The sea transgression during Sarmatian age with marine regression at the end of this age. The climate during Miocene was subtropical/warm-temperate and humid (Ivanov et al., 2011). The Neogene sediments were deposited in marine and brackish environment. The hill Pastrina was one of the islands, and the Palaeo-Botunya River was flowing south from this hill. Nowadays this valley is occupied by another tributary of the Ogosta River – the Shugavitsa River (Spiridonov and Jelev, 2013). During Pliocene and Quaternary, the area was developed under continental conditions with clear indication of the surface uplift. The climate during the Quaternary period was dry and cold, with sequence of glacial and interglacial stages.

Geological and hydrogeological settings

The oldest rocks outcropping on the hill are Middle Jurassic, mostly mudstones and marls (Fig. 2). The Yavorets Formation (Middle Jurassic – Low Cretaceous) and the Salash Formation (Low Cretaceous) in the area are built from micritic limestone. The younger Cretaceous rocks in the area are mainly marls and sandstones (Filipov, 1995b).

Neogene sediments are built from clays, sands and locally reef limestone. The most permeable is the Dimovo Formation built from sands, sandstones and sandy limestone. Quaternary sediments are of different genesis – alluvial, proluvial, deluvial, colluvial. The oldest Quaternary deposits are covering gravels of alluvial-proluvial genesis thick several meters found at high elevations above ~ 190 m. A thrust is identified along the Botunya River near to the spring issue. It is shown on the geological map and on the cross-section (Filipov, 1995a).

Fissured-karst groundwater system was developed in Mesozoic carbonate rock. The recharge of karst waters occurs on the account of precipitation. The groundwater is discharged by several springs, the most important of which are Palilula and the spring in the village of Belotintsi, with a flow rate of 10 l/s (Antonov, Danchev, 1980). The main drainage artery northeast from the Pastrina hill is the Botunya River. The groundwater is partly drained by the Shugavitsa and Ogosta Rivers through the alluvium in the reaches where their valleys cross the outcrops of limestone of Mesozoic age (near the village of Erden and southeast of the village of Nikolovo). The specific discharge of the karst aquifer is assessed as 5 l/s.km² (Antonov, Danchev, 1980). In the exposed part of the aquifer, the groundwater is vulnerable to pollution from the surface.

The surface catchment area of the Palilula spring is only 24.5 km² (Fig. 3) which may contribute not more than one half of the spring discharge. Certainly, additional recharge of karst aquifer from river waters occurs.

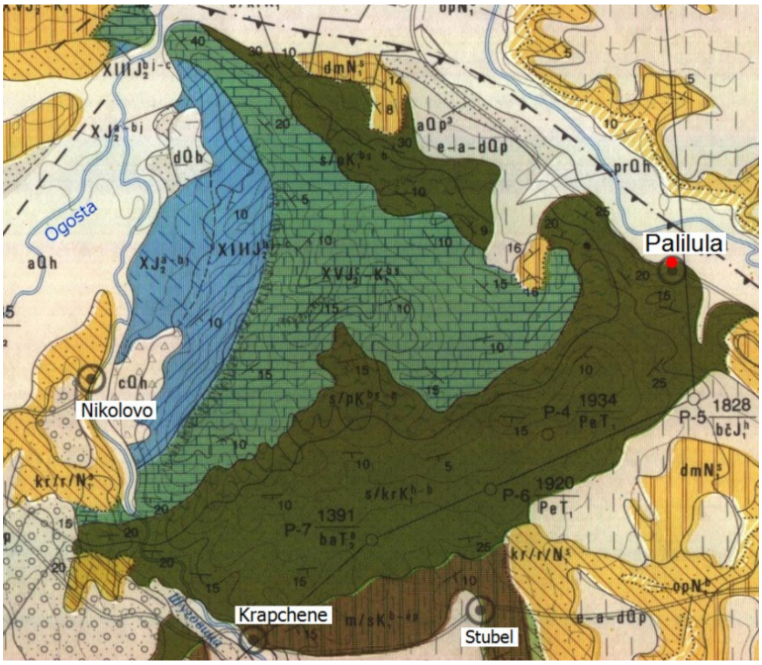

Fig. 2. Fragment of the geological map (Fillipov, 1995a) (aQ – Quaternary gravel, sand, loess; N_1s – Neogene clay, sand, limestone; sK_1h-b – Salash Formation - limestone, marls)

From spring to autumn 2004 hydrogeologists P. St. Petrov and P. Gerginov performed field explorations of the Pastrina hill and its surroundings. They determined strike and dip of beds and joints in outcrops uphill from the village of Palilula and proved the main direction of the karst waters – from southwest to northeast towards the spring issue (Fig. 3). During several observations of the Shugavitsa River in the vicinity of the villages of Dolno Belotintsi and Nikolovo they registered intermittent drying of this river in separate reaches (in summer and autumn).

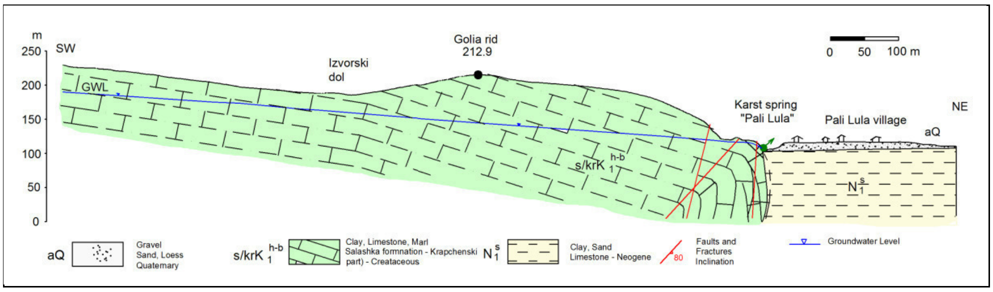

Fig. 3. Geological/hydrogeological cross-section of catchment area of Palilula karst spring by P.St. Petrov and P.Gerginov (aQ – gravel, sand, loess; N_1s – clay, sand, limestones; s/krK_1h-b – clayey limestone, limestone, marls; GWL – groundwater level)

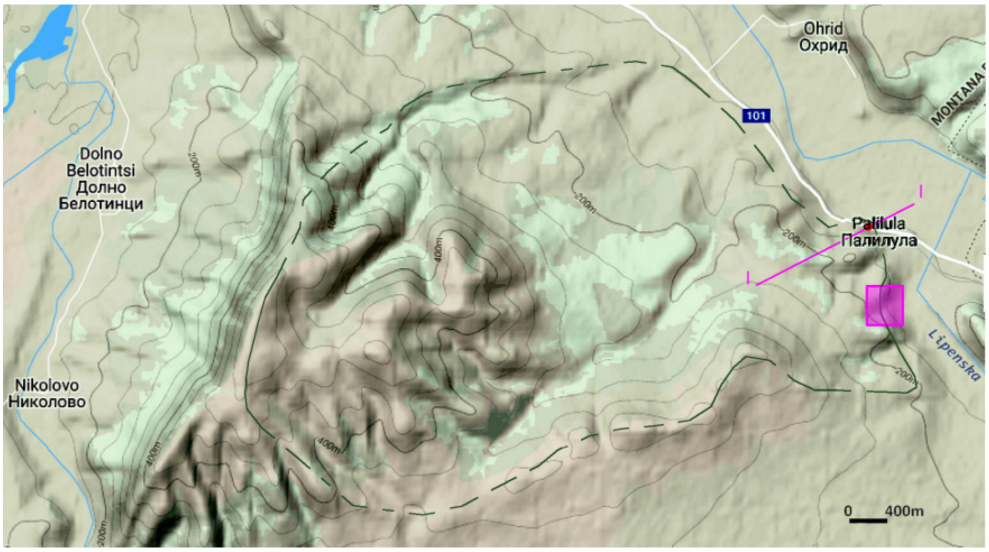

Fig. 4. Catchment area of Palilula karst spring on topographic map (dashed line – catchment area; I-I – cross-section; square mark - possible location of river water inflow into karst system)

During field trips in 2004 they confirmed that the groundwater receives additional recharge from inflow of river waters. About 1325 m south of the spring issue in the locality Yamite at elevations from 127 to 123 m, the Lipenska River (a tributary of the Botunya) is meandering and strongly reduces its discharge. From there, about 600 m downstream, the river is losing. Obviously, influation of the river waters into karstified rocks, which occurs through the alluvium, contribute to increasing spring discharge (Fig. 4).

The geological structure shows that the amplitude of heights was higher before the deposition of Neogene sediments, compared to the present-day relief, mostly on the account of the deep erosion valleys (about one hundred meters deep). Steep topography favored development of karst conduits that ended with palaeo-springs. Subsequent deposition of the Neogene sediments led to rising of the erosion level and subsequently rising of the springs' issues. In such way older conduits were flooded, as a result they enhance the storage capacity of the spring. Similar development is described by Bakalowicz (2015) for the Mediterranean karst systems related to basins and grabens.

Regime and specific features of the karst spring Palilula

The karst spring Palilula appears at the contact of the Mesozoic and low permeable Neogene rocks at elevation 104 m asl. It is measured using a current meter once or twice a month since 1959. Daily data on water stage are available from 1964, which are transformed to daily data of discharge by means of rating curves. The spring is used for rural water supply, it is tapped by a drainage long 35 m. The average annual spring discharge for the period 1960-2016 is 265 l/s. The groundwater is fresh (TDS about 500mg/l) of calcium-bicarbonate type with medium hardness (Tzankov, 1993). The waters sporadically show enhanced ammonium content slightly above 0.5 mg/l. This fact along with the observed turbidity of the spring (2-3 hours after rainfalls) and episodically registered adverse microbiological status of the spring water may be explained by water inflow from the Lipenska River close to the spring.

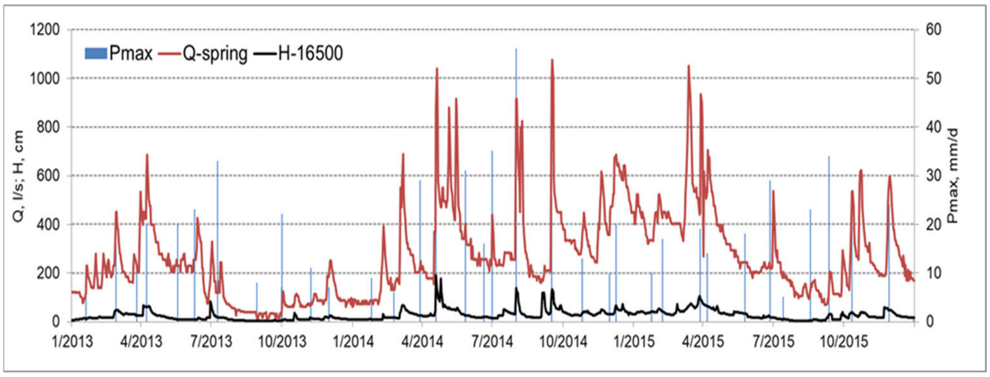

Fig. 5. Daily time-series of the karst spring discharge (Q, l/s), water stage at gage station N 16500 (H, cm) and monthly maxima of daily rainfall for station Montana (Pmax, mm/d)

To analyze the flow regime of the spring, the time-series of the spring discharge for the period 2009-2016 are put together on the graph with the monthly maxima of daily rainfall for station Montana (information taken from the monthly bulletins of the National Institute of Meteorology and Hydrology). The spring shows fast reaction to these monthly extreme rainfall events (Fig. 5 – for the period 2013-2015). The time-series of the springflow correlate with the water stage of the gage N 16500 – the Botunya River at Stoyanovo, upstream to the studied spring. These facts are evidence of the close relations of the aquifer with the land surface.

The temperature of karst water varies from 9.2°C to 16.4°C with mean value about 14°C. This enhanced and rather stable water temperature compared to the mean air temperature of the area (11°C) is evidence of deep circulation of a part of karst waters discharged in spring.

Conclusion

The specific features of the karst spring Palilula in Northwest Bulgaria are as follows:

- average annual spring discharge of 265 l/s;
- fast reaction of the discharge to the rainfall events;
- episodic signs of turbidity and microbial contamination;
- low variability of the water temperature (about 14°C).

In general, this karst aquifer presents a complex system where a mixture of warm groundwater and surface waters occur. Based on field explorations of the area, most possible location of inflow of surface waters is the Lipenska River (tributary of the Botunya River) in the locality "Yamite" south to the spring issue.

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GEOLOGICAL INDICATORS OF ACTIVE KARST IN THE REGIONS OF SULFATE-CARBONATE STRUCTURE (PERM REGION, RUSSIA)

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Abstract: Since the late 40's-early 50-ies of XX century to the present time, studies of the karst of the Perm school of the karst scientists based on regional geological, hydrogeological, structural-tectonic of a study regions, areas and sites. Long-term geological researches of areas of sulphate-carbonate deposits development allowed to establish a number of regularities in the distribution of the surface and underground karst forms. The main regularities in the form of graphic and cartographic models are presented in this paper. These regularities reflect the influence on the activity and intensity of karst phenomena of structural and tectonic elements, elements of the roof relief of karst deposits, the thickness and lithology of cover sediments, chemistry and groundwater level regime. Regularities have a prognostic value for the assessment of karst hazards.

Key words: region, geological factors, karst forms, karst hazard

Introduction

Perm Krai is located in the east of the Russian Plain (80% of the territory) and the western flank of the Ural mountains (20% of the territory). Most of the territory is composed of Paleozoic rocks, among which 72% is occupied by rocks of the Permian geological system. To be exact, among the Permian rocks have developed complex carbonate, sulfate and chloride formations exposed to intensive influence of karst process. In the region, the intensively karsted rocks (limestone, dolomite, gypsum, anhydrite, salt rock) aged from the Proterozoic to the upper-Permian crop out or underlay shallow on the areas over 30 thousand km^2 (Kataev & Ermolovich 2014).

The practice of karst forecasting recommends evaluating karst activity on the basis of individual features or a certain set of them, on the basis of preliminary zoning of the territory. This approach is rational, quite informative. But at the same time, this approach does not allow to receive full information about the nature and direction of the development of the karst process in order to build a forecast territorial model.

Geological structure and karst phenomena

The practice of karstological studies shows that the spatial combination of soluble and insoluble layers is one of the geological criteria of karstological evaluation. Analysis of the geological structure of the karst massifs allows to distinguish in their composition typical lithological complexes that determine the type of karst, often its morphological features and distribution of the surface and underground forms, and as a result – degree of stability of the investigated territory.

As an example, we present data on the types of geologic section and distribution of karst forms in the city of Kungur, Perm region. The results of drilling on the territory of Kungur allow to identify 7 basic types of combinations of karsting and overlying sediments with different structure and origin. The karst forms of Kungur are also characterized by highly heterogeneous distribution with high density of karst forms in some areas and practically no karst forms in others, which is due to peculiar features of the geological structure (Fig. 1).

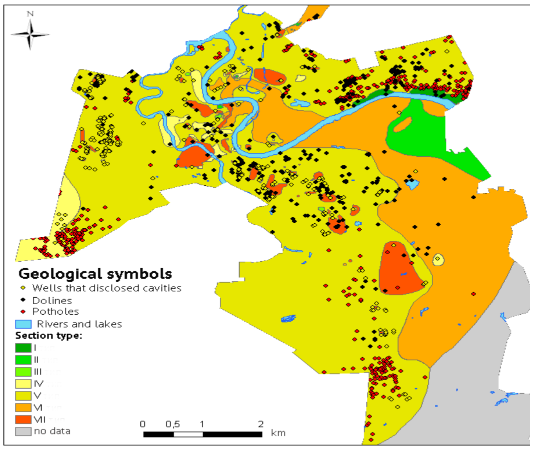

Fig. 1. Distribution of the different types of the geological sections and karst forms on the territory of North Kungur

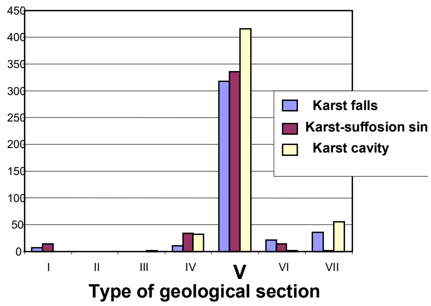

Fig. 2. Frequency of occurrence of karst forms within the territories with a certain type of geological section

Type **V** includes interbedded sulfate-carbonate sediments of the Iren horizon which are overlain by landslide-karst sediments of the Neogene-Quaternary age which, in turn, are covered by the Quaternary alluvial-deluvial deposits. This type occupies more than 60 % of the territory. Most of the karst forms dedicated to this type of geological section: 336 potholes, 318 dolines, and 416 cavities (Fig. 2) (Kovaleva & Kataev 2014).

Note that the same regularities in the distribution of the surface and underground karst forms are recorded and on the territory of Dzerzhinsk city (Nizhny Novgorod region, Russia), where among of the 4 types of geologic cross-sections more than 60% of sinkholes and karst sinkholes were formed within the limits of I and II types of geologic cross-sections, which combines layers of gypsum (P_1s), limestone and dolomite (P_2kz), overlain by clays ($P_{3(TT)}$) or sand (Q_{I-IV}) (Mulder et al. 2004).

Tectonic disjunctives and karst forms

Structural and tectonic features of the massif are primary "background framework" on which dynamic processes of natural or natural-technogenic modeling of karst are development. Detection of the structural regularities of near-surface part of a massif and their connection with the karst phenomena – composite process and not always effective. Nevertheless, such of regularity and such connections, though and in the latent shape, but exist in the nature. Their installation much more easies the solution of the theoretical and practical problems of the karstological forecast.

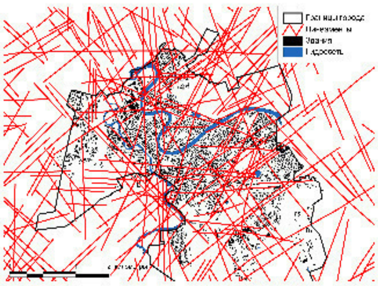

Fig. 3. Map of the lineaments distribution on territory of the Kungur city, Perm Krai

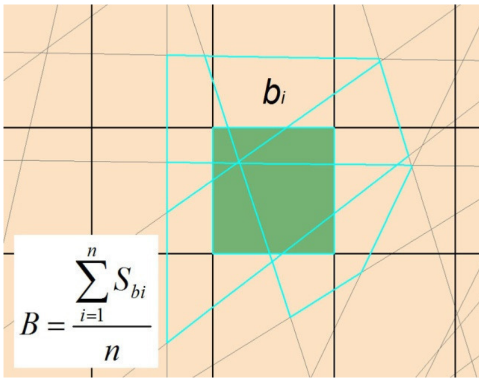

Fig. 4. An example definition of indicator B – the size of the blocks bounded by lineaments

Thus, establishing the degree of spatial correlation of fault tectonics and karst manifestations is an important criterion of karst prognosis. Geodynamic activity of the territory can be determined by results of aerospace mapping of lineaments and construction of special maps (Fig. 3). The spatial configuration of the lineament network can be estimated through four experimental indicators established for a conditional unit of the investigated area: linear density of lineaments (L); the number of lineaments intersections (K); the distance of the karst form from the lineament (U); the size of the blocks bounded by lineaments (B) (Fig. 4) (Zolotarev et al. 2009). The most bright regularities in the form of graphic models identified for areas of sulfate-carbonate karst development are shown in the figures 5 and 6.

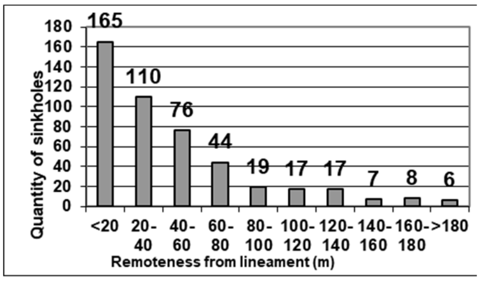

Fig. 5. Ratio of remoteness from lineament axial zone (axis X) to number of karst collapse (axis Y)

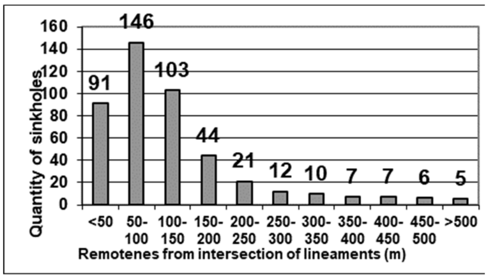

Fig. 6. Ratio of remoteness from lineament intersections (axis X) to number of karst collapse (axis Y)

The activity of karst phenomena depending on the thickness of karsted deposits and thickness of cover deposits

Data on the thickness of karsted strata and overlying sediments combined with the karst environment are the criteria of karstological assessment (Kataev et al. 2009). It is obvious that the thickness of karst rocks, being in the zone of active water exchange, is the main element of the geological section, which coincides with the interval of active development of underground (cavity) forms of karst. Thickness of karsted bed varies and, accordingly, this change is changing the intensity of karst forms. In the distribution of cavities in General revealed the following dependence: the majority of them are encountered in the drilling of cavities corresponds to the thickness of karsted rocks from 30 to 45 m. as decreasing thickness from 30 m to 5 m number of cavities decreases proportionally. The number of cavities decreases and the thickness increases from 45 to 55 m and more.

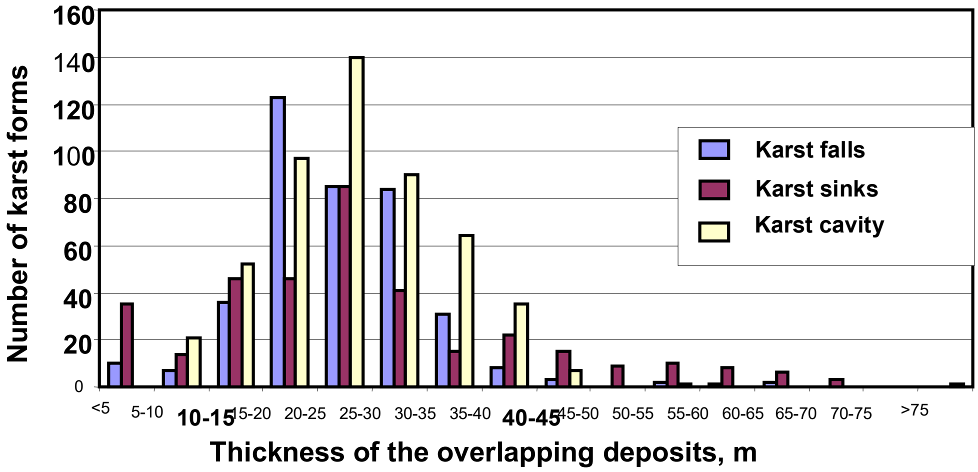

Fig. 7. The frequency of occurrence of the karst forms within the territories with different thickness of the overlapping deposits

As a rule, within the areas where the complex of overlapping deposits has a thickness more than 50m, the degree of manifestation of karst forms is low. A high degree of manifestation of karst forms is present in areas where the power of the covers from 10 to 30-35m (Fig. 7). In the General case, the karst territory, overlain by sandy sediments in karst respect more dangerous than the territory, overlain by clayey and loamy sediments. For example, under conditions of territories with carbonate and sulfate karst development in Priuralie (Russia) where the capacity of solikamsk blocking deposits is less than 50 m (at the average capacity of the horizon 105 m), surface karstic forms develop everywhere regardless from geomorphological characteristic of sites with their maximum occurrence in river valleys and in arches of tectonic elevations.

Underground water, their chemistry and karst occurrence

In massifs of karsted rocks there is an effect of local dynamic changes of the hydrogeological parameters, spatially connected with zones and sites of the in-creased density of fissures, breakage, faults zones. The effect intensifies within the areas of neotectonic activity. Here specific water inflows reach maxima, the mineralization of underground waters sharply raises. Changes have a wide range of the periods, in-cluding intra-day.

As a result of the conducted researches it became obvious that the karst prediction has to be based on the revealed local regularities of dynamic changes of parameters of a water abundance and a chemical composition of the underground waters which are at the same time an indicator of activity of hydrogeological processes, including processes of an under-ground erosion and dissolution. Territorially places of similar changes are sites and zones of potential development of underground karst cavities. In practice, the sites, characterized by hydrogeological and hydrogeochemical parameters with short cycles of variations (sites of an unstable chemical mode, sharp changes of water level), localize sites of potential collapse hazard (Kataev & Ermolovich 2013).

Spatial comparison of sites with different intensity of karst cavities development and sites characterized by different degree of underground waters mineralization from the horizon of the karst rocks suggests that most of the uncovered karst cavities identified within areas where present waters with mineralization from 2 to 4 g/dm^3 (Fig. 8). The number of cavities fixed during drilling is sharply reduced in areas with higher or lower mineralization values.

Correlation analysis between the squares of the areas of spread of underground waters with different values of mineralization and the number recorded within karst sinkholes and cavities, shows their close relationship. The correlation coefficients are 0.98 and 0.97, respectively.

The facies composition of groundwater iranskogo aquifer are quite diverse. According to the results of chemical testing of groundwater, 18 types of facies are identified, of which the predominant in the area ratio is hydrochemical facies SO_4-Ca-HCO_3, which occupies most of the surveyed area (Fig. 9). This diversity of underground water facies is largely due to both the solvent activity of karst waters and the influence on the chemical composition of industrial and domestic wastewater. From the above data, it is clear that the predominant majority of karst dips and karst cavities are confined to the territories with the distribution of groundwater of SO_4-Ca-HCO_3 composition.

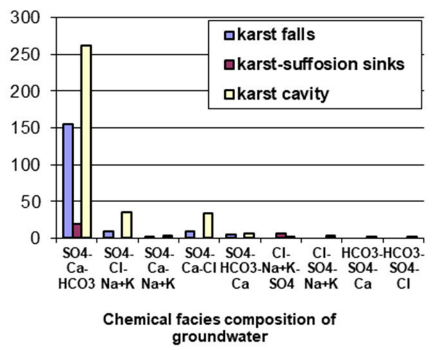

Fig. 8. Mineralization of underground waters (mg/dm^3) and karst forms (axis Y)

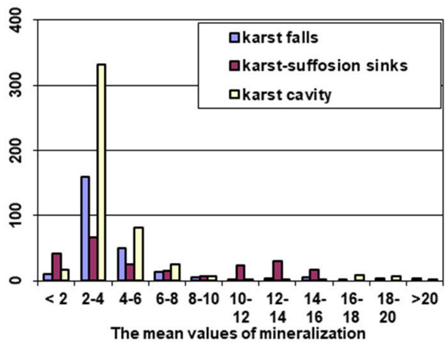

Figure 9. Frequency of occurrence of karst forms (axis Y) within the areas with different facies composition of groundwater

Conclusions

To date, a large number of various methods for estimating and predicting karst activity at different scale levels, based not only on the established regularities of spatial manifestation of karst on the earth's surface, have been recommended for practical use. Despite this, the problem of integrated assessment of karst hazard, which is based on the most complete account of the features of the structure of the study area, remains very relevant. Especially difficult is the assessment of karst hazard and its forecast within the boundaries of urban agglomerations, where the man-made impact on the natural regime of karst processes is becoming more and more large in time. The analysis of features of geologic structure of the territory, expressed quantitatively and their further spatial comparison to sites of the karst forms development allows to carry out quantitative and qualitative karst forecast with the big degree of confidence.
The listed factors, being criteria of the geological and hydrogeological analysis have to be considered in a complex, as they supplement each other, and are form in aggregate the geological situation in which karst process develops.

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KARST HYDROGEOLOGICAL SYSTEM KALIPOLJE – BUKOVIK (JAVOR MOUNTAIN, SOUTHWESTERN SERBIA)

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Abstract:
The karst hydrogeological system Kalipolje-Bukovik consists of several hydrogeological and morphological phenomena forming two hydrogeological cycles in the karst: Korićansko spring, Kalipolje river, Kalipolje valley, the swallow hole of the Kalipolje river, Bukovik cave and Vrševina spring. It is located in the area of the village of Bukovik, on the massif of the Javor mountain. Korićansko spring is the permanent and contact gravitational karst spring. The karst spring forms the flow of the Kalipolje river that runs down the Kalipolje karst valley all the way to ponor. The ponor consists of several holes in the limestone rock mass in which water sinks. Bukovik cave is a typical multi-storey cave with three levels. Vrševina spring is also a permanent gravitational karst spring. In 2009, the flow of Vrševina disappeared twice at the same site downstream from the spring. The swallow hole was closed, and the flow reversed to its bed.

Key words: Kalipolje-Bukovik, Korićansko karst spring, Karst spring of Vrševina, Kalipolje river, Kalipolje valley, Bukovik cave

INTRODUCTION

Bukovik cave was placed under protection in 1975 as a Natural Monument. Research was conducted between 2002 and 2015 for the purpose of revising the protection status. On that occasion, it was established that the cave is one of several phenomena functionally interconnected into a single karst hydrogeological system (KHS) called "Hydrological Complex Kalipolje-Bukovik".
KHS is located in the village of Bukovik, on the southwestern slopes of the Javor mountain, on the right bank of the Sjenica lake (Uvac river), on the territory of the Municipality of Nova Varoš. Korićansko spring, Kalipolje river, Kalipolje valley, the ponor of the Kalipolje river are located in the hamlet of Korićani (Ljepojevići), while the Bukovik cave and Vrševina spring are located in the hamlet of Kurćubići (Ljepojevići).

KORIĆANSKO SPRING

Korićansko spring is located on the eastern edge of the Kalipolje valley, 100 m below the old road Ivanjica-Sjenica (X–4809714; Y–7422529; Z–1232).
Korićansko spring (Fig. 1) is a permanent gravitational karst spring. Its position is predisposed by the contact of karstified Middle Triassic limestone with

impermeable or less permeable Late Triassic schistous substrate of Kalipolje. Concentric outflow is predisposed by the point of intersection of the traverse crack with the inter-layer discontinuity. Crack from which water probably flows out during the high water level period is located about 1 m above the outflow point.

The spring drains a large Middle Triassic limestone karst massif in the hinterland north of the spring (Figure 2), which stretches around Jankov vrh peak (1492) towards the site of Stena and Saborište peak (1344). The karst massif is open to the surface and karstified evidenced by numerous, linearly positioned sinkholes located on the flat areas of the massif, thus conditions for recharge from precipitation are highly favorable.

The spring is primitively tapped for the water supply of rural households, and the flow is used to water cattle. Remains of a water mill are located next to the spring.

Fig. 1 Korićansko spring

Observed characteristics of spring and water:

- July 23, 2009: Yield estimated at about 100 l/s;
- June 16, 2014: T=8.6°C; pH=7.5; Ec=380 μS/cm; Q=105.7 l/s;
- October 6, 2014: T=8.5°C; pH=7.72; Ec=370 μS/cm; Yield greater than the previous time.

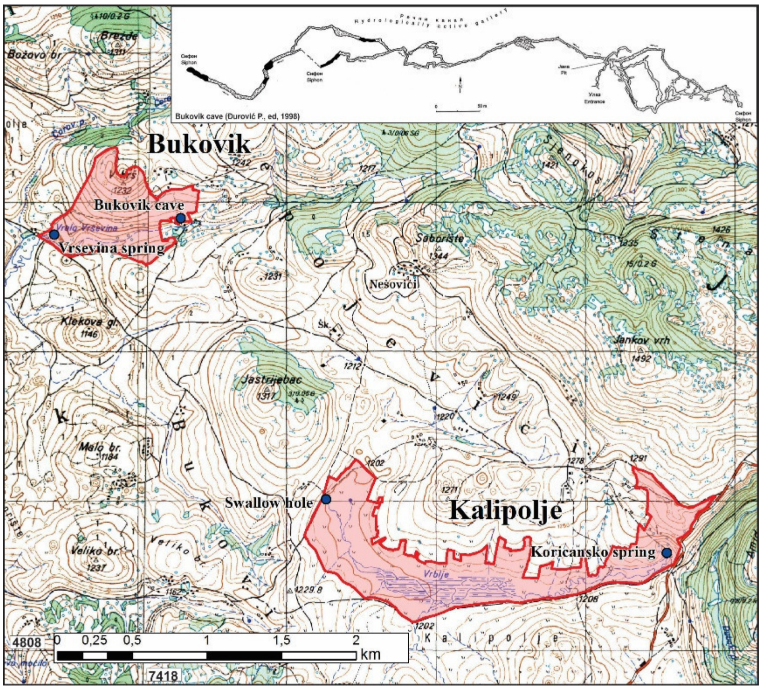

Fig. 2. KHS Kalipolje – Bukovik – the borders of the Natural Monument and cave layout

KALIPOLJE – KALIPOLJE RIVER VALLEY

Korićansko spring forms the flow of the **Kalipolje river** which runs in the east-west direction through the Kalipolje valley to the pomor on the western edge of the valley. **Kalipolje** is a large depression, flattened at the bottom, through which the Kalipolje river runs. It represents the widened valley of the Kalipolje river. Like the river, Kalipolje begins at Korićansko spring in the east and ends as a steephead valley at the ponor of the Kalipolje river in the west. Kalipolje resembles a karst field.

Small wetland of Vrblje with characteristic vegetation has been formed in the central part of Kalipolje.

PONOR (SWALLOW HOLE) OF THE KALIPOLJE RIVER

Swallow hole (ponor) of the Kalipolje river is located in the north-western edge of the Kalipolje valley, just below the old road Bukovik – Ljepojevići (X–4810020; Y–7420257; Z-1209). It consists of several holes in the limestone rock mass in which water sinks. Downstream from the recent sinking point there is a series of paleoponors in which the river sank in the past, and with the development of the karst process, the sinking point regressively receded. Paleoponor have recently gone through fluvial process and have the form of small alluvial sinkholes. Some paleoponors active during the high water level periods when the recent sinking point cannot receive water. Their swallowing capacity is reduced due to fluvial filling and waters ponds up.

BUKOVIK CAVE

Bukovik cave has formed in the elongated limestone massif of Golo brdo (1232) and Čekarevina (1232), which slightly rises above the vast area of Bukovik (Petrović J., 1988).

The entrance to the Bukovik cave is located on the southern slope of the limestone Gola glava, at an absolute height of 1162 m, behind the Kurćubić family home. The entrance is 2.5x1.5 m and is located at the bottom of a small vertical escarpment (X–4811883; Y–7419277; Z-1163).

"Bukovik cave is the only spring-type cave which is located high above the Uvac canyon on the southern slope of the Javor mountain" (Petrović J., 1988).

Bukovik cave is a typical multi-storey cave with three levels: Upper Passage (Gornji kanal), Middle Passage (Srednji kanal) and Lower Passage (Donji kanal).

Bukovic cave is a geoheritage site according to the Inventory of Serbian Geoheritage Sites (2005) – Speleological heritage sites (No. 8).

Upper Passage (level)

According to J. Petrović (1988) – Entrance Gallery (Ulazna galerija). This is the highest level of the cave and is located just below the surface of the southern slope of Golo brdo, at a relative height of about 10 m from the Vrševina river basin (Petrović J., 1988). Upper Passage is simple, moderately winding, and relatively short. After the narrow entrance, the entrance passage further narrows and after about 30 meters is between 0.5 and 1 m in height and width. The bottom is covered with dry clay deposits. The passage then widens into a 12 m wide, 6 m high chamber which is predominantly dry and has speleothems. There is a narrow opening in the floor in the central part of the chamber which connects Upper Passage to Middle Passage and Lower Passage through a large chamber.

Middle Passage (level) – passage with speleothems

At the twelfth meter from the opening in the floor of the Upper Passage there is a shelf which represents an entrance from the Central Chamber to the middle level of the cave or the Middle Passage, according to J. Petrović (1988) – Gallery of maze channels, the most complex and diverse part of the cave system, below which is the entrance to the Lower Passage. The Middle Passage is at the same level as the underdeveloped basin of the Vrševina river.

The Middle Passage consists of two semicircular passages which include a number of galleries, chambers and narrow side-passages. Chambers are interconnected with passages, corridors, and often narrow passages. Parts of the Middle Passage are partially connected with the Lower – river level with vertical and subvertical passages. The wide entrance to the Middle Passage is open to the vertical level, Central Chamber, that is, to the Lower, River Passage. J. Petrović (1988) in the Middle level highlights several significant units such as – Kristalni kanal, Viseći kanal, Široki hodnik, Kanal deda-mraza, Kosi hodnik, Viseći kanjon and Laktasti kanal.

Stalactites are of medium thickness and different lengths. Stalagmites are rare and usually short. Salivary stones dominate in the aforementioned chambers and galleries. Almost all of them are large, lavish and colorful. Salivary stones often close or mask passages between chambers. There are also tufa tubs in the floor and other forms (Petrović J., 1988).

Kristalni kanal begins with a 14 m wide and 12 m high chamber and continues with a 3-15 m wide and up to 15 m high passage. It consists of multiple chambers, corridors, verticals and blind passages, and it is the central and most important part of the Middle level and J. Petrović describes it as "the backbone of the second gallery and the whole cave system".

The floor of the Middle Passage is predominantly covered with tufa deposits.

Lower Passage (level) – River Passage

Vertical passage or the central chamber which stretches from the opening in the floor of the Upper Passage is intersected by the Lower Passage at the bottom level. This passage is the lowest level of the cave and it is hydrologically active, i.e. permanent subterranean flow runs through this passage. The Lower Level is represented by a long, relatively simple (moderately branched) passage. General orientation of the Lower Passage is east-west, generally at right angle to the direction of the Upper Passage.

According to J. Petrović (1988) this River Gallery is 30-40 m below the level of the Vrševina river basin.

The Lower passage begins with a small chamber 20x30 m with a siphon lake (Petrović J., 1988). This siphon lake feeds the flow which runs along the entire Lower Passage. The chamber ends with a 10 m cascade which forms a waterfall (Petrović J., 1988). Downstream of the waterfall there are a dozen smaller cascades. At this point, the Lower Passage is 25 m below the Middle Passage and 40 m below the Upper Passage (Petrović J., 1988). The Lower Passage is between 1 and 3 m wide. Flattened shelf up to 10 m wide stretches along passage at a height of 20-25 m.

At several places, starting from the siphon, the Lower Passage is connected to the Middle Passage through sloping and vertical passages, ending with the Central Chamber through which it is connected to the Upper Passage.

In canyon parts of the Lower Passage there are giant pots with gravel and sand fpoм schists and ultramafites.

J. Petrović (1988) claims that the flow from the Lower Passage of the Bukovik cave drains part of the southern slopes of the Javor mountain and the most of the Bukovik area. He argues that this is evidenced by the absence of large sources in the right side of the Uvac canyon.

Microclimate

The average annual air temperature of the Bukovik area is 9.5 °C. The air temperature in the Lower Passage is 11.5 °C. The warmest part of the cave is the Middle Passage with a temperature of 12.5 °C (Petrović J., 1988). The air temperature of the Upper Passage varies drastically and is in line with the outdoor temperature, ranging from -12 °C to 16 °C. The Upper Passage has strong air flows, which in winter reach up to 4 m/s (Petrović J., 1988).

VRŠEVINA SPRING

Vrševina spring is located about 30 m from the local road, near the road Nova Varoš – Štitkovo (X–4811799; Y–7418412; Z–1120), at the end of the lower river passage of the Bukovik cave.

Vrševina spring is a permanent gravitational karst spring. It position is predisposed by the contact of karstified Middle Triassic limestone with impermeable substrate formed by quartz conglomerates and Permian-Triassic sandstone. The spring is represented by a source consisting of three large concentric outflow phenomena whose flows merge after about 10 meters forming a single course of the Vrševina river which flows into the Uvac river downstream from the Rastoka dam.

On the massif of Gola glava, 13 m above the spring, there is a notch from which water flows out during the high water level period. This is evidenced by a dry shallow basin from the notch to the permanent sources whose steep bottom is covered with large debris and limestone blocks. Therefore, during this period, the water level in the cave, i.e. in the Lower, River Passage increases by at least 13 m.

Vrševina spring is named by J. Petrović (1988) as Spring in Čekarevina. According to this author, the yield of the spring is from 0.18 to 7.6 m^3/s. The primary maximum is in the spring after snow melting and secondary in autumn.

The primary minimum is during the winter, and the secondary is at the end of the year. The water temperature in the spring ranges from 6.5 °C to 10.5 °C (Petrović J., 1988). Waters of the Vrševina spring are used for the pond located next to the spring. Downstream from the spring the entire flow is used to water cattle.

Observed characteristics of spring and water:
June 29, 2009: Yield estimated at about 500-600 l/s.

June 18, 2014: T=9.3-10.5°C; pH=7.4-7.6; Ec=170-190 μS/cm; Total yield: Q=457,6 l/s.

October 6, 2014: Ec=620 μS/cm; Yield greater than the previous time.

DISAPPEARANCE OF THE FLOW OF VRŠEVINA
Vrševina spring forms the Vrševina river which after 7 km flows into the Uvac river as it right tributary, about 5 km downstream from the Rastoka dam.
In the summer of 2009, about 300-500 m downstream from the spring, the flow of the Vrševina river disappeared twice at the same site.

Figure 3: Site where the flow of Vrševina disappeared

First time, between July 8 and 9, the flow of Vrševina opened a sinkhole in the basin and disappeared in karst subterrain. Its basin, located downstream from that site, dried up. This event caused serious problems to the local people who used the flow to water cattle. The local Municipality took action. The swallow hole was closed and the flow reversed to its bed.

Several days later on July 21, the flow opened up a swallow hole at the same site and disappeared underground again. Another intervention followed, the swallow hole was closed, and the flow reversed to its downstream bed.

It remains unknown to this day whether the Vrševina river has disappeared again. Unfortunately, no research has been conducted in order to establish any details related to the disappearance of the flow of the Vrševina river, primarily where it might re-appear.

PROTECTION

After the conducted research in the procedure for the revision of the protection of protected natural area – Natural Monument "Bukovik cave", in addition to the cave itself, the other previously described phenomena was recorded and their interrelated functional connection to a unique karstic hydrogeological system with high natural values and properties of a natural area was established. On the basis of the results of the research, a Conservation Study was drafted which proposes a much wider area for protection, which includes all aforementioned phenomena.

The karst hydrogeological system called "Hydrological Complex Kalipolje-Bukovik" was designated as a "Natural Monument" in accordance with the legislation in force. It was evaluated as a natural area of the II category – Protected area of regional or great importance. The protection regime of II degree was proposed as well as the protected area equal to 139.2145 ha divided into two sections. The western, smaller section "Bukovik" includes the previously protected Bukovik cave and Vrševina spring. The eastern, larger section "Kalipolje" includes Korićansko spring, Kalipolje river, Kalipolje valley with the small wetland of Vrblje, and the swallow hole of the Kalipolje river. The adoption of a new protection act is in the process.

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KARST SUFFOSION PROCESSES IN MOSCOW CITY AND THE PROBLEM OF EVALUATING THEIR HAZARD

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Abstract: One of the serious problems creating a real threat to existing buildings in Moscow is the possibility of developing karst suffosion processes with the formation of sinkholes on the surface of the earth. The work presents a fundamentally new mechanism for the development of these dangerous processes, the principles of zoning the city on the basis of typing geological and hydrogeological conditions for the development of suffosion sinkholes are proposed. Based on a deep engineering and geological analysis of the data obtained, it is recommended to improve the regulatory and methodological base for engineering surveys in the karst areas of Moscow.

Key words: Karst suffosion processes (KSP), suffosion sinkholes (SSH), karst suffosion hazards (KSH), Zoning by conditions of karst suffosion hazards, SSH forming mechanism.

Dedicated study of processes resulting in formation of craters on the ground surface in Moscow city started at the end of 1960s. Cases of deformation and destruction of buildings were known by that time.

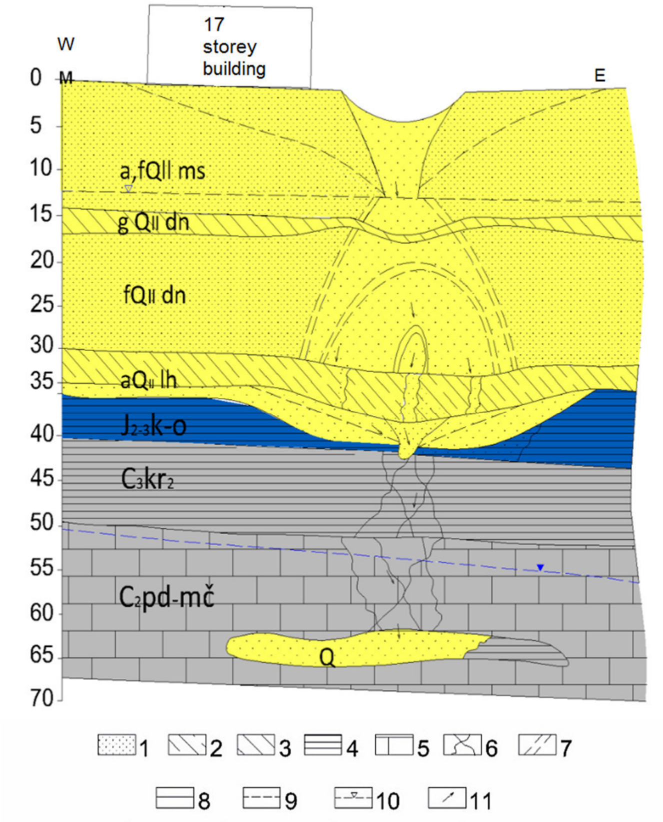
By now 42 suffosion sinkholes (SSH) have been found, all of them are in the north-western part of Moscow; 4 residential buildings have been destroyed, all their residents have been timely evacuated, no one has been harmed in the incidents. This indicates that hazards of developing of karst suffosion processes (KSP) on the territory of Moscow are quite real. Importance of evaluating karst suffosion hazards (KSH) is beyond doubt.

Contemporary methods of evaluating KSH on the territory of Moscow are regulated by the following documents: SP (Regulations) 47.13330.2012, SP 22.13330.11, SP 24.13330.2011 (8-10), Map of Hazards for Ancient Sinkhole Forms and Contemporary KSP in Scale 1:10,000 (2), «Guidelines …» (1). When doing so, it is first determined what hazard zone a site of detailed geotechnical survey belongs to (usually in scale 1:200–1:2,000). If such sites happen to be situated in hazardous or potentially hazardous area, then, according to (11), it is necessary to obtain the value of sinkhole calculated diameter. Applying this parameter can often result in insufficient protection of buildings and structures at really hazardous areas, and, on the contrary, to overrating the required protection measures at potentially hazardous areas, which, after the detailed geotechnical survey, turn to be non-hazardous. Majority of experts acknowledge that the content of geotechnical survey regulations for areas prone to formation of sinkholes needs to be changed and improved. The existing calculation schemes are often used without sufficient grounds, and the result is sometimes adjusted to fit the values required by designers and builders.

Probabilistic statistical methods are used for karst areas, but they are inapplicable for Moscow because, in the first place, Moscow is prone to karst suffosion subsidence, not sinkholes, and, secondly, there is not enough data for applying these methods.

The caving mechanism in many calculation schemes often assumes presence of a karst cavern in the karsted calcareous soil block top, into which the overlaying Jurassic and/or upper coal clays with subsequent suffosion of the overlaying sand material into the karst caverns and cracks.

As a result of comprehensive geotechnical studies in the north-west of Moscow, a mechanism of SSH formation (3-7) was revealed, which significantly differs from the ones described above (Fig.). Thus, an abrupt change of the ground water level in the coal formations (about 2-5 m for 1-2 days) results in hydrodynamic fracture of relatively watertight clays in the places of their increased fissuring and lesser thickness. Such zones can be very small, 0.1–0.5 m in diameter. Under impact of vertical infiltration gradient, the water breaks through discontinuity of the confining layer and Quaternary sands suffuse the karsted calcareous soil block. Due to this, the lower part of the sand formation above this zone becomes loose. Then the process develops bottom-upwards, taking over more and more parts of the section. A particular “loosened dome” is formed in the aquifer. When the “dome” reaches the ground waters level (GWL), the sand mass of the aeration zone is redistributed, and a “loosened cone” with its point directed downwards is formed there, below which the subsidence crater appears.



1-sand, 2 – sand dust, 3 – loam, 4 – clay,
5 – limestone, 6 –fracture; Geodynamical disturbed zones identified by: 7 – results of VES,
8 – results of dynamic penetration tests,
9 – proposed;
10 – groundwater level,
11 – direction of moving of sand masses

Fig.1. Formation of Karst Suffosion Sinkhole

The dimensions and rate of the crater development are determined mainly by the GWL depth, location of piezometric surface of ground water in coal formations, presence of clayey interlayers in the aquifer and in the aeration zone, their thickness and depth, as well as the amount of sand material able to suffuse the karsted soil block. Spreading of loosened zones from the Jurassic clay top to the ground surface can last up to 2 months (4), thus in the Moscow region we deal not with fast caving in but with relatively slow karst suffosion subsidence. Unfortunately, a calculation scheme adequately describing the suggested KSP mechanism has not been developed yet. It is the subject of further studies of this paper's authors. Analysis of all the studied craters demonstrated that their average size in plane is 13.1 m, varying from 1.5 to 53 m; there are such sizes as 20, 22, 24, 28, and 40 m. Whereby all calculations for possible crater diameters performed when doing geotechnical survey in Moscow are often reduced to values below 3 m, sometimes reaching 5-6 m and rarely 10-12 m.

Therefore, it doesn't seem possible to apply to Moscow any of the existing calculation schemes for SSH diameter evaluation, and substantiating karst hazards mainly depend on accuracy and correctness of evaluating KSH by the existing and prescribed Zoning Map ... (2) and «Guidelines ...» (1).

Detailed examination of the above regulatory documents demonstrated urgency for their review, change and improvement taking into account the new results of detailed surveys at the sites where SSH develop (6).

Another approach was suggested in the work (5). Based on comprehensive geotechnical surveys, a detailed datasheet was compiled for each of the 42 known craters containing the following information: crater number, location, year of formation, size, structural position, paleogeomorphological characteristic, geomorphological characteristics of the surface, depth of the calcareous rock top, degree of cavernous porosity of the calcareous rock, confinement to ancient sinkholes, thickness and depth of aquifers, thickness of industrial sediments, depth of ground water level, vertical infiltration gradient. These SSH data were processed and the conditions of their formation were typified by similarity of the sites geo-hydrological structure. After that a surveyed site was evaluated in terms of its KSP hazards in relation to the revealed conditions types. The work was performed in 1:2,000 scale. Thus, in the first place, the method takes into account specific types of conditions in which all known SSH in Moscow actually were formed, secondly, zoning by conditions of ancient karst development at the highest taxonomic level allowed performing an overall territory evaluation in terms of KSH, as karst was the primary process. This approach to zoning allowed singling out two taxonomic levels within the territory - areas and districts. The sites are defined only within hazardous districts for approximation of those conditions differing in their complexity which are important in designing facilities with high criticality rating.

Based on the above, when performing specific zoning by degree of karst suffosion processes, it is necessary to take into account main criterial characteristics according to which the following territories were defined:

1. **Hazardous** - thickness of Jurassic clays is up to 5 m (presence of clays is mandatory).
The territory is characterized by high vertical infiltration gradient (more than 5), high degree of cavernous porosity of the calcareous rock, often with open karst caverns.
Construction of buildings and structures on such territories is not recommended. For existing buildings and structures, it is necessary to make regular geodetic observations, and on sites with abnormally fast surface subsidence - equipping the bearing structures with special deformation sensors transmitting the data to the regional monitoring panel. For such sites it is

necessary to envisage regular observations of ground water level with intervals not less than 3 times a month. At sites with active KSP, it is necessary to take sinkhole protection measures with consideration of specific geotechnical conditions and the buildings' design features.

2. **Potentially hazardous** - thickness of Jurassic clays are 5-10 m.
The territory is characterized by vertical infiltration gradients from 3 to 5. There is also high fissuring of the calcareous soil block.
During the design works, it is necessary to perform detailed geotechnical survey for each building, with drilling the karstified soil block up to 50 m from its top. It is recommended to erect buildings only on condition of taking sinkhole protection measures. For existing development area, it is necessary to make regular high precision geodetic observations at the sites with presence of ancient sinkholes and revealed zones with abnormally fast ground surface subsidence.

3. **Non-hazardous** - karst suffosion craters on the surface are absent, thickness of Jurassic clays exceeds 10 m, the total thickness of Jurassic and upper coal clays exceeds 12 m.
The territory is characterized by vertical infiltration gradients less than 3, low degree of cavernous porosity and fissuring of the calcareous soil block. It is sufficient to perform standard geotechnical survey for civil construction.
The presented approach to zoning and evaluation of karst suffosion hazards of surveyed areas, in our opinion, will allow performing maximally realistic evaluation of hazards for Moscow city territory in terms of KSP development. It is necessary to survey the whole north-western part of the city to carry out zoning of the territory. This will allow updating (1) and free geotechnical engineers from performing unnecessary calculations of sinkholes diameters. These calculations do not correspond to the KSP mechanism and result in inadequate evaluation of an areas hazards when performing geotechnical surveys.

Based on the performed analysis, we can recommend the following:
1. Carry out typological geotechnical zoning of the whole north-western part of Moscow in terms of KSH, taking into account a comprehensive analysis of particular conditions resulting in SSH development.
2. Develop a regulatory methodological basis on the ground of the existing "Guidelines..." (1), having updated it with new data on SSH formation conditions; in particular, to substantiate and select the criteria for KSP evaluation, and formalize them for greater convenience of use by geotechnical engineers.

3. Exclude from SP requirements the mandatory calculations of sinkhole diameter, as so far there is no adequate algorithm for such calculations for the territory of Moscow.
4. It is expedient to unite the efforts of specialists in creating mathematical tools for calculating SSH possible diameters and evaluating their hazards.

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THE SHOW CAVES IN NORTH BULGARIA: POSSIBILITIES FOR TECTONIC MONITORING

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Abstract: About a quarter part of the territory of Bulgaria (110,994 km^2) is occupied by karstified carbonate rocks of various ages – from Proterozoic to Neogene. More than 6,085 caves are mapped out to the present. The show caves in Bulgaria are twelve as eight of them are located in North Bulgaria. From west to east these caves are: Magura, Venetsa, Ledenika, Saeva Dupka, Bacho Kiro, Orlova Chuka, Biserna (Zandana) and at Kaliakra cape. Extensometers TM-71 are installed in four of them for monitoring of microtectonic movements. This paper points out the show caves in the karst regions of North Bulgaria and mentions the tectonic monitoring in some of them.

Key words: karst, show caves, tectonic monitoring, North Bulgaria.

The karstified rocks (marble, limestone, dolomite) in Bulgaria are exposed on 26,170 km^2 or 22.7% of the territory of the country (Popov, 1970). The karst is developed in carbonate rocks of different age – from Proterozoic marble in the high mountains of southern Bulgaria to Neogene limestone in NE Bulgaria. 6,085 caves are surveyed till now in the country according to Bulgarian Federation of Speleology Cave's Data Base. The longest cave in Bulgaria is Duhlata Cave in the south slope of Vitosha Mountain – multilevel maze system with surveyed length of 18,200 m. According to new discoveries in the last two years of "Pod Raba" Caving Club, village of Tserovo, the deepest cave is Kolkina Dupka Cave in West Stara Planina Mts. – 541 m till now. According to the hydrogeological conditions in Ponor Mountain, the depth potential of this 10300 m complicated active cave is more than 700 m (Benderev, 1989, Benderev *et al.*, 1987).

The main aim of this paper is to point out the show caves in the karst regions of North Bulgaria and to mention the tectonic monitoring in some of them.

Development of the cave tourism in Bulgaria: brief overview

The first data of tourist interest in caves dates back to the 70s and 80s of the 19th century. In 1882 a large expedition was organized in the town of Sliven for the study of Zmeevi Dupki Cave in the Balkan Range (Stara Planina Mt.). The "Savetnik" newspaper reports that the members of the expedition are accompanied to the cave by many people (Jalov, 2009[a]). At the end of the XIX century the popularity of the cave tourism increased. In 1899 the members of the first Bulgarian tourist society organized an excursion to the Shishmanitsa Cave (101 m long) near the Cherepish Monastery in the Stara Planina Iskar Gorge. Tourists also visit the caves near the village of Madara after the discovery, archaeological excavations and popularization of the Madara Horseman – the only rock bas-relief in Europe, currently on the UNESCO World Cultural and Historic Heritage List.

The most visited caves with local guides at this time were Bacho Kiro Cave, Temnata Dupka Cave, Ledenika Cave in Stara Planina (Balkan) Mts. and Lepenitsa Cave in Rhodopes Mts., South Bulgaria.

The organized speleology in Bulgaria begins in 1929 when the Bulgarian Caving Society was found from leading scientists of the Bulgarian Academy of Sciences and Sofia University. In 1930 a branch of the society was established in the village of Rakitovo in the Rhodope Mountains, and its activities consist mainly of organizing visits to the Lepenitsa Cave with mining lamps and guides. To prevent cave vandalism, the Rakitovo branch also appoints a guard of the cave (Jalov, 2009[b]).

In 1927 the members of the tourist society in the town of Dryanovo built an iron door at the entrance of Bacho Kiro Cave (Photo 1). In 1937 part of the cave was electrified for organized visits.

Photo 1. Members of Dryanovo Tourist Society at the entrance of Bacho Kiro Cave, twentieths of XX century (Dryanovo municipality archive http://www.dryanovo.bg.html).

Only 12 Bulgarian caves are electrified as show caves. Eight of them are located in North Bulgaria (Fig. 1). Several other caves are popular touristic landmarks without permanent lighting and guided tours with local cavers.

Microtectonic monitoring in Bulgarian caves

The mechanical extensometer TM-71 was developed in the Czech Republic by Dr. Blahoslav Kostak (Kostak, 1991). The gauge permit detection of extremely slow movements with accuracy of 0.05-0.0125 mm in all three space co-ordinates. TM-71 works on the principle of mechanical interference – Moiré effect, which records displacement as a fringe pattern on superposed optical grids. The details about the principle of the gauge are published in Kostak (1991). During the last decades the usage of extensometers TM-71 has been applied in several caves in Czech Republic, Slovakia, Belgium, Slovenia, Bulgaria and Poland (Šebela *et al.*, 2009).

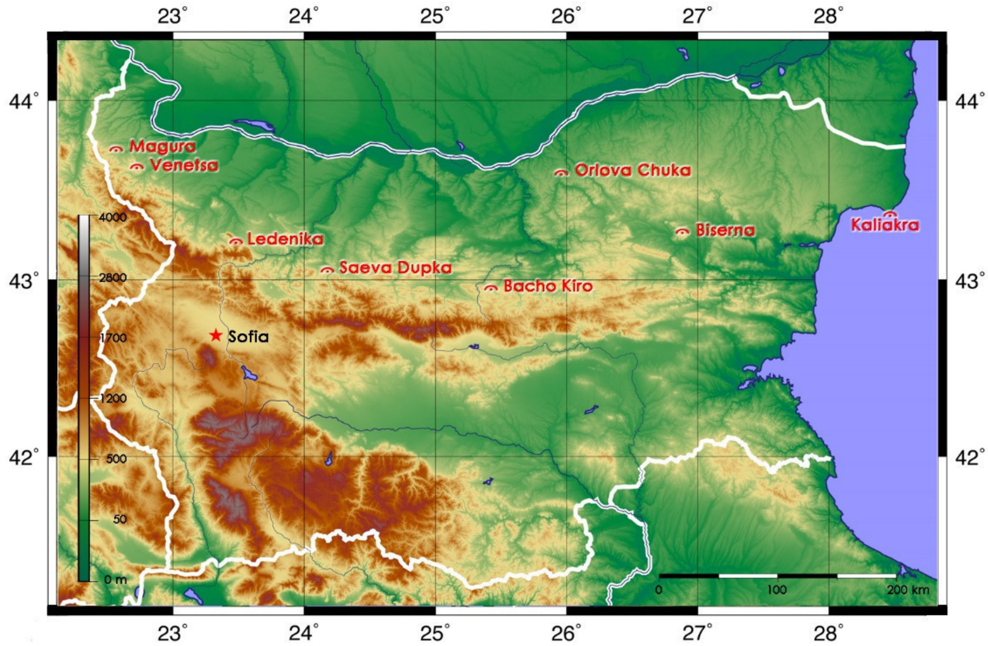

Fig. 1. Locations of the show caves in North Bulgaria

In seven Bulgarian caves are installed extensometers. The first one is Golyamata Tsepnatina Cave near the village of Madara, where TM-71 was installed in April 1990. The gauge is a part of monitoring system for study of the recent microdisplacements around the UNESCO monument Madara Horseman, together with other two gauges TM-71 near the Horseman bas-relief and a few pin marks. The data from the instruments are monitored by the authors several times during the year.

The show caves in North Bulgaria

The first electrified cave in Bulgaria is **Bacho Kiro**, Strazhata Plateau, Central Fore-Balkan, about 30 km SW of Veliko Tarnovo. The total length of this dry maze cave is 3,500 m and its entrance parts are partially electrified in 1937. In 1964 another 450 m are open for tourists. The first speleological explorations are performed in 1890 by St. Yurinich. The first archaeological excavations are performed in 1920 and 1924 by Prof. Rafail Popov from Sofia University. The excavations of the American scientist Garod in 1937-1938 are continued in 1971-1976 by common study of the Archaeological Institute of the Bulgarian Academy of Sciences and Jagello University of Krakow, Poland. Some artifacts from the Middle Paleolithic Age till the Eneolithic are discovered.

In 2012 an extensometer TM-71 is mounted in Bacho Kiro Cave for monitoring of the microtectonic movements (Briestensky *et al*., 2015).

The **Magura Cave** is located in NW Bulgaria, near the village of Rabisha, 45 km SW of Vidin. The first written data on the cave belongs to Marinov at 1887 (Popov, 1965). The cave is World famous for its more than 1,000 prehistoric guano drawings with possible Early Bronze Age (Photo 2). The age of the guano was determined in 2014 as 4,996 ± 114 yrs BP (Kunov *et al*., 2014). The total length is more than 3,000 m (new discoveries from “Helictite” Caving Club, Sofia in 2013). The biggest chamber is The Triumph Hall which is 128 m long and 58 m wide (5,720 m^2). Magura Cave is electrified and open for public visits in 1961.

Orlova Chuka Cave was found by Spasov from Pepelina village in 1941. The second longest Bulgarian cave is located 22 km south of Rousse. 13,437 m is the total length of its galleries. The tectonic settings of this large fossil maze system are investigated by Evlogiev *et al*. (1997) and the Quaternary deposits are studied by Radulov (2006). The cave is developed in Aptian limestone, 80 m above the local base level – Cherni Lom River. The cave is electrified between 1956 and 1961. Orlova Chuka Cave is declared as Protected Natural Monument together with 7.6 ha adjacent area in 1963.

Photo 2. Prehistoric guano drawings in Magura Cave.

Archaeological finds from the Middle Paleolithic – East Balkan Musterien are found (Beron *et al.*, 2006). The Geological Institute of the Bulgarian Academy of Sciences is planning to install in the cave a mechanical extensometer TM-71 for monitoring of the microtectonic movements.

Venetsa Cave near the town of Belogradchik NW Bulgaria is the newest show cave in the country. This 230 m long cave is open to public in 2015. The entrance was open during blasting works in the quarry near Oreshets Railway Station in 1970. The cave is remarkable because of plenty of helictites.

Ledenika Cave in Vratsa Mountain, NW Bulgaria is between the most visited Bulgarian show caves. The cave is electrified in 1961 and consists of several big chambers with plenty of speleothems. The length of the cave is 236 m. The dimensions of the biggest Concert Hall are 60x45x23 m. Between November and June, at the entrance parts of Ledenika are accumulated substantial ice masses.

The cave at Kaliakra Cape is located on the NE Bulgarian Black Sea Coast, at the frames of Kaliakra National Archaeological Reserve. In this small artificial cave is situated the exhibition of the Historical Museum of Kaliakra, branch of the Historical Museum of Kavarna. In the frames of MARINEGEOHAZARD project between Romania and Bulgaria, in 2013 on the ceiling of the cave is installed extensometer TM-71, data of which are collected every two months by the authors. Together with the gauges TM-71 in another four caves and rock niches in the area, the extensometer is a part of monitoring system for study of the microtectonic movements on the NE Bulgarian Black Sea coast. The first results of the monitoring are published in Dobrev *et al.*, 2014, 2015, 2017.

Saeva Dupka Cave is located in Central Fore-Balkan, near the village of Brestnitsa, Lovech Region. The entrance is situated on the south slope of the small Brestnitsa Polje with area of 9 km^2 (Popov, 1978). The 206 m long cave with denivelation of 22 m is developed in Upper Jurassic (Tithonian) limestone. The first information about the cave was published by the geologist G. Zlatarski in 1883 and the Czech scientists Hermengild and Karel Škorpil in 1898. The research of the brothers Škorpil on the underground rivers and caves in Bulgaria is between the first published monographs in the Édouard-Alfred Martel's famous journal "Spelunca" (Škorpil, H, K. Škorpil, 1898).
Detailed survey and geomorphological study were done by the geographer V. Popov in 1968 (Popov, 1978). Seismotectonic research with measurement of the preferred direction of the deformed speleothems was performed by Kostov (2008) and Shanov & Kostov (2015).

From morphological point of view Saeva Dupka consist of five chambers and the biggest one is The Breakdown Hall (53x26x17 m). According to the variety of different speleothems, Saeva Dupka Cave is between the beautiful caves in Bulgaria. The cave is electrified in 1967. Saeva Dupka is a Protected Natural Monument since 10.10.1962. An extensometer TM-71 is mounted on a crevasse on the ceiling in the third hall Harmana in 2012 (Photo 3).

Zandana (Biserna) Cave is situated 1 km west from the town of Shumen, on the NE slope of Shumen Plateau, NE Bulgaria. This 2,716 m long active cave is prepared for tourist visits since 1985 but still is not open to public. Zandana Cave has been a source for drinking water for Shumen since 1897. The first information about the cave is reported in 1828 by the French geographer Barbier de Bocage (Beron *et al.*, 2006). For the preparing of Zandana into a show cave, A. Spasov from the Shumen Caving Club made in 1979-1980 a detailed instrumental survey (Spasov, 1988). During the last five years a new lighting system was mounted, together with three extensometers TM-71 and system for the monitoring of the bat population.

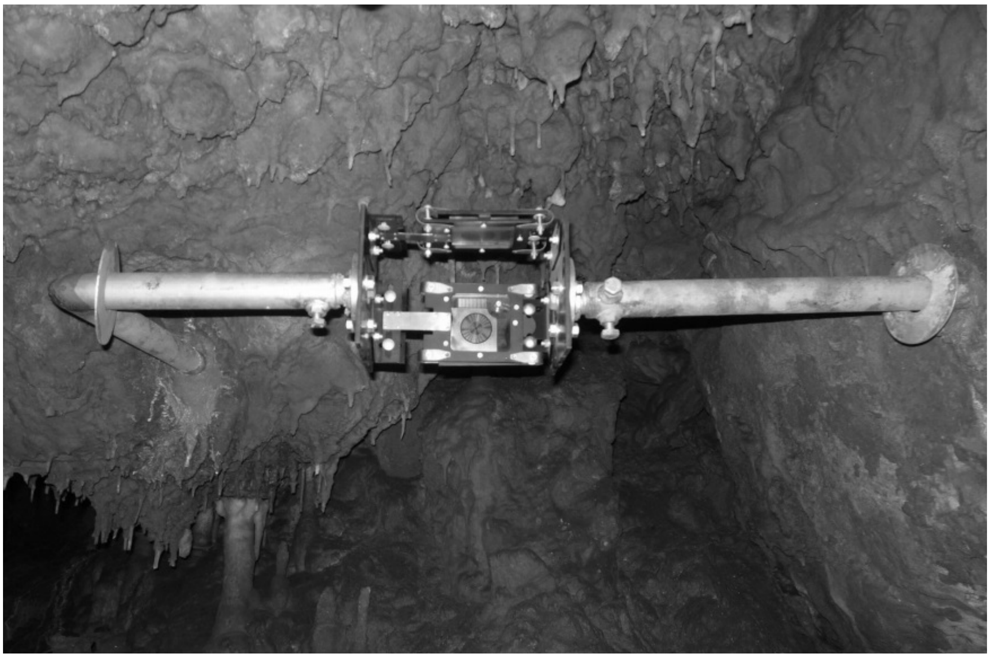

Photo 3. Extensometer TM-71, installed in Saeva Dupka Cave (Shanov & Kostov, 2015).

Conclusion

The extensometers TM-71 are approved their quality as reliable instruments for monitoring in the severe cave conditions. They are suitable in high humidity and low temperature environment as in the karstic caves. The existing network of TM-71 in Bulgarian caves needs to be expanded by new gauges installed in appropriate passages on faults. Such passages are located in both Orlova Chuka Cave and Magura Cave.

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DISSOLUTION PROCESS: WHEN DOES THE PROCESS START?

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Abstract: Dissolution process is important for the development of carbonate reservoirs that are important for storage water and hydrocarbons, fundamental resources for the economy of our planet. Dissolution process is a complex phenomenon governed by several factors as like lithology, porosity, stress orientation, environmental conditions, pre-existing network of fractures.

Traditionally, in the field on karstology (Forti, 2007), water circulation is commonly thought to be related to extensional structures (as faults and joints) assuming that these features are more favourable to water circulation. In fact, the fault zone has a high permeability only in the early stages of the movement but shortly the process of recrystallization and reprecipitation reduce the permeability greatly within them. In this context, features formed in a compressional setting have never been taken into consideration thinking that in compressional structures is not possible any circulation of water and that therefore there is no fluid-rock interaction. Instead the few studies (Alsharhan & Sadd 2000) on this topic are showing the opposite.

The focus of the research is to investigate the starting point of the dissolution and the micro mechanisms that lead to the formation of the caves. The research is focused on understanding when a structure reduces or enhance porosity/permeability.
Then the research follows two different paths:
1. Macroscopical analysis
2. Microscopical analysis.

The macroscopic analysis consists of a structural geological reconstruction carrying out in a karst area in South Italy. A detailed study of the relationships between tectonic and dissolution was conducted.

In addition to this we have carried on chemical and petrographic analysis using SEM, FTIR, and XRD. These analyses are helping us to characterize the porosity and permeability near these structures.

Despite to the common thought, where there is a presence of clay minerals, the dissolution/precipitation process can begin. Interesting early correlations between tectonic structures, mineralogy and dissolution have been founded.

We present the first results of the field and chemical/petrographic analysis carried out.

Recently, fluid-rock interactions and their impact on carbonate rocks is becoming very important as a consequence of a progressive deterioration of the quantity and quality of the groundwater.

Keywords: fluid-rock interaction, permeability, karst dissolution

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VERTICAL DISTRIBUTION OF DISSOLVED INORGANIC CARBON IN A KARST GROUNDWATER-FED SURFACE WATER RESERVOIR IN GUANGXI, SOUTH CHINA

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Abstract: Surface water reservoirs are often used to resolve water shortages. However, little attention is given to the hydrogeochemical processes of nutrients in karst groundwater-fed reservoirs. This study examines the Dalongdong Reservoir (DLD), located in a karst peak-cluster area in South China, as a study site to investigate the vertical distribution and temporal variation of dissolved inorganic carbon in July, August, and November 2014 and March 2015. According to water temperature variations, the DLD reservoir has three temporal periods: thermal stratification period, interim period, and blend period. In the water profile, the DIC concentrations increased and $\delta^{13}C_{DIC}$ values gradually decreased with depth in the thermal stratification periods (July and August), but there were few DIC and $\delta^{13}C_{DIC}$ differences in the whole column in the blend period (November). The DIC status of March showed a small increase and $\delta^{13}C_{DIC}$ showed irregular variations, so that month is placed in the interim period. Reservoir stratification, CO_2 exchange, photosynthesis, and respiration controlled the DIC variations in the water column. This study shows that to accurately assess the carbon sink effect in a karst reservoir or lake, a stratification monitoring strategy for carbon content needs to be considered.

Key words: Dissolved inorganic carbon, vertical distribution, thermal stratification, karst reservoir, south China

Introduction

Water shortages are a common problem globally. Therefore, surface water reservoirs are often built to mitigate such problems and increase water supplies. Many reservoirs have been built in the south China karst since the 1950s (Yuan, 1991). Most attention has been paid to dam engineering, and reservoir water volume and quality. Little attention has been given to the hydrogeochemical processes within the reservoir.
Reservoir construction obviously changes the regional hydrological cycle and plays a new and important role in the nutrient geochemical cycle in a karst catchment (Raymond et al., 2013). Carbon is a core element for life and the environment and is closely related to the biogeochemical cycle of other important elements (Yu et al, 2008). Karst water is often rich in dissolved inorganic carbon

(DIC) because of carbonate dissolution by carbonic acid generated during the hydration of CO_2. As a result, it is closely related to the global carbon cycle (Yuan, 1997; Pu et al., 2017a). The distribution and cycling of DIC in a karst reservoir could thus exert important impacts on water quality, plankton growth, and carbon source/sink effects (Cole et al., 2007, Liu et al., 2015).

Recently, numerous studies have focused on biogeochemical processes of carbon in surface water reservoirs in the south China karst (Yu et al, 2008; Ji et al., 2016; Wang et al., 2011, 2013, 2014, and 2016). However, the vast majority of researched reservoirs are fed by surface rivers, such as Wujiang River with a drainage area of 87,920 km2, the largest tributary of the upper Yangtze River in its south bank (Yu et al, 2008; Ji et al., 2016; Wang et al., 2011, 2013, 2014, and 2016). In those cases, the DIC in reservoir water could be impacted by weathering processes of non-carbonate rock, soil erosion, and human activities. In south China, some karst springs and subterranean streams have also been dammed for use (Pu et al., 2017b). Numerous water tanks and reservoirs in karst areas appear to disturb the natural DIC cycles of the drainage karst systems and change their eco-environment status.

This study uses the Dalongdong Reservoir (DLD), located in the south China karst, as a study site to investigate the vertical distribution and temporal variation of DIC. The drainage area of the DLD Reservoir is located in a typical karst peak-cluster area and is filled mainly by karst groundwater, which should give us a better understanding of DIC characteristics in a reservoir entirely located within a karst area.

Material and Methods

Study site

The DLD Reservoir has a surface water catchment area of 310 km^2. It was built in the 1950s and is located in the south China karst region (23°30'01″–23°40'08″N, 108°30'02″–108°36'04″E, Fig. 1A). The mean water surface area is about 8.79 × 106 m^2 and the reservoir has a storage capacity of 1.51 × 109 m^3. The landform in the catchment area is typical karst peak-cluster (Fig. 1B and 1C) and the outcropping formations are carbonate rocks of the Carboniferous and Devonian periods (Li et al., 2015). DLD reservoir was originally a natural karst depression and was dammed as a reservoir with a hydroelectric station (Fig. 1C). At present, the reservoir is mainly filled by the inflow of karst subterranean streams (Fig. 1C). The average water depth of the DLD reservoir is about 11 m. A calculated volume of 99% of the reservoir's water is derived from subterranean streams based on 2013 mass balance values of the reservoir's capacity (1.51 × 108 m^3), annual precipitation (1,487.3 mm), annual evaporation (1,736 mm), and dam leakage (2.84 × 107 m^3), about 99% of reservoir water comes from the subterranean streams (Huang et al., 2018).

The climate in the DLD reservoir area is a subtropical humid monsoon type. The mean annual air temperature is 21.7°C, and the mean annual atmospheric precipitation is ~1,294 mm. Rainfall mainly occurs during the monsoonal season from April to September. Human activities caused serious rocky desertification in the reservoir catchment area, much of which has been restored. Vegetation cover was 13.00% in 1960, while it reached a maximum of 55.72% in 2014 due to the implementation of the "Grain for Green" policy and a comprehensive treatment project of rocky desertification. Around the reservoir, the main human activity is now agriculture and tourism without any industries.

Sampling and measurement

A sampling site was chosen in the downstream part of the DLD reservoir, where there was open water with an average water depth of 14.0 m during the four sampling periods. The sampling site was about 70 m from the bank of the reservoir, which is formed of steep limestone mountain slopes. Water samples and field monitoring was carried out in July, August, and November 2014 and March 2015.

Water samples were collected from the surface to the bottom at 2.5-m intervals using a 2-L depth-setting sampler (HYDRO-BIOS Ruttner). Seasonal differences resulted in different water depths for each sampling period. Temperature, pH, DO and specific conductivity (SpC) were measured in situ using multi-parameters meters (WTW 3430, WTW GmbH, Weilheim, Germany). The instruments were calibrated according to the manufacturer's specifications prior to deployment. Unfiltered sub-samples were titrated for HCO_3^- in the field to an accuracy of 0.05 mmol L^{-1} using a portable testing kit by Merck KGaA Co. (Germany). Collected water samples were immediately filtered through a 0.45 μm cellulose acetate membrane. Filtered water was sub-sampled for major cation (Ca^{2+}, Mg^{2+}, K^+ and Na^+), major anions (Cl^-, SO_4^{2-}), DIC, and $\delta^{13}C_{DIC}$ analysis. The results are expressed as $\delta^{13}C_{DIC}$ (‰) with respect to the Vienna Pee Dee Belemnite (V-PDB) standard. All lab analyses were carried out at the Environmental and Geochemical Analysis Laboratory of the Institute of Karst Geology, Chinese Academy of Geological Science (Pu et al., 2017a). The hydrochemical data sets were processed with the program PHREEQC to calculate partial pressures of CO_2 (PCO_2) in stream waters and saturation indices of calcite (SIC).

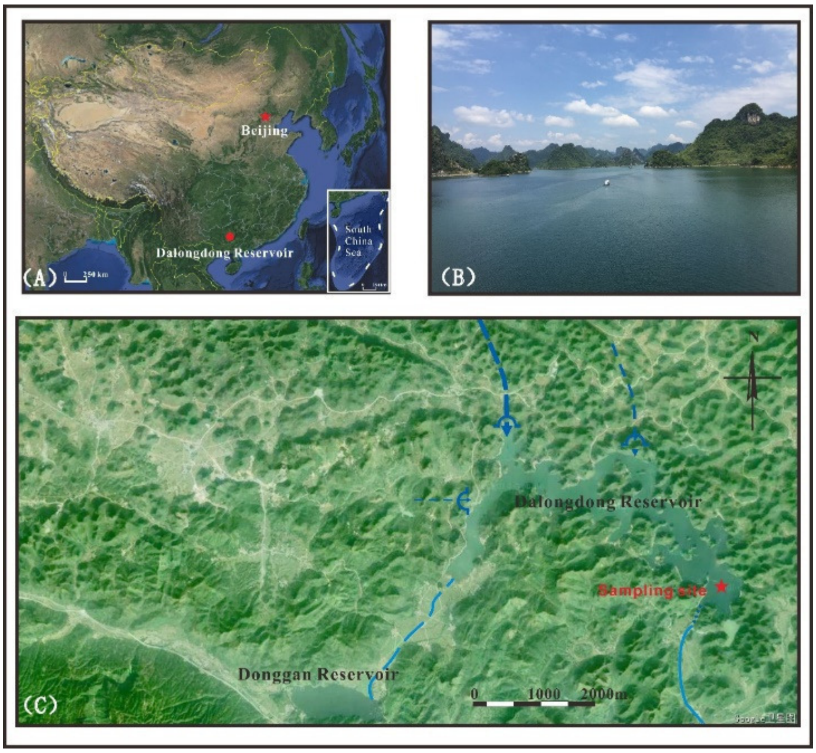

Fig. 1 Location of the Dalongdong Reservoir
(A is a map of China; B is a photograph of the DLD Reservoir; and C is a remote sensing map of the catchment area of the DLD Reservoir. The red star is the sampling site. The short blue dashed lines with arrows are subterranean karst streams. The thicknesses of the blue lines represent the relative flow volumes of the subterranean streams, with thicker lines indicating greater volumes. A long dashed blue line shows an ephemeral stream. A blue solid line shows a canal, which is connected to the reservoir by a tunnel near the bottom of the reservoir.)

Results and Discussion

Temperature and thermal stratification

Water temperature in a reservoir is impacted by solar radiation, wind disturbance, water mixing, and water movement. Except for the water samples from November 2014, the water temperature generally decreased from the surface to the bottom of the DLD reservoir (Fig. 2). The decrease in temperature was 0.82 and 0.52℃/m in July and August, respectively, showing thermal stratification (Kirillin & Shatwell, 2016). Thus, the water column could divide into epilimnion (0-5 m depth) and thermocline (>5 m depth) in July and August (stratification period). The water temperature in November showed little difference in the whole column (varied from 21.5~21.8℃), indicating the water was well blended and there was no stratification (blend period). The water temperature gradient was 0.40°C/m in March, showing a neutral status (interim period).

DIC, carbon isotope and hydrochemical parameters

Because HCO_3^- constitutes >90% of DIC over the pH range of 7.3-8.5 (Rice et al., 2012), we used HCO_3^- concentration as an approximation of DIC concentration for this study. The means of water DIC concentrations in the epilimnion (0-5 m depth) in the DLD reservoir were 195.2 mg/L, 154.5 mg/L, 204.4 mg/L, and 179.0 mg/L in July, August, November and March, respectively (Fig. 2). However, in the thermocline, the mean DIC concentrations were 241.0 mg/L, 248.9 mg/L, 203.6 mg/L, and 189.1 mg/L in July, August, November and March, respectively (Fig. 2A). Except for the water samples in November, the DIC concentration in the thermocline were higher than in the epilimnion. Obvious seasonal variations of DIC also could be observed in all epilimnion water samples, showing lower values in July and August, mid-values in March and higher values in November. Conversely, in all thermocline water samples, DIC concentrations were higher in July and August, mid-range in November and lower in March (Fig. 2A). In the vertical profile, the DIC concentrations increased with depth in the thermal stratification periods (July and August), showing obvious differences in the whole water column. However, there was little DIC concentration difference in the whole column in the blend period (November) (Fig. 2A). The DIC status of March shows a small increase, so it is placed in the medium position.

The means of water $\delta^{13}C_{DIC}$ in the epilimnion are -8.15‰, -3.86‰, -10.47‰, and -5.86‰ in July, August, November and March, respectively (Fig.2F). In general, the values are more positive in the stratification periods than in the blend periods in the epilimnion. In thermocline, the means of water $\delta^{13}C_{DIC}$ are -12.49‰, -11.51‰, -10.97‰, and -7.37‰ in July, August, November and March, respectively (Fig. 2F), showing more negative values in July and August than in November and March. In the profile, the $\delta^{13}C_{DIC}$ values gradually decreased with depth in July and August. In the blend period (November), $\delta^{13}C_{DIC}$ showed less vertical variations in the whole column (Fig. 2F). In the interim period (March), $\delta^{13}C_{DIC}$ showed irregular variations from the surface to the bottom.

pH, PCO_2 and SIC also show vertical variation from the surface to the bottom in the thermal stratification and interim periods. Both pH and SIC increase slightly from the surface to a 2.5-m depth in the epilimnion, and then sharply decrease with depth. PCO_2 also slightly decreases from the surface to the 2.5-m depth in the epilimnion, and then increases rapidly with depth. PCO_2 in the thermocline is far higher than in the epilimnion in July, August and March. For the water samples in the blend period, the value difference of pH, PCO_2 and SIC from the surface to the bottom are less, and even plot as a relatively vertical line (Fig. 2C, 2D and 2E). On the seasonal scale, the variations of pH and SIC show decreasing values from the interim period to the thermal stratification period to the blend period. PCO_2 variations show the opposite order of increasing values.

Factors controlling the spatiotemporal variations of DIC

DIC concentrations are affected mainly by the following three factors in the DLD reservoir: (1) DIC from karst groundwater (carbonate rock weathering and soil CO_2); (2) CO_2 exchange across the water-air interface; and (3) photosynthesis and respiration. Similarly, water $\delta^{13}C_{DIC}$ is also affected by the above three factors (Yu et al., 2008).

The DLD reservoir is filled mostly by karst groundwater, which controls DIC concentration and $\delta^{13}C_{DIC}$. Consequently, DIC and $\delta^{13}C_{DIC}$ distribution in the DLD reservoir should show homogeneous water quality. However, the obvious seasonal and vertical variations of DIC and $\delta^{13}C_{DIC}$, and even of pH, PCO_2 and SIC, shown in Fig. 2 indicate the presence of other processes that affect these parameters.

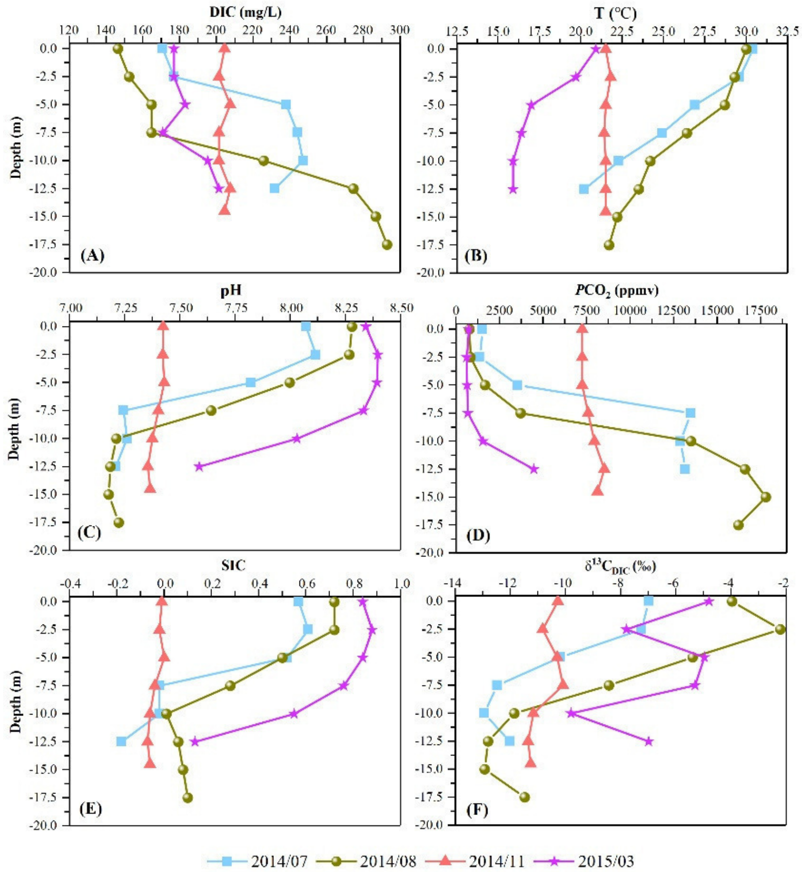

Fig. 2 DIC, temperature, pH, PCO_2, SIC and $\delta^{13}C_{DIC}$ in the water column in the DLD reservoir.

Additional observations of the above results are that DIC increases with depth in three of the four sampling periods, and significantly so in two, while $\delta^{13}C_{DIC}$ decreases with depth in all of the sampling periods but dramatically during the thermal stratification period (July and August), irregularly during the interim period (March), and only slightly during the blend period (November) (Fig. 2A and 2F). The significance of this inverse relationship is best seen in the DIC concentration and $\delta^{13}C_{DIC}$ in the July and August samples (Fig.3). Thermal stratification is maintained in the DLD reservoir water column during those months (Kirillin & Shatwell, 2016), effectively constraining mixing between the stratified water bodies. At the same time, extensive growth of subaquatic species induces significant differences both in DIC concentrations and in $\delta^{13}C_{DIC}$ between the epilimnion and the thermocline (Fig. 2A and 2F). In the epilimnion, lower DIC concentrations and high $\delta^{13}C_{DIC}$ values can be explained by the following:

1） a large amount of water (karst groundwater discharge and rainwater dropping on the water surface) enters the DLD reservoir in July and August (the storm and high flow period) which dilutes DIC in the DLD reservoir water body, decreasing DIC concentrations and increasing $\delta^{13}C_{DIC}$;

2） stronger solar radiation and higher air/water temperature in summer and autumn, photosynthesis in the subaquatic community consumes DIC in the epilimnion, also decreasing its concentrations while increasing $\delta^{13}C_{DIC}$ (Nimick et al., 2011); and

3） warmer temperatures also increasing the degassing of CO_2 from the water, $\delta^{13}C_{DIC}$further decreasing DIC concentrations and enriching $\delta^{13}C_{DIC}$ (Doctor et al., 2008).

In the thermocline, higher DIC concentrations and lower $\delta^{13}C_{DIC}$ values can be explained by the following thermal stratification factors:

1） lower photosynthesis rates due to light extinction at depth and a volumetrically smaller subaquatic community, resulting in less DIC consumption;

2） higher decomposition rates of organic matter due to higher water temperature and abundant, newly-formed, organic particles in the water column which release large amounts of $^{12}CO_2$ into the water, leading to more DIC and more negative $\delta^{13}C_{DIC}$. The higher decomposition rates of organic matter also result in lower pH and SIC values and higher PCO_2 in the thermocline.

Thermal stratification was not present in the DLD reservoir in November, placing that month in the blend period (Fig. 2B). The mixing of water between the epilimnion and thermocline can reduce the differences in DIC concentrations and $\delta^{13}C_{DIC}$ values, evenly distributing them in the water body from the surface to the bottom. pH, SIC and PCO_2 also showed even distributions in the water column because of the influence of this water blending. Additionally, this mixing trigger the upward movement of respiration-derived

DIC at the bottom to the epilimnion, resulting in a decrease in $\delta^{13}C_{DIC}$ and an increase in DIC concentrations. Thus, in comparison with the thermal stratification period, the blend period shows higher DIC concentrations and PCO_2 and lower $\delta^{13}C_{DIC}$, pH, and SIC in the epilimnion (Fig.2). Moreover, in the blend period, water body mixing results in the coexistence of multiple origins of carbon in the water column, which reduces the correlation of DIC vs. $\delta^{13}C_{DIC}$ (Fig. 3).

The interim period (March) shows the initial stage characteristics of thermal stratification in the DLD reservoir. The variation trend of DIC in the water column shows minor degrees of stratification, with the DIC increase amplitude lower than in the stratification period yet higher than in the blend period. Water temperature in the interim period is relatively lower than in the stratification period, thus restricting the decomposition rate of organic matter, which leads to lower production of CO_2 in the thermocline. This also reduces PCO_2 and increases pH and SIC values. $\delta^{13}C_{DIC}$ shows complex variations from the epilimnion to thermocline due to mutual inference of stratified water and blended water, which sharply reduces the correlation of DIC vs. $\delta^{13}C_{DIC}$ (R^2=0.31) (Fig. 3), compared to the stratification period. While this study sampled the DLD reservoir during March when the interim period reflected changes from the blend to stratification periods, a reverse interim period must exist between the August and November sampling periods when conditions change from the stratification to the blend periods.

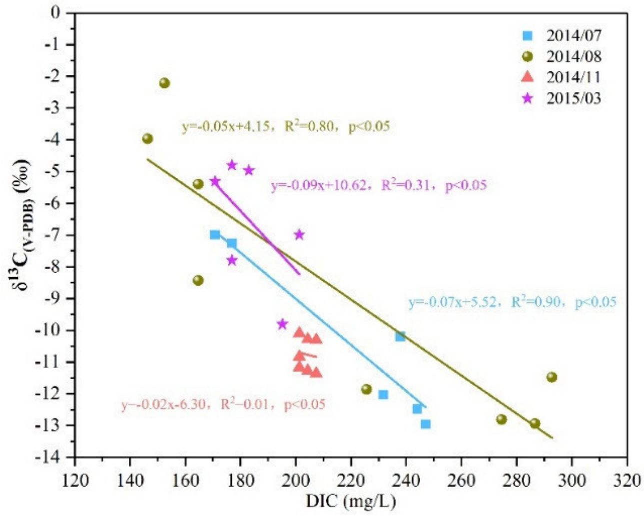

Fig. 3 Relationship of DIC and $\delta^{13}C_{DIC}$

Implication for carbon cycle in karst areas

Surface water reservoirs in karst areas that are fed by karst groundwater, significantly change the nutrient cycles (carbon, nitrogen, phosphorus, etc.) in their watersheds. Compared to sites of natural karst groundwater out-flows, groundwater discharge into a reservoir results in the buffering of solute transport, transfers and cycles, diminishing the degree of changes while extending the period of changes. Due to the seasonal influence of differences in solar radiation, water temperature, and water density, the thermal stratification, interim period, and blend period will occur successively in a karst surface water reservoir, changing carbon cycle processes. The reservoir will extend the residence time of carbon, resulting in higher rates of biological use by photosynthesis and an increase in the production of DOC and POC, which could sequester carbon that originated in the karst aquifer and make such reservoirs into local carbon sinks. Thermal stratification also constrains CO_2 and other solute exchange between the epilimnion and thermocline, increasing the residence time of carbon in a reservoir.

This study shows that the seasonal thermal stratification, interim, and blend periods of a reservoir will obviously result in seasonal changes on carbon cycle and carbon sink processes in karst surface water reservoirs. This implies that the accurate assessment of carbon sinks in karst areas within surface water reservoirs and natural lakes needs to be reappraised based on strategies than consider the hydrobiochemical stratification in the water bodies and development of appropriate monitoring strategies. The preliminary results of this study suggest that year-round sampling on a more frequent basis is needed to better model these seasonal changes, determine the effects of specific storm events, and quantify the rate, amount, and residence time of carbon held in these reservoirs.

Acknowledgments

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MICRO-TECTONIC MOVEMENTS IN POSTOJNA CAVE (SLOVENIA) AND EARTHQUAKE ACTIVITY

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Abstract: The monitoring of micro-tectonic displacements in Postojna Cave started in May 2004 (Postojna 1) and in February 2004 (Postojna 2). The gauge system TM-71 enables three-dimensional detecting of relative spatial movements between two fault faces or two blocks. Readings from the installed devices for the time interval from February 2004 to August 2011 have been taken irregularly. The deformations detected in three components X, Y and Z axes have been converted into relative total deformations. Variogram Analysis and Kriging were used for simulating regular monitoring of 15 days. A model anomaly before earthquakes of M>5 has been created after review of the graphs with seismic activity in radius of 300 km from the site Postojna Cave (Slovenia). The analyses by the Method of Inverse Probability show that the model could recognise the approaching seismic events of M>4 in this area 2-3 months before their occurrence.

Key words: Postojna Cave, extensometer TM-71, seismicity, Geostatistics, Inverse Probability

Introduction

The monitoring of micro-tectonic displacements in Postojna Cave started in May 2004 (Postojna 1) and in February 2004 (Postojna 2) after installation of two extensometers TM-71. The sites are 260 m apart. At Postojna 1 the extensometer is installed in the contact between the NW-SE oriented fault plane, representing the Velika Gora collapse chamber's northern wall, and a 2 x 2 x 1 m collapse block of limestone. The Postojna 2 site is an artificially enlarged narrow (1-1.5 m wide) natural cave passage (Gosar et al., 2011).

Several publications give important information concerning the type of recorded displacements. The idea that the gauges record real tectonic microdisplacements, excluding other causes such as influence of karst water oscillation or karst collapses (Gosar et al., 2011) gives reason to check the data for possible, but not directly evident information for Earth stress oscillations related to the processes inside the nearest seismically active areas. It was reported that Postojna 1 and Postojna 2 sites present different behaviours (Gosar et al., 2007; Šebela, 1998; Šebela et al., 2009). Gosar et al. (2009) explained the recorded peaks as temporary changes in the Earth's crust stress field that can coincide with earthquakes.

The tectonic setting of W Slovenia (following Gosar et al., 2009) is characterised by NW-SE trending dextral strike-slip fault systems and moderate seismicity. The extensometers in Postojna Cave were installed at the fault zone, which extends about 1km northeast from Predjama Fault, but the area is not considered as seismically very active. The devices recorded similar reactions to earthquakes with magnitude range 3.1-5.2 and epicentral distance of 12-95 km during the studied monitoring period. The authors' conclusion is that "…it is difficult to find some very good coincidences between earthquakes and tectonic movements. However, some sharp peaks coincide with earthquake occurrences".

Starting from the statement of Gosar et al. (2009) that the results of 3D monitoring show stability of both monitoring sites with occasional well-expressed peaks connected with changes in Earth's stress field, and taking into account the published results pointing on the significance of the data obtained from the extensometric monitoring for understanding the ongoing dynamic processes in the Earth, especially the seismic activity (Shanov, 1993; Shanov, Dobrev, 1997; Briestensky et al., 2007; Stemberk et al., 2008; Shanov, Dobrev, 2011), we have used advanced statistical techniques for demonstrating that the micro-tectonic movements recorded in Postojna Cave have significant relationship to the seismic processes in larger area than the adjacent active tectonic structures.

Data processing

TM-71 extensometer enables three-dimensional detecting of relative spatial movements between two fault faces or two blocks, as low as 0.01 mm/year. The three spatial axes correspond as follow: X – fault zone widening, Y – horizontal shearing, and Z – vertical shearing. The total length of the relative deformation vector between two consecutive reads of device indicators is simply:

$$U = \sqrt{X^2 + Y^2 + Z^2} \qquad (1)$$

For the purposes of the present study it was necessary to simulate regular time interval of the records on the base of the irregular records taken from sites Postojna 1 and Postojna 2 for the period from February 2004 to August 2011. The estimation was done for regular step of 15 days using the methods of Variogram Analysis and Kriging (Matheron, 1970). The experimental variograms, separately for the Postojna 1 and Postojna 2 sites, were obtained using the equitation:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [U(x_i + h) - U(x_i)]^2 \qquad (2)$$

U (x_i) is the length of the displacement vector at time x_i, *h* is the time interval between every two measurements (data pairs), *N* is the number of pairs belonging to the time interval *h* and U(x_i+h) is the length of the displacement vector at time x_i+h.

The experimental variograms were fitted to the most appropriated theoretical ones. Kriging procedure (Matheron, 1970; Armstrong, Carignan, 1997) was applied for evaluation of the most probable values of the relative displacement for sequence of 15 days. The processing of the data was done using the software Surfer 8.

Variogram analysis

Site Postojna 1. The average length of the relative total vector of displacement is 0.0597 mm and standard deviation ±0.0168 mm. The experimental variogram is fitted to a model with two structures (Fig. 1): $\boldsymbol{\gamma = 0.00001 + 0.000275\, Exp(130)}$**.** The first structure is the so called "nugget effect" and it explains the erratic part of the variability of the data that can't be mathematically structured. In this case 3.5% of the variability of the data has random origin. The other 96.5% of data variability is well structured and fitted to exponential type of variogram of length of 130 days. The analysis of the structure of the variogram gives reason to speak about the "rock memory" of approximately 390 days (the sill of the exponential curve is attained practically after 3 x 130 days). In other words, the measurement at given moment reflects the cumulative stress effect on the system rock-fault with gradually decreasing impact from 390 days backwards. Outside this time interval the data are not correlated.

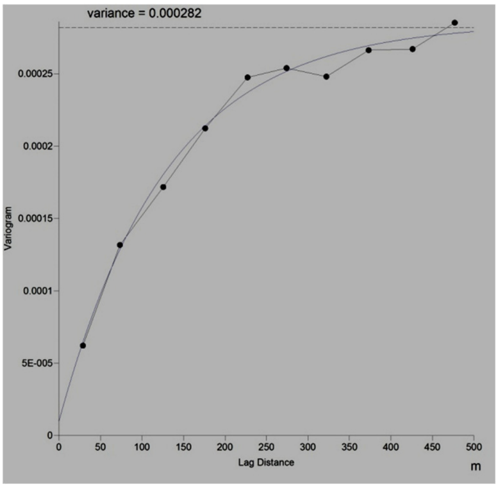

Fig.1 Experimental and theoretical variogram for the total vector of deformations on site Postojna 1. The theoretical variogram is

$$\boldsymbol{\gamma = 0.00001 + 0.000275\, Exp(130)}$$

Site Postojna 2. The average length of the relative total vector of displacement is shorter than at site Postojna 1 and it is 0.0403 mm with standard deviation ±0.0109 mm. The experimental variogram is fitted to a model with two structures (Fig. 2): $\boldsymbol{\gamma = 0.00004 + 0.00008\, Exp(23)}$**.** The first structure is the "nugget effect" and it is 33.3% of the data variability. In this case the random variability of the data is important. The other 66.7% of data variability is structured and also fitted to exponential type of variogram of length of only 23 days, i.e. 69 days of correlation time interval. Thus, the extensometer of site Postojna 2 is kipping information for relatively faster processes that generate stress changes, than these ones recorded on site Postojna 1.

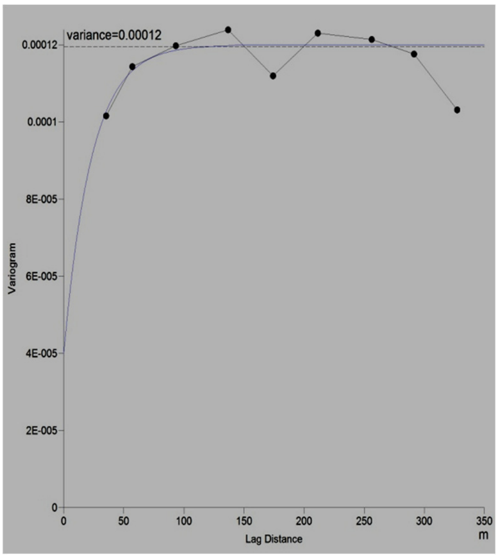

Fig.2 Experimental and theoretical variogram for the total vector of deformations on site Postojna 2. The theoretical variogram is

$$\boldsymbol{\gamma = 0.00004 + 0.00008\ Exp(23)}$$

Kriging interpolation

Kriging interpolation was applied for generating regularised records with a step of 15 days. The resulting graphs (blue line) are represented on Fig. 3 for site Postojna 1 and on Fig. 4 for site Postojna 2. The area of the Kriging deviation (red line) and the original data (red dots) are also plotted.

The graphs from the two sites demonstrate different variability. Important anomalies on the graph from site Postojna 1 are not expressed on the graph from site Postojna 2 (note that the monitoring on site Postojna 1 started 90 days later than on site Postojna 2). Nevertheless, both devices give evidence for disturbances of their records surely due to the stress variations in the rock structures. These changes could be related to displacements after earthquakes from the nearest vicinity, as well as it could be postulated that specific stress anomaly of several months before earthquake can impact the graphs. For the second statement the logical approach is an attempting to find acceptable model of pre-seismic signals, even hidden from random variations.

Method of Inverse Probability

The separation of weak signals from the background noise can be performed using optimum operation realised by mutual correlation between the recorded data and the model of the expected signal. The Method of Inverse Probability (called also Bayesian Probability) was successfully used in geophysical prospecting. The solution proposed by Shanov (1993) is based on Bayes formula but applied on normalised values through the average and the standard deviation of the records for a length equal to the length of the expected also normalised anomaly – with average 0 and standard deviation 1.

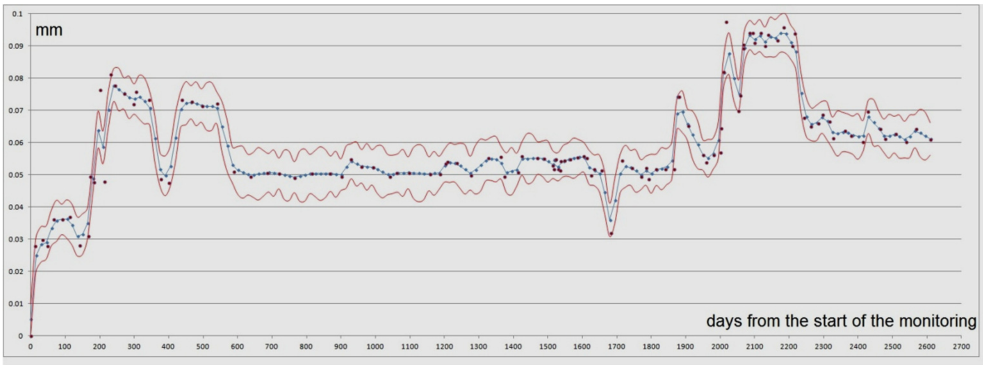

Fig. 3 Regularised records of the relative deformations with a step of 15 days for site Postojna 1

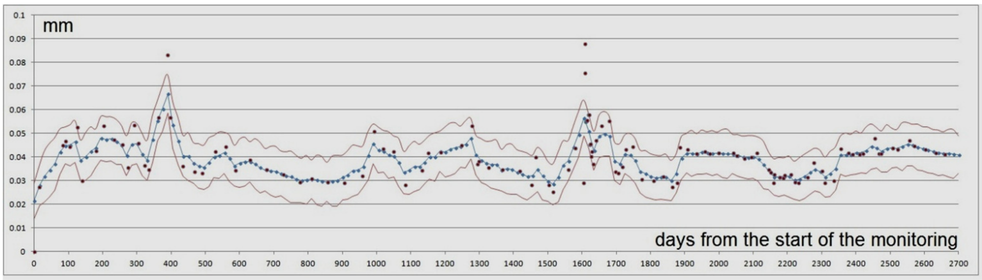

Fig. 4 Regularised records of the relative deformations with a step of 15 days for site Postojna 2

The cumulative function K_F is obtained by constant step multiplication of the normalised observed data and the model values $F_n(x)$, both of equal length of m values:

$$K_F = \sum_{j=1}^{m} F_n(x_j).\, a(x_j) \qquad (3)$$

K_F is attributed to the last record (the most recent) of the data segment for every step of moving of the model along the chain of records. The probability for existing of the expected anomaly can be calculated:

$$p = \frac{e^{K_F - r}}{e^{K_F - r} + 1} \qquad (4)$$

$e^{K_F - r}$ is the coefficient of probability, $r = m/2$ is the half of the length of the expected anomaly.

Elaboration of pre-earthquake model

A model anomaly before earthquakes of M>5 has been created after qualitative review of the graphs with seismic activity in distance of about 300 km from the site Postojna Cave. This distance was arbitrary determined on the base of previous experiences (Shanov, Dobrev, 1997; Shanov, Dobrev 2011). Earthquakes' coordinates and magnitudes were taken from the Catalogue of

EMSC (https://www.emsc-csem.org/Earthquake). The first earthquake of M=5.2 at 70 km from Postojna Cave (Krn, 12.07.2004) was not considered because the number of TM-71 records before its occurrence is insufficient. Two earthquakes from the area have been considered as informative for creating a model – from 24.11.2004, M=5.3 (280 km from Postojna Cave), North Italy, and from 23.12.2008, M=5.4 (320 km from Postojna Cave), North Italy. The period of 150 days before the earthquakes was chosen as containing the expected anomaly itself and the warning period of approximately 30 or more days before the earthquake realisation. On Fig. 5 the normalised records from sites Postojna 1 and Postojna 2 during 150 days before the events are plotted, as well as the elaborated possible and most corresponding model of anomalous changes of the vector of deformations related to the stress variations in the rock massive.

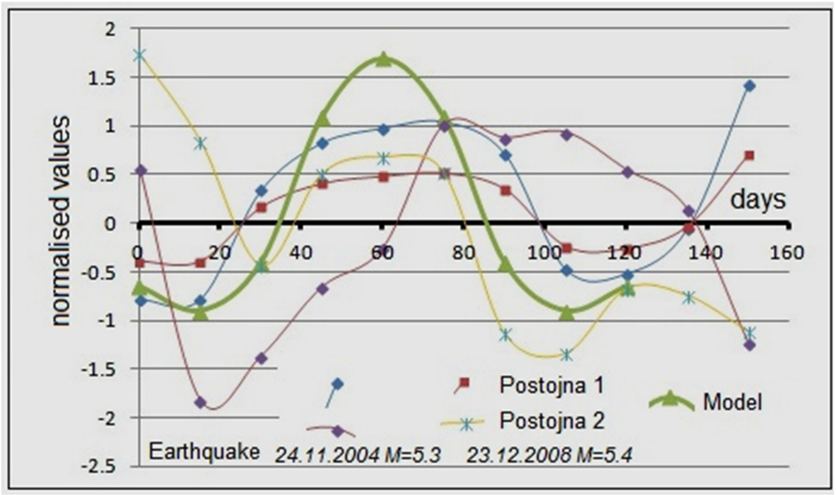

Fig. 5 Normalised records of 150 days length from sites Postojna 1 and Postojna 2 (data recorded before two strong earthquakes inside the area of 300 km around Postojna Cave) and the elaborated corresponding model of anomalous behaviour of the total vector of relative deformations

Data processing and interpretation (retro analysis)

The processing of the data has been done using the regularised values from sites Postojna 1 and Postojna 2 and the created model of the anomaly that can be related to pre-earthquake processes. The resulting graphs for sites Postojna 1and Postojna 2 contain the values of the probability for earthquake occurrence during the period from the beginning of the year 2004 to 23.08.2011. These probabilities were compared to the earthquakes of magnitude M ≥ 4 recorded inside the area of 300 km around Postojna Cave (Fig. 6).

The analysis has shown that the 2 events of magnitude M > 5 used for the creation of the model were preceded by probability higher than 0.5. Site Postojna 1 has shown 0.94 probability 32 days before the earthquake from 24.11.2004 (M=5.3), when the site Postojna 2 has shown 0.91 probability 97 days before the event. The ambiguity here is that the next day (25.11.2004) an earthquake of magnitude M=5.2 occurred at 300 km from Postojna Cave in Adriatic Sea, as well as that on the probability graph for site Postojna 2 exists a maximum of 0.89 probability 2 days before the event. The earthquake from 23.12.2008 (M=5.4) was preceded by 0.86 probability 23 days earlier on the site Postojna 1 and of only 0.2 probability 23 days earlier on the site Postojna 2.

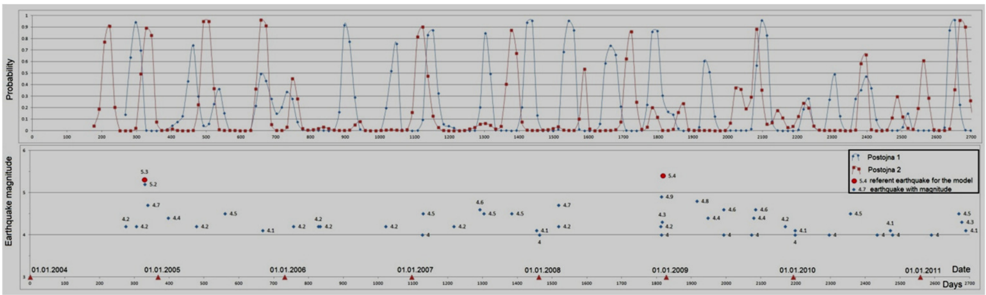

Fig. 6 Plot of the probability to find the model anomaly before earthquakes on the records of the relative vector of deformations on sites Postojna 1 and Postojna 2. The earthquakes of magnitude M ≥ 4 from the area of 300 km around Postojna Cave are also plotted.

When looking for approval of the other picks on the graphs showing probabilities higher the 0.5 it is evident that practically it can be postulated that all seismic events of magnitude greater than 4 have indications for approaching realisation, but not with conformity on the presented graphs. Even the calculated probabilities are quite different for the two sites.

Conclusion

The presented analysis demonstrates that the monitoring with TM-71 of the movements along active faults or adjacent to them fractured zones, especially inside cave systems with almost constant ambient temperature, gives valuable information for the stress reactions of the system “rock-fault”. The retro-analyses by the Method of Inverse Probability show that the model could recognise the approaching seismic events of M>4 inside the 300-km area 2-3 months before their occurrence. The ambiguity of the results comes from the fact that often multitude of events of magnitude M ≥ 4 occurred inside the area of 300 km for a relatively short time interval.

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COVERED KARST LANDFORMS: COMPLEXIFICATION OF METHODS TO ESTIMATION OF MORPHOMETRIC PARAMETERS IN ENGINEERING PURPOSES

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Abstract: In paper analysis of methods to prognosis of surface karst deformations (sinkholes, subsidence), formed in covered carbonate-sulfate karst, are given. Classification of such methods of prognosis was proposed. Features of estimation of parameters of surface karst deformations for every method with qualitative characteristic of its accuracy and laboriousness are shown.

Key words: karst, karst hazard, sinkhole, subsidence, diameter.

Introduction

Today's methods of direct investigations of soil massifs (drilling, geophysics) in conditions of covered karst are not allow with high precision determine age and mechanism of establishment of surface karst forms and also places of occurrence and dimensions of underground karst features (cavities, fractured zones). Such limitations in the ways of studying surface and subsurface karst forms essentially affects on the quality of prognosis of sizes of sinkholes and subsidence inherent at the moment of their occurrence. For increasing of authenticity of such prognosis should be simultaneously used different methods of estimations, based on both an investigation of dimensions of observed surface karst forms in situ and on studying of soil massifs behavior above karst cavity. The present practice of karst prognosis in different degrees applies next methods for estimation of sizes of surface deformations (table 1): a) expert or method of analogies; b) probabilistic; c) deterministic or calculated method; d) full-scale or method of physical modeling.

Expert method

Expert method, also known in geological sciences as analog method, is one of the base methods of qualitative prognosis of sizes of karst deformation on the earth surface. This method and in present days widely used in purposes of karstological estimations. Its essence is turning to next: investigated site provides with qualitative estimations of karst hazard, obtained from some etalon area. Validation of such analogy becomes possible when conditions of karst development on the both sites roughly the same, that's appears in generality of structural and tectonic, engineering geological, geomorphological and hydrogeological factors within their borders.

Probabilistic method

Within probabilistic approach to prognosis of parameters of karst deformations can be single out three independent directions, which using in scientific and engineering practice.

First most widely known and frequently applied method of probabilistic analysis is based on studying of statistical array of values, for example, diameters of sinkholes (subsidence) earlier formed in investigated area (Tolmachev et al, 1986; Shcherbakov, Kataev, 2013; table 1, method S1). If accurate data about sinkholes occurrence in the studied area is missed, statistical array can be constructed with using: 1) results of field karst survey of already existed sinks and lows in the relief; 2) results of analysis of large-scale satellite imagery and topographic plans, both actual on the moment of investigations and compiled in the past years. Working with representative sampling of researched parameter of karst deformation, which usually exceeding 20-30 values, then can be easy obtained an integral and differential curves or histograms of its distributions. Analysis of such curves allows obtain type of theoretical distribution and define mean and maximum values of studied morphometric parameter. Thus, at present day are known that distribution of diameters and depths of karst deformations on the ground surface obey lognormal and, less commonly, normal distribution law (Tolmachev, Reuter, 1990; Erofeev, Kataev, 2010).

Second and third directions of estimation of morphometric parameters of karst deformations on the surface with using probabilistic approach are based on multidimensional statistical analysis and relationships definition between: 1) underground (cavities, fractured zone) karst forms and its effect on surface karst forms (table 1, method S2); 2) factors of karst development (structural and tectonic, geological, hydrogeological, geomorphological etc.) and its impact on the sizes of karst deformations on surface (table 1, method S3). For solving tasks of revealing mentioned above relationships applies correlation-regression analysis combined in different ways with factorial, dispersion, cluster and other types of multidimensional statistical analysis. As an example of realization of prognostic relationship between average diameters of sinkholes and heights of underground cavities and fractured zones (table 1, method S2) using two-dimensional correlation-regression analysis can be served territory of Perm Ural (Shcherbakov, Kataev, 2013).

In the practice of karst engineering, tasks of revealing of relations between factors of karst development and karst activity (table 1, method S3), most often solve conformably to prognosis of parameters of areal karst development, such as density of karst forms or intensity of its appearance (Galve et al., 2009; Tolmachev et al., 1986; Erofeev, Kataev, 2010; Shcherbakov, Kataev, 2011). In the last years there is a tendency to using such approach for estimation sizes of surficial karst deformations (Scherbakov, 2013; Shcherbakov, Kataev, 2016; Shcherbakov, Drobinina, 2016).

Deterministic method

Deterministic or calculated method assumes definition of sizes of surficial karst deformations with using analytical solutions (table 1, method D1) or numerical computer models (table 1, method D2).

As a base for model in deterministic approach is serve dividing of soils, laying above karst cavity, on the engineering geological layers or elements, characterized with generality of composition, conditions and physical-mechanical features within all of them. In calculations also concerns levels of ground water, can be considered fracturing in soils and external pressure from constructions. Theoretical base of deterministic method is a known mechanical strength laws of soils. Most often in practical calculations applies failure criterion of Coulomb-Navier or Coulomb-Mohr, less commonly – Hoek-Brown, Drucker-Prager etc. A common moment of all theories is in assumption of falling cover soils into karst cavity of critical diameter along circular cylindrical sliding surface. If value of diameter of cavity is less then some critical value, then the cover soils above cavity has a sustainable position. Otherwise the cover soils are inevitably falling.

Easy to see that's mentioned above failure criterions may be in defined way applied to prognosis of sizes of karst collapse sinkholes. If considered estimation of sizes of sinkholes and especially subsidence, which formed by suffosion and collapse-suffosion mechanisms, math solutions in such cases becomes significantly complicate, because suffusion flowing of soils to the cavities and fractures in karst rocks has no sustainable solutions within known soil strength theories.

In Russian practice of karst engineering wide development found analytical solutions (table 1, method D1). The main advantage of such solutions is their primordial adaptation conformably karst tasks. Analytical solutions have based on kit of formulas, which allow calculate concrete parameters of karst deformations – in most cases it is diameters of sinkholes. Many of them detailed analyzed in works of V.V.Tolmachev and F.Reuter (1990), V.V.Tolmachev el al.

(1986), V.M.Kutepov (1986), V.P.Khomenko (2003), A.V.Anikeev (2017). In the world's karst engineering, outside the Russia, analytical solutions are also well known (Aderhold, 2010). But degree of developmental and schematization in conformity to concrete practice tasks significantly rebate to native analogs.

Today are developed both universal analytical solutions, oriented to revealing karst sinkholes diameters in the conditions of various of soils bedding, and schematize solutions, which application are reasonable in specified cover soils layering and hydrogeological conditions. Prognostic ability of schematized solutions is more effective in comparison to universal analytical approaches. For example, universal analytical solutions are often leads to overstating of sinkholes diameters when thickness of cover soil is high and exceeds 20-30 m or mainly composed by clays. From the other hand, approaches based on schematization of geological-hydrogeological section are purely individual and, as a rule, oriented to solving tasks for particular cases.

Since 2000s with expansion of computer counts in geology was outlined the tendency to application of numerical methods for prognosis of karst deformations on the earth surface (table 1, method D2). Most widely such approach applied today by American and Chinese researchers and engineers (Long Jia el al., 2015).

Full-scale physical modeling

As monitoring of behavior of cover soil above cavity in natural conditions is unreal considering of some objective reasons, single method which obvious demonstrate karst process of soil collapsing is physical laboratory modeling in special stands with transparent walls. Stand for physical modeling allows reproduce scaled-down similar of soil massive, bedded above karst cavity or fissures in karst rocks. In dependence from construction of stand can be organized monitoring both in one dimension (flat stands) and in volumetric view, in different geological and hydrogeological conditions and filtration regime of ground water, thus modeling different scenarios and mechanism of sinkhole occurrence. As a materials for physical modeling of soils are using next: 1) real soils, sampled on the investigated site; 2) soil materials, which have physical and mechanical properties closest to real soils in conditions of natural bedding (for example, dry dense quartz sand in modeling without accounting hydrogeological conditions can behave like water-saturated sand massive); 3) equivalent or artificial materials, which have physical and mechanical properties closest or similar to real soils (concrete mixtures, alabaster, talc, powder clay materials, mica etc.).

No.	Method	Description of method variations		Types of surface karst deformations	Prognostic parameter*	Accuracy**	Difficulty***
1	Expert (analog method)	E	Estimation of parameters of karst deformations as a result of assigning values from other area with well-known engineering geological conditions of karst development. Geological and hydrogeological conditions must be the same on the investigated area and the analog site.	sinkholes, subsidence	diameter, depth	+	+
2	Probabilistic	S1	Analysis of parameters of earlier occurred karst deformations and/or of existed karst forms in the relief (sinkholes, lowering).	sinkholes, subsidence	diameters, depth	++++	++
		S2	Correlation-regression analysis of parameters underground karst forms (cavities, fractured zones) and its influence on parameters of karst deformations on the earth surface.	sinkholes, subsidence	diameter, depth	++	++++
		S3	Analysis of factors of karst development and its influence on parameters of karst deformations on the earth surface (correlation-regression, dispersion, factorial, claster, neuron networks and other statistical procedures).	sinkholes, subsidence	diameter, depth	++	++++
3	Deterministic (calculated method)	D1	Analytical math equations and relationships, based on well-known strength criteria of disperse soils.	sinkholes	diameter	++	+++
		D2	Numerical computer modeling of karst process with finite element method, based on well-known strength criteria of disperse soils.	sinkholes, subsidence	diameters, depth	++	+++
4	Full-scale (physical modeling)	N	Physical modeling of karst process in laboratory on the open or closed stands.	sinkholes, subsidence	diameters, depth	+++	+++++

* Parameters of surface karst deformations named in plural if their prognosis can be achieved in different cut sets.
** Accuracy of estimation higher if more pluses.
*** Difficulty is an integral index which is characterized volume of material and time efforts to produce the analysis. Difficulty is higher if more pluses.

In Russian practice of karst engineering series of experiments to physical modeling of sinkhole collapse process was purposeful organized in 1970-1980s in the Dzerzhinsk karst laboratory of PNIIIS (today's name JSC "Karst-Control and Bank Protection"; Tolmachev, Reuter, 1990). Since 1990s and beginning from 2000s full-scaled laboratory experiments are carrying out in JSC "Karst-Control and Bank Protection" (Dzerzhinsk, Russia), Moscow State University of Civil Engineering and in Perm State University. In the world's karst engineering practice physical modeling is widely apply from the end XX – beginning of XXI century mainly in China and USA (Tao et al., 2014).

Complexification of methods

In complexification of prognostic methods to estimation of parameters of karst deformations on the surface should be maximum concerned natural and technogene conditions of karst development, such as: 1) surficial karst distribution within researched territory (development of sinkholes, sinks, lowerings in relief, karst ravines and huge depressions, their density and orientation in area); 2) tectonic structures (faults and zones of active neotectonic movements), geological and hydrogeological conditions of site with engineering typification of geological section; 3) project stage and level of responsibility of construction object.

In itself presence within the studied area of surficial karst forms, make probabilistic method of analysis (table 1, method S1) of its sizes to be priority. The priority of method is then higher, than age of karst forms, developed in the area, is younger. If have a data of long term monitoring of sinkholes occurrence such approach can be applied without using other methods.

Expert method (table 1, method E) is expedient to apply, when data about surface karst forms are absent. This method should be notice only for construction with low and, rarely, medium level of responsibility of objects. For high responsible objects analog method should only be used in reference purposes. Expert method is expedient to consider as a base method on the first stages of projecting.

The basis for prognosis approximate sizes of karst deformations on surface can be served probabilistic methods from groups S2 and S3 shown in table 1. Such methods especially useful when in investigated area already established regional statistical prognostic relationships.

Deterministic methods (Table 1, methods D1, D2) are recommended to priority consider in regions, where data about karst distribution on surface almost absent or where developed only old karst sinks and lowerings in relief, mainly saucer-shape or cup-shape in profile, which was formed 20-100 and more years ago. To increasing the objectivity of deterministic methods in situations mentioned above there are recommended to complex thus methods with physical laboratory modeling of sinkholes collapse (table 1, method N), probabilistic methods (table 1, methods S2, S3) and expert approach (table 1, method E).

Methods of physical modeling (Table 1, method N) should be noticed when accurate mechanism of sinkhole occurrence on the earth surface is unknown and hard reachable using others methods of prognosis. Also full-scale method is recommended to use for constructing of especially dangerous objects, located in complex geotechnical conditions.Table 1. Methods to prognosis parameters of surface karst deformations

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SPELEOTHEMS STORED IN THE "EARTH AND MAN" NATIONAL MUSEUM, SOFIA, BULGARIA

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Abstract: A rich collection of cave formations from 49 caves from Bulgaria and 14 from abroad is stored in the "Earth and Man" National Museum. The collection mainly includes cave formations from caverns and mining excavations discovered during mining activities and rarely from private collections. In the present work, the speleothem diversity from now-defunct karst cave called "Obrechenata" ("Doomed") is presented. Stalactites, coralloids and helictites are the most widely distributed in the cave, while stalagmites and crystallictites are rare. Mineralogical investigations have been carried out on coralloids, covering the bottom of a small sinter pool, which were found to have grown over earlier formed fragments of cave rafts and spherulites. Brawn coloration of all these formations was found to be caused by structurally disordered clay minerals, jarosite, for the first time identified in the cave formation of Bulgaria, and ferric iron oxides formed after jarosite.

Key words: coralloids, cave rafts, spherulites, jarosite

Introduction

Various speleothems are formed in the karst caves. The most common calcite deposits in caves are single formations as stalagmites, stalactites and coralloids, although stalactite-stalagmite columns and stalactite-helictites are also widespread. All they develop from the slow accumulation of calcite after degassing of carbon dioxide from percolation water in caves (Baldini, 2010, Perrin et al, 2014). Speleothem type morphology is controlled by one or several hydrologic mechanisms including dripping, flowing, pool, geyser, capillary, condensation, and aerosol water (Hill, Forti, 1995). As speleothems grow in response to specific physical and chemical processes within the caves, every cave is characterized by its individual set and characteristics of speleothems and minerals. In the cave's deposits formed in limestones and marbles, calcite is the main mineral - about 95%, the other polymorphic modification of calcium carbonate - aragonite is 2-3%, gypsum is to 2 %, and other minerals occur in minor amounts and their presence mainly depends on the host lithological medium.

In Bulgaria the karst occupies 22.7% of the country's area. Karst caves have been found in limestones, dolomites and marbles of different age. The first museum collection of cave formations, created in 1950 in town of Chepelare, later in 1980 became the Museum of Speleology and Bulgarian Karst. It houses the most complete collection of cave formations in the country.

The collection of cave formations in the "Earth and Man" National Museum started to fill up in 1987 firstly with samples from the now-nonexistent karst cave "Obrechenata" ("Doomed"). Todays, the collection includes more than 600 museum pieces of cave formations from 49 caves of Bulgaria and 14 caves from abroad – Ukraine, Serbia, Hungary, Romania, Papua New Guinea, Russia and other countries. The collection mainly includes cave formations from caverns and mining excavations discovered during mining activity. A smaller part of the cave exhibits is donations of private persons. The mineral composition of speleothems stored in the "Earth and Man" National Museum is relatively simple. They are mainly composed of calcite, aragonite, gypsum and minor minerals as hydromagnesite, huntite, dolomite, magnesite, alumohydrocalcite, barite, celestine, diaspore, todorokite, hematite (Janakieva, Maleeva, 2011). Totally 53 mineral species have been identified in speleothems in Bulgaria so far (Shopov, 2005).

The purpose of the present work is to present the speleothem collection from now-defunct karst cave "Obrechenata", stored in the "Earth and Man" National Museum.

Geological setting

The "Obrechenata" cave was incidentally discovered in 1987 during blasting operations in a limestone quarry nearby the village of Karlukovo, Northwestern Bulgaria (Fig. 1Aa). The territory belongs to the Karlukovo karst complex, where the karst processes have created many surface and underground karst forms. Because of the numerous caves - about 600, some of which are natural landmarks, the Karlukovo karst complex is included in the list of protected areas in Bulgaria. The karst is developed in Upper Cretaceous (Maastrichtian) grey-whitish thick-bedded limestones with thickness of 20-30 m. The limestones are organogenic (bio-detritic and biomorphic) with various biogenic components including fragments of bryozoans, mollusks, brachiopods, echinoderms, and rarely ammonites (Tzankov et al., 1994).

Cave description

The destroyed karst cave consisted of horizontal and vertical parts. The horizontal gallery was narrow (1.5 m) and sinuous with uneven floor and length of 16 m. Its direction was controlled by the host limestone beds. Half of the gallery was without any cave formations on the walls and ceiling. In the other half, where the horizontal gallery connected with the vertical part of the cave, a variety of speleothems were formed. The gallery ended with a dried-up sinter pool with dimensions 1 m x1.5 m and depth 0.3 m. The vertical part of cave was controlled by fault. This part was almost vertical about 23 m deep, started with a narrow section and then down widens to 7 m. In the bottom there were fallen rocks and a siphon filled with water. After the destruction of the cave and siphon, the karst spring near the quarry dried up.

Cave formations

Due to the impossibility of preserving the cave in the limestone quarry, all speleothems - 296 samples were carefully taken from the cave - before it was destroyed, and then became the first exhibits of the collection of cave formations in the "Earth and Man" National Museum. This saving operation has been carried out by the Bulgarian speleologists and representatives of the "Earth and Man" National Museum, including one of the coauthors of the present report (Zh. Janakieva) (Janakieva, Maleeva, 2011).

Stalactites are the most widespread speleothems. They are conical in shape and 10-50 cm in size. Rarely, they grow together, and their common surface is overgrown with a spherulitic crust. In cross section, the stalactites are circular or elliptical with a pronounced concentric zone texture; the zones are with variable width (<1 mm - 2 cm) and color (from white to brawn). Coloring is associated with clay, manganese and iron oxide impurities (Janakieva, Maleeva, 2011).

Stalagmites are rarer and occur as single zonal formations to 30 cm in height and 15 cm in thickness.

Crystallictites are rare dendritic-grown skeletal calcite crystals found on the walls of the horizontal gallery.

Helicties are widespread. They are abundantly distributed on the walls of the cave being with varying shape and sizes from first mm to 6 cm and colored from yellow to brawn.

Coralloids are widespread. They are found on the periphery and on the bottom of sinter pool and at the lower part of the cave walls. They are with radial-fibrous texture and concentric zonality expressed as alternation of calcite strips of different color and size of the crystalline individuals. In our further consideration, particular attention is paid to the coralloid speleothems formed in the sinter pool.

Coralloid speleothems formed in sinter pool

These coralloids occur as single formations or groups up to 25 cm high colored in brawn (Fig. 1Ab). Their longitudinal and transverse cross-sections reveal complex internal structure (Fig. 1B, C). It is found that the coralloid bodies include plates of cave rafts 1-2 mm in thickness and spherulites, all colored from white to different nuances of yellow and brawn. The cave rafts are flat planar speleothems formed on the surface of pool. Dripping water breaks them causing their randomly oriented deposition on the pool bottom. Besides planar material, the formed heapings contain also spherulites (Fig. 1D, E). These primary aggregates then are overgrown by spheroidalite individuals forming the coralloid body (tower). The raft plates as well as the internal spherulites are observed at different places throughout the height of coralloids (Fig. 1B), thus indicating that the mineral forming processes were periodical.

It is found that among the all parts of coralloid body, the internal spherulites are more intensively colored in brawn and contain a central dark-brawn round core with diameter 1-2 mm (Fig. 1D, E). Optical microscopy and scanning electron macroscopy examinations of coralloid cross-sections show very good correlation between the coloring in brawn and the size of crystals constituting the coralloid body. The smallest crystals of 1-3 μm in size are determined for the most dark-brawn cores of internal spherulites while the largest crystal individuals up to 1-3 mm are found in the colorless and transparent zones overgrowing the spherulites and fragmented cave raft plates (Fig. 1F). The colored in brawn micro-inclusions are found in calcite crystals and in the boundaries between growth zones of radial calcite (Fig. 1J).

Electron probe microanalyses of differently colored parts show that the calcium is a prevailing chemical element in all examined areas of coralloid cross-sections (CaO 51.7-55.3 wt.%). The magnesium, although in small quantities, (MgO 0.1-0.3 wt.%) is present in all analyzed areas. It is found that the coloring in brawn well correlates with the presence of such elements as Si, Al and Fe – their maximal contents are detected in the spherulite cores (in wt.%): SiO_2 up to 1.69, Al_2O_3 up to 0.9 and Fe_2O_3 up to 0.41, which indirectly points to the presence of clay minerals (Fig. 2A, B). Other minor elements as K and S well correlate with the iron being (in wt.%) up to 0.05 (K_2O) and up to 0.20 (SO_3).

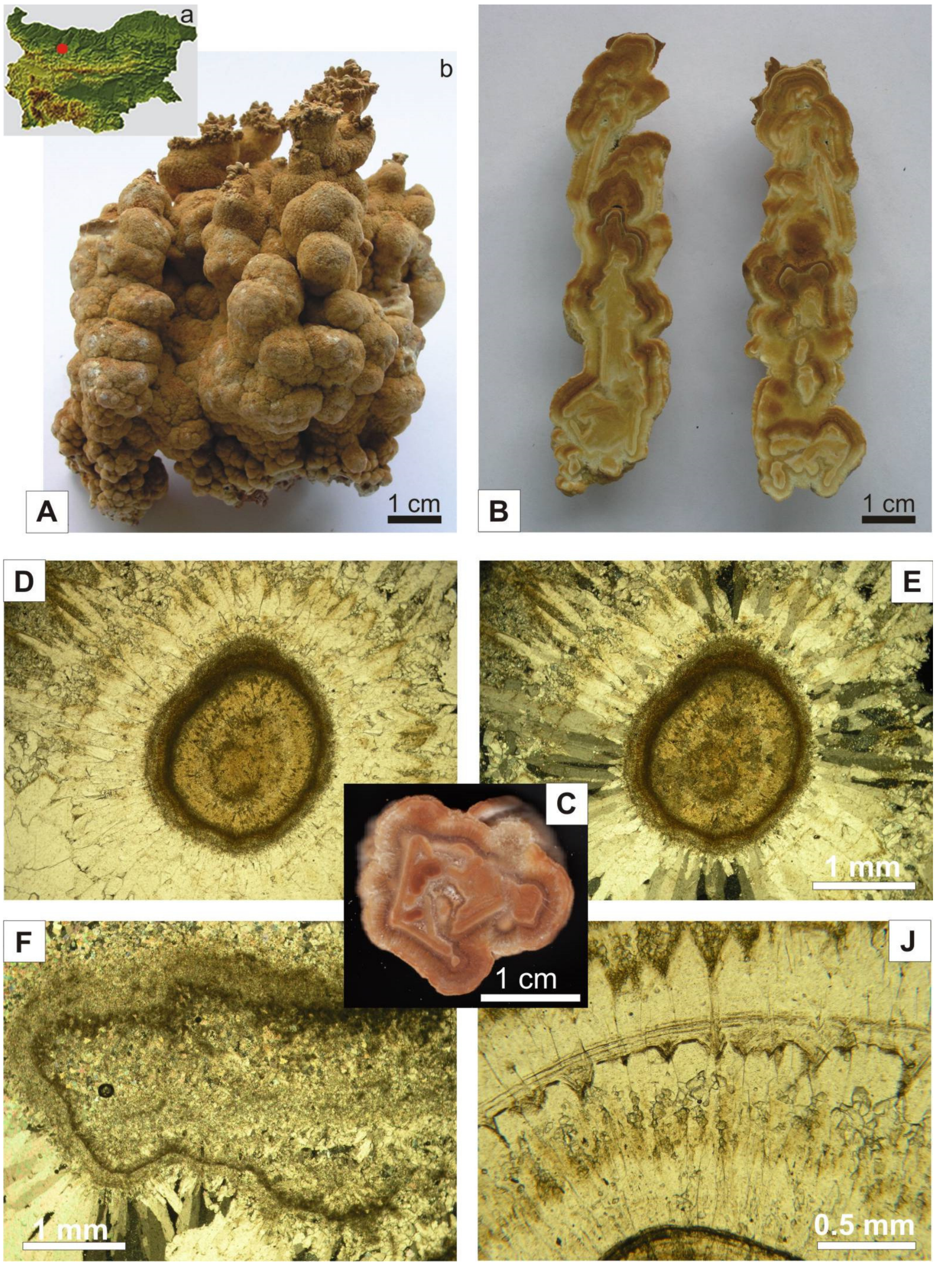

Fig. 1. A.a. Location of Karlukovo karst complex (red circle) in the map of Bulgaria; b. Macroscopic view of coralloid from a sinter pool. B. Longitudinal section of a single coralloid. At the top there are fragments of a cave raft. C. Transverse section of a single coralloid. D, E, F, G. Micrographs of thin section in polarized light (D, E, F, J) - parallel nicols and (E, F) crossed nicols. D, E. Spherulites with radial arrangement of calcite individuals and core of fine grained calcite aggregate. F. Fragment of cave raft overgrown by radially arranged calcite crystals. J. Colored in brawn micro-inclusions in calcite crystals (i) and in boundaries between growth zones of radial calcite (ii).

Powder X-Ray diffraction (XRD) analysis of the coralloid fragments shows that well crystallized calcite is an absolutely dominant mineral in them. No any diffraction reflections of clay minerals were found on the XRD patterns thus indicating that they are presented by structurally strongly disordered varieties. Besides calcite, the XRD analysis reveals traces of jarosite ($KFe_3(SO_4)_2(OH)_6$) in the studied material. This finding although well correlated with the chemical composition of the spherulite cores intensively colored in brawn, raises a question about the physicochemical conditions of mineral deposition in the cave as the jarosite is a mineral stable in strongly acid media (pH<3) and this mineral is found by us in very aggressive alkaline carbonate surrounding. Most probably the observed very intensive coloring of the spherulites cores is due to the replacement of initial jarosite by ferric iron oxides as is expected to be in alkaline media.

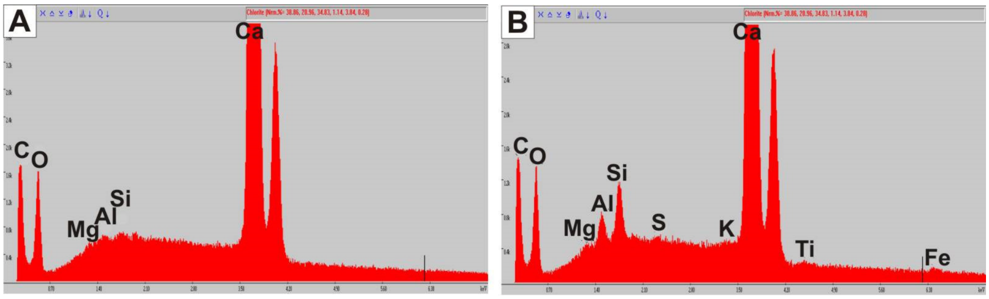

Fig. 2. A. EDX spectrum of radially arranged calcite crystals. B. EDX spectrum of spherulite core.

Conclusion

The "Earth and Man" National Museum is a cultural and scientific institution, where mineral collections, including that of cave formations, are stored, systematized and studied. Although the "Obrechenata" cave is a bitter example of destruction of natural phenomena by humans, the preserved collection of all the speleothems from this cave in the "Earth and Man" National Museum is also an example of positive thinking and concern for the future generations. The "Obrechenata" cave, though a small karst formation, is characterized by a variety of speleothems. Coralloid speleothems formed in the sinter pool and studied by us in more detail represent a unique cave formation not only because of the specific tower type morphology, but also because of the complex internal structure and the presence of jarosite, for the first time identified in the cave formation of Bulgaria.

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GEOCHEMICAL CHARACTERISTICS OF SOME THERMAL KARST SPRINGS – INSIGHT INTO THE HYPOGENE KARST SYSTEMS IN MARIOVO, MACEDONIA

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Abstract: Hypogene karst in Mariovo (Macedonia), manifested by caves and thermal springs, have been mainly studied through morphological, mineralogical and geochemical research on caves and cave deposits. Here we present preliminary results of a geochemical study of two hypo-thermal (Melnica Spring, Karši Podot) and one sub-thermal (Gugjakovo Springs) karst springs, as a contribution to the understanding of the hypogene karst systems in the area. The long-estimated groundwater residence time, coupled with chemical and isotopic composition, and trace element concentrations confirm previous assumptions that the hypogene karst systems have deep groundwater flow, with increased temperatures due to increased geothermal gradient connected to the Kožuf-Kozjak volcanism.

Key words: hypogene karst, thermal karst, karst springs, geochemistry, Macedonia

Introduction

Hypogene speleogenesis in Macedonia has been registered in few areas, but more detailed studies were done on the hypogene karst in Mariovo. In general, hypogene karst systems in Macedonia share some similar characteristics, such as hydrothermal dissolution, with the hydrogeological control and increased geothermal gradient connected to the extensional tectonic evolution in Macedonia during the Cenozoic (Temovski 2017).

In Mariovo, hypogene karst development has been registered in three localities (Melnica, Podot and Kožuf), mainly based on morphological, mineralogical and geochemical studies on caves and cave deposits, as well as some preliminary work on thermal karst springs. The main identified speleogenetic mechanism is dissolution due to cooling of rising CO_2-rich thermal waters, locally coupled with additional processes/mechanisms (i.e. sulfuric acid speleogenesis and ghost-rock weathering) due to geological or lithological control (Temovski 2016).

Here we will present preliminary results of a geochemical study of three karst springs in Melnica and Podot localities (Mariovo), as a contribution to the understanding of the hypogene karst development in the area.

Mariovo hypogene karst and thermal springs

Both Melnica and Podot localities are situated on the eastern edge of the Pelagonian Massif, on an N-S oriented stripe of karst rocks, starting with Precambrian dolomite marble, covered by Cambrian calcite marble, followed by a thin section of Upper Cretaceous clastic sediments and thick section of Upper Cretaceous limestone. Two of the studied springs are low-temperature (hypo-) thermal springs, with water temperatures of 23 °C (Melnica and Karši Podot) and one sub-thermal spring (Gugjakovo Springs) with temperature of 17 °C. The estimated mean annual air temperatures are 12.4 °C for Podot and 11.3 °C for Melnica (Temovski 2016).

Melnica Spring is located in a small gorge where Buturica River cuts the carbonate stripe, with water discharging at few close locations along a phyllito-micashist lens within the Cambrian marbles, on the left bank of the riverbed. The spring is located ~110 m below Provalata Cave, a fossil hypogene cave with cave passages formed in two phases by successive thermal carbonic and sulfuric acid speleogenesis.

Karši Podot Spring has no clear surface manifestation, but thermal water appears in Karši Podot Cave, located in Podot locality, 15 m above the riverbed, on the right side of Crna Reka Valley, where the river cuts the same carbonate stripe, 8 km to the north from Melnica. The cave is developed in Precambrian dolomite marble covered by Quaternary clastic sediments and thick travertine deposits. The development of cave passages in Karši Podot Cave is attributed to ghost-rock weathering in the dolomite marble, where calcite minerals were preferably dissolved by thermal waters, leaving in-situ dolomite sand residue, preserving primary structural features of the bedrock (Temovski 2016).

Gugjakovo Springs are located opposite of Karši Podot Cave, discharging at several nearby locations from travertine deposits at the contact with the alluvial sediments on a terrace, 5 m above the riverbed. The temperature is lower than at the other springs, but it is well above the mean annual air temperature, and the springs are considered as sub-thermal.

Three other low-temperature thermal karst springs (Kisela Voda, Topli Dol and Toplek) are also found at about 15 km to the east, in the Kožuf locality (Boev & Lepitkova, 2003).

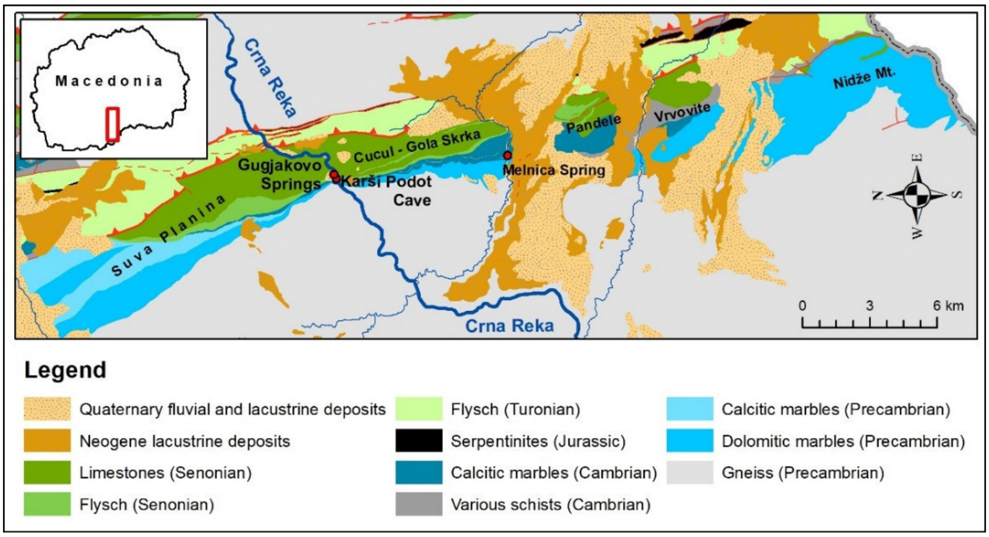

Figure 1. Geological setting of the studied karst springs (modified after Temovski 2016)

Methodology

Water temperature, pH and electrical conductivity were measured on field using HI 98129 multi-parameter tester. Major anions were measured using Metrohm 850 Professional IC and major cations were measured using Agilent 4100 MP-AES. Trace elements were measured using Agilent 8800 Triple Quadrupole ICP-MS. Isotope analyses of water and dissolved inorganic carbon were measured using an automated GASBENCH II sample preparation device attached to a Thermo Finnigan DeltaPlus XP mass spectrometer (Vodila et al., 2011). Radiocarbon measurements were done on an accelerator mass spectrometer designed for carbon isotopes (EnvironMICADAS AMS) (Molnár et al., 2013). The water samples for dissolved noble gases were stored in copper tubes sealed by stainless-steel pinch-off clamps. Noble gas measurements were performed by a VG5400 (Fisons Instrument) noble gas mass spectrometers (Papp et al., 2012). Tritium concentration in water was determined using the ^{3}He ingrowth method (Palcsu et al., 2010). All measurements were done at the Isotope Climatology and Environmental Research Centre, Institute for Nuclear Research, Debrecen.

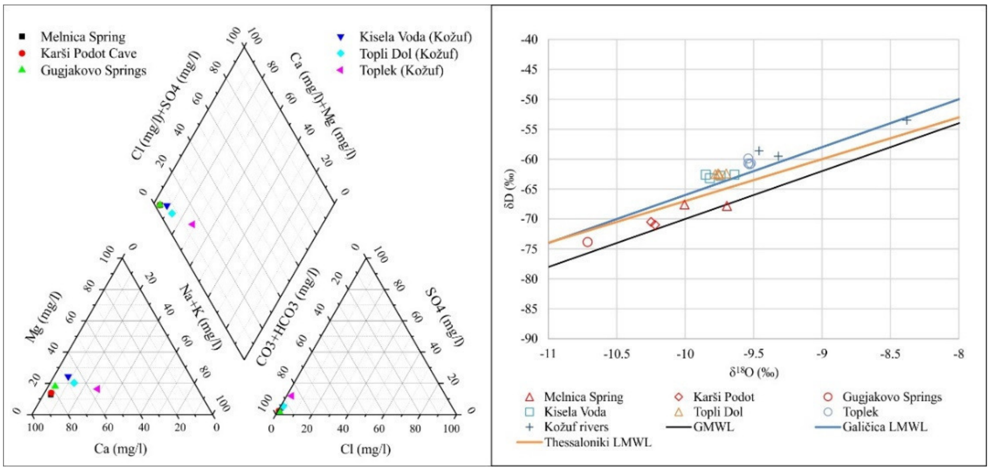

Figure 2. Piper plot of Mariovo thermal karst springs (left) and their water stable isotope composition (right). Data for Kožuf area from Boev & Lepitkova (2003) and Boev & Jančev (2014).

Results and discussion

Chemical characterization

The three studied springs have similar chemical composition (Ca-HCO_3 type), same cation composition (Ca^{2+} > Mg^{2+} > Na^+ > K^+) with Melnica and Karši Podot having almost identical dissolved content. Gugjakovo Springs have lower dissolved content and slightly different anion composition (HCO_3^- > Cl^- > SO_4^{2-}), compared to Melnica and Karši Podot (HCO_3^- > SO_4^{2-} > Cl^-), but all of them show typical karst water major-ion composition (Fig. 2).

The Ca/Mg molar ratios (2.64 to 3.99) indicate dissolution of both calcite and dolomite along the flow path, with higher dolomite contribution at Karši Podot and Gugjakovo Springs (Tab. 1), which is consistent with the hydrogeological setting of the aquifers. Melnica Spring discharges from calcite marbles, but it is highly likely that at depth the water circulates within (or at the contact with) the dolomite marble formation as well. The water at Karši Podot has slightly lower Ca/Mg ratio, and although this is higher than expected for water discharging from dolomite marbles, it is consistent with the observations from the cave (Temovski 2016) that calcite is preferably dissolved to dolomite by the slowly upward-moving thermal waters, leaving dolomite sand as residue (i.e. ghost-rock weathering). Most surprisingly, Gugjakovo Springs, discharging from the tufaceous limestones overlaying the different carbonate formations, have the lowest value (2.64), probably due to mixing of different waters (also indicated by the lower temperature), and based on the Ca/Mg ratio the cold water contribution is probably from the Precambrian dolomite marble formation to the north, instead of the Cretaceous limestone formation, as was previously considered (Temovski 2016).

Table 1. Chemical composition of the studied springs

Spring	Date	T °C	pH	EC µS/cm	mg/l						
					Ca	Mg	Na	K	Cl	SO_4	HCO_3
Melnica	3. ‘16	23.1	7.15	866	184.0	28.0	7.3	2.5	4.6	15.0	601.0
Karšii Podot	3. ‘16	22.9	6.7	935	170.0	27.7	6.5	2.7	3.8	14.0	593.0
Gugjakovo Springs	8. ‘16	17.3	7.06	761	125.6	28.9	5.1	1.2	7.5	8.3	515.6
Spring	µg/l								SI		
	Li	As	Sr	B	Zr	Cs	Ba	U	arag.	calc.	dol.
Melnica	47.1	206.0	339.4	531.0	35.1	14.0	28.3	3.4	0.54	0.68	0.88
Karši Podot	27.5	129.0	241.0	330.0	10.8	7.4	25.0	3.8	0.06	0.20	-0.06
Gugjakovo Springs	52.4	28.3	154.6	137.7	73.2	8.1	11.7	1.5	0.17	0.32	0.24

All of the spring are supersaturated with regards to calcite and aragonite and dolomite, except only Karši Podot being slightly undersaturated with regards to dolomite.

A number of trace elements are present in all of the studied springs, of which some are present in higher amounts. Boron and strontium are the most abundant of them in all of the springs, with other significantly abundant trace elements being arsenic, lithium, barium, and zirconium. Based on trace element concentration (as well as on major ion concentration and temperature), Melnica Spring and Karši Podot have similar composition and are different to Gugjakovo Springs. Although not as high, the trace element composition is similar to the thermal springs from Kožuf area, where the source is attributed to water-rock interaction with the Kožuf Mountain volcanic rocks (Boev & Lepitkova 2003, Boev & Jančev 2014). The high arsenic content is particularly indicative, as the Allchar ore deposit (where Toplek spring is located) is known for arsenic and thallium-rich minerals.

Melnica Spring has the highest arsenic content of the studied springs, which is comparable to the one in Kožuf springs. The small number of samples didn't allow for more thorough statistical examination but using our data and the data from Boev & Jančev (2014) for Kožuf springs we have calculated Spearman's correlation coefficients for some elements to look for possible relationships among them. Strong correlation was found between arsenic and most of the other elements, but this can be not only due to having similar source. Calcium is most certainly deriving from the carbonate rocks in which the aquifer is developed, which cannot be the source for arsenic, but their correlation can be due to hydrogeological conditions, where deep circulating waters have higher calcium content due to longer residence time, but also higher arsenic content due to interaction at depth with arsenic-rich rocks related to the Kožuf-Kozjak volcanism. Cesium most likely have the same source as arsenic, and also boron (measured only in our study) which shows strong correlation with arsenic.

Stable isotopes

The water isotopic composition ($\delta^{18}O$, δD) of the studied springs (Fig. 2) shows their meteoric origin, as their values lay close to the GMWL. Compared to LMWL in the region (Galičica Mt. to the west, and Thessaloniki to the south), the $\delta^{18}O$ is slightly shifted to more positive values, which is likely due to exchange of oxygen isotopes with the aquifer bedrock due to longer groundwater residence times. The longer interaction of groundwater with bedrock is also indicated by the higher $\delta^{13}C$ values of the dissolved inorganic carbon (DIC), which are close to the values of the aquifer carbonates. Gugjakovo Springs have the lowest $\delta^{13}C$ and $\delta^{18}O$ values as a result of a higher contribution of shallower and younger water, which probably has more negative water isotope composition as recharge areas are located further to the north (continentality effect).

Noble gases, tritium and radiocarbon

Radiocarbon, tritium and noble gases concentrations were used to establish the mean residence time of the groundwater (Table 2). Radiocarbon (^{14}C) activity was measured in water samples from Melnica Spring and Karši Podot Cave. The ^{14}C activity of the DIC in Melnica Spring is 9.74 (±0.08) pMC and in Karsi Podot Cave is 16.25 (±0.11) pMC, which gave uncorrected radiocarbon apparent ages of 19251 and 15022 years BP. Both springs have rather high $\delta^{13}C$ DIC values, which indicates significant contribution of carbon isotopes to the DIC from dissolution of the marble bedrock, thus rendering the radiocarbon ages as overestimations. To correct for this, we applied the Pearson model (Plummer & Glynn 2013) to estimate the initial ^{14}C activity, using $\delta^{13}C$ soil DIC value of -12 ‰ and bedrock $\delta^{13}C$ value of +2.3 ‰ (average value including both the Precambrian dolomite marble and Cambrian calcite marble; unpublished data) which gave corrected radiocarbon apparent ages of 4521 and 3381 years BP for Melnica Spring and Karši Podot Cave, respectively. Tritium was detected in all springs, indicating that there is also a fresh component in the water, as a result of which the calculated radiocarbon ages of the old component may be somewhat underestimated. Gugjakovo Springs have the highest tritium concentration (3.84 TU) which based also on other parameters (stable isotopes, temperature, dissolved content), indicates that there is a larger contribution from the younger water component, and Melnica and Karši Podot Cave have lower concentrations of 1.73 and 1.93 TU, respectively. Noble gas concentrations are close to equilibrium values with the atmosphere. Melnica Spring has slightly elevated helium concentration and T-^{3}He age of <47 years was calculated. Significant tritiogenic ^{3}He cannot be detected at Karši Podot Cave and Gugjakovo Springs as they have ^{3}He/^{4}He ratios close to or lower than the atmospheric isotope ratio. The high helium concentration and ^{3}He/^{4}He ratio (R/R_a) at Gugjakovo Springs indicates crustal and mantle origin of helium in the groundwater.

Table 2. Noble gas and tritium concentrations, helium isotope ratios and carbon isotopes

Spring	Date	He $\cdot 10^8$	Ne $\cdot 10^8$	Ar $\cdot 10^4$	Kr $\cdot 10^8$	Xe $\cdot 10^9$	R/R_a	^{3}H (TU)	δ^{13}C DIC	^{14}C (pMC)	^{14}C age (years BP)
		ccSTP/g									
Karši Podot	3. ‘16	4.97	10.0	2.69	5.67	7.85	0.905	1.73 (±0.05)	-1.16	16.25 (±0.11)	3381
Melnica Spring	3. ‘16	46.7	4.99	2.55	5.89	8.13	1.094	1.93 (±0.06)	-0.07	9.74 (±0.08)	4521
Gugjakovo Springs	8. ‘16	877	25.7	3.66	8.10	10.8	0.770	3.84 (±0.10)	-7.07	/	/

Conclusion

The preliminary results of this geochemical study of some low-temperature thermal karst springs supports the previous information about the hypogene karst system in Mariovo. The long residence time of the groundwater is confirmed by the apparent radiocarbon age, as well as by their high dissolved content and isotopic composition. Trace element composition also supports the assumptions of deep flow of the groundwater, being heated due to increased geothermal gradient connected to the Kožuf-Kozjak volcanism. As expected, highest contribution of younger and shallower groundwater is found at the sub-thermal Gugjakovo Springs, but young component was found in all of the studied springs.

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DETERMINATION OF GROUNDWATER CIRCULATION VELOCITY OF KARST SPRINGS WITH GRAVITATIONAL CIRCULATION BY ISOTOPE AND THE NOBLE GAS METHOD – CASE STUDY OF VELIKO VRELO AND MALO VRELO SPRINGS OF THE BELJANICA MASSIF

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Abstract
Defining groundwater circulation velocity and residence time in the karst is of particular importance, especially for purposes of water supply use. Investigations were performed at Veliko Vrelo and Malo Vrelo springs, which are typical gravitational circulation karst springs of the Beljanica massif, for determining groundwater residence time, both during the high-flow period, which is characterized by rapid water circulation (spring period), as well as in the recession period (end of summer) when water circulates significantly more slowly through smaller and relatively deeper karst channels. For purposes of defining the different groundwater residence times and circulation velocity, besides tracer test (Na-fluoresceine) also stable isotope methods ^{18}O, ^{2}H, ^{13}C as well as radioactive isotopes ^{3}H and ^{3}H +^{3}He were used. Additionally, in order to determine the temperature conditions that prevail, as well as recharge duration in the vadose zone during the groundwater recharge period, the content of noble gases in groundwater was measured. The results reveal the dual development of karst conduits, where the first circulation zone is characterized by larger channel dimensions where groundwater rapidly circulates over a period of only several days, while the second zone consists of smaller channels and cracks, in which the waters reside three or four months during the recession period.

Keywords: karst, isotopes, noble gases, rapid circulation, residence time

Introduction

Large amounts of groundwater can accumulate in karst aquifers and this groundwater is generally characterized as having good physico-chemical properties providing an excellent drinking-water supply source. On the other hand, it is characterized by a pronounced vulnerability to pollution, due to its low self-purification capacity and variable outflow (Vasić, 2017). For these reasons, one of the basic objectives in the exploration of karst groundwater is the determination of groundwater residence times and flow directions.

The springs presented in this paper belong to the Beljanica massif, which is part of the Carpatho-Balkanides karst in the eastern part of Serbia (Fig. 1). The springs can be viewed as a unique kart system of gravity springs during high-flow conditions and as a separate system during the low flow recession stage, during which recharge occurs predominantly through concentric sink zones. Veliko Vrelo spring emerges from scattered drainage zone that move vertically depending on the groundwater level, with a flow of 0,085-7,0 m^3/s. Malo Vrelo spring, with a flow of 0,002-2,5 m^3/s, emerges from a cave with a total explored length of 145 m and depth of 5 m. The distance between these two karst springs is approximately two kilometers.

A tracer test performed at the Rečka sinkhole on the mountain plateau in the spring period revealed a link with Malo Vrelo spring, where the tracer appeared after 110 hours (4.5 days). The distance from the sinkhole to the spring is 4.8 km, with a height difference of 638 m, which indicates that the groundwater velocity is 43 m/hour. By tracing the Busovata sinkhole, a connection with Veliko Vrelo spring was revealed, where the tracer appeared after five days, covering a distance of 7.8 km and a height difference of 585 m, in 133 hours (5.5 days), which indicates that the average groundwater velocity is 56.4 m/hour (Stevanović, 1981; Milanović, 2010; Vasić, 2017). It is these data that testify to the rapid flow velocities of groundwater through large channels during the high-flow period (Fig. 1).

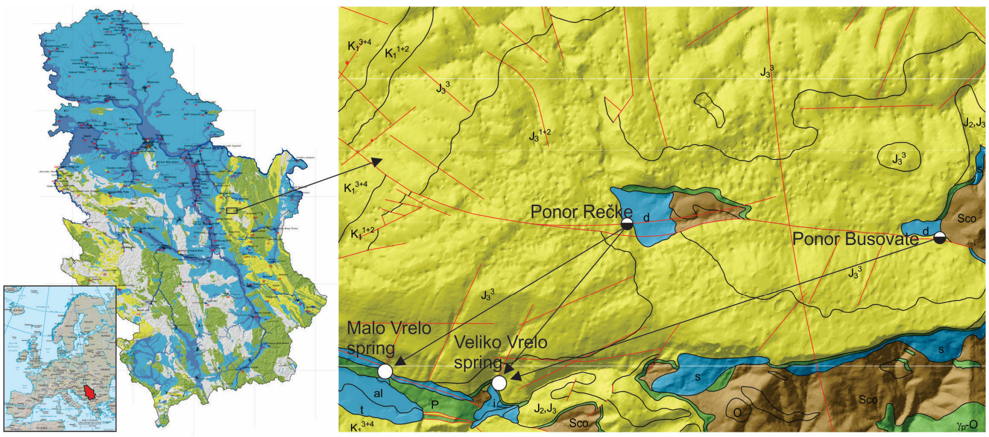

Fig. 1. Geographical position and hydrogeological map of studied area and established links between the Ponor Busovata and Rečka with Veliko Vrelo and Malo Vrelo springs (Milanović, 2010, Vasić, 2017)

Although it is typical for karst springs to have large fluctuations both in terms discharge rate and qualitative characteristics of the water, due to rapid groundwater circulation, there is a notable difference in these characteristics in the spring and summer periods. These differences indicated the existence of different zones of groundwater flow circulation, which led to the need to perform more complex investigations such as physico-chemical tests, isotopic methods, as well as methods for determining noble gas content in groundwater.

The geological and hydrogeological background

The geological characteristics of the karst aquifer recharge zone micro-location is represented by the contact between the green schists of Beljanica and Jurassic carbonate deposits, where the concentric ponors of Busovata and Rečka appear (Figure 1). The drainage zone occurs at the contact of Jurassic limestone with a layer of red Permian sandstone and crystalline schists, which serves as a groundwater flow barrier around 600-900 m hypsometrically lower than the recharge zone (Stevanović, 1991; Milanović et al., 2010).

Materials and methods

For purposes of defining groundwater circulation velocity through the karst system, investigations of physico-chemical and isotopic characteristics of groundwater were performed, as well as determination of the content of noble gases in water. Water sampling from the Rečka and Busovata sinkholes, as well as from Veliko Vrelo and Malo Vrelo springs was performed quarterly during one hydrological year. In order to better understand groundwater isotope measurements, the LIML created for the Kučaj-Beljanica massif was used (Vasić, 2017).

During sampling, a total of 16 water samples were collected from the springs and sinkholes for ^{18}O, ^{2}H and ^{13}C stable isotope analysis, as well as 2 samples for ^{3}H, ^{3}H+^{3}He noble gas isotope analysis. The stable isotope values of δD and $\delta^{18}O$ were measured in the laboratory of the *International Research Center on Karst (IRCK)* in China, by a LGR LWIA-V2 water isotope analyzer. The value of $\delta^{13}C_{DIC}$ in water samples was determined by a MAT253 stable isotope mass spectrometer with a precision better than ±3%.

1L glass bottles were used for ^{3}H sampling, and small plastic 30 ml bottles were used for stable isotopes ^{18}O and ^{2}H, while a sampler with copper tubes for noble gases was used for ^{3}H + ^{3}He content analyses, as well as for noble gas content in water

Samples were transported to the laboratory of the *Institute for Nuclear Research, Hungarian Academy of Sciences Bem tér 18/c, 4026 Debrecen, Hungary,* where they were prepared and analyzed**.** Tritium, ^{3}H + ^{3}He and noble gas content were determined using a VG5400 noble gas mass spectrometer (Palcsu et al. 2010, Papp et al. 2012).

Results and discussion

The waters of the Veliko Vrelo and Malo Vrelo springs are low-mineralized, with a pH value ranging from 7.3 to 8.4, indicating rapid groundwater circulation and a direct connection to the sinkholes, where the pH value is generally above 8. The water temperature at the springs ranges from 8 ^{0}C to the maximum recorded 10 ^{0}C, indicating inflow of water from higher altitudes and rapid groundwater circulation. The values are highest in the summer period, which indicates seasonal temperature fluctuations.

The content of stable carbon $\delta^{13}C$ in the waters of the Veliko Vrelo and Malo Vrelo springs ranges from -11.86 to -7.77 ‰, indicating water contact with the host rock, while $\delta^{13}C$ at the sinkholes ranges from -15.83 to -12.37 ‰, indicating an insignificant change in carbon content in relation to that of the isotopic composition of the soil layer in the sinkhole zones, which could belong to the mixed group C3 - C4 (-12) - (-25) ‰ based on the surrounding plant growth.

Based on the results of the stable isotopes $\delta^{18}O$ and $\delta^{2}D$ for the spring waters of the Veliko Vrelo and Malo Vrelo springs and their plotting on the LIML diagram (Figure 2) of the Kučaj-Beljanica massif (Vasić, 2017), a strong connection with precipitation waters is revealed, which is indicative of typical karst water with rapid circulation, which almost completely reflects the precipitation content. This leads to the conclusion that residence times of water in the karst system range from several days (results of tracer testing) to several months (results of stable isotope contents). Values obtained for September 2014 and 2015, represent an exception, falling just below the local meteoric line, indicating longer contact of groundwater with the host rock (Figure 2).

In order to determine the age of the waters of the Veliko Vrelo and Malo Vrelo springs and confirm the assumption of gravitational circulation, where during periods of water recession groundwater circulation velocity is significantly reduced and water flows from inflow to outflow through the channel system that penetrates deeper into the karst system, water was sampled and analyzed for radioactive isotopes ^3H and $^3H/^3He$.

A tritium content of 6.56 TU in the waters of Veliko Vrelo spring, indicates that these are very young waters. The results of the $^3H/^3He$ analysis on Veliko Vrelo spring indicate that in the recession period (September), when outflowing waters are characterized with the longest residence times in the system, the age of the waters is 0 years, which is young water with a groundwater residence time of less than 12 months.

The results of the Malo Vrelo spring water samples analysis indicated that the tritium content was 6.09 TU, where by using helium in further calculations the estimated water age is 0 years, which indicates, as in the case of Veliko Vrelo spring, very young water with an underground residence time of less than 12 months.

However, in order to specify the age of water during the recession period, a noble gas analysis was performed based on which the temperature conditions in the vadose zone at the time of groundwater recharge were calculated resulting in a temperature of 10.69°C for Veliko Vrelo spring. By comparing this value with the temperature conditions that prevailed in the recharge zone (air temperature data obtained from the Crni Vrh meteorological station (Vasić, 2017)), it can be concluded that water with a temperature of 10.69°C was infiltrated either between the winter and spring (February-March) or between the spring and summer (May-June). Therefore, the water from Veliko Vrelo spring, which flowed out at the beginning of September 2015, had a maximum age of 7 months and a minimum age of 3 months.

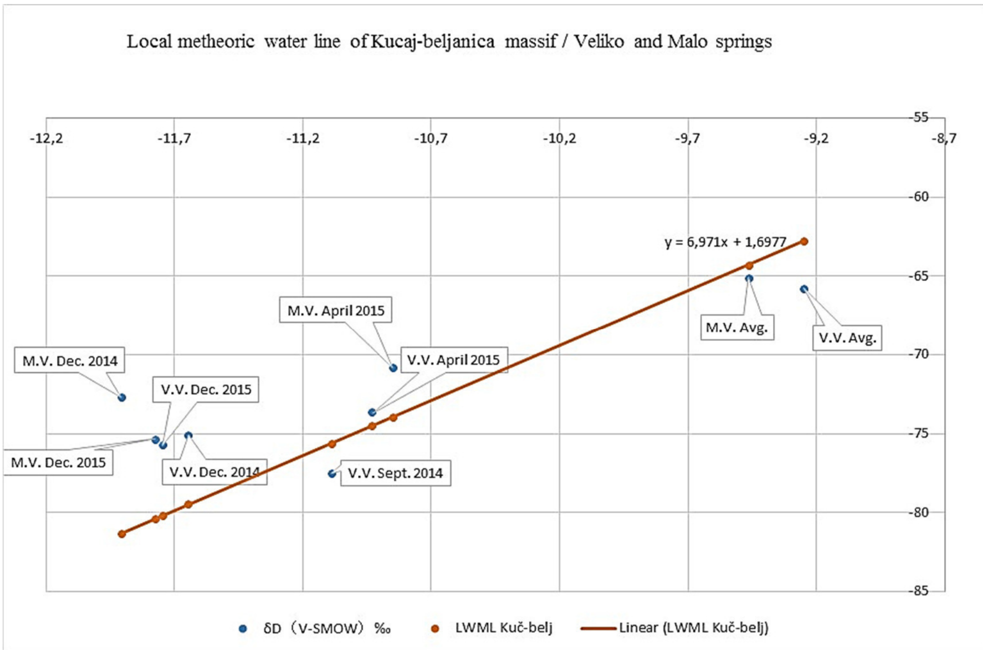

Fig. 2. Diagram of the dependence of stable isotopes $\delta^{18}O$ and δD in the waters of Veliko Vrelo and Malo Vrelo springs and LIML for the Kučaj-Beljanica massif

Analysis of noble gases in the Malo Vrelo spring water lead to the conclusion that temperature conditions are 10.95°C in the recharge zone at the time of groundwater infiltration. In order to determine the time of water infiltration, the average air temperature at the time of infiltration was taken. According to data obtained from the meteorological station Crni Vrh, it can be concluded that groundwater infiltration occurred at the end of April or in early May, and that the age of the water, determined by ^3H and $^3H/^3He$ analysis, is younger than 12 months, and approximately 4 months at Malo Vrelo spring, with the longest groundwater retention time in the system of about 122 days.

Conclusion

From the investigation results for tritium content in water at Veliko Vrelo spring (6.56 TU), and Malo Spring (6.09 TU), it can be concluded that the waters of Malo Vrelo spring have a slightly longer underground retention time. As investigation results indicate, the groundwater water retention time of Malo Vrelo spring is approximately 4 months, then the initial estimation that the groundwater retention time for Veliko Vrelo spring is either 7 or 3 months narrows, leading to the conclusion that the maximum groundwater residence/retention time for Veliko Vrelo spring is about 3 months, or 90 days.

Finally, it can be concluded that there is a zonal development of karst channels, in the zone of Veliko Vrelo and Malo Vrelo springs. The first zone consists of channels with larger dimensions located at shallow depths, where water rapidly circulates during the period of average and high flows. The second zone consists of smaller channels where water circulates and which are located deeper than the larger karst conduits. Tracer test results revealed that in the period of average and high flows, a total of about 4.5 days is needed for water to flow underground from the entrance to the exit – Malo Vrelo spring (channels t1, figure 3 on the left). However, in the period of recession this time goes beyond 4 months or 122 days (channels t1, figure 3 left). The investigation results for Veliko Vrelo spring reveal that during high-flow periods, the time needed for water to flow underground from the entrance to Veliko Vrelo spring is 5.5 days (channels t1, figure 3 right), while in the period of recession, groundwater residence time increases to 92 days (channels t2, figure 3 right). The water ages of 4-5 days for the rapid circulation of both springs (channels t1), certainly refer to the waters that are sinking directly in the sinkholes in privileged flow directions (large karst channels) towards the drainage zone (Figure 3). All other waters that recharge this aquifer over areas with significantly weaker filtration characteristics (channels t2), make up the waters related to the final part of the recession period, and therefore their age, i.e. the time it takes for the water to reach the drainage zone, is significantly longer and amounts to 122 days.

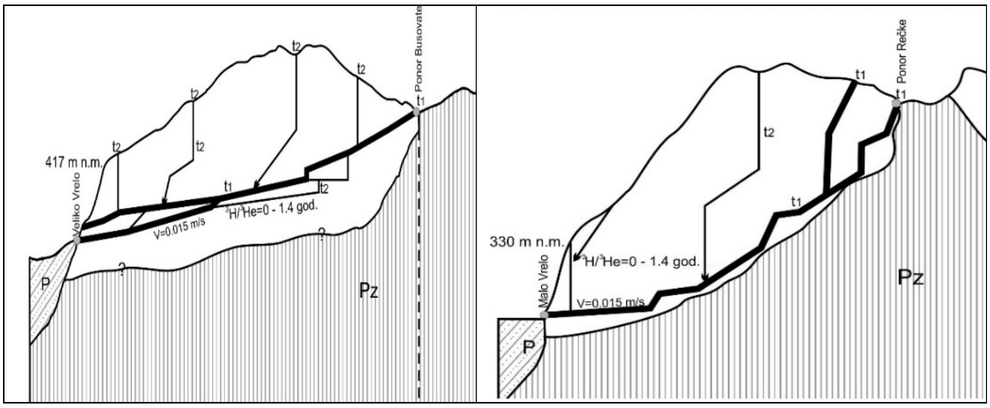

Fig. 3. Schematic representation of karst conduits based on groundwater retention times for Malo Vrelo spring (left) and Veliko Vrelo spring (right) (Vasić, 2017)

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APPLICATION OF LINEAMENT ANALYSIS IN KARST EXPLORATION

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Abstract: The article deals with using of lineaments as applied to karst investigations on the territories, characterizing by high intensity of karst form emergence. Main goal of the study was to establish the spatial selectivity of the forming sinkholes and the values of the diameters of collapse sinkholes in dependence on the organization of the lineament network. The modern approach was concluded in using the indexes of lineament tectonic based on research of tectonic fracturing and its juxtaposition with karst forms and them morphometric parameters with definition predictive equation karst sinkhole diameters depending on the lineament tectonic index. Main conclusion of the study is that the zones of lineaments and nearby areas present actually weakened sections of the karst massif, to which most of the surface and underground forms of karst are confined.

Key words: lineaments, karst forms, morphometric parameters, collapse sinkhole, cavities

Introduction

Modern problems of karstology are oriented to a quantitative forecast of karst development. As the actual material accumulates, the priority is the establishment of quantitative dependencies between the manifestations of the karst process and the factors of its development.

The purpose of this study is to establish links between the parameters of lineament network and karst formation at the local level.

The explored region is the segment of Western Urals in particular in borders of Permskiy krai, which is complicated by karst processes. Karst on this area characterized some features: different lithological karst types, various kinds of surface and underground karst forms and their genetic types, presence all kinds of karst in depend on overlapping rocks (Kataev et al, 2013). For this research was chosen territory of Kungur-city with a high degree of study of the natural conditions, located on carbonate-sulfate karst massif. The roof of gypsum-anhydrite and limestone layers is deep enough here, an average of more than 30 m, which ultimately leads to large-sized karst sinkholes.

Lineament interpretation technique

Fractures and faults on remote sensing materials are fixed by rectilinear lineaments, which are narrow extended systems of relief shapes of different genesis, traced along a single line over considerable distances. The interpretation and tracing of rectilinear lineaments was performed on a complex of geomorphological and soil-botanical indicators.

Geomorphological indicators of rectilinear lineaments are most widely developed, including:
1) Linear straightened denudation ledges on the slopes of valleys and watersheds; rectilinear concave bends on the slopes, limiting plots with different steepness; the central parts of the saddles on the watersheds, etc. These indicators are the most clearly manifested in region with increased dissected relief.
2) Erosion relief forms in the form of rectilinear segments of channels, thalwegs and sides of the river valleys; knee-like bends of temporary and permanent watercourses. This group of indicators the most common and the most recognizable on the snapshots and space images, is one of the main signs of detection rectilinear lineaments.
3) Line-oriented negative elements of relief in the form of chains of karst sinkholes, suffusion lowering, linear chains of hollows, old depressions, flooded wetlands on the accumulative surfaces of terraces and their rectilinear restrictions.

The soil-botanical features of rectilinear lineaments are reflected in the vegetation and soil cover in the form of thin rectilinear phototonal bands and strokes on the photo image caused by a change in the character of the vegetation in the more flood or drained zone above the lineaments.

On the areas of the aligned and intensely swamp landscape, the main indicated features of lineaments are the linearly extended accumulative manes of fluvioglacial and alluvial sands, straightened restrictions of plots of various genetic types of Quaternary sediments, and phototonal bands on open spaces of marshes.

As a rule, rectilinear lineaments are distinguished and traced along a set of features that replace one another along outstretch or overlap one another.
The tectonic block structures revealed on space images and aerial photographs as rectilinear lineaments, are reflected in orohydrography and other elements of the landscape. In order to identify and trace the lineaments of regional and zonal extent, cosmic spectrozonal and black-and-white images of the average resolution level were used.

As a result of structural interpretation of space images and aerial photographs revealed a network of multidirectional rectilinear lineaments that supposedly displayed narrow, subvertical linear zones of fractures and faults and flexural fault structures of the Paleozoic sedimentary cover and foundation activated in the recent time. The manifestation of such structures in the structure of the earth's surface is due to the revival of block movements in the modern tectonic stage of the development of the earth's crust. In length, lineaments form three groups: regional (over 100 km), zonal (25-100 km) and local (less 25 km).

Based on the analysis of the available geological and geophysical materials, and also taking into account the extensive domestic and foreign experience, it should be assumed that the extended linear lineaments of the regional and zonal taxonomic ranks reflect faults in the crystalline basement and in the lower part of the sedimentary cover. Higher in the section, these faults pass to the ledged and flexural bends of the layers and are fixed in the Paleozoic strata by linear zones of intensive fracturing, which, as a rule, is underlined by the increased permeability of the rock thickness. Short and local lineaments found on aerial photographs probably reflect linear zones of tectonic cleavage enhancement in the upper parts of the sedimentary cover, and cleavage in near-surface and surface deposits.

Karst forms

During the monitoring of the karst territories of the Permskiy Krai archival materials of karstological studies, engineering geological and hydrogeological surveys were collected, followed by the creation of databases with spatial reference of karst forms and their detailed description.

Among the variety of karst forms there were chosen collapse sinkholes, cones and cavities. The breaking zones were included in analysis too. The surface karst forms were identified during geological reconnaissance and were digitized from snapshots. Cavities and breaking zones were detected in time of drilling. Breaking zones are identified in karst massif as clots of karst rocks which characterized high degree of rotting, crumbling. Such clots of the karst massif are the most perspective for the karst cavities formation. Analysis of subterranean karst forms revealed that their generation mainly timed to gypsum, anhydrite and limestone. Single cavities were fixed in the thickness of dolomite. Besides the quantified characteristic of karst forms were fixed their morphometric parameters. For the collapse sinkholes and cones was calculated average diameter received by averaging of length and width and for the underground forms was accepted vertical capacity.

A quantified characteristic and morphometric peaks of karst forms and breaking zones are shown in Table 1.

Table 1. Quantified characteristics of karst forms and breaking zones in a border of Kungur-city

	Quantity, PC	Maximal value of morphometric parameter, m
Collapse sinkholes and cones	774	35.7
Cavities	508	17.8
Breaking zones	372	13.8

Research methodology

The spatial configuration of the lineament network is estimated by the author through two most optimal indexes (Zolotarev, Kataev, 2012, 2013):
1) Linear density of lineaments (L, km/km^2) is calculated as their total length in the grid square. This indicator allows us to estimate approximately the degree of fracturing and fragmentation of the karst massif, indicating the potential directions of transit of groundwater:
2) Remoteness of the investigated area from the lineament (U, m), on which we can purpose the degree of preservation and relative fracturing of rocks in this place.
Obtaining statistical data for the analysis of the relationship of the distribution of karst forms depending on the lineament tectonics can be realized by different methods.

Firstly, it is the construction of vector models of interpolation of factors of lineament tectonic. At the same time, the values of these indicators are grouped into classes (intervals), after which the number of karst forms that fall into this or that interval is counted. The final statistical result is the construction of diagrams, histograms of karst form distribution.

The second method consists in the construction of maps of lineament indicators and maps of densities of karst forms. Based on the results of the mapping, the fields (intervals) of the values of the indicators relative to each other are compared.

Most accurate method obtaining statistical data is based on assigning to each karst form a point value from the cartographic model of lineament parameter.
Since the karst is characterized as a multifaceted process, depending on the many parameters of the karst massif structure, it is often difficult to single out the effect of a particular factor (especially within the territories with an anthropogenic load) on the process of karst formation. Thus, in our case the

third method is applied as more accurate and convenient for quantitative prediction of the karst process.

A comparison of the distributions of morphometric parameters of surface and underground karst forms with lineament indicators is carried out by adduction them to a general view. To do this, each particular value of the morphometric and lineament characteristics under consideration is divided by its territorial maximum (the maximum value within the entire study territory). As a result, the researcher gets the opportunity to use index estimates of the morphometry of karst forms, crushing zones and lineament parameters.

The advantage of using index estimates lies not only in the ability to compare different dimensions with each other, but also as a result of this operation, the new values of each of the indicators vary in the same range – from 0 to 1. In order to get the true value of the characteristic, it is enough to perform the reverse operation – multiply its index value by the territorial maximum.

On the basis of comparison of the morphometry of karst forms with maps of lineament indicators, fields of points of scattering of parameters relative to each other were obtained. In the overwhelming number of cases, the field of the points of two dependent parameters is extremely unrepresentative and chaotic. To implement the conditional forecast, it is necessary to solve the problem of rejecting values from the general population. The solution of this problem lies in finding the trend of the dependence of the average values of the morphometric parameters of karst forms on the parameters of lineament tectonics. After this operation, the most deviating values are extracted from the observed dependence, and for the remaining data set, the prognostic equation, reflecting the dependence of the morphometric characteristic of the karst form from the index of the lineament tectonics. Thus, the prognostic equation is compiled only for small of the data part.

Research results

The sulfate-carbonate massif in a borders of Kungur-city is dissected by a set of regional disjunctives, forming in the central part of the city a wedge-shaped tectonic block of the northern end of the Bashkir anticline, which is a third-order structure (Kataev, Kadebskaya, 2010).

The interpreted set of lineaments spatially coincides with the fault zones and stretches in all main directions, quantitatively dominating in the meridional and north-east directions.

Within the city, the linear density of lineaments varies in the range 1.1-12.4 km/km^2. Areas with maximum values of L-factor are located near the northern bend of the river Sylva and to the south of the narrowest part of the interfluve of the rivers Sylva and Iren. These areas spatially do not coincide with the areas of maximum development of karst. Territorially there are several locations with intensive karst and they are all developed within the limits of the average or close to them values of linear density. With respect to the U-factor, the intensity of the karst form generation decreases as increase remoteness from the axial zone of the lineament (Fig. 1).

Visual analysis of cartographic models is confirmed by statistical analysis, carried out through the index values of the factors in question (Fig. 2).

Regardless of the type of karst form, their distribution relatively to the pattern of the lineament network is almost identical. A distinctive feature is in the distribution of karst forms according to the values of linear density of lineaments. Most cavities are laid on territories with an L-factor index of 0.4, while most of the dips are laid in areas with index values of the L-factor of 0.5, it corresponds to the more shattered sections of the karst massif.

As for the diameters of surface and vertical height of underground karst forms and zones of crushing, their variability in the values of the U-factor is not traced. According to the method of research from a chaotic field (Fig. 3) after culling the values was found the dependence of the decrease in the sizes of the karst forms, according to which the predictive equation was calculated (Fig. 4).

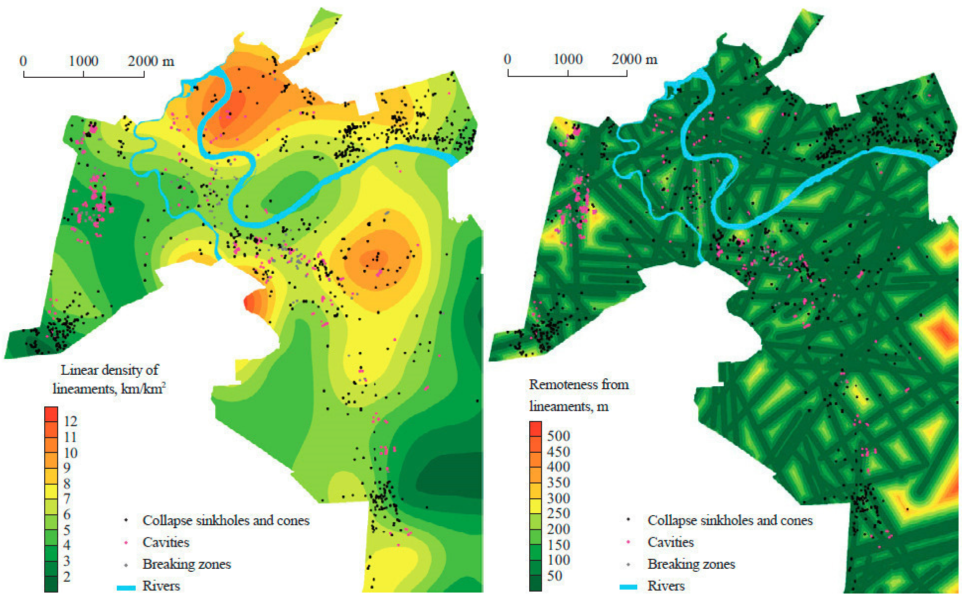

Fig. 1. Maps of spatial distribution of karst forms with respect to factors of lineament tectonics within the city of Kungur

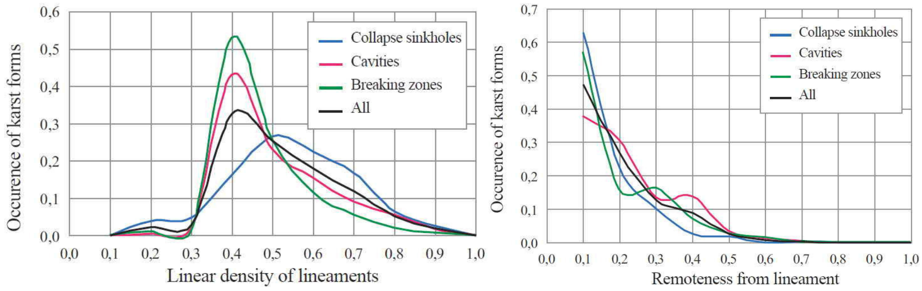

Fig. 2. The frequency of occurrence of karst forms within different intervals of values of lineament factors, expressed in the index form

Besides determining the statistical regularities of the influence of lineaments on the process of karst formation, the important task is to interpret the results obtained from geological positions. Since, by their nature, lineaments are closely intertwined with fault tectonics and fracture systems in the near-surface layers of the sedimentary cover, it is reasonable to justify the relationship between lineaments and karst from the point of view of fracturing.

The areas with the minimum values of the concentration of lineaments correspond to weakly crushed areas in the tectonic sense. In such an environment, the fracturing system is depressed, and the process of karst formation proceed passively. Much more intensive development of karst is affected by areas with developed fracturing systems - these are areas with an average and maximum concentration of lineaments, (which we observe at the local level of the study).

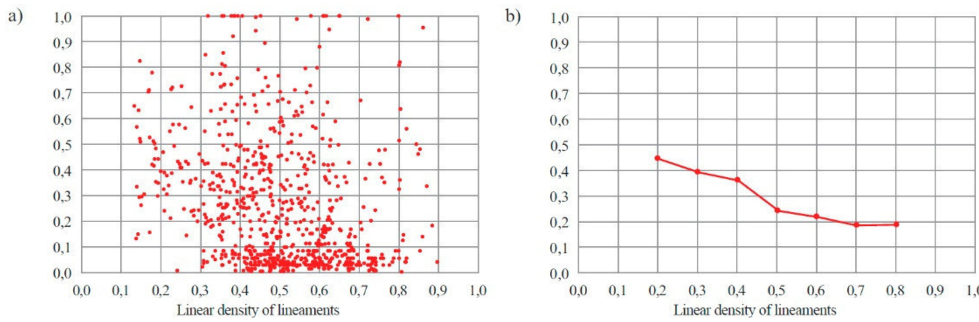

Fig. 3. The field of points of scattering of the diameters of the collapse sinkholes with respect to the linear density of lineaments (a) and the curve of change in the average diameters of the collapse sinkholes on the intervals of linear density of lineaments (b)

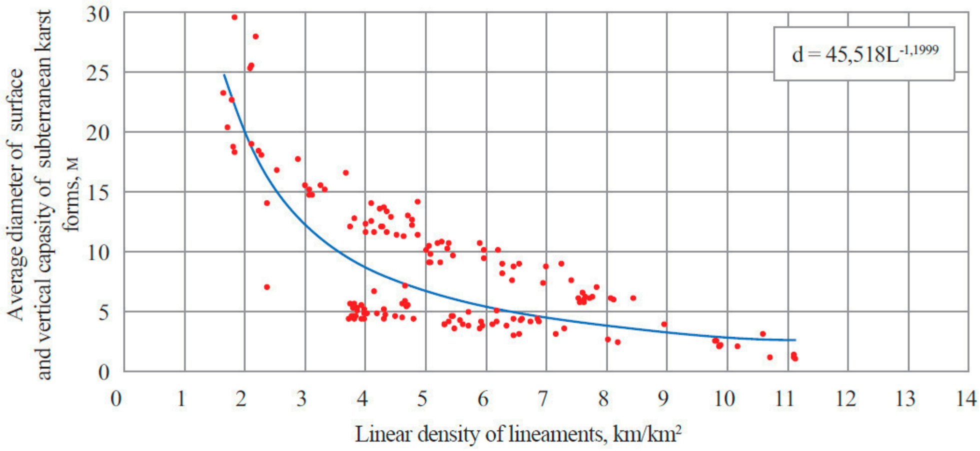

Fig. 4. The predictive equation of the mean diameter of all karst forms as a function of the linear density of lineaments

As the main conclusion, it should be noted that the karst growth decreases with decreasing fragmentation of the array and at a certain distance from the lineaments (U≥0.8) completely damps.

Peripheral and central sections of blocks are characterized by different conditions of karst formation. Thus, the thickness of the deposits overlapping the karst stratum at the contacts of tectonic blocks and blocks of lower order is lower than in the central parts of the massif. However, at the remote to the deeps into the massif, the karstic rocks are characterized by a purer lithological composition and, due to depressed fracturing, are relatively monolithic zones.
The considered methodological approach is suitable for determining the impact of any natural and anthropogenic factors on the karst process. The results of lineament analysis introduced to a comprehensive assessment of the karst hazard of the territory.

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Management and Sustainable Use of Karstic Water Resources

INVESTIGATION OF HYDROCHEMICAL CHARACTERISTICS OF THE TREBIŠNJICA RIVER CATCHMENT USING MULTIVARIATE STATISTICAL ANALYSIS

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Abstract: Conceptual commitment to integrated water quality management of the Trebišnjica River catchment is inconsistent with modest results of hydrogeochemical research. In such circumstances, optimal conditions for water quality management in the Trebišnjica River catchment have not been created. Because of that, the main objectives of this study are to determine the chemical characteristics and the dominant chemical processes, which control the water composition of the Trebisnjica River catchment. In order to fulfill these objectives, the multivariate statistical analysis was used.

Key words: hydrogeochemical processes, multivariate statistical analysis, water quality, Dinaric karst, Trebišnjica River catchment

Introduction

Water is the most important natural resource in the Eastern Herzegovina. This fact led to the realization of the "multi-purpose Hydrosystem Trebišnjica project", which included the construction of seven dams, six reservoirs, six tunnels with a total length of 57 km and 4 channels, 74 km long. According to Milanović (2006), at the beginning with dominant power utility intention, the conception is transformed into an integral solution of multipurpose use and water protection in the region of the Eastern Herzegovina and the Dubrovnik Littoral.

Integrated water management means finding quality solutions that would be acceptable to all parts of the water system and all water activities. The quality and compatibility of the solutions depend on the input data and the level of research of the subject area. However, this is precisely a significant problem in the Trebišnjica River catchment.

In the Trebisnjica River catchment, there is no a database in digital format, which would include all physical and chemical, bacteriological and radionuclides analyzes that have been done in that area. In such circumstances, it is evident that optimal conditions for water quality management in the Trebišnjica River catchment have not been created.

Because of that, the main objectives of this study are to determine the chemical characteristics and the dominant chemical processes, which control the water composition of the Trebisnjica River catchment. In order to fulfill these objectives, the common statistical methods were used during the process of collecting, systematisation and data processing.

Description of the study area

The Trebišnjica River catchment is located in the southeast of the Republic of Srpska and Bosnia and Herzegovina, in the region known as Eastern Herzegovina (Fig. 1). According to Milanović (2006), the areal extent of the catchment, including the Trebišnjica Springs, is about 1150 km^2.

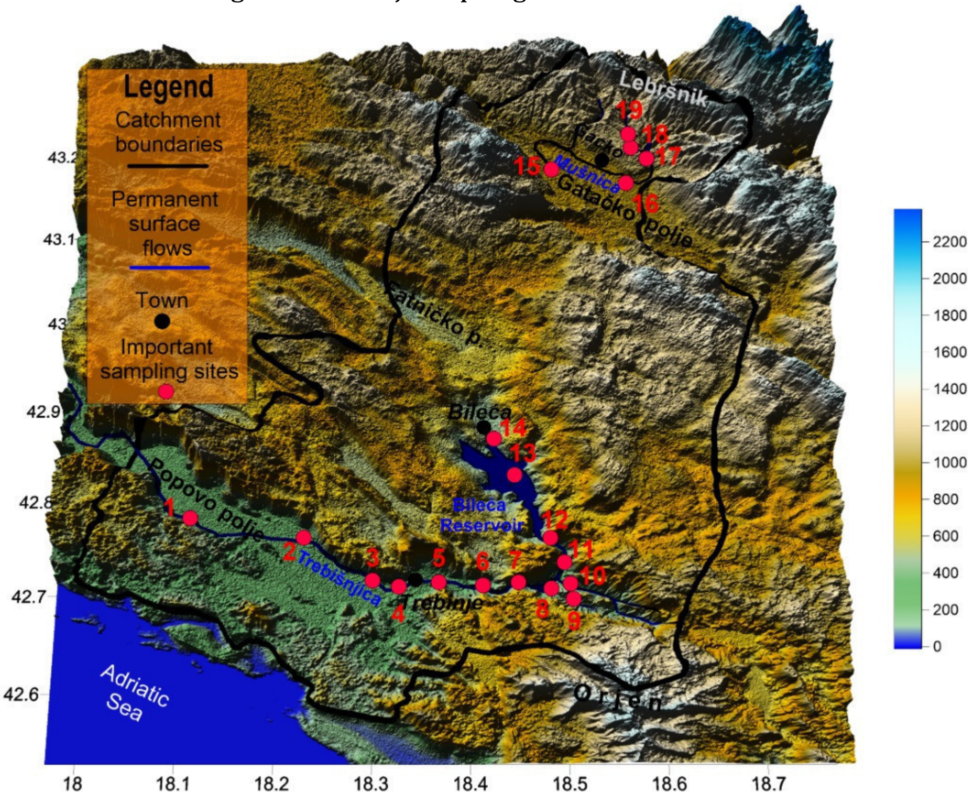

Fig. 1. Location of the Trebišnjica River catchment

The Trebišnjica River catchment is a sparsely populated area, with a total of 52 700 inhabitants (2013). Most of the population is concentrated in the main administrative centers: Trebinje, Bileća and Gacko. However, the sewage system has not been established in the whole area of these settlements. It is similar to large industrial facilities, such as the Coal power plant Gacko and Swisslion tools factory Trebinje. Therefore, these settlements and industrial facilities are the main polluters of water, land and air in the Trebišnjica River catchment.

In the study area, the geological formations are developed from the Upper Triassic to the Quaternary (Fig. 2). The Upper Triassic is represented by dolomites. They cover a small surface but play an important hydrogeological role, especially if they are situated at the anticline cores. Also, Jurassic carbonate formations are not significantly present in the Trebisnjica River catchment. On the contrary, Cretaceous sediments are the most developed stratigraphic unit. They are represented by limestone and, rarely, dolomites. Jurassic and Cretaceous limestone and dolomite have been locally affected by karstification (Natević, 1970).

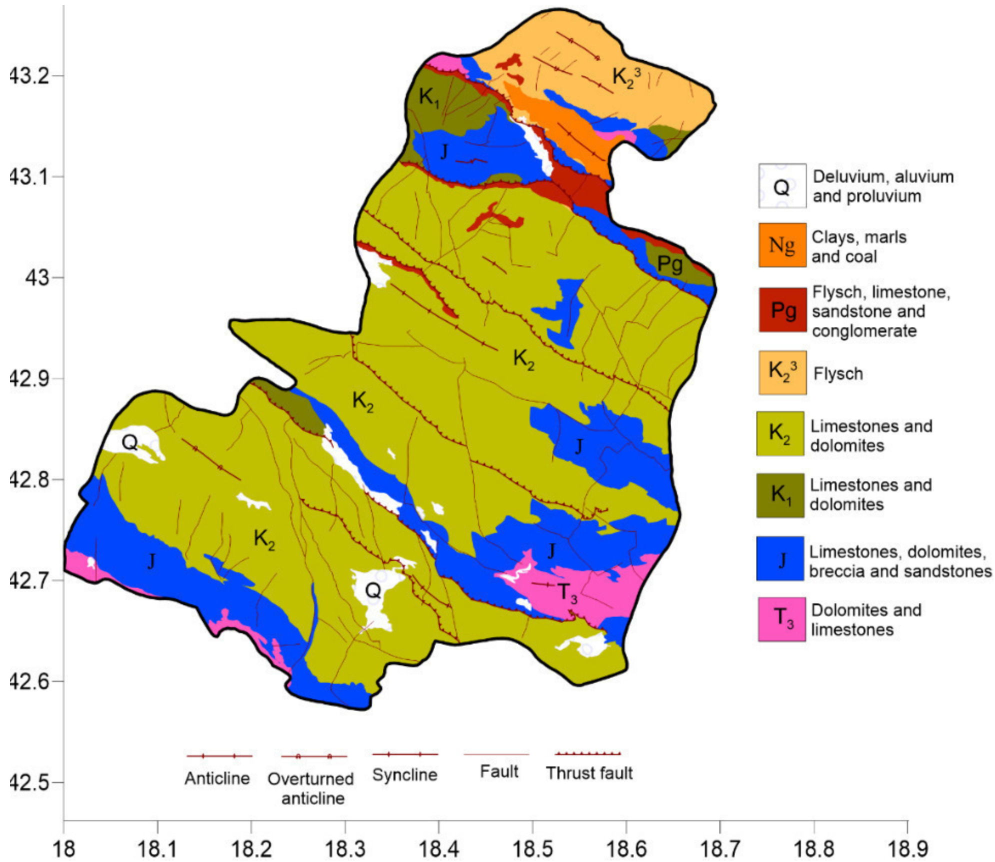

Fig. 2. Generalized geological map of the Trebišnjica River catchment

Only the northeastern part of this catchment is covered by low-permeable and impermeable Upper Cretaceous flysch. The Eocene flysch does not represent a significant lithostratigraphic formation. However, according to its hydrogeological role and location at the many of poljes in Eastern Herzegovina, it has a huge effect on karst aquifers (Milanović, 2006).

Quaternary was distinguished in the larger poljes and sinkholes and is represented by alluvial, proluvial and diluvial deposits and by terra rossa (Natević, 1970).

The tectonic framework of the study area is very complex. The dominant structural elements of this area are thrust faults, which extend from northwest to southeast, and faults of the longitudinal direction (Milanović, 2006).

In the Trebišnjica River catchment three main physical-geographic regions have been established: Humine (up to 400 m a.s.l.), Rudine (from 400 to 600 m a.s.l.) and Planine (mountains, over 600 m a.s.l.) (Gnjato, Jevtić, 1989). The most important morphological features within the mentioned regions have step-like system of karst poljes.

Rainfall in the Trebišnjica River catchment region is among the highest in this part of Europe. Its amount ranges from 1500 mm in poljes to 2700 mm in the mountains. Rainfall is seasonally distributed, with the highest values between October and March, and lowest from April to September.

The zonal arrangement of karst poljes causes complex and specific hydrogeological conditions of drainage and distribution of groundwater, for which the Adriatic Sea is the absolute erosion base. In the lowest part of Gatačko Polje there is a swallow hole zone, which serves as an outlet of much of the Mušnica River water. This is the start of the longest continuous underground flow, which ends at the Trebišnjica Springs, filling the artificial Bileća Reservoir (Milanović, 2006).

Downstream of the Bileća Reservoir, the River Trebišnjica flows through Trebinjsko and Popovo polje. The Trebišnjica River water sinks in numerous swallow holes and appears at the sources along the coast of the Adriatic Sea and in the Neretva river delta.

Methodology

Sampling and chemical analysis

The water samples were collected from the Trebišnjica Hydro Power Plant Company (HET), once to four times per year between 1997 and 2015. Samples were analyzed for the major ions (Ca^{2+}, Mg^{2+}, Na^{+}, HCO_3^{-}, SO_4^{2-} and Cl^{-}) air and water temperature, colour, turbidity, odour, taste, pH, dissolved oxygen, oxygen saturation, BOD5, COD (with KMnO4), CO2, electrical conductivity (EC), total dissolved solids (TDS), total hardness, alkalinity, permanent hardness, SiO2, NH_4^+, NO2 -, NO3 -, P, Fe and Mn.

Water samples were analyzed following the protocols according to the Analytical methods for the examination of the surface water (Official Gazette of the Republic of Srpska 2001). Sampling was performed at 50 locations along the Trebišnjica River system, including the reservoirs and springs (Fig. 1).

Multivariate statistical analysis

The SPSS for Windows release 20 (SPSS Inc, 2011) software package was utilized for the descriptive and multivariate statistical analysis – hierarchical cluster analysis (HCA) and factor analysis. A total of 929 water samples were used in the statistical analyses, based on 10 parameters, such as: pH, electrical conductivity Ca^{2+}, Mg^{2+}, Na^+, HCO_3^-, SO_4^{2-}, Cl^-, NH_4^+ and P. Unlike HCA, Factor analysis was realized with the TDS parameter instead of Na^+, due to the inadequacy of the sample, which was assessed by the Kaiser-Meyer-Olkin (KMO) test. In the case of HCA, all data were transformed and subsequently standardized to their standard scores (z-scores).
Factor analysis has proved useful in the analysis of large quantities of hydrogeochemical data and reduces the data to a small number of variables called factors. In this way, the factors are extracted, and each of them is explained by some hydrogeochemical process (Papić, Stojković, 2012). In this work, a Principal Components analysis (PCA) analytical approach was applied.
Hierarchical cluster analysis is used to classify the samples into distinct hydrochemical groups (Q-mode) based on their similarity (Güler et al, 2002). The relative similarities between the samples were quantified using the Euclidean distance. Ward's method was used to combine the clusters.

Results and discussion

General hydrochemistry

The prevailing surface water type in the Trebišnjica River catchment is Ca-HCO_3. This water type is, in fact, a reflection of the predominant carbonate material in the study area.

Corresponding to the carbonate water system, the water is alkaline, with a pH value of 7.04 to 9.1. Concentration of major ions such as Ca^{2+}, Mg^{2+}, Na^+, HCO_3^-, SO_4^{2-}, Cl^- and also EC and TDS increase to the downstream part of the surface flows, where their velocity is smallest. In addition, the groundwater is more mineralized than the surface water, which is a result of the different hydrodynamic conditions of their genesis.

The surface water in the lowest part of the Mušnica and Trebišnjica River has the highest values of pollution indicators (NH_4^+ and P), as result of domestic and agricultural wastewater influence.

Factor analysis

The results of the factor analysis are summarized in Table 1. Four factors explain 68.13% of the variance of the original data set. The First factor (F1), which explain 32.08% of the total variance, includes significant and positive loadings for HCO_3^-, TDS, Ca^{2+}, EC and a negative loading for pH. This indicates that F1 represents the dissolution of calcite, under the influence of CO_2.

The second factor (F2) explains 13.17% of the total variance within the dataset and has significant and positive loading for Mg^{2+} and not so significant for Cl^-. This primarily indicates the dissolution of dolomite and, to some extent, halite.

The third factor (F3) explains 12.32% of the variance and has significant and positive loadings for P and NH_4^+. Therefore, F3 represents the influence of anthropogenic activities in the Mušnica River catchment.

The fourth factor (F4) explains 10.56% of the total variance, and includes a strongly positive loading for SO_4^{2-}, and less pronounced NH_4^+. This primarily indicates the dissolution of gypsum, but significant loadings for ammonium ion could be used to explain the impact of anthropogenic activities on water quality.

Table 1. *Factor loadings and percentage of variance explained by the four extracted components, with Varimax rotations (values in bold represent loadings >0.5)*

Parameters	Factors			
	1	2	3	4
HCO_3^-	**0,885**	0,213	0,021	0,077
TDS	**0,810**	0,240	0,082	-0,016
Ca^{2+}	**0,808**	-0,365	0,140	0,254
EC	**0,652**	0,388	0,034	-0,142
pH	**-0,509**	-0,289	0,282	0,123
Mg^{2+}	0,195	**0,871**	-0,067	-0,002
Cl^-	0,197	**0,458**	0,215	0,185
Phosphate	0,119	-0,118	**0,812**	-0,234
NH_4^+	-0,069	0,282	**0,685**	0,302
SO_4^{2-}	0,023	0,062	-0,019	**0,911**
Explained variance (%)	32,082	13,166	12,323	10,557
Cumulative % of variance	32,082	45,248	57,571	68,128

Hierarchical cluster analysis

The hydrochemical data were also classified by HCA, and the result is presented in Table 2. Two groups are selected by visual examination of the dendrogram, the first of which is characterized by fewer values of the analyzed parameters, with the exception of pH, NH_4^+ and P.

Table 2. *Median of hydrogeochemical composition of groups and subgroups; n – number of samples in the group/subgroup; concertation in mg/l, electrical conductivity (EC) in μScm^{-1}*

Group/ Subgroup	*n*	pH	EC	Ca^{2+}	Mg^{2+}	Na^+	Cl^-	HCO_3^-	SO_4^{2-}	NH_4^+	Phosph.
I	858	7,96	234	57,54	6,71	6,28	2,3	194,36	21,13	0,05	0,008
I-1	403	7,96	239	62,59	5,77	7,99	2,7	201,3	25,62	0,05	0,01
I-2	455	7,95	229	52,74	7,23	5,02	2,0	184,3	19,22	0,04	0,006
II	71	7,57	343	62,81	25,83	6,79	4,0	292,8	22,6	0,04	0,004

The first group is further classified into two subgroups representing different mineralization and anthropogenic influences. In comparison with the second subgroup, the first subgroup is characterized by higher values of the analyzed parameters, except Mg^{2+}. All of the samples clustered in this subgroup are from the lowest part of the Mušnica and Trebišnjica River, with the highest impact of anthropogenic activities on water quality.

The second subgroup contains water samples which are relatively free from anthropogenic influences. This subgroup includes the water of the higher parts of the Trebišnjica River catchment and Bileća Reservoir.

The second group is characterized by higher values of most parameters, especially Mg^{2+}. It contains water samples from all water resources types, which are located mainly on lithology of Upper Triassic dolomites.

Conclusions

Conceptual commitment to integrated water quality management of the Trebišnjica River catchment is inconsistent with modest results of hydrogeochemical research. In such circumstances, optimal conditions for water quality management in the Trebišnjica River catchment have not been created. Because of that, the main objectives of this study were to determine the chemical characteristics and the dominant chemical processes, which control the water composition of the Trebisnjica River catchment. In order to fulfill these objectives, the factor analysis and hierarchical cluster analysis were used. Factor analysis enabled the grouping of parameters into coherent, independent sets, which preliminarily determined the main hydrogeochemical processes in the Trebišnjica River catchment. This technique confirmed the key importance of calcite dissolution on the chemical characteristics of the water in the study area. The processes of dissolution of dolomite, halite and sulphate as well as anthropogenic influences were also identified.

HCA has shown that lithological composition is a key factor in grouping water samples into different groups. Therefore, water samples which were located on lithology of dolomites were grouped into a separate group from other samples, mostly from limestone terrains. In the classification of subgroups other factors have been identified, such as the different values of water mineralization and anthropogenic influences.

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TRANSBOUNDARY GROUNDWATER RESOURCE MANAGEMENT – MONITORING OF CIJEVNA RIVER BASIN (MONTENEGRO – ALBANIA)

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Abstract: Ineffective transboundary management of water resources by one or more countries sharing them can lead to a reduction in water resources or water pollution, which then threatens local ecosystems. Montenegro shares groundwater with all of its bordering countries (Albania, Croatia, Serbia and Bosnia and Herzegovina). In Montenegro, about 92% of the population is supplied from groundwater, mostly from karst aquifers. This fact indicates the importance of this resource and the importance of its preservation. To date, groundwater flow has largely been unexplored, which results in recharge zones and also groundwater body protection zones being undefined. This paper presents a management model (DSS-Decision support system) for the sustainable use of water resources through the initial stage of establishing continuous monitoring. The approach is based on the groundwater vulnerability model, taking the Cijevna River Basin shared by Montenegro and Albania as a case example.

Key words: Transboundary water management, Monitoring, Groundwater vulnerability, DSS-Decision support system.

Introduction

More than 40% of the world's population lives within river and lake basins shared by two or more states, with over 90% living in countries that share the basins. The existing 263 transboundary (lake and river) basins cover almost half of the Earth's surface and are estimated to provide about 60% of (drinking) freshwater. A total of 145 countries have their territory within these transboundary basins, while 30 countries lie entirely within the catchment areas. Worldwide, approximately 2 billion people depend on groundwater, originating from 300 transboundary aquifers (UN Water, 2008).

Water resource management seeks to ensure a harmonious relationship between society and nature in order to preserve water resources for future generations. Previous experience regarding the use of water resources indicates that the principle of functioning of the whole society is based on economic growth, and it is most often realized without the presence of an ethical and moral component in relation to the natural environment and water resources.

There is no single definition of Integrated Water Resources Management (IWRM), although the most commonly used is the definition of Global Water Partnership (GWP), according to which IWRM is an integration of multiple sectors: water, land and other related sectors, in order to maximize the resultant economic and social welfare in an equitable manner, without compromising the sustainability of vital ecosystems (GWP, 2004). In fact, this approach is increasingly represented and is known as "Nexus".

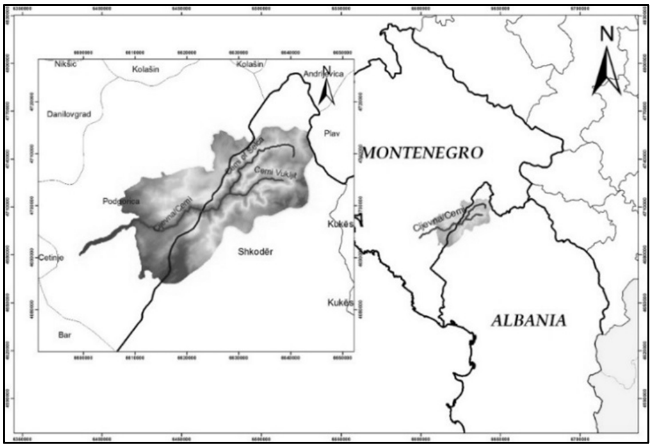

Fig. 1. Overview of the study area of the transboundary Cijevna river basin (Montenegro – Albania)

The basis for any management model or decision making is information. The initial information about a basin is the state of the water resources in the basin itself, which is obtained only by in-field monitoring.

Under conditions of insufficient information, a methodology for establishing transboundary monitoring in the study area of the Cijevna river basin (Fig. 1) has been developed, which is based primarily on the preservation of the status of groundwater bodies, in line with the principles of integrated management.

The Cijevna river is one of the larger rivers flowing through the Albanian Alps. The length of the Cijevna river flow is about 62.2 km and consists of two parts: Cemi Seljces and Cemi Vukljit. Cemi Seljces is about 22.5 km long and represents the northern part (branch) of the stream that originates from the springs of Koprishti, while Cemi Vukljit is about 17.9 km long and originates from the Vujlji/Vukli spring (Luga). These two rivers meet at Tamare in Albania, where the Cijevna river is formed. The Cijevna river continues to flow through the limestone blocks of Mizhdrakuli and Kapezdroja near Grabomi, where it leaves the territory of Albania. The Cijevna river flows through the Zeta Plain, forming the southern and south-western border of the Kučka Krajina (Fig. 1). Defining the area of the river basin in karst is one of the more complex tasks, bearing in mind that a part of the Cijevna river flow in Montenegro sinks in the summer period and feeds intergranular aquifer of the Zeta Plain, while another part of the water feeds water sources along the periphery of the Zeta Plain, such as Ribnicka Vrela, Vitoja and others.

The Cijevna River Basin recharges the Tuško Field, which is one of the largest aquifers in Montenegro. The Tuško Field provides additional quantities of water for the water supply to Podgorica and other parts of Montenegro. The water supply system of Podgorica includes exploration and exploitation wells in Miljes, Konik (200 m from the Ribnica watercourse) and Dinosa (about 80 l/s), which are hydraulically connected with the waters of the Cijevna River Basin. These systems provide additional quantities of water that ensure continuous water supply throughout the season.

Pollution of one of the above-mentioned sources can cause irreparable damage to the future generations, thereby undermining the concept of sustainable development.

Methodology

The methodology is based on the use of the DSS-Decision Support System with the GIS tools for assessing the groundwater vulnerability, which incorporates the results of previous hydrogeological surveys whilst also providing reference to current legal and strategic frameworks.
The current state of monitoring of the transboundary Cijevna River Basin is based on individual measurements undertaken solely for the purposes of projects or regional studies. To date, a complete overview of the transboundary aquifer monitoring has not been carried out and consequently a groundwater monitoring model is yet to be developed.
The use of the DSS tools (Fig. 2) includes the assessment of groundwater vulnerability and the proposal for establishing monitoring in accordance with the defined legal procedures.

Groundwater vulnerability assessment of the transboundary Cijevna river basin was performed using the two methods: EPIK for karst-fissure groundwater bodies, and DRASTIC for karst fissure and intergranular unconfined groundwater bodies.

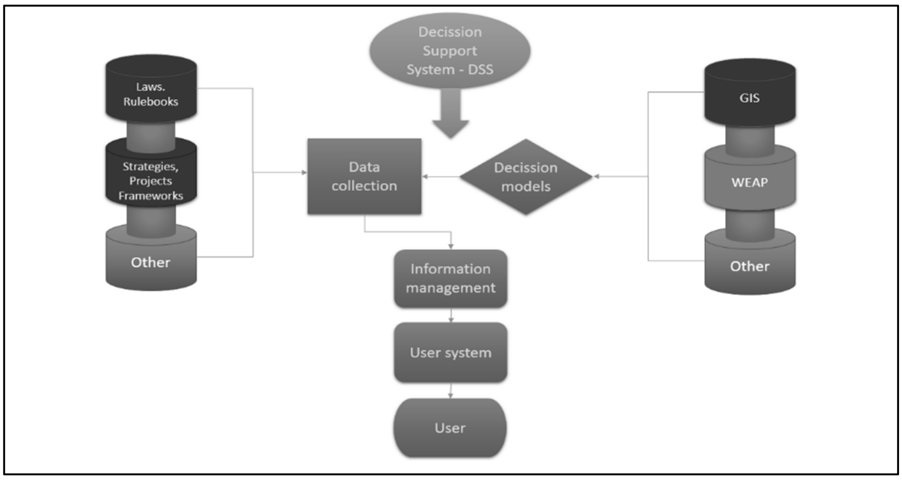

Fig. 2. Flowchart of DSS model for the integrated management of the transboundary Cijevna River Basin (Montenegro – Albania)

Results

The EPIK index for the entire study area was calculated by combining all four parameters, using the standard formula (Döerfliger & Zwahlen, 1997):
F = 3E + P + 3I + 2K

The terrain was classified based on the rate of the vulnerability index, with four distinct classes of groundwater vulnerability (Fig. 3).

The DRASTIC index was obtained using the following formula (Aller, 1985):

Vulnerability index = $D_r \cdot D_w + R_r \cdot R_w + A_r \cdot A_w + S_r \cdot S_w + T_r \cdot T_w + I_r \cdot I_w + C_r \cdot C_w$
where: r – parameter value at a given point, w – parameter weight.

Figure 4 below shows all 6 classes in the area of the Cijevna river basin. The zones defined as very high vulnerability are the result of weights of factors A, S, I, and C. However, the zones of certain sources (Vitoja, Krvenica, Traboin) are located in the medium, high to high vulnerability zone, which was influenced by factor D (depth to water).

Comparative analysis of the results obtained by these two methods shows that most of the terrain is of high to very high vulnerability, which is a realistic picture taking into account that almost 80% of the basin is built by karst and carbonate rocks.

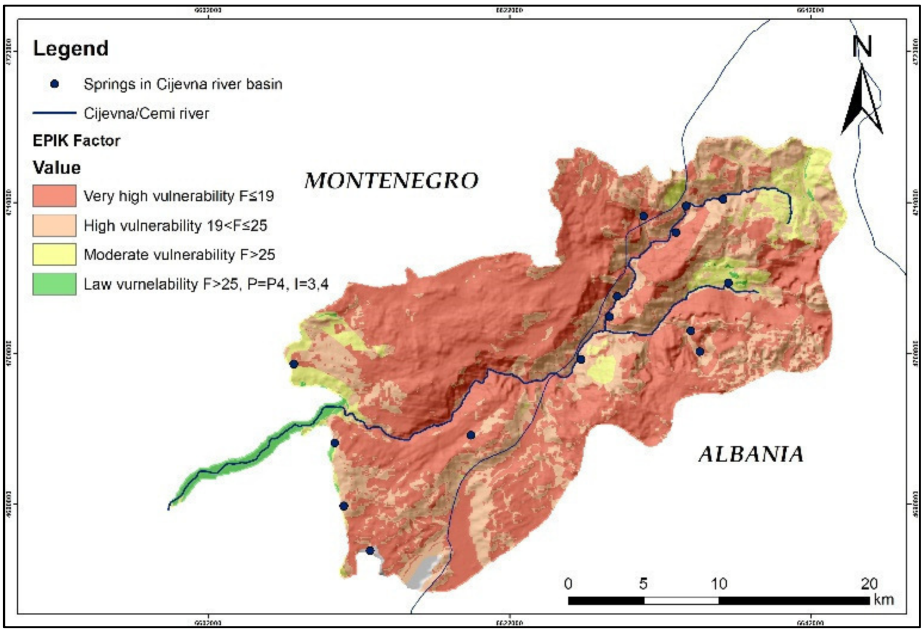

Fig. 3. Groundwater vulnerability map by using EPIK method

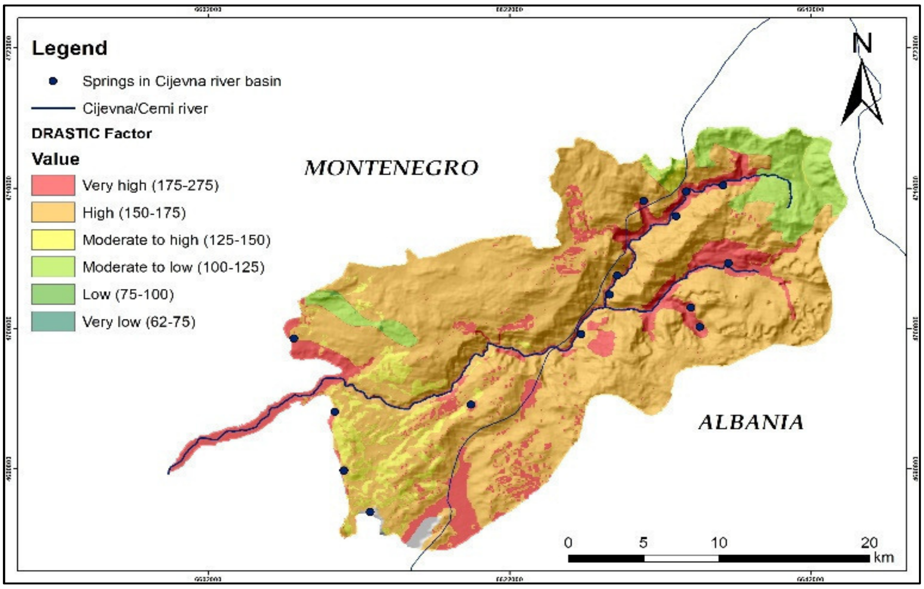

Fig. 4. Vulnerability map using the DRASTIC method

The largest surface areas within the river basin are of High Vulnerability according to the DRASTIC method, while the EPIK method shows that Very High Vulnerability areas represent the large percentage (Fig. 5).

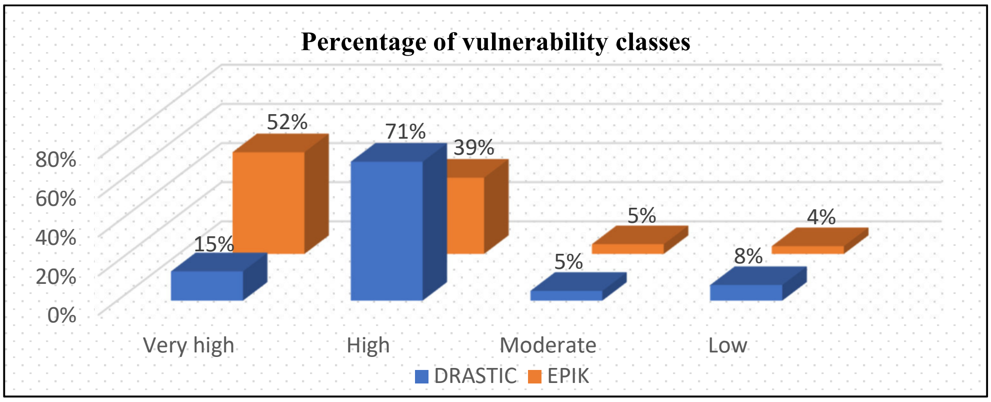

Fig. 5. Comparative chart showing groundwater vulnerability class percentages using EPIK and DRASTIC

Discussion – Monitoring Network Development

The future monitoring of the transboundary Cijevna River Basin must be established in compliance with the Water Framework Directive with observation points positioned at key locations in both surface and groundwater bodies. In addition, when crossing from the territory of Albania to Montenegro it is particularly important to observe the flow and quality of water at the Cijevna River border, since such data will reflect the state of the water quality and ecosystem in the upstream stretch (output for Albania) that will affect the downstream section (input for Montenegro).

In the case of the Cijevna River Basin which drains within the territory of Montenegro (joining the Moraca River near Podgorica), monitoring must be carried out at all control points (in this case, all the water sources through which the basin drains) as indicated by the results of groundwater vulnerability analysis using DRASTIC and EPIK methodologies. Furthermore, monitoring needs to be established in the glaciofluvial sediments, which are recharged by the Cijevna River at the very ending of the canyon segment of its flow. In this zone, it is necessary to set a number of piezometers to monitor the quality and level of groundwater in order to define the hydraulic interaction between the Cijevna River and the groundwater of glaciofluvial sediments of the Zeta Plain.

With respect to surface water, for the accurate measurement of the amount of water that sinks before the confluence it is necessary to reconstruct a hydrological station at Trgaj, where it existed in the past, and also before the confluence with the Moraca River.

The proposal for a monitoring network on all drainage sources and additional piezometers in the transboundary Cijevna River Basin is presented in Figure 6.

Each karst aquifer is unique in terms of characteristics; however, some structural components are widespread (Ford and Williams, 2007). Data on groundwater in karst areas, as in the case of transboundary Cijevna River Basin, can only be obtained by monitoring hydrogeological phenomena and objects such as sinks, cave streams, springs and wells.

The final results of groundwater vulnerability analysis and the established monitoring are in fact inputs for the adaptation of the River Basin management system and for the creation of appropriate laws and secondary legislation in order to adjust the system to natural conditions on the field.

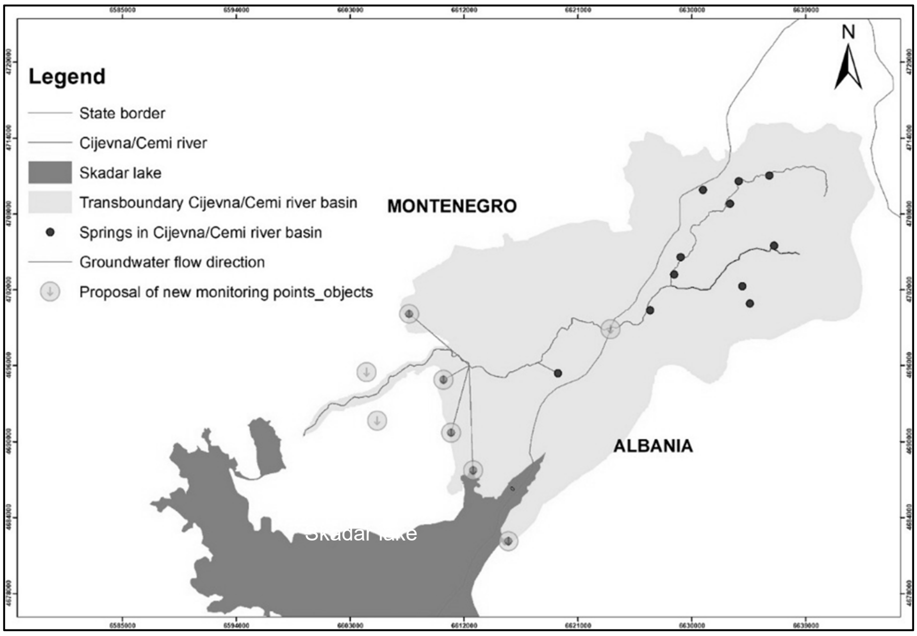

Fig. 6. Proposed monitoring network on all drainage sources and additional piezometers in the transboundary Cijevna river basin

Conclusion

The management of transboundary water resources is one of the most complex challenges in the water sector today. To this end, the use of DSS will act to synchronize a variety of sectoral activities and pressures (water supply, agriculture, irrigation, fishery, tourism) and will function according to the "nexus" approach. This paper represents only the first step in integrating the sectors in transboundary groundwater management.

The transboundary Cijevna River Basin is currently unexplored in terms of vulnerability assessment and lacks a suitable monitoring network, both in Montenegro and Albania. This study shows the effectiveness of the EPIK and DRASTIC models for the determination of the groundwater vulnerability assessment in karst and intergranular groundwater bodies, respectively. To assess the potential of this catchment area for future effective (shared) sustainable water use requires the implementation of an adequate WFD-compliant monitoring network.

The integration of monitoring information into the DSS will allow for effective assessment of the water balance of the basin, thereby defining the integrated transboundary basin functioning model, which will provide a sound-scientific basis for a framework agreement between Montenegro and Albania in transboundary management of the Cijevna River Basin.

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ANALYSES OF VRANA LAKE (ISLAND OF CRES, CROATIA) MEAN ANNUAL WATER LEVEL

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Abstract: The paper analyses complex hydrological behaviour of Vrana Lake mean annual water level during the time period 1929-2017 (89 years). A large mass of fresh lake water body (average volume of approx. 220×10^6 m^3) fills up deep cryptodepression located in the completely karstified small Adriatic island of Cres (405.71 km^2). A strong and dangerous drop in the level of water started in 1983. The paper deals with the explanation of this phenomenon. By using autocorrelation, single and multiple linear correlation methods, the analyses of the relationship between the mean annual water level (as a dependent variable) and the mean annual air temperature, annual precipitation and volume of annual water pumping from the lake (as independent variables) are conducted. It is concluded that the long-lasting memory effect (about six years) of the large water body of Vrana Lake plays a crucial role in the hydrological behaviour of its water level.

Key words: air temperature, precipitation, Vrana Lake (island of Cres), water level, precipitation, water pumping

Introduction

The Island of Cres extends in the northern Adriatic Sea shelf between the Istria Peninsula and the northern Dinarides (Fig. 1). The Vrana Lake on the completely karstified island (405.71 km^2) represents the largest natural fresh water body located on a small Mediterranean island (less than 1000 km^2), and possibly in the entire world (Bonacci 1993). The maximum depth of the lake bottom is 61.3 m below sea level. The surface area of lake water for the minimum (8.56 m a.s.l.) and the maximum (16.86 m a.s.l.) measured water levels was 5.28 and 5.98 km^2, respectively. The volume of water for the minimum and maximum water levels was 197×10^6 and 241×10^6 m^3, respectively (Bonacci, 2017).

The water budget method was used to define the lake catchment area at approximately 25 km2 (Bonacci 1993). This figure was confirmed by the measured tritium values, which established lake water's mean residence time of 30-40 years (Hertelendi et al. 1995). The same investigations determined the atmosphere to be the main origin of the lake water. Water in many karst islands water bodies is brackish, whereas in Vrana Lake the average value of salinity is only 72 mg/L, and varies in the narrow range between 62 mg/L and 92 mg/L.

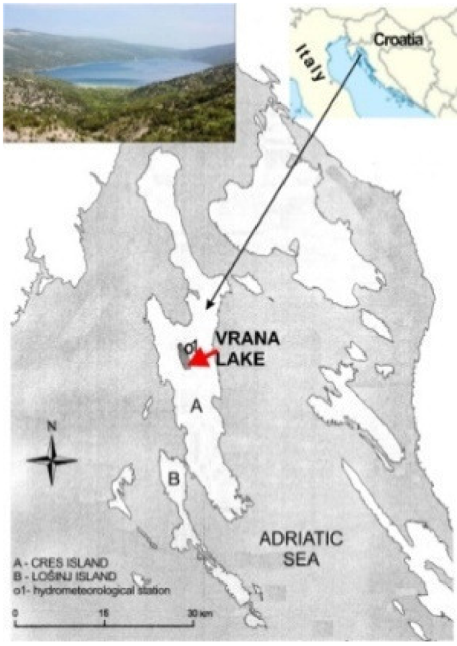

Fig. 1. Map of Cres Island and Vrana Lake

The time data series of the mean annual lake water levels for the time period of 1929 – 2017 is provided in Fig. 2. The average mean annual water level during the whole analysed time period is 12.57 m a.s.l. A strong and dangerous drop in the level of water started in 1983. In the first subperiod (1929-1982), the average annual water level was 13.45 m a.s.l. The mean annual lake water level ranges between 11.53 m a.s.l. (1946) and 15.84 m a.sl. (1936). In the second analysed subperiod (1983-2017), the average annual water level was 13.45 m a.s.l. The mean annual lake water level ranges between 9.38 m a.s.l. (2012) and 12.14 m a.sl. (2010).

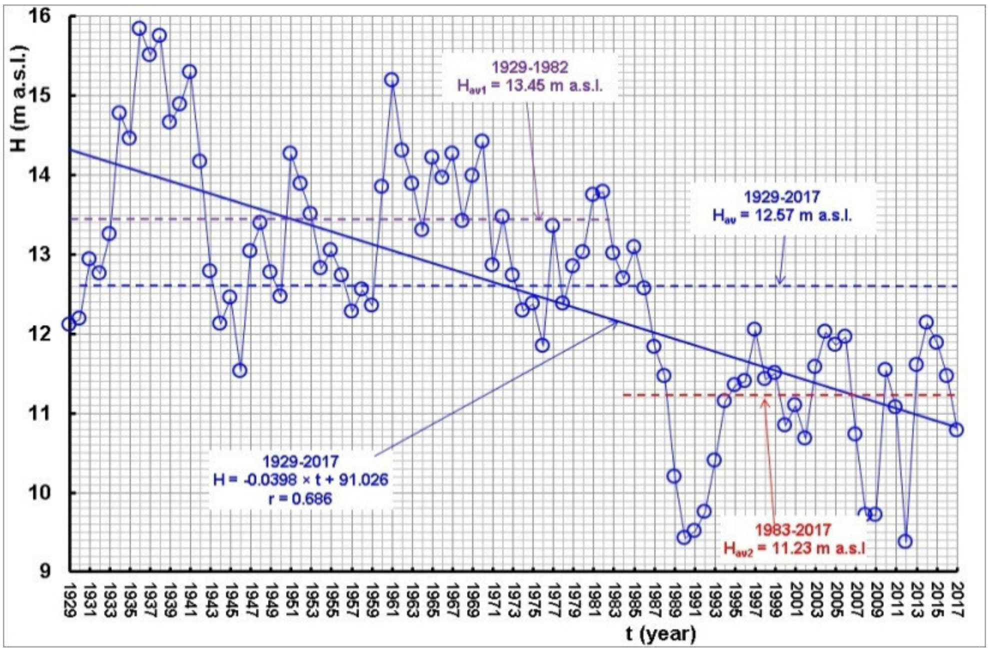

Fig. 2. Time data series for the mean annual lake water levels (1929-2017)

Precipitation, air temperature and water pumping

The average annual precipitation in the time period 1929-2017 was 1076 mm. The minimum and the maximum annual precipitations are 686 mm (2011) and 1743 mm (1960), respectively. There is no trend in annual precipitation, and the redistribution of precipitation during the year in the whole analysed time period (Bonacci 2017).

The average mean annual air temperature in the time period 1929-2017 was 14.65 ^{0}C. The minimum mean annual air temperature was 13.5 ^{0}C (1980) and the maximum was 16.73 ^{0}C (2014). The linear trend is statistically significant ($p<0.01$) with a linear correlation coefficient, $r=0.426$. The second-order polynomial trend with a coefficient of nonlinear correlation of $R=0.621$ is considerably higher. A strong increasing trend of air temperature during the approximately 40 past years is established.

Water pumping from the lake started in 1965. In 1983, the quantity of extracted water reached the value of C=1.82×106 m3, and in 2015 it reached the maximum value of C=2.60×106 m3.

Autocorrelation analyses

Autocorrelation, also known as serial correlation, is the correlation of a signal with a delayed copy of itself as a function of delay. It can be defined as the correlation between the elements of analysed series and others from the same series separated from them by a given interval. If sufficiently long series are available, it is possible to perform autocorrelation analyses to gain insight into the causal relationships between the analysed time series (Ristić Vakanjac et al. 2017).

Figure 3 shows the mean water level auto-correlograms for three different time periods: (1) 1929-2017; (2) 1929-1982; (3) 1983-2017. For the longest time period (1929-2017), the auto-correlogram shows the optimum internal connection between the mean annual water levels. The auto-correlograms for two subperiods (1929-1982 and 1983-2017) are considerably steeper than in the entire period (1929-2017).

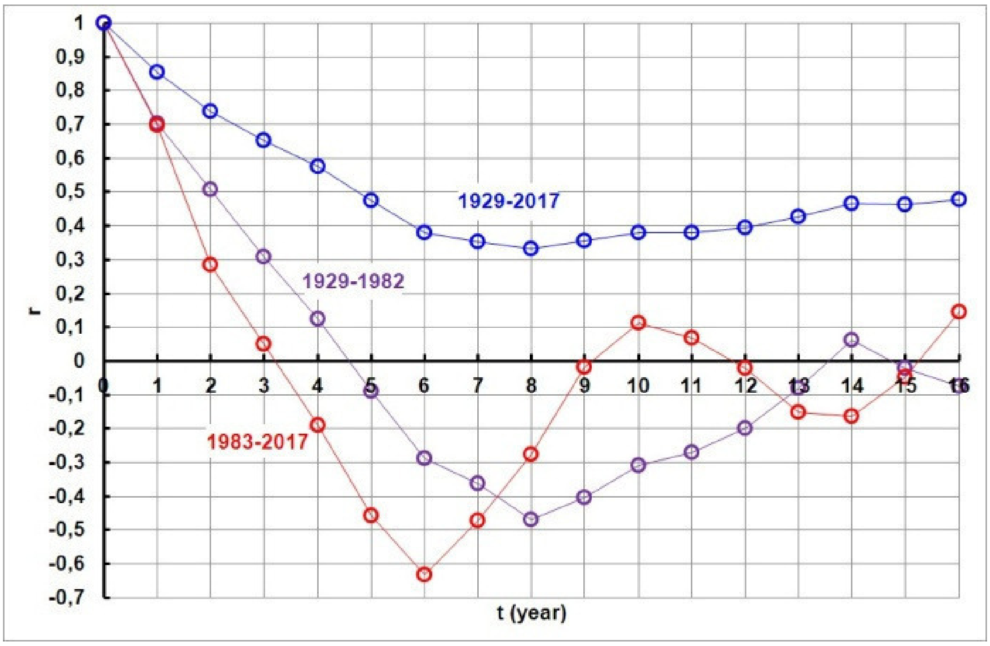

Fig. 3. Three autocorrelation functions for the: (1) 89-year time series (1929–2015); (2) 54-year (1929-1982); (3) 35-year (1983-2017) for the mean annual lake water level, H

Figure 4 shows three autocorrelation functions for the 89-year time series (1929–2015) for the mean annual water level, H, mean annual air temperature, T and annual precipitation, P. This illustration shows that the memory effect in the case of the time series of the mean annual air temperature, T, is considerably higher than in the case of time series of annual precipitations, P. In the case of the mean annual air temperature, T, the autocorrelation coefficient, r, reaches the value of 0.2 in 10 years. According to Mangin, (1984) any time series is to be autocorrelated until the time the correlation coefficient becomes less than 0.2.

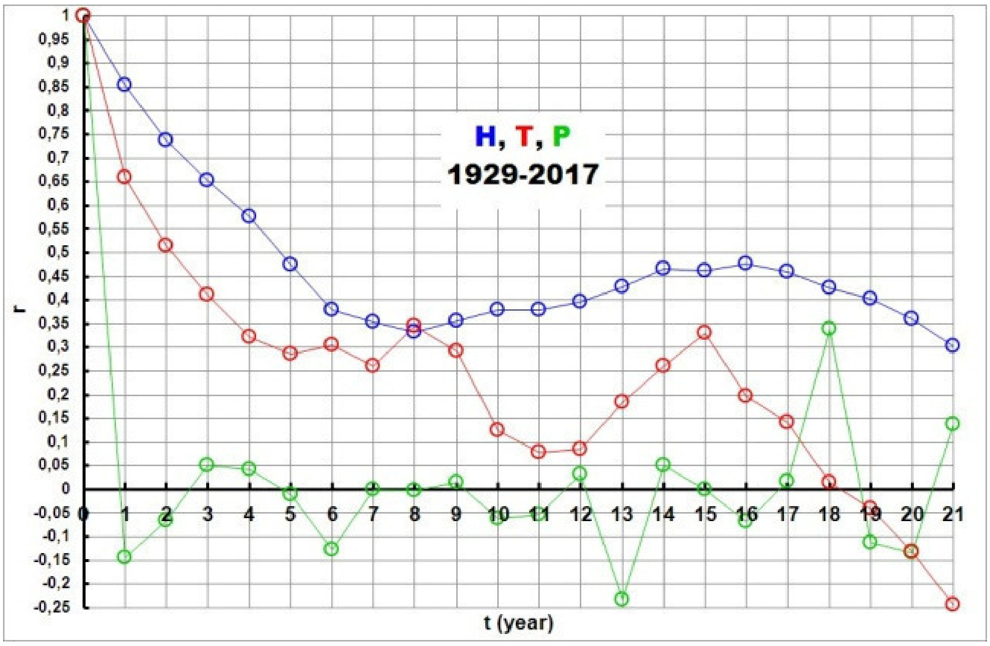

Fig. 4. Three autocorrelation functions of the 89-year time series (1929–2015) for the mean annual water level, H, mean annual air temperature, T, and annual precipitation, P

Correlation analyses

Figure 5 presents three time series of values of linear correlation coefficients between the mean annual lake water level, H (as a dependent variable), and the sum of annual precipitation, ΣPi (i=0, 1, 2, 3, 4,… 12) during, i, preceding years. This illustration clearly shows that precipitation falling in year i=0 (year of the mean annual water level) is not important for this year mean annual water level. As the lake has large volume of water, its water level is controlled by the long-lasting previous precipitations which vary between five and six years.

Table 1 presents the values of linear correlation coefficients, r, between the mean annual lake water level, H (as a dependent variable), and the following independent variables: (1) annual precipitation, P; (2) the sum of annual precipitation during the last six years, ΣP6; (3) the mean annual temperature, T; (4) annual water pumping, C. The r values are calculated for six different time periods: (1) 1929-2017; (2) 1935-2017); (3) 1929-1982; (4) 1935.1982; (5) 1983-2017).

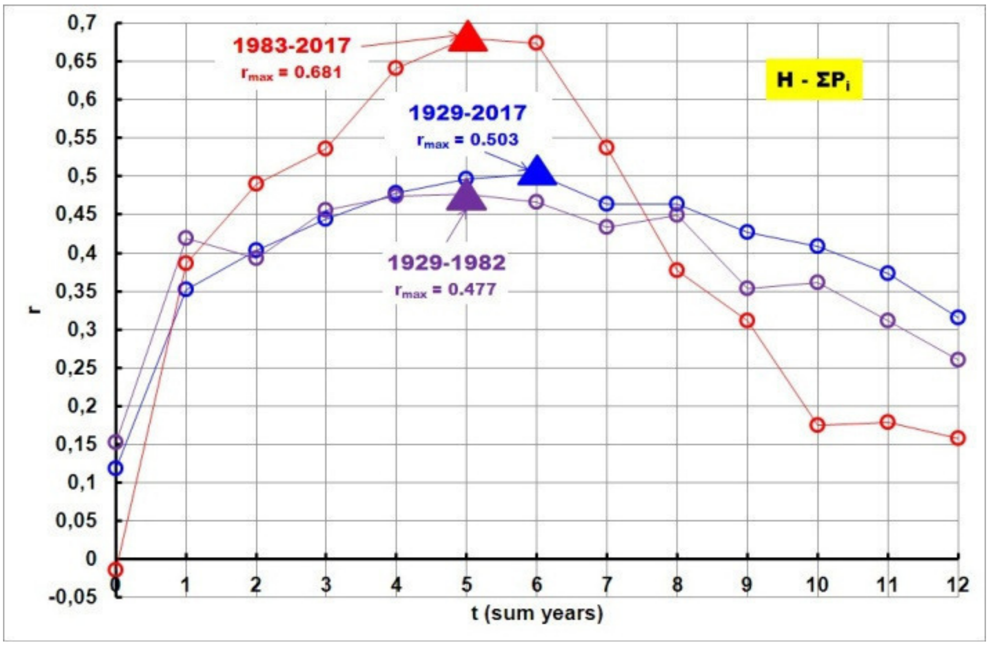

Fig. 5. Three time series of coefficients of linear correlation, r, between the mean annual lake water level, H, and the sum of annual precipitation, ΣP_i

Table 1. Values of linear correlation coefficients, r, between the mean annual lake water level, H (as a dependent variable), and four independent variables (P, ΣP6, T, C)

r	H-P	H-ΣP_6	H-T	H-C
1929-2017	0.118	-	-0.397	-0.706
1935-2017	0.100	0.503	-0.409	-0.723
1929-1982	0.153	-	-0.0436	-0.190
1935-1982	0.133	0.467	-0.107	-0.238
1983-2017	-0.0141	0.673	-0.299	0.007

Table 2 presents the values of multiple correlation coefficients, R, between the mean annual lake water level, H (as a dependent variable), and the independent variables: (1) P; (2) ΣP6; (3) T; (4) C for four different time periods.

Table 2. Values of multiple correlation coefficients, R, between the mean annual lake water level, H (as a dependent variable), and four independent variables: P, ΣP6,T ,C

R	H-(P,T,C)	H-(ΣP_6,T,C)
1929-2017	0.730	-
1935-2017	0.737	0.887
1935-1982	0.345	0.724
1983-2017	0.348	0.783

The equation of multiple linear correlations between the mean annual water level as a dependent variable and three independent variables (sum of six years` annual precipitation, ΣP6, annual lake water pumping C, and the mean annual air temperature, T, defined for the recent time period 1983-2017 is:

$$H = 6.54 + 0.00150 \times \Sigma P6 + 0.000522 \times C - 0{,}432 \times T \qquad (1)$$

where, H, is provided in m a.s.l.; ΣP6, in mm; C, in L/s and T in ºC. The sum of six years` annual precipitation, ΣP6, is a more important parameter than the annual lake water pumping, C with a ratio of 4.2:1, and the mean annual air temperature, T with a ratio 11:1.

Conclusions

The analyses have demonstrated the changes in lake hydrological regime during different time periods. Vrana Lake is a very complex hydrological and hydrogeological system, which is under strong anthropogenic influences due to water pumping from the lake. Additionally, its functioning is impacted by climate changes/variations. This is mostly related to the impact of the increase in air temperatures. Due to the large water surface, an increase in the mean annual air temperature of 1 ºC causes the annual increase in evapotranspiration from the free water surface of approx. 5.8×106 m3 of water, and the increase in evapotranspiration from the land surface basin of approx. 1×106 m3 of water (Bonacci 2014).

The threatening lake water level drop is caused by natural (global warming) and anthropogenic (water overexploitation) drivers. The climate change poses especially significant risks to all small Mediterranean islands. Most climate change projections show important decreases in water availability in the Mediterranean region by the end of this century (Pascuala et al. 2015).

Tourism causes high seasonal water needs. Because of its very intensive, unforeseen and difficult to control development, it is realistic to expect more pressure on lake water pumping, which can result in new and dangerous lake water level decreasing trend.

Investigations conducted in the paper have pointed to the necessity of performing further interdisciplinary measurements and analyses. The analyses and their results provided in this paper did not answer the crucial question of explaining the dangerous drop of the mean annual lake water level, but they will contribute to a better understanding of a very complex Vrana Lake hydrological behaviour.

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170 YEARS LONG CONTINUOUS RECORD OF PLANINSKO POLJE (CENTRAL SLOVENIA) FLOODING – PRELIMINARY ANALYSIS OF DATA SERIES

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Abstract

Long and continuous data sets of hydrological variables are extremely important in studying various processes in hydrological cycle. Among them are not the least important the trend and frequency analysis of flooding. Poljes of Dinaric karst are phenomena which are flooded on an annual basis, but the lengths and intensities of floods are variable from year to year and from decade to decade. Nowadays, questions are often raised if the appearance and nature of floods and droughts is changing and if it is time depended.

Planinsko polje (central Slovenia) is the most northern polje in the system of Notranjska poljes developed along the strong regional Idrija fault. In the area of Planinsko polje several long and well-developed caves are present. In the area there is also a system of springs and ponors as well as many other karstic phenomena. The main river course on Planinsko polje is the Unica river. Planinsko polje is frequently flooded.

Hydrological station Hasberg on the River Unica is one of the oldest operating stations in Slovenia. From the web archive of Slovenian Environment Agency first daily data are available from year 1926 until present. In this archive some longer data gaps are present. It was previously known from the literature that hydrological measurements at Hasberg hydrological station were already performed in 19th century but data were not available. It was believed that data are lost.

With careful analysis of older literature and various archival material in the Archive of Republic of Slovenia we were able to reconstruct nearly continuous data set of Unica river stages from the Hasberg hydrological station. Data are available on the daily basis starting in the year 1844. In the available data set some shorter gaps are present. However, the data set can be considered as continuous. At the moment it represents the longest available hydrological data set in Slovenia. We believe that this set is also one of the longest if not the longest globally available hydrological data set from karstic poljes which represents important basis for their hydrological behavior analysis.

In the paper data set and its characteristics are presented. Preliminary analysis of trend and frequency of flooding level will be given.

Key words: Planinsko Polje, flooding, The Unica River

HYDROGEOLOGICAL FEATURES OF THE VALJEVO KARST AREA (WESTERN SERBIA)

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Abstract: "Valjevo karst" is a merokarst area of about 320 km² in the Inner Dinarides of Western Serbia. In the litho-stratigraphic view, the karstified limestones of Middle-Upper Triassic dominate, in which karst aquifers are formed. Brief analysis and systematization of available data of hydrogeological and other relevant research was carried out. Complex underground traces between swallow holes and discharge points (zones) are presented. Main features of 13 karst springs or discharge zones as well as of 8 (group of) wells are also exposed. Groundwaters of Valjevo karst represent exceptional multipurpose resources. However, an adequate systemic monitoring has not been established so far.

Key words: limestone, karst aquifers, groundwater resource

Introduction

"Valjevo karst" (VK) covers the area from Valjevo-Mionica Neogene basin (VMB), in the North, to the northern slopes of Valjevo Mountains range: Suvobor Mt., Maljen Mt., Povlen Mt., Jablanik Mt, Medvednik Mt., in western Serbia (Fig.1), with a frame range of altitudes of 160-1300 masl. On the West-East direction, it is stretched from the Jablanica River Basin to the Toplica River Basin. Geographically, it belongs to the Kolubara river basin, and administratively to the Kolubara District and (mostly) to the municipalities of Valjevo and Mionica. The total area, with few smaller isolated karst oases is about 320 km². Field hydrogeological researches were carried out at various locations and were partial both in terms of the size of the researched areas and in terms of time continuity: short-term flow-rate monitoring of few karst springs, tracing tests, exploratory drilling, well-drilling for water supply of few settlements and commercial water bottling, thermal water capture. The paper gives the analysis and systematization of available relevant research data.

Geomorfological and geological outlines

VK belongs to the geotectonic region of the Inner Dinarides and by type is a merokarst. In the litho-stratigraphic view, the karstified Medium-Upper Triassic limestones are dominant (Fig. 2), the thickness of which is estimated to be 300m [2] and, in which, the karst aquifers are formed. To a much lesser extent, karstified Upper Cretaceous limestones, up to 50 m thick exist in the catchments of the Jablanica and Sušica (the largest tributary of the Jablanica R.) rivers. Other geological units, starting from the Upper Miocene deposits of VMB, to the Paleozoic formations, represent (relatively) impermeable rocks i.e. the barriers for karst groundwater flows. The intense radial tectonics, followed by volcanic activity, formed the block structure of the terrain, which was the main predisposition for an intense karstification [4,5].

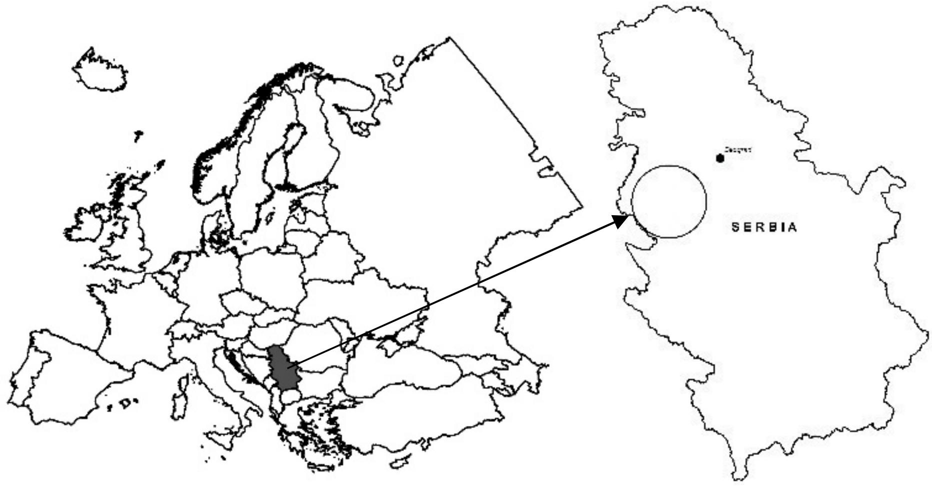

Fig. 1 Geographical position of the Valjevo karst area

The karst relief is made up of karst plateaus separated by the valleys (canyons) of Sušica, Gradac, Lepenica and Ribnica River, oriented in general, in the South-North direction. The dominant surface karst forms are sinkholes, with the average density higher than 10/km^2. A total of 195 underground forms i.e. speleological objects, have been detected: 134 caves and 61 potholes. The total length of the explored caves is 6122 m, and the total depth of the potholes is 1178.5m [1].

Tracing tests showed high development of the karst channels and complex underground traces between the swallow holes (ponors) and the springs [6]. Triassic limestone was discovered (by drilling) below the Upper Miocene deposits of VMB in the villages of Petnica, Mionica and Vrujci. It is possible, but unproven, that these limestones continue to extend to the north, to the zone (karst oasis) of Nepričava village, on the left side of Kolubara valley). It is likely that, in the southern part, under the Jurassic and Cretaceous formations, the limestones are continuously extended to the karst oases of Gornja Trešnjica, Taor springs and the Kosjerić village (Fig. 2).

Hydrogeology

According to the available data on groundwater traces and spatial distribution of the most important discharge points and zones of the karst aquifers, the following division on subareas is adopted for further exposure: 1-Lelić karst subarea, that includes: Sušica River catchment, Lelić plateau, Gradac valley and Bačevac plateau; 2-Banja River catchment; 3-Catchements of Lepenica, Ribnica and Toplica River; 4-Outer karst oases. Lelić karst subarea**:** Within this area an extensive karst aquifer is formed and is mostly drained by Paklje spring and Gradac springs (discharge zone) [5,7]. On the Lelić and Bačevac plateaus there are no permanent streams because all precipitations infiltrate through the dense network of sinkholes and swallow holes. At the site of the Lelić Monastery (407masl), a borehole of 147 m depth was drilled for local water supply. The depth to the groundwater was 60 m and about 1 l/s of water could be pumped out [8].

The Sušica River is formed by merging of the Povlenska and Polička River. The most remarkable spring in the upper Sušica catchement is Povlen spring (app. 930 masl) with minimum flow rate estimated at around 20 l/s [8]. In its upper stream, but only in high water periods, the Sušica River flows through a 4 km canyon, along which there are several ponor zones. The ponor zones that are downstream from 400 masl act as temporary springs (estavelles), but only during the rainy periods. Further downstream, in the range of 335-360 masl, there is another zone of some 15 ponors and temporary springs, as well as the only permanent spring Savinac with a minimum flow rate of about 3 l/s [7]. Underground flow traces to the Paklje spring and to the Gradac springs have been detected by marking of the ponors in Sušica valley [6] (Fig. 2). Downstream, surface flow to the Jablamica River exists only in high water periods.

The appearances of the Paklje spring and Gradac springs is caused by the position of the Triassic porphyrite and Lower-Triassic sediments (Fig. 2) that represent hydrogeological barriers. Depending on the data source [5,6,7], the Paklje spring altitude is 256-260 masl, and is partially captured (up to 300 l/s) for the municipal water supply of Valjevo. There is no continuous flow rate monitoring and the only longer observation period was 1972-76, during which the flow rate was in the range of 0.2-2 m^3/s, and the average value was 0.3 m^3/s [5]. The Gradac discharge zone consists of several springs in the Gradac canyon, on both valley sides, in the altitude range of 261-265 masl, from where the permanent river flow begins. Upstream, the surface flow exists only after abundant rains or snow melting.

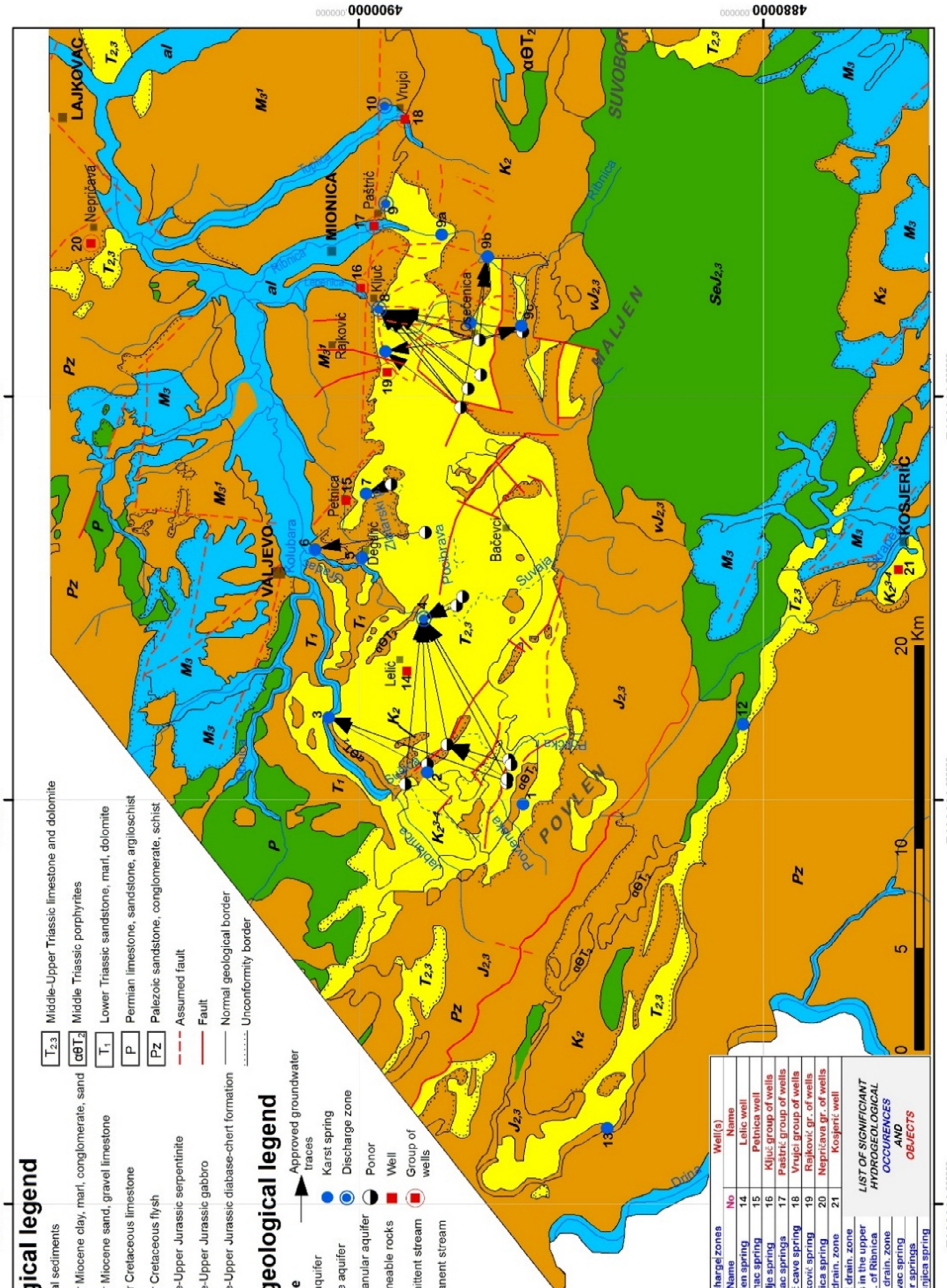

Fig. 2 Hydrogeological map of the Valjevo karst area [3-adapted]

The dry river valley has a lot of ponor zones and the tracing tests showed groundwater traces to the Gradac springs [6] (Fig. 2). For the 1972-76 period, the total flow rate of Gradac springs was in the range of 0.4-10 m^3/s, and the average value was 1.1 m^3/s [5]. Downstream, the karst aquifer is drained through several minor springs and discharge zones along the Gradac River: Degurić cave (216 masl, Qmin=12 l/s), Novaković spring (195 masl) etc. The average annual flow for the Gradac River on the hydrometric profile Degurić (201 masl) (Fig. 2), for the 2000-2015 period, was 2.58 m^3/s, and the average annual flows vary from 1.49 to 3.81 m^3/s. The average monthly flows range from 1.2 m^3/s (Sept.) to 5.28 m^3/s (March) [9]. Downstream of the Degurić profile, a part of the Gradac River flow is captured for the municipal water supply of Valjevo, as a supplement to the Paklje spring in recession periods. Basic chemical features of Paklje and Gradac waters are typical for karst aquifers: TDS=180-230 mg/l and belong to the carbonate class and the calcium group [3].

Total average discharge of the Lelić karst aquifers was estimated at 2.5-3 m^3/s [3,5,7].

Banja River subarea. Banja River originates from the Banja spring, near Petnica village. There are two streams in the topographic catchement of Banja: Zlatar and Pocibrava, and both of them lose water on the karst terrain. Tracing tests showed the connection of a ponor in Zlatar stream and the Banja spring, while a ponor in Pocibrava stream is connected with Novaković spring, in the Gradac valley [6] (Fig. 2).Banja spring appears in Petnica Cave (181 mnm), and the drainage is conditioned by the barrier of the Miocene sediments of VMB. The spring is featured by an intermittent character with visible daily flow rate fluctuations [6,7]. For the period 1972-1976, the flow rate of the Banja spring varies from 0.1-1 m^3/s, Qav = 250 l/s [4]. For the period 1991-2000 the average annual flow rates were 109-252 l/s [10]. In the vicinity of the spring, thermal water occurs in the Banja riverbank. This phenomenon initiates drilling of a deep well which captures about 15 l/s of water of 29^{o}C, from the deeper parts (232-500 m) of the karst aquifer [8]. The water is low mineralized (330 mg/l) and belongs to the carbonate class and the calcium group [3]. It is used for swimming pools.

Lepenica-Ribnica-Toplica subarea: Tracing tests in the Ribnica and Lepenica catchments showed the "crossing" of underground streams [6] (Fig.2). Several discharge zones are detected in this subarea and are featured by the occurrences of thermal waters (Fig. 2). The Ključ springs (discharge zone) appear in the zone of contact with the barrier of Miocene sediments of VMB, along the Lepenica riverbed (165-205 masl). Cold (9-11^{o}C) and subthermal (15-17^{o}C) spring waters are detected. The estimated total flow rate is in the range of 0.12-4 m^3/s [7]. Several wells have been drilled in this zone for local water supply, commercial water bottling, swimming pools, etc. [8].

The Paštrić discharge zone also appear in the contact zone with the Miocene sediments, along the Ribnica river bad, in the length of about 3 km (192-234 masl), while the zone of temporary springs appears about 2 km upstream. The estimated total minimum flow rate is about 30 l/s and the average one is about 0.6 m^3/s [7]. In this zone, the Mionica municipal water supply source is located. Several deep wells capture about 40 l/s of groundwater, below the 20-100m thick Miocene sediments [8]. Orlovac spring, in the village of Osečenica, is also captured for the water supply of Mionica. The minimum yield is about 20 l/s and the average is about 40 l/s [8]. In the village of Rajković, there are several wells that capture karst groundwater, among other purposes, for commercial water bottling [8].

The Vrujci discharge zone is formed by an upward mechanism of outflow of thermal (26-27 ^oC) water with the appearance of gases. The outflow is ostensibly from the alluvial deposits of Toplica River in the range of 180-185 masl. Total outflow rate is difficult to determine due to the outspread and the secondary character of the discharge zone and mixing with river water. Estimated range is 0.2-0.5 m^3/s [7]. In this zone, several drilling wells capture thermal water for swimming pools and commercial bottling [8].

The karst groundwaters of this zone are low mineralized (TDS<1 g/l) and belong to the carbonate class and the calcium or calcium-magnesium group. Estimated total average discharge, including the Banja River subarea, is about 3.5 m^3/s [7].

<u>Outer karst oases</u>: The source for municipal water supply of Lazarevac and Lajkovac (loc. Nepričava) (Fig. 2) is based on the six deep (120-350m) drilled wells that capture app. 120 l/s of karst groundwaters [11]. Total thickness of overlaying Miocene and alluvial sediments is 20-100 m.

Two springs are noteworthy in the southern oases, in the contact zone with the Paleozoic formation (Fig. 2): GornjaTrešnjica (Q_{av}=80 l/s) and the Taor springs (discharge zone), that is partially captured for municipal water supply of the Kosjerić village. The flow rate of non-captured part of the Taor springs varies in the range 17-250 l/s [8]. Supplement water supply of Kosjerić is based on the capture of karst water by a well (Fig. 2), during the recession of Taor springs [12].

Discussion and conclusion

The area is featured by complex underground hydrography and discordance of topographic and hydrogeological (sub)catchments, that makes difficulties for precise water balancing. Besides, there is no adequate (systemic) quantitative monitoring of karst groundwater, neither in terms of spatial schedule of points, nor in terms of continuity. None of the springs or discharge zones is observed, and the only relevant hydrometric profile is in Degurić. Total average discharge of Valjevo karst aquifers is estimated at up to 6-6.5 m^3/s, with note (without entering the methodology and accuracy of the estimate) that it depends on the annual quantity and seasonal distribution of precipitation. Based on the available data, the Qmin/Qmax flow regime varies from 1:10 (Paklje and Banja springs) to 1:25 (Gradac springs), which makes these resources, under natural conditions, relatively unreliable in the dry periods. The possibilities of discharge regulation have been considered by some researchers [7], but the realization did not happen given that the construction of the "Stubo-Rovni" dam and reservoir (on the Jablanica and Susica rivers) was planned several decades ago, for the purpose of water supply of the entire Kolubara district [11]. In the eastern part of the area, regulations have been successfully carried out at several sites by groundwater capturing with deep wells, for municipal water supply, thermal water use and commercial bottling. Regardless of the national and district water management plans (which will not be commented here) the karst aquifers of VK area should be kept under continuous quantitative and qualitative (high vulnerability due to the high karstification) monitoring, in order to preserve and keep this exceptional natural water reservoir in good status.

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STREAMS OF INCOME AND JOBS: THE ECONOMIC SIGNIFICANCE OF THE NERETVA AND TREBIŠNJICA RIVER BASINS

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Abstract: This study examined three water-dependent sectors that are interlinked with each other: hydropower, agriculture, and public water supply in the municipalities in the Neretva and Trebišnjica basins in Croatia, the two entities in Bosnia and Herzegovina, and Montenegro. It also took an in-depth look at three economic activities that are particularly important to the regional economy and are critically dependent on water: tangerine farming, wine production, and tourism in selected parts of the basins. Collected data shows gross primary returns totaling almost ***€450 million a year***, generating values of between €0.04-6.8 per m^3 of water. Tens of thousands of jobs also depend directly on these water-based activities. Overall, the study found that the Neretva and Trebišnjica basins are of critical economic significance. As such, it is in everybody's interests to ensure that these shared water resources are managed in an integrated way.

Streams of Income and Jobs: The Economic Significance of the Neretva and Trebišnjica River Basins

This study provides economic evidence as to why it is critically important that the Neretva and Trebišnjica basins are managed in an integrated and transboundary way. Through this study the World Wide Fund for Nature (WWF) and the Open Regional Fund for South-East Europe – Biodiversity (ORF BD) "Ecosystem services and valuation in future course of action in South-East Europe Region (ESAV)" implemented by Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH (GIZ) and funded by German Federal Ministry for Economic Cooperation and Development (BMZ) set out to identify how many jobs and how much revenue is dependent on waters from the Neretva and Trebišnjica basins.

The study provides baseline information about the role of water in key sectors in the basins' economies. It is a snapshot of 'what's at stake,' as decision makers in Croatia, Bosnia and Herzegovina, and its two entities of Federation

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Bosnia and Herzegovina and Republika Srpska, and Montenegro weigh their options to manage shared water resources for sustainable development, environmental management and protection, and disaster risk reduction. This information is critical. Decision makers across the region lack a comprehensive understanding of the value and interdependence of their shared water resources, and conversely, of the common costs that will result to all parties if the natural ecosystems that guarantee the quality and availability of these shared water resources are degraded or depleted.

The natural water regime in the basins has already been permanently altered. Stretches of the Neretva and Trebišnjica are channelized for navigation and to fuel complex hydropower systems; and surrounding wetlands drained for agriculture. While the largest threat to the natural ecosystem of the basins has already been realized – the altered water regime – additional threats of increased salt-water intrusion and vulnerability to climate change are further impacting on already damaged ecosystems. While these threats are widely known, the four jurisdictions covered in this study are continuing to make separate water management decisions that can and do negatively affect both their own and each other's communities, economies, and the environment.

Communicating baseline information about what is at stake economically **– about €450 million a year and tens of thousands of jobs** – is a crucial step to being able to model future scenarios for how water management decisions could impact on different economic sectors and communities across the region – let alone biodiversity and the environment.

Highlights – The Value of Water for Electricity: Hydropower provides a particularly high economic return in terms of revenue and jobs from Neretva and Trebišnjica basin waters. Some of the water that is managed through the network of dams and tunnels goes on to provide public water supplies or is used for irrigated agriculture, thereby generating even more value-added to the economy. As such, hydropower production decisions – how much water is released, to where, and at what times during the year – have a major impact on other sectors in the basins. This study shows the amount of cubic meters (m3) of water used annually to produce hydropower in the study area, and what this translates to in terms of revenue and jobs.

The value of the Trebišnjica hydropower system: Three jurisdictions are operating hydropower facilities in the Trebišnjica basin, sharing about 2.7 billion cubic meters (m^3) of water per year and generating more than 2,000 gigawatt hours (GWh) of electricity in 2016. This is about 20 percent of the total electricity supply for Republika Srpska, 9 percent for Federation Bosnia and Herzegovina, and 4.3 percent for Croatia. The combined total revenue attributable to this hydropower was €156 million in 2016. This equates to about 19 m^3 of water to generate every €1 of revenue. The GWh generated and revenue attributable to this production is summarized below.

Table 1. Summary of Trebišnjica hydropower system 2016

Country/Entity	No. Facilities	Installed capacity (MW)	GWh generated	% of Country/ Entity Total	Total attributable revenue (€)
Croatia	1 (shared)	208	730.00	4.3%	83,000,000
Republika Srpska	3 (1 shared)	296	1,188.95	20%	56,000,000
Federation B&H	1	440	145.25	9%	16,900,000
Total	**4**	**944**	**2,064.20**		**155,900,000**

The value of the Neretva hydropower system: Two electricity utilities in Federation Bosnia and Herzegovina are operating a total of seven hydropower facilities in the Neretva basin. The utility in Western Herzegovina, Elektroprivreda Hrvatske zajednice Herceg Bosne (HZHB) sources 68 percent of its electricity from four hydropower plants, while Elektroprivreda Bosnia i Herzegovina (BiH) sources 19 percent from its three facilities. Overall in 2016 the total revenue attributable to the more than 2,400 GWh of hydropower production in the Neretva basin was about €219 million. In terms of m3 of water required for €1 of revenue, the average across the Neretva basin is 35.5 m3 for €1.

Table 2. Summary of Neretva hydropower system 2016

Federation Bosnia and Herzegovina	No. Facilities	Installed capacity (MW)	GWh generation	% of Public Utility Total	Total attributable revenue (€)
Elektroprivreda BiH	3	505	1,394.40	19%	90,287,620
Elektroprivreda HZHB	4	327	1,047.61	68%	128,284,720
Total	**7**	**832**	**2,442.01**		**218,572,340**

The value of employment in hydropower: The research team collected employment data for the production of hydropower. Below is a summary of the number of people employed in the hydropower plants in the study area by jurisdiction, and in the case of Federation Bosnia and Herzegovina by utility as there are two. The table also includes the total 2016 GWh of hydropower generated. By looking at these two sets of figures it is possible to show a ratio of how many GWhs each 'job' generates. This ratio of GWhs per job in a hydropower facility is shown in the final column in Table 3 below.

Table 3. Jobs per GWhs of hydropower

Location	Jobs in hydropower production	Amount Generated (GWh)	Ratio GWh per Job
Croatia	58	734	13 GWh to 1
Republika Srpska	695	1,190	2 GWh to 1
Elektroprivreda BiH (Federation B&H)	120	1,394.40	12 GWh to 1
Elektroprivreda HZHB (Federation B&H)	358	1,192.86	3 GWh to 1

Analysis: While Croatia, Republika Srpska, and Federation Bosnia and Herzegovina all benefit from hydropower in the Neretva and Trebišnjica basins, the jobs dependent on this production is relatively more important for Republika Srpska and the area in Federation Bosnia and Herzegovina serviced by Elektroprivreda HZHB (Herzegovina), than Croatia and the part of Federation Bosnia and Herzegovina serviced by Elektroprivreda BiH (Bosnia). These differences could reflect differing perspectives among decision-makers (i.e. preference for profit maximization and efficiency v. preference for higher employment). They also show that a significant disruption to the Trebišnjica or Neretva systems would adversely impact the economy of Republika Srpska and Herzegovina much more than Croatia or Bosnia.

Highlights – The Value of Water for Agriculture: Agriculture is another primary sector that relies on water from the Neretva and Trebišnjica basins and about 20 percent of the total study area, 343,241 hectares, is arable land. To understand the value of water in the Neretva and Trebišnjica basins in terms of revenue and jobs from irrigated agriculture, this study set out to determine the m^3 of water required annually for irrigation. As the amount of water used for irrigation in Federation Bosnia and Herzegovina was not recorded in any of the jurisdictions in the study area, this was calculated by applying average crop water requirements to the yield of 28 irrigated crops, and then comparing this to crop revenues. In Croatia, conflicting data about the hectares of agriculture land means that it was only possible to value tangerines (the major cash crop) in the Neretva Delta. Similarly, in Republika Srpska, data limitations meant that analysis was confined to calculating the value of irrigated water to the key sector of wine production. The key findings are below by jurisdiction.

The Value of Water for Irrigated Agriculture in the Study Area in Federation B&H:

- About 23 percent of agricultural production in Herzegovina-Neretva Canton is irrigated and 26 percent in West Herzegovina Canton (around 16 percent of total agriculture land)
- In 2016, irrigated agriculture required 3,387,488 m^3 of water, and €23,074,801 in revenue is attributable to it
- 6.8 m^3 of irrigated water equates to €1 of agriculture revenue
- About 5 percent of the population (16,406 people) are supported by agriculture as either a primary or secondary source of income

The Value of Water for Tangerines in the Study Area in Croatia:

- In the Neretva Delta about 11,088 people, or 1/3rd of the population, are supported by agriculture as either a primary or secondary source of income
- Over the past five years average annual revenue from the sale of tangerines from Dubrovnik-Neretva County is about €15 million a year
- While the average is €15 million a year, over the past five years revenue from tangerines has fluctuated greatly, from €17 million in 2012 up to €23 million in 2014 and down to €8 million in 2016
- On average about 5.8 m^3 of water is equal to €1 of tangerines

The Value of Water for Wine Production in the Study Area in Republika Srpska: The study examined the four largest commercial vineyards in the Trebinje municipality, which together account for 40 percent of all wine production in the study area in Republika Srpska. In 2016 these vineyards produced about 560,000 liters of wine generating €4.6 million in revenue. During dry years up to 80 percent of commercial wine production near Trebinje is dependent on irrigation. In the dry year of 2015, €3.8 million in revenue from commercial vineyards is attributable to water from the Trebišnjica basin.

Analysis: As noted above, data limitations meant that it was only possible to value irrigated tangerine production in the Croatian part of the study area, and for wine production in Republika Srpska. It should however be emphasized that further data and analysis are required to assess the value of agricultural water use. This could be accomplished by applying the methods developed by the current study to value irrigated production in Federation Bosnia and Herzegovina to other parts of the basins. This analysis is important as without data on the amount of water needed for irrigation decision-makers do not have enough information to evaluate the potential impact on agriculture communities of reduced irrigated water supply. Such reductions are a very real possibility. Already salt-water intrusion is increasing into the Neretva Delta, degrading the quality of freshwater and agriculture land. Furthermore, if new hydropower infrastructure were to be built on the coasts, more freshwater would be diverted and released into the Adriatic Sea. Less would be available to divert to agriculture areas, particularly the Neretva Delta. As such, it is important for water managers and policy makers in the Neretva and Trebišnjica basins to understand just how much agriculture in their jurisdictions is dependent on irrigation.

Highlights – The Value of Public Water Supplies: Municipal water supply is another demand on the finite water resources of the Neretva and Trebišnjica basins. Also as tourism in the study area expands, particularly in coastal areas of Croatia and Montenegro, there is an overall increasing demand for water. To show what is at stake for this sector the study investigated the amount of water from the Neretva and Trebišnjica basins currently being supplied into public water systems and distributed to end users. The key results are below:

- In Republika Srpska 1.1 m^3 of distributed water equates to €1, but losses are estimated as high as 48 percent in the system. If those losses are taken into account, about 2 m^3 of supplied water equals €1
- In Federation Bosnia and Herzegovina 1.2 m^3 of distributed water equates to €1, but average losses of supplied water are between 60 to 70 percent. If those losses are taken into account, up to 4 m^3 of supplied water equals €1
- In Herceg Novi in Montenegro 1.3 m^3 of distributed water equates to €1. No data on losses was found
- The research team was unable to analyze this sector for the part of Croatia in the Trebišnjica and Neretva basins due to a lack of municipal-level data. Nation-wide data was available, showing overall losses of 38 percent

Analysis: Overall the findings for revenue from distributed water for Republika Srpska, Federation Bosnia and Herzegovina, and Montenegro are largely consistent, between 1.1 to 1.3 m^3 per €1 in revenue. However the picture changes if losses are taken into account, with up to 4 m^3 per €1 in revenue in Federation Bosnia and Herzegovina. The high level of losses indicates weaknesses in the municipal water systems, infrastructure in need to repair and unrecorded/unpaid water users. As these water losses are not tracked, it is another indication that water managers and policy makers do not have a clear picture of how the basins' water resources are being used. But, as for agriculture, this information is fundamental to being able to make informed decisions. As a growing number of people are visiting the area, particularly the coasts of Croatia and Montenegro, having secure public water supply is increasingly important.

Highlights – The Value of Water for Tourism: The beauty of the natural environment and the rich cultural traditions of the Neretva and Trebišnjica basins are attractive and tourism to the study area is growing, in particular to Croatia. In 2016 in Dubrovnik-Neretva County revenue from tourism was about €613 million – about half of that county's GDP and 12.3 percent of Croatia's total tourism revenue. The study focused on bird-watching tourism to the Neretva Delta, finding that that tourism to the area is increasing rapidly and is largely dependent on the freshwater ecosystems of the area. Key findings are:

- The number of tourists served by nine companies in the delta shows an average 224 percent increase in only 5 years; from 66,000 people in 2012 to 148,000 in 2016
- In 2016, 83 percent of visitors, 122,300 people, came to experience the unique water values of the area
- In 2016 the revenue attributable to this water-based tourism was €6.67 million and if current trends continue this number will increase.

Analysis: Revenue from tourism is growing rapidly. In contrast, revenue from tangerines is in a steep decline – from €17 million, in 2012 to €8 million in 2016. While it is simplistic to suggest that the increase in tourism revenue could or would offset the drop in revenue from tangerines to the population, it does suggest 1) that tourism is an increasingly important economic activity for communities in the Neretva Delta, and 2) that more than 80 percent of this tourism is based on the wetlands and water ecosystems of the delta.

Conclusion: The study found that the Neretva and Trebišnjica basins are of critical economic significance. As such, it is in everybody's interests to ensure that these shared water resources are managed in an integrated way. Just looking at a partial picture of the economics of water use in the four sectors are investigated by the study – hydropower, public water supplies, tourism, and selected agriculture production – shows gross primary returns totaling almost €450 million a year, generating values of between €0.04-6.8 per cubic meter of water. Tens of thousands of jobs – and hundreds of thousands of livelihoods – depend directly on these water-based activities. Taking into account the substantial multipliers which link these sectors to additional jobs, earnings, and production in the rest of the economy would increase these values many times over.

The study has however also highlighted some major data gaps, which hinder understanding and awareness of the full economic value of water in the Neretva and Trebišnjica basins. Clear and comprehensive data is readily accessible about how water is being used for hydropower and its contribution to revenue and jobs. The electricity sector results of the study reinforce what is already commonly known, that hydropower is a significant source of revenue and jobs in the study area in Republika Srpska and Federation Bosnia and Herzegovina. In contrast however, data on the use of water for agriculture and municipal water supplies is not readily available and in many cases is contradictory. But these sectors are also significant users of water and the study shows that many communities are dependent on these water resources. For example, 1/3rd of the population of the Neretva Delta is supported by agriculture.

Without a clear picture on how much water from the Neretva and Trebišnjica basins is needed for these sectors, decision-makers are limited in being able to prioritize investments in improving water-related infrastructure. Moreover, they cannot fully evaluate the economic impacts of decisions to divert water away from agricultural areas for use in different parts of the Trebišnjica hydropower system. Water managers are also limited in their ability to make other decisions, such as which adaptation measures to implement for climate change or disaster risk reduction – let alone to ensure sufficient water resources to support the basins' ecosystems and biodiversity.

Towards this end, WWF and GIZ/ORF BD are working to establish a permanent and vibrant inter-governmental platform for dialogue between decision-makers about the management of the basins. Such structured discussion will result in better coordination, implementation, and strengthening of the existing Transboundary River Basin Management Framework and its constituent management plans, and other mutually agreed principles and action plans intended to guide the joint development of a transnational Neretva and Trebišnjica water management system. A joint system will allow for coordinated climate change adaptation, disaster risk reduction, electricity generation and secured livelihoods; all while minimizing further damage to critical ecosystems.

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KARST AND KARST WATER RESOURCES OF ALBANIA

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Abstract: The karst landscape in Albania covers about 6,750 km^2, nearly 24% of the country's territory. In Albania there are about 110 springs with a mean discharge more than 100 l/s. The mean discharge of Bistrica spring, the biggest Albania's spring, is18.4 m^3/s. The total renewable karst water resources are estimated with about 227 m^3/s, representing 80 % of the groundwater resources of Albania. About 70 % of the population of the cities, including the capital Tirana, are supplied by karst water. Most important thermal springs of Albania issues from the karst aquifers also. The main human negative impacts on karts water are related to urbanized areas, agriculture activity and quarrying. Combined stable isotope and hydrochemical studies are successfully applied for understanding the recharge mechanisms and groundwater mixing.

Key words Karst aquifers, karst water resources, karst water quality, management, Albania

Introduction

Albania is situated in the western part of the Balkan Peninsula, (Fig. 1); the total surface reaches 28,748 km^2. The country is mainly mountainous, the mean elevation is 764 m above sea level (asl) and many peaks higher than 2000 m asl are associate mostly with karst areas. The climate is typical Mediterranean; the annual mean air temperature varies around 16°C in the coastal and around 10° C in mountainous areas. The mean precipitation reaches about 1450 mm, but in North Albanian Alps are measured more than 3000 mm. Albania is part of the Mediterranean Alpine Fold belt and fits in the Dinaric-Hellenic range. There are two major geological units: Internal Albanides to the East and External Albanides to the West (Xhomo et al. 2003). *Internal Albanides* comprise mainly the Korab (Pelagonian) Zone consisting mostly of Paleozoic terrigene metamorphic rocks with two tectonic windows embodying Permian gypsum-anhydride rocks, and Mirdita (Subpelagonian) Zone consisting by an ophiolite belt with some big Mesozoic limestone structures overthrusted on magmatic rocks. *External Albanides* comprise the Albanian Alps Zone, representing the southernmost part of High Karst Zone, as well as, Kruja Zone (Dalmatian Zone of Dinarides or Gavrovo Zone of Helenides) and Ionian Zone and Sazani (Paksos) Zone consisted of some elongated SE-NW direction anticline and syncline belts. The anticline carbonate structures of Mesozoic to Eocene rocks successively overthrust to the west on Paleogen flysch formations. In central Albania outcrop the important gypsum Dumre plateau. The karst rocks in Albania cover about 6,750 km² or nearly 24% of the county's territory. Some 25 independent karst regions are known, 23 of them consisting of carbonate rocks and two regions with a total surface a 260 km² are representing gypsum layers (Eftimi at al. 1985). In Ionian and Kruja Zone, including the Adriatic depression, the carbonate rocks are covered by thick flysch and molasses deposits.

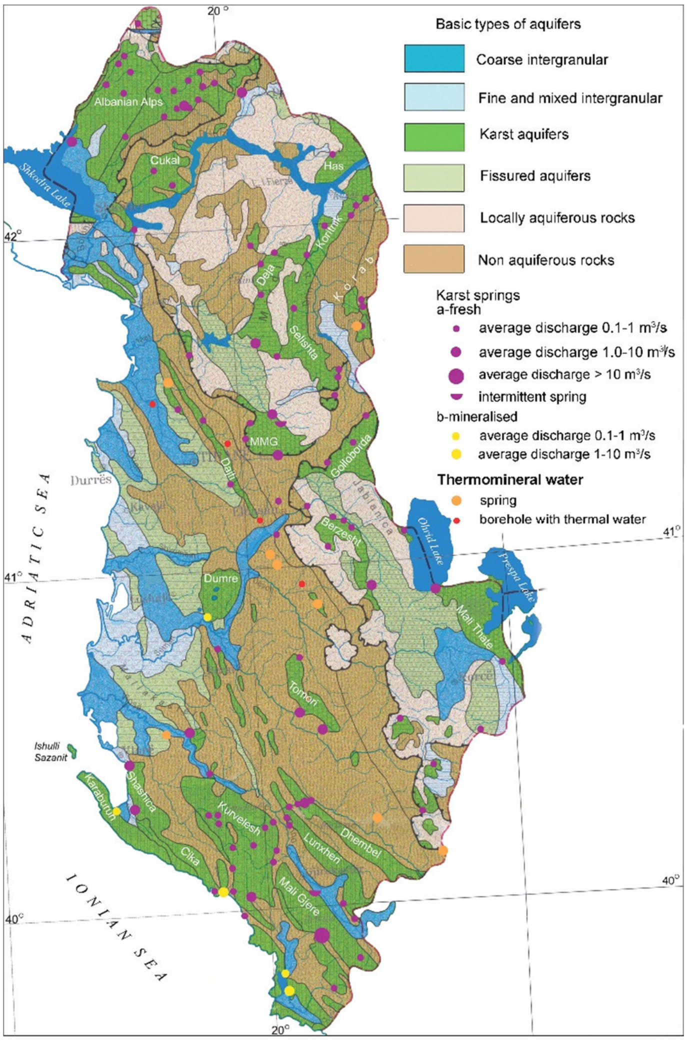

Fig. 1. Karst water of Albania (adapted from Hydrogeological Map of Europe sc. 1:1.500.000)

Karst geomorphology

The carbonate rock structures generally occupy the higher elevated areas. Intensive erosion started in Oligocene and particularly developed during the

Tertiary, as well as the Pleistocene glaciations have contributed in formation of u-shaped valleys incised in Mesozoic carbonate rocks of Albanian Alps Zone, and of numerous imposing deep and narrow canyons crossing the carbonate structures of Kruja and Ionian Zones controlling the drainage patterns of the karst aquifers. Karst is intensively developed in wide horizontal or gently sloping massive and thick bedded Triassic and Cretaceous carbonate formations. Karst morphology is very rich, representing all surface and underground phenomena like karren, sinkholes, poljes, dead valleys, karst plateaus, collapse lakes, vertical shafts, swallow holes and caves (about 1000 registered) (Fig. 2).

Most imposing and very reach in karst landforms are karst plateaus, developed in Albanian Alps Zone and in Inner Albania. Among them, differ Mali me Gropa (MMG) plateau total surface of about 100 km^2, with innumerable and different karst forms (Fig. 2). Some small collapse lakes (Fig. 2) on Shkodra lakeside karst platform testify the advanced karst development (Ford and Williams 1989). There are also two Triassic evaporate karst massifs; Korab massive surface 90 km^2, known for sulphide thermal springs, and Dumre massive, surface 170 km^2 known for the presence of 80 karst mainly collapse lakes.

Fig. 2. Some karst forms: ***a*** *Karen field in Saranda, South Albania;* ***b*** *collapse lake diameter about 30 m, in Shkodra lakeside karst platform,* ***c*** *part of MMG karst platform at elevation about 1600 m asl;* ***d*** *Vali dead valley in MMG karst massif at elevation about 1250-1000 m asl*

Water budget, karst water hydrology and springs

The areal infiltration of precipitation directly to the carbonate rocks is most widespread recharge process, but infiltration of surface river or lake waters or the inflow from shallow gravely aquifers happens in some important karst aquifers (Eftimi at al 2017). The water budget of karst massifs are roughly calculated using the well known empiric methods of Turc and that of Kessler. The empiric methods are quite applicable in engineering practice and fit very well with the APLIS method (Andreo et al. 2008). The absolute values of the mean annual infiltration range in a wide scale from about 400 to 1250 in Central and South Albania and to about 2000 mm in central part of North Albanian Alps. The karst network is placed quite different from the fracture pattern of respective karst structures (Bakalowicz 2005), and it is operating as a fluvial system.

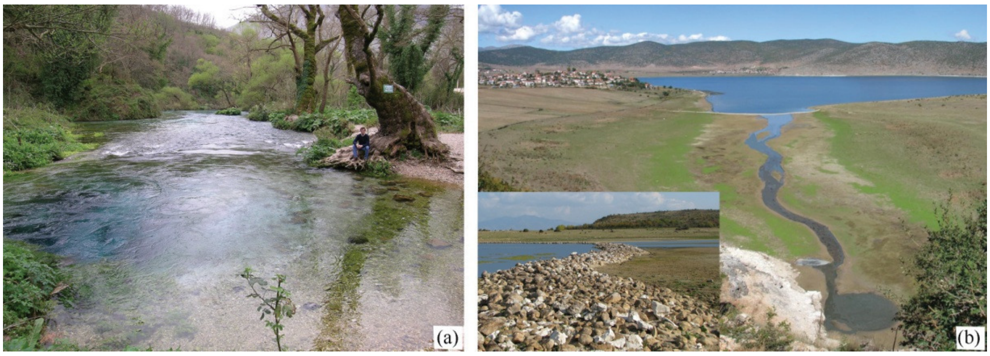

*Fig. 3. **a** Blue Eay Spring, the main issue of Bistrica spring; **b** Zaver swallow hole where Prespa lake water disappear to reappear in Ohrid Lake coastal karst springs of St. Naum and Tushemisht (photo of 2008). On this year the lake level reaches the lowest historical of the last 200 years, or about 8 m below the mean lake level. The detail shows the ancient "road", which by every probability is a dam kipping the lake water higher.*

The general, the direction of karst groundwater is governed towards the local and regional erosion basis, which not necessarily coincides with the development of secondary porosity in carbonate rocks. For example, the groundwater flow direction recharging Bistrica spring, the biggest karst spring of Albania, Q_{mean}=18.4 m^3/s (Fig. 3a) moves in the direction perpendicular to the well developed stratification fractures. Disappearing and reappearing rivers in karst could be observed in some karst areas of Albania. Some cases of the "karst piracy" are observed also; a hydrologic basin having lower hydraulic head is recharged through a karst massif, by another basin having higher hydraulic head (Fig. 3b).

In Albania are mapped 110 karst springs with average discharges exceeding 100 l/s, among them 17 outflows discharge more than 1,000 l/s. The maximal discharge of Viroi Spring, the biggest temporary spring is about 50 m^3/s. The karst springs appear mainly: a) in the periphery of geological structures, like most of the karst springs of Mirdita Zone; b) at the valley floor of river canyons cutting the carbonate massifs (Albanian Alps and Kruja and Ionian zones); at the western tectonic contact of the carbonate rocks overthrusted on flysch formations (Kruja and Ionian zones). The recession period of karst springs lasts about 5 to 7 months, depending on the precipitation regime, and correlation coefficient, reflecting discharge versa precipitation per year, reaches the value 0.7.

Important karst aquifers of South Albanian coastal chain 154 km long drain to Ionian Sea about 17-18 m^3/s, directly to the sea as diffuse drainage, as coastal or submarine springs, or over complete barriers (Stevanovic 2014). Many underground flows towards the sea and is still waiting to be identified. As resulted from speleodiving the siphons of some big karstic springs in South Albania are quite dip: Kelcyre 63 m, Viroi 83 m, Blue Eay 70 m and Skotini 72 m but the biggest depths are not jet discovered.

Karst water quality

Most of karst waters in Albania are of HCO_3-Ca type, while the HCO_3-(SO_4)-Ca-(Mg) type is characteristic for–some dolomite massif of Kruja Zone (Eftimi 2010). Some HCO_3-Ca springs reach CO_2 pressure, which is degassed at the mouth of the springs and travertine deposits are formed as a result of oversaturation. The HCO_3-SO_4-Ca-Mg type is related to limestone with contact to evaporate and evaporate breccias of the Ionian Zone. Along the southern Ionian carbonate rock coast, there are some big mineralized karst springs of Cl-Na type.

The correlation between physical characteristics of karst springs and temporal variations in spring water chemistry used to infer physical attributes of karst systems is successfully applied also for hydrogeological characterization of the karst aquifers recharging big springs in Albania (Eftimi 2010). During last decade this method is enriched applying several specific hydrogeochemical approaches.

Environmental isotope investigations

The karst water investigation becomes often a difficult task by the high heterogeneity and low predictability of the karst aquifers (Bakalowicz 2005). Environmental techniques, often used together with hydrochemical methods, are successfully applied for the determination of karstwater recharge and of relations between surface and groundwater. Most important in this respect are the stable isotopes oxygen-18, deuterium and tritium expressed as

$\delta^{18}O$, δD and T. Two processes changing the isotopic composition of surface and groundwater: a) the mixing and b) the evaporation are successfully applied to solve some hydrological problems, in Albania. Some of them are the following:
a) The recharge, of Tushemisht and St Naum big karst springs issuing at Ohrid Lake coastal line, by Prespa lake water (Anovski at al. 1991, Eftimi at al. 1996);
b) Identification of recharge sources of Bistrica springs the biggest karst springs of Albania, (Eftimi at al. 2017),
c) Estimation of the recharge of Poçemi springs by the Vjosa River and possibility of escape of the water from a future lake formed by a dam 110 m high planned to be constructed on Vjosa River (Eftimi at al 2017).

According to an artificial tracer experiment in Mali Thate – Galichica karst massive separating Prespa Lake from the Ohrid Lake the measured karst flow maximum velocities (from 70 h to 2700 m/h) indicate the presence of differently developed karst conduits at small-scale distances. According to a multi-tracer experiment performed in Mali me Gropa the maximum measured flow velocity varies from about 10 to more than 600 m/h.

Karst thermomineral water

With regard to its geology Albania is not very rich on thermal water (Eftimi & Frasheri 2017). There are missing high enthalpy thermal water at relatively small depths. Important thermal waters are localized in deep lying carbonate karst rocks of Kruja and Ionian zones, overlaid by thick flysch and molasses deposits covering about 10.000 km^2, which consists nearly 33% of the country's territory. Generally, the temperature at a depth of 100 m ranges at about 16.4°C, at a depth of 500 m from 21 to 27.7°C and at a depth of 6,000 m up to 100-110°. Most important thermal waters of Albania (Table 1) are those of Kruja zone (in carbonate karst aquifers) and in Korab zone (in gypsum deposits). Karst thermomineral waters of Albania are widely used for balneotherapy.

Table 1. Main data of sulphide thermomineral groundwater used for balneology: Q-Discharge l/s; T-temperature ^{0}C; TDS-total dissolved solids

Spring (s), deep well (w)	Q l/s	T °C	TDS mg/l	H_2S mg/l	CO_2 mg/l	Br mg/l	J mg/l	Chemical type
Llixha Peshkopi -s	23	43.5	4480	49.5	542	2.1	0.6	SO_4-Ca
Mamurras – s	70	22.5	5300	358	358			Cl-Na
Ishmi 1 - w	6.6	59.0	14.650	1220		27.3	4.0	Cl-Na
Kozan 8 - w	4.4	54.3	4100	400		6.75	1.8	Cl-SO_4-Na-Ca
Llixha Elbasan – s	15.0	48-58	6880	335-408	176	2.8-5.0	1.3	Cl-SO_4-Na-Ca
Hidraj Elbasan - s	10.0	55-58	6745	378	176	2.8	1.0	Cl-SO_4-Na-Ca
Holta Gramsh, s	20-50	24.0	2224	2.0-5.0				SO_4-Mg-Ca
Benja Permet, s	70-150	23-30	1564	2.0-6.0				Cl-Na-Ca
Leskovik - s	15.0	26.5	1000	7.0				Cl-Na-Ca

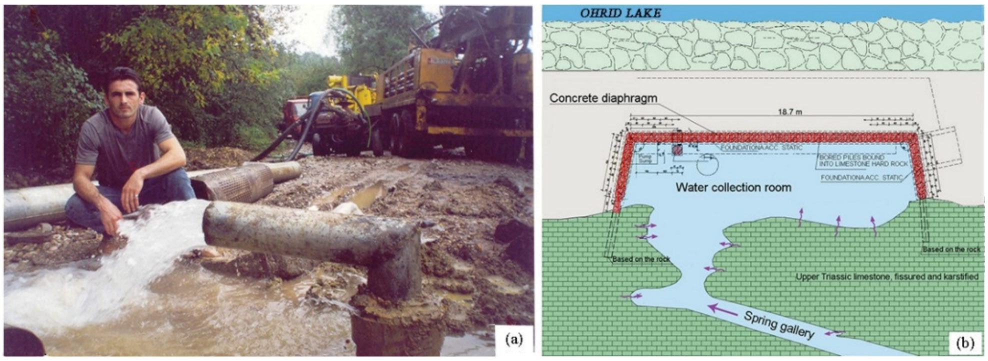

Fig. 4. ***a*** *An artesian well depth 50 m free flowing about 50 l/s tapping a Low Cretaceous karst aquifer, Makaresh karst massif used for Mamurras city water supply;* ***b*** *Tushemisht Spring Intake structure, the collection room is isolated from the Ohrid lake by an impermeable concrete curtain*

Karst water resources and their sustainable management

The total natural karst water resources of Albania are calculated with $7.15*10^9$ m^3/y (227 m^3/s, or 34 $l/s/km^2$). About 80% of the urban population in Albania including the big cities like Tirana, Peshkopi, Kukes, Pogradec, Gramsh, Berat, Vlora obtain the water from big karst springs. Although some approaches to karst water tapping are known (Milanović 2000, Stevanovic 2014), the most widely used in Albania are a) drilling wells, most successfully resulted those located near the springs (Fig. 4a), and b) pumping from natural siphons or galleries sometimes discharging to more than 2-2.5 m^3/s. A particular intake is that of Tushemisht spring capacity 180 l/s at Ohrid Lake cost line, successfully protected by polluted lake water by an impermeable concrete curtain, consisting of 74 alternating cemented and reinforced boring piles diameter 600 mm and maximal depth 7.5 m resting on compact limestone rocks (Fig. 4b). Another intake to be mention is that of Uji Ftohtë Springs, at Ionian limestone coast near Vlora city capacity about 700 l/s, consisting of horizontal tunnels and galleries at sea level; the TDS of the captured springs vary about 250 to 500 mg/l according to the seasons.

Conclusions

In Albania could be distinguish the following karst domains (Bakalowicz 2015) a) "high-mountain karst system" is developed in North Albanian Alpe Zone, b) "karst system related to inland basins and grabens" is developed in Mirdita Zone, Kruja Zone and in eastern carbonate anticline chains of Ionian Zone, and c) "karst system related to the Mediterranean Sea level changes" is developed in the western Ionian coastal carbonate anticline chain. Karst waters consist about 80% of groundwater resources of Albania. Their investigation, sustainable development and management represent most important challenge regarding the natural resources of Albania.

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THE UPWELLING WATER FLOW FEEDING KARST SPRINGS

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Abstract

In spring discharge areas, the upwelling groundwater flux can be deducted by the increasing of the hydraulic head in depth, which allows the estimation of ascendant hydraulic gradient and groundwater velocity, during dry and wet seasons. A specific analytical solution has been provided to estimate the zone involved by the ascendant flow and has been applied in the area of Serino springs, Southern Italy.

Key words: upwelling flux, hydraulic head, ascendant hydraulic gradient, spring, Southern Italy.

1. Introduction

Following the model of regional groundwater flow (Hubbert, 1940; Toth, 1963; Domenico and Schwartz, 1990) the discharge areas are located in depressed zones which increases the river discharge by diffused recharge or by springs. In these areas, the vertical component of the flux can be higher than the horizontal one, and the water flux develops in a typical ascendant path.

Karst aquifers, characterized by high transmissivity and generally by capacity to store large volumes of groundwater (Ford and Williams, 2007; Stevanovic, 2005), can allow deep water circulation which leads to the start of the ascendant flux in the discharge zone.

A method used to estimate the wideness of the zone involved in the ascendant flux has been provided. The estimation is an important tool for delineating the protection zone of springs characterized by ascendant flux and has been applied for the Serino springs in Southern Italy; more details can be found in Fiorillo et al. (2018).

2. Material and Methods

Figure 1a shows the estimation of the vertical hydraulic gradient by the hydraulic head measurements in wells; here the difference in the hydraulic head measured into two close boreholes is caused by the vertical (ascendant) flux. This estimation is based on the assumption that no horizontal component of the flow occurs, and the hydraulic head is lost during the ascendant path of the flow.

To estimate the influenced zone of the aquifer by the drainage tunnel, a simple 2D model is provided under a non-hydrostatic initial condition, where an ascendant hydraulic gradient causes the upwelling flow. The aim is not to estimate the inflow or the discharge in steady-state conditions, which would need a more complex approach (which is beyond the scope of this work), but to analyze the role of ascendant hydraulic gradient on the wideness of zone involved by the ascendant flow, namely the influenced zone. This aspect plays a fundamental role in delimitating the protection zone of springs and their tapping systems.

To estimate the width of the influenced zone, with distance R from a drainage tunnel or from a spring, the analytical solution assumes: (i) constant hydraulic conductivity in all directions, (ii) high aquifer thickness to guarantee vertical flow lines below a specific depth from the drainage system or spring, (iii) each flow line follows the direction of "maximum slope".

Under these assumptions, the drainage system induces a potential hydraulic gradient, i_T, in each generic point P of the aquifer (Fig. 1b); a generic flow line continues along its vertical ascendant path for i_T<ia, and up to $i_T=i_a$. When the condition changes, $i_T>i_a$, the flow line diverges from the vertical and tends to reach the drainage system (or springs). From figure 1b, the ascendant hydraulic gradient, i_a, and potential hydraulic gradient, i_T, are computed as:

$$i_a = \frac{(H_P+D+Z_P)-(D+Z_P)}{Z_P+D} = \frac{H_P}{D+Z_P} \tag{1}$$

$$i_T = \frac{(H_P+D+Z_P)-Z_P}{\sqrt{L_P^2+Z_P^2}} = \frac{i_a(D+Z_P)+D}{\sqrt{L_P^2+Z_P^2}} \tag{2}$$

where H_P is the excess hydraulic head of the point P with respect to the undisturbed water table; D is the elevation difference between the undisturbed water table and drainage system; Z_P is the depth of point P with respect to the drainage system; and L_P is the distance of point P from the drainage system.

If equations are related to the spring outlet, then the parameters D, Z_P and L_P have to be replaced by D', Z_P' and L_P' (Fig. 1b).

Equations 1 and 2 have been used in the area of Serino springs, southern Italy. The Serino springs are formed by the Acquaro–Pelosi springs (377–380 m a.s.l.) and the Urciuoli springs (330 m a.s.l.), located in an alluvial plain of Sabato river; they are fed by the Terminio massif (Civita, 1969; Fiorillo et al. 2007) with an overall mean annual discharge of 2.25 m^3/s.
The Acquaro-Pelosi springs area is located 3 kilometers uphill of Urciuoli springs (Fig. 3 and 5), in a flat area along the Sabato river (370-380 m a.s.l.). Uphill this area, the river Sabato is completely dry, and it is only after rainy days that the runoff can occur. Before the tapping, numerous spring outlets existed locally; the construction of tunnels in 1934 has tapped most of these springs, and only a few spring points discharge after wet periods.

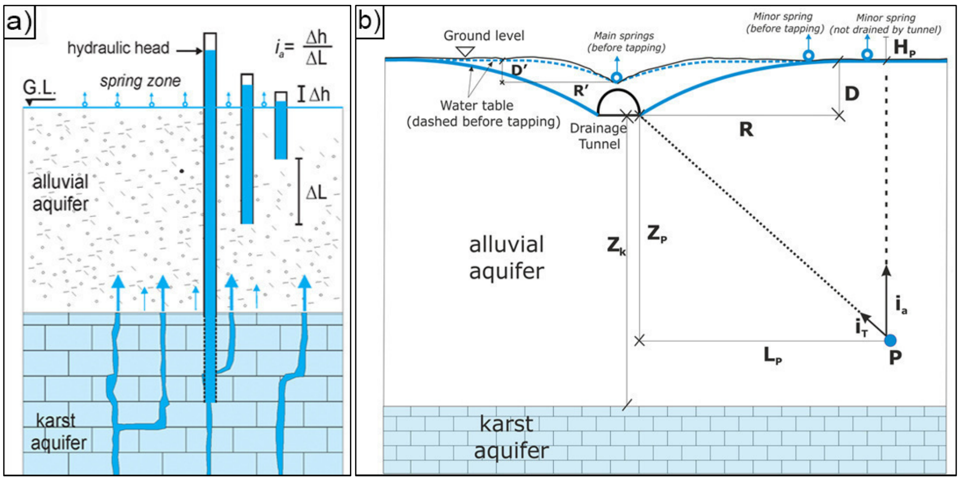

Fig. 1. a) Ascendant flux connected to artesian conditions of karst aquifer covered by alluvial deposits. Hydraulic head observed in close boreholes with different depths allow to estimate the ascendant hydraulic gradient, i_a. b) Sketch of estimation of the ascendant hydraulic gradient, ia, and of the potential hydraulic gradient, i_T, in the point P; H_P, excess of hydraulic head of the point P respect to undisturbed water table; D, elevation difference between undisturbed water table and drainage system; R, width of water table involved by drainage (influenced zone); L_P, horizontal distance of P from drainage; Z_P, depth of P from drainage; Z_K, depth of the karst substratum.

Two main tunnels are excavated into alluvial deposits, and are 400 m long, and 4 to 7 m deep. Water is drained through loopholes in the concrete structure of tunnels along their bases and sides. The tunnels convey water to a storage tank, then toward Urciuoli springs.Ten wells are located inside the protected area of Pelosi and Acquaro springs, around the two drainage tunnels, and have depths between 30 and 93 meters. They cross the alluvial deposits constituted by sands, gravels and clays. Inside each well, a piezometer tube has been placed, which is slotted at the bottom part; this means that the water level measured into the piezometer has to be connected to the hydraulic head at the bottom part.

The entire water discharged by the Serino springs is linked to a deep karst substratum, as shown in Figure 1b, connected to a recharge area of the Terminio massif. In the Acquaro-Pelosi spring area, the karst substratum has not been reached by wells, and it has a depth of 350 m below the Sabato river (Fiorillo et., 2018).

Figure 2 shows the piezometer levels in the period 1963-1969, characterized by continuous records. As can be deduced from Figure 2, the distribution of the hydraulic head into alluvial deposits is not phreatic, as it generally increases in depth. In fact, the deepest piezometers show a higher hydraulic head than the shallower piezometers, especially during the April - June period. These characteristics are shown in Figure 3, with data plotted as mean values in the period 1963-1969, during which a continuous record occurred for all piezometers. The dependence of the hydraulic head on the piezometer depth is obvious (Fig. 3a), as well as the hydraulic head range (Fig. 3b).

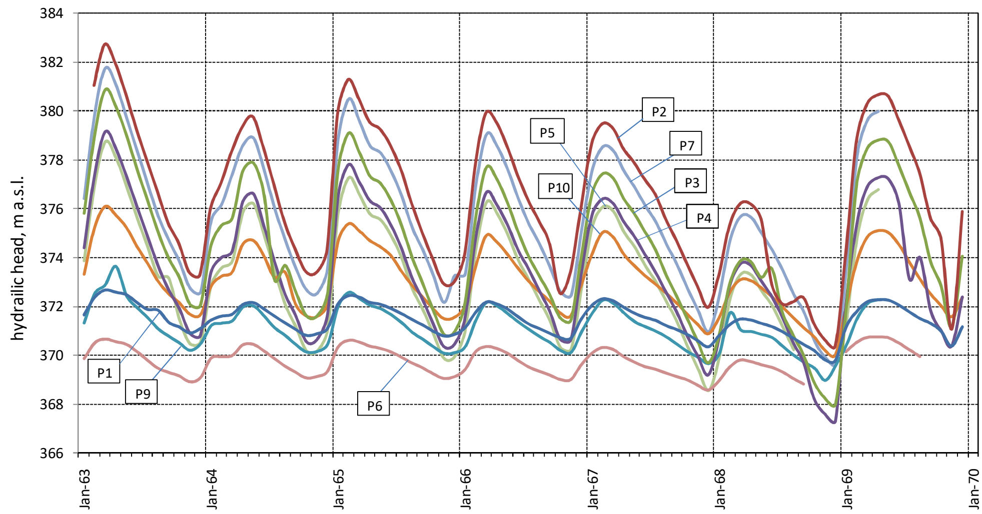

Fig. 2. Hydraulic head during the period of 1963-1969, characterized by almost continuous records. The depth of each piezometer is shown in Figure 3.

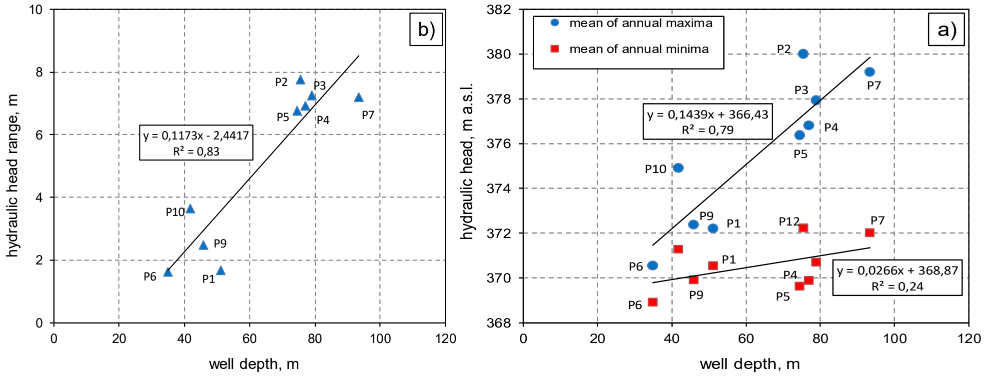

Fig. 3. Correlation between well depth and hydraulic head during high (mean of annual maxima, period between 1963-1969) and low flow periods (mean of annual minima, period 1963-1969). b) Correlation between well depth and hydraulic head range (mean values, period between 1963-1969).

3. Outcomes

The correlations of Figure 3 indicate that the hydraulic behavior of the alluvial aquifer is characterized by an upwelling flux during the high flow period, where the slope of the interpolation line (equation y = 0.1439x+366.43, Fig. 3a) can be assumed as a first coarse estimation of the hydraulic gradient, i_a. Due to the non-isotropic behavior of the alluvial deposits, this hydraulic gradient has to be assumed as the mean value of the ascendant flow into alluvial deposits during the high flow period.

During the low flow period, the behavior appears more complicated. Considering the mean of annual minima (Fig. 3a), an ascendant hydraulic gradient can be roughly estimated by the slope of the interpolation line (equation y = 0.0266x+368.43; Fig. 3a).

Another main consideration can be done as shown Figure 3b: the hydraulic head range appears to be clearly dependent on the depth of the well, indicating a wider oscillation of the hydraulic head into deepest deposits.

Equalizing equations 1 and 2 by fixing i_a=i_T, the distance L_P will coincide with R, and thus:

$$L_P \equiv R = \sqrt{D\left(1+\frac{1}{i_a}\right)\left[D\left(1+\frac{1}{i_a}\right)+2Z_P\right]} \qquad (3)$$

Figure 4 shows the dependence of the zone influenced by the drainage system (R-value) in the function of Z, for a different ascendant hydraulic gradient, i_a, including the maximum and minimum observed (0.15 and 0.026). The depth of the value of karst substratum, Z_K (Figure 1b), has been estimated by Fiorillo et al. 2018.

4. Discussion

In general, the presence of an ascendant flux could be very difficult to detect in many hydrogeological contexts. For example, in an alluvial plain characterized by sand deposits and ascendant water flux with vertical hydraulic gradient i_a= 0.01, two distinct piezometers, close together, but having 10 m depth difference, would measure a hydraulic head difference of 0.1 m. This hydraulic head difference could be misleading of a prevalently horizontal flow, and similar considerations can also be provided for other aquifer types, karst included. The possibility of measuring and quantifying the ascendant hydraulic gradient depends on its magnitude and on the depth of the piezometers.

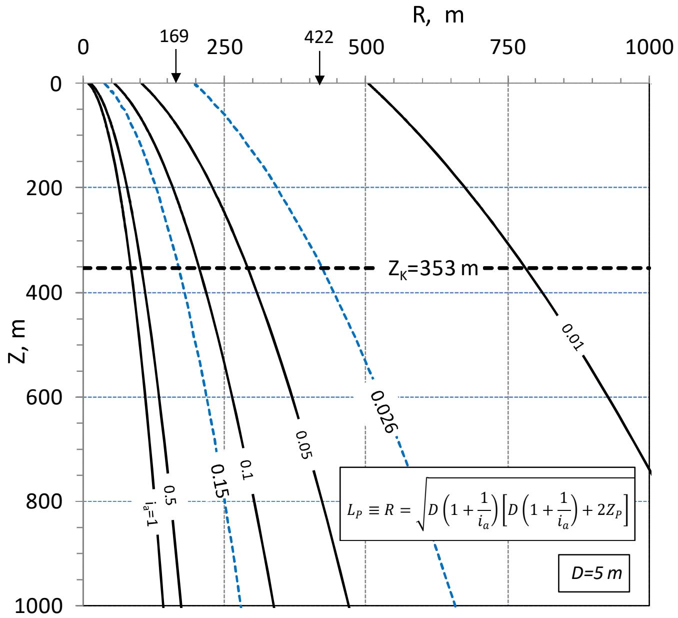

Fig. 4. Width of the influenced zone, R, induced by drainage system at depth D, in relation to depth, Z, and for a different ascendant hydraulic gradient, ia. Z_K is the depth of karst substratum.

The ascendant flow of the Serino springs is connected to a presence of a buried karst substratum, covered by thick alluvial deposits. In the alluvial deposits, the flux is widespread and circulates in a porous medium; the recharge area is Terminio karst massif and its endorheic areas. In particular, in the Piana del Dragone, the main local endorheic area, the hydraulic head varies between 506 and 554 m a.s.l. in the period between 2003-2008 (Fiorillo et al., 2018), and controls the hydraulic head observed in the piezometers of the Serino plain, which have a range up to 8 m (Fig. 3b).

5. Conclusions

The ascendant water flux which feeds the springs belong to a wide hydraulic phenomenon involving wide areas and deep portions of aquifers. It is always connected to specific hydrogeological conditions, coming from tectonic and geomorphologic evolution. In a karst environment, the ascendant flux can be particularly developed because of the carbonate dissolution along the shorter flow lines, characterized by the higher hydraulic gradient and forming karst conduits as well as allowing the water flux to siphon under no-karst terrains. This phenomenon is still poorly quantified, as deep hydraulic measurements are generally missing.

Equation 3 provide a simple estimation of the area involved by the ascendant flow and appears a useful tool to define the discharge zone of springs, and, thus, a more efficient local planning in order to correctly manage and preserve the quantity and quality of groundwater resources.

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HYDROGEOLOGICAL CHARACTERISTICS OF THE CARBONATE COMPLEXES IN REPUBLIC OF MACEDONIA

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Abstract: Republic of Macedonia is characterized by quite complex geological tectonic characteristics of the terrain. From an aspect of groundwater reserves, apart from the alluvial non-cohesive lithological formations, the carbonate complexes have the greatest significance. Carbonate complexes in Macedonia are built by different types of rocks. Precambrian marbles, paleozoic marble limestones and Mesozoic limestones are mainly detected. Nearly all of them have developed karst-cracking porosity and formed the so-called karst-crack type of aquifers with different hydrogeological and hydrodynamic characteristics. In such carbonate complexes there are springs usually with a yield of 10-100 l/s, but often there is the appearance of karst springs with a yield of more than 100 l/s, sometimes more than 1000 l/s. There are about 40 springs with a capacity greater than 100 l/s. The total area of this type of aquifers in the territory of the Republic of Macedonia is about 2 620 km^2, which is 10.2% of the country's territory. An unevenness in spatial distribution is detected. The total average yield of springs of this type of aquifers is about 25 m^3/s.

Key words: aquifers, karst-cracking, yield, marbles, limestones

INTRODUCTION

Up to date, special investigations of the karst terrains in Republic of Macedonia (RoM) as part of the geological sciences have not been performed. Partial investigations have been performed on several sites, mainly related to solving of the water supply and construction of hydro-power structures.

In the fund documentation a great number of professional and scientific records have been left, as well as discussions and opinions of the known karstologists of the XX century coming from the territory of former Yugoslavia, but also from Europe.

The majority of these papers has been sublimised in the proper fundamental papers for the geology in RoM, especially in the Geological and Hydrogeological map in scale 1:200.000 and the Geological and Hydro-geological maps on the territory of RoM in scale 1:100.000.

Karst in RoM is dispersed in the Palaeozoic, Mesozoic and Tertiary terrains part of the Western Macedonian tectonic zone as well as in the Precambrian marbles in the Pelagonia massif. The Western Macedonian zone is a continuation of the structures of the Dinarides from Croatia, Bosnia and Herzegovina and Montenegro. Contrary to the karst in the Dinarides, which has a continuous stretch of cca. 700 km and thickness of 2.000-3000 m, here these structures have been intersected in bigger or smaller masses, which depending on the position in the local geological structure, have different hydrogeological properties and functions. A great influence on the degree and dimensions of the karst processes as well as to the hydrogeological matters in these dispersed karst provinces and zones comes from the intense tectonic cracks, block sections and their spatial and hypsometric disposition.

In our karst terrains most of the known surface and ground geomorphological karst forms have developed, among which the most frequent are: sinkholes, uvalas, smaller poljes, ponors, caves and caverns. In our terrains the feeding of the formed karst aquifers usually comes from the surface flows of atmospheric and river water, partially from ground flows from higher aquifers, lake water or water from artificial reservoirs. The collecting surface areas of aquifers usually are not entirely determined, except for a small number of aquifers whose water has been collected for water supply of bigger consumers.

The drainage of the aquifers takes place on different levels even at the same regions and aquifer zones. The main circulation directions of the groundwater flows are oriented towards the basins of Radika and Crni Drim – Adriatic, i.e. Treska, Vardar and Crna Reka – Aegean.

The aquifers formed in carbonate rock masses with karst fissure porosity, a.k.a. karst fissure type of aquifers feature spring yield usually of 10-100 l/s, but frequently occur karst springs a.k.a. large-capacity springs (Vrela) with the yield bigger than 100 l/s and even more starting from 1000 l/s to several m^3/s. On the entire territory of Macedonia, in the karst terrains around 40 springs with the average multiannual yield bigger than 100 l/s have been registered. Part of these springs, cca.. $5m^3$ have been collected for the purposes of water supply of settlements and cities.

The total average yield of springs of this type is around 25 m^3/s. The precipitation quantity in these regions varies from 800-1100 mm/year. What is characteristic about this type of aquifers is their uneven distribution, they are almost completely absent in the Eastern part of the country. These aquifers feature with module of underground run-off usually in the limits of q=6-12 l/s/km^2.

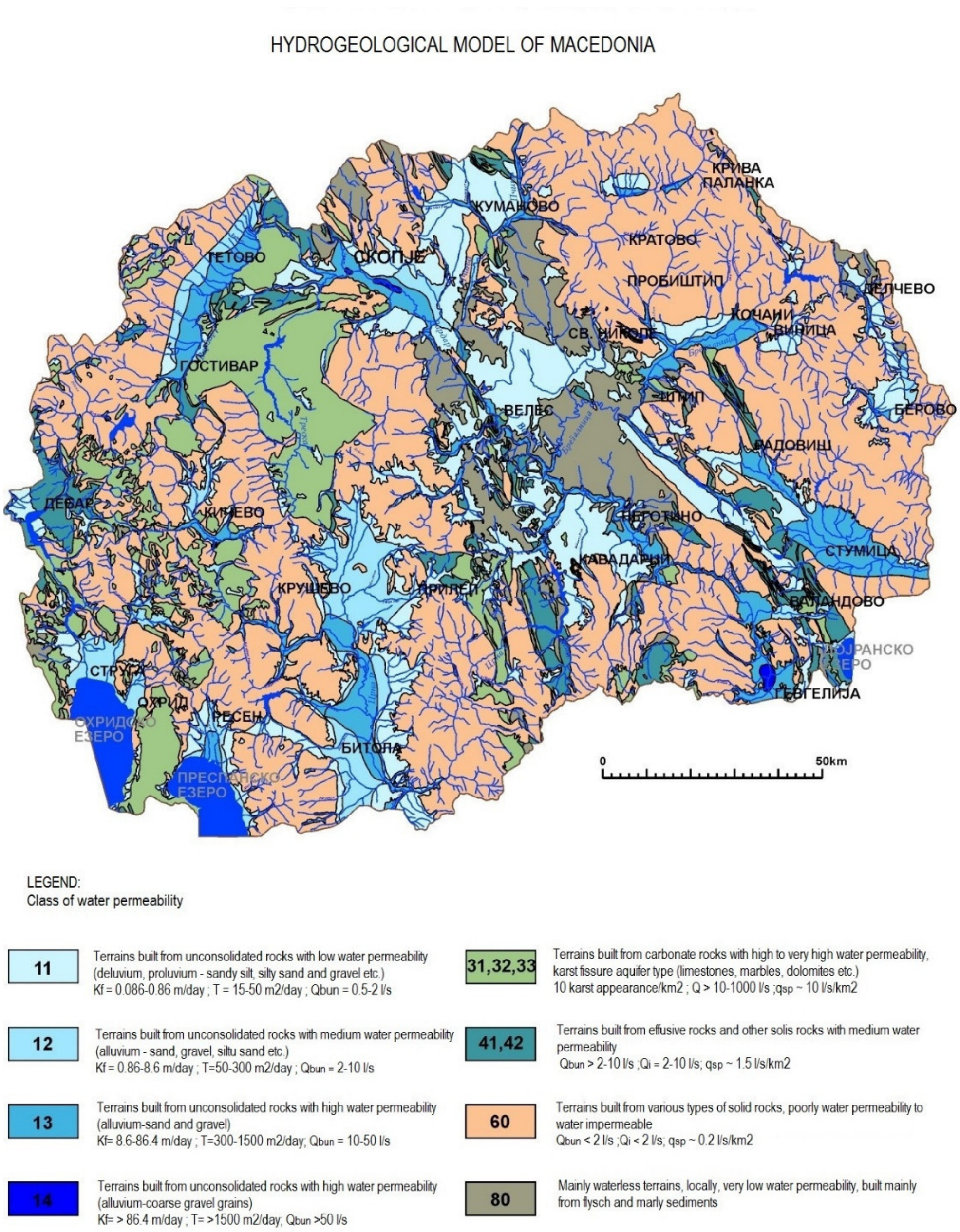

Fig.1. Hydrogeological model of Republic of Macedonia

The precipitation infiltration in such carbonate complexes usually varies between Q%P=20-40%. The effective porosity of these rock masses is 3-5 %. In

terms of water quality, it can be concluded that it can be good in aspect of its usability as potable water, with an intensified trend of gradual endangerment of certain aquifers. Almost all of them have been classified as highly vulnerable. Zones for sanitary protection have been established only at the springs used for public water supply. Potentially the most endangered are the bigger aquifers and spring zones, such as Rashche, Vrutok, Izvor on Treska River, Shum, etc.
The total surface area of this type of aquifers on the territory of R. Macedonia is around 2620 km^2, Ilijovski (2013) which represents 10.2 % of the territory of the country, and out of them around 2520 km^2 are in Western Macedonia and only 100 km^2 on the territory of Eastern Macedonia.

According to Temovski, who has made a detailed analysis of the distribution of the karst terrains in Macedonia, this surface area amounts to 3078 km^2. According to Kolchakovski and Boshkovska (2007) the surface area is 2724 km^2.

Table 1. Aquifer types present in Republic of Macedonia

Description of the aquifer	Class of water permeability	Surface area [km^2]	Percentage of the surface of the RoM
Unconsolidated lithological formations (silty sand, sandy clay, sand, gravels) - dense porosity aquifer with a free level of groundwater;	11, 12 12, 22 13 14	5000	19.5%
Solid carbonate rocks with carst-fissure type of aquifers;	31, 32, 33	2620	10.2%
Effusive and other solid rocks, cracked and water permeable under the surface of the terrain, aquifers occur more locally;	41, 42	900	3.5%
Intrusive and high grade metamorphic rocks (granites, gneisses, different types of shale), cracked and permeable just locally, aquifers appear locally shallow under the surface of the terrain;	60	16000	62.0%
Flysch marly sediments and low grade metamorphic rocks, without aquifers or they appear very rarely;	80	1200	4.6%

POSITION AND SIGNIFICANT CHARACTERISTICS OF THE KARST REGIONS

The classification of the regions according to their geographical and geomorphological belonging and main common characteristics, can conditionally be done in the following major regions:

- Ohrid-Struga region;
- Bistra, Stogovo;
- Karst massif Ljuben, Baba Sach, Ilinska Mountain;
- The valley of Treska River;
- Polog Region;
- Other smaller karst sites.

Ohrid-Struga region

In this region, these are the sites with karst porosity in the carbonate rocks and formed aquifers: Galichica and Jablanica mountains, Debarca and the Northern perimeter of Strushko Pole.

Quite frequent is the karst type of aquifer in the Triassic limestones on Galichica and Jablanica mountains, which is drained through numerous springs, and the biggest large-capacity spring in RoM is St. Naum with the capacity between 5.5-9.5 m^3/s. The large-capacity is of fissure type with 15 surface points and around 30 underground points of springing out. The water feed comes from the sinking of water of Prespa Lake which is 140 m higher that Ohrid Lake and from the precipitation of its own basin. Biljanini Izvori (0.2-1 m^3/s), Bej Bunar (40-100 l/s), Vevchani (1.5 m^3/s), Shum (1 m^3/s), Beli Vodi (300 l/s). Spring Kalishta, Spring Izdeglavje, Petrchanski spring, Springs Lukovo, etc.

Part of these springs are collected for water supply of Ohrid and Struga, as well as local water supply.

Region Bistra - Stogovo

The water-bearing karstified rocks in this region are represented by the Palaeozoic marbles and Triassic limestones, which in many parts of the terrain have been brought to the same hypsometric level by the radial tectonic movements. The karst is well developed in both mediums of the entire profile, up to erosion base on the level of Treska River. In this region several separate aquifer zones have been registered, with their own basins, however very often with variable zone boundaries.

The drainage of this aquifer occurs through numerous karst springs, among which the more significant are the following: Studenchica, which occurs on the South-Eastern side of Bistra Mountain on the level of 970 m in the contact between the limestone and limestone shales. This spring is being collected for the water supply of Kichevo, M. Brod, Krushevo, Prilep and other settlements and its yield is 0.905-2.77 m^3/s, the average 40-annual yield is around 1.4 m^3/s. Other karst springs are the following: the source of Treska River (0.283-5.5 m^3/s, average 1.396 m^3/s), spring Rosoki with the capacity up to 2.0 m^3/s , spring Tresonechki springs with the capacity up to 0.3-1.5 m^3/s, Popolzhani, Belichki springs, Tajmishte, etc.

Karst massif Ljuben - Baba Sach - Ilinska Mountain

It is a karst massif of Devon marbleized limestones and Triassic limestones with the surface area of around 180 km^2. It covers the mountains Baba Sach, Ljuben and the Eastern slopes of Ilinska mountain. The drainage occurs through two karst large-capacity karstic springs – Pitran and the springs of Crna Reka, as well as several smaller springs. There is one small karst field where Cerska River sinks in completely.

The karst large-capacity spring Pitran is in the valley of Treska River, it is a contact overflow type of spring with capacity of 140-980 l/s, average capacity of 420 l/s, and according to other data 150 l/s. The Crna Reka spring is an fissure spring on different levels which depending on the hydrological situation are either active or dry. Only one spring is of permanent character. The capacity of the entire spring is from 0.5 to 5.6 m^3/s, its average capacity is 1.121 m^3/s, according to some data 2 m^3/s, and to other 0.85 m^3/s.

Treska Valley Region - Porechie

This karst massif belongs to the tectonic unit of Pelagonija massif and it is located along the Treska River valley to the North of Makedonski Brod up to Skopje. It covers the central Macedonian mountain massif of the mountains Jakupica, Dautica and Karadzhica.

In this biggest per surface area carbonate province in RoM, made up of Precambrian marbles with the surface area of cca. 1.050 km^2, the karstification processes are developed and the formation of karst aquifers.

According to the studies of many international and domestic authors, the karstification of this marble complex is coordinated with the development of a river valley. However, in the more recent studies of the sites for construction of dams (Kozjak, Sv. Petka, Belica) karst processes have been registered even deeper from the bottom of the river, on Kozjak and Sv. Petka even down to 150 m.

In this rock massif the aquifer waters are drained from a large number of springs on both sides of the river and the lateral tributaries. The biggest drainages occur at the springs Belica between 0.5-6.5 m^3/s, spring in the lake Matka with capacity even bigger than 5 m^3/s, spring Asenoec, Devichki springs, springs below the village of Grgurnica and spring below Matka Lake. In this area there is a large number of karst forms of sinking rivers (Krapska River), pits, collapse sinkholes, caves and karstic channels (Slatinska cave, Matka, Orle) of larger scale, which recently have become subject to investigation of world-known speleologists.

Polog region

Zhedenska karst aquifer was formed in the boundaries of quite karstified limestones, which entirely form this mountain. The karstification base is deeper than the drainage level of Rashche spring, cca.. 300 m, because karstic processes have been registered even at the depth of 120 m under the level of Rashche.
The yield of Rashche spring varies between 2.0-8.0 m^3/s, which is only part of the water that is being accumulated or flow out underground under the level of 300 m.

The City of Skopje is supplied with water coming from the spring of Rashche.
Suvogorska karst aquifer has been formed in the thick masses of intensively karstified limestones, with well-developed all known surface and ground karstic forms. In the transitional hydrogeological zone in the karst aquifer of Suva Gora a drenage divide is formed and from this watershed the water flows on one side towards Polog, the Vardar River Basin, and on the other side towards the Treska River basin.

The drainage of this aquifer is bigger in the Polog part, where through the springs Chegrane, Forino and Volkovija around 1.230-3,290 m^3/s of water flows out. The source of Vardar River is formed in a relatively small marble mass near the village of Vrutok in Gostivar area, through which pass the waters of the higher karst zone in Mavrovo and Vlajnica. The source has variable yield from 0.400-4.800 m^3/s, which is partly collected for the water supply of Gostivar;

CONCLUSION

- Special thematic research is necessary for defining the distribution and genesis of karst on the territory of RoM with a complex approach;
- There are insufficient studies of the basic hydrogeological characteristics of the karst aquifer water in total and per separate sites. Even the collected karst large-capacity springs have not been investigated to a level in which hydrotechnical interventions could be done for maintaining and improving the flowing out regime, the in-takes' capacity, artificial feeding, protection from contamination.
- Special investigations need to be planned in the area of establishing an efficient monitoring of the conditions for feeding and drainage of the aquifers and efficient protection of the water quality.

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WATER BALANCE ANALYSIS OF THE KARST POLJE BY DYSTRIBUTED HYDROLOGICAL MODELING

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Abstract: The paper presents results of the physically based, distributed hydrologic model for simulation of runoff in karst areas. The 3Dnet-HET model is developed for simulation of river Trebišnjica catchment, however, in this study it is applied for simulation of a long-term time series (50 years hydrological input) of the Dabarsko polje catchment, as well as the river Bregava catchment. The model is firstly calibrated based on recorded water levels in the Dabarsko polje and flow discharges at the Bregava spring. Obtained model is utilized to analyze the Dabarsko polje water balance and possible effects of the planned hydropower plant "Dabar". Results indicate a high flow variation and that water management of the whole Trebišnjica system will require an integrated real-time management.

Key words: distributed hydrological modeling, karst catchment, Dabarsko polje

Introduction

The Trebišnjica River catchment area in Eastern Herzegovina is one of the most complex karst areas in the Balkan region. It is characterized by complex karst landforms and drainage systems including karst poljes, ponors, springs, estavelles, developed underground connections, as well as underground bifurcation zones. Detailed description of the area is presented in Milanović (2006). In order to prevent flooding of karst poljes and to keep water in the reservoirs being used for different purposes the complex water resources system was planned. Its construction has begun the 1960s and still last. Realization of the part so-called "The Upper Horizons" require the analysis and prediction of flow regime in physically changed conditions. That is reason why development of hydrological a mathematical model for this area was required.

The basic task of hydrological models is to describe the hydrological processes by connecting relevant parameters by application of numerical modeling techniques and to enable predictions of system properties in different conditions. In general, the hydrological model describes the transformation of precipitation (as inputs) into the runoff and the new conditions of the system (as output).

Due to the complexity and uncertainty of underground flow paths, runoff modeling in the karst basins is a challenge (Makropoulos et al, 2008, Kovacs et al, 2005). Generally, two approaches for mathematical modeling of precipitation transformation into the runoff are possible. One is a 'black box' model with statistical relations between the individual water balance processes, based on recorded time series. It has been shown that application of modern techniques for calibration of involved parameters provide possibilities to simulate hydraulic quantities in complex karst systems very well (Makropoulos et al, 2008).

Another approach is utilization of physically based relationships to describe the individual components of the runoff processes. This approach clearly requires a much more detailed understanding of the conditions in the basin and implies a significant number of model parameters that are subject to calibration. However, the application of such models, with an acceptable level of complexity and with quality-implemented calibration, can provide a reliable model that can be used for predictive purposes, even when some structural changes are expected in the basin, as in the case of the construction of objects that are changing water balance in individual parts of the basin (hydropower plants, reservoirs, derivations, etc.).

This paper presents a case study of Dabarsko polje, a karst polje in Bosnia and Herzegovina, where a distributed, physically based model 3DNet-HET (Faculty of Civil Engineering, University of Belgrade) was utilized for simulation of the discharges in the basins of the Trebišnjica River and the river Bregava in eastern Herzegovina. A 50 years hydrological input was applied to the model in order to obtain detailed insight of the water balance of the DP in the context of the future water management strategies at the basin.

Brief model description

The 3Dnet-HET hydrological model belongs to a group of physically based distributed models (Jaćimović et al, 2015). The term "distributed" means hydrological model which is spatially decomposed into a number of smaller sub-basins. Surface and subsurface runoff from these sub-basins reach the control profiles of the hydrographic network - hydroprofiles (HP) or karst aquifers (KA).

The adopted hydrological model is entirely based on physical laws describing the transformation of precipitation into surface and groundwater recharge. Spatial decomposition of the model implies the division of the catchment area into elements of arbitrary shape, each element being described by a certain number of characteristic values (coefficient of vertical filtration, porosity, characteristic humidity, etc.). Calculations are functionally divided into two parts, where the output from the first part represents the input to the second part. The first part simulates the vertical movement of water and the formation of the underground and surface runoff.

Calculation of the vertical water balance in the hydrological mathematical models for very karstified catchments is especially significant. Input data for the calculation of the vertical balance are precipitation and potential evapotranspiration, given in the form of flux on the surface, as well as the characteristic air temperatures (T_{max}, T_{min} and T_{aver}). If data from multiple meteorological stations are entered in the model, spatial interpolation and height correction of precipitation and temperature are applied, so each sub-catchment has its unique 'own' input meteorological data (Fig. 1).

The vertical balance is calculated for each sub-catchment (CATCH) and the components of the surface runoff (Q_{surf}), percolation into deeper layers (W_{perc}) and change in the amount of water in a sub-basin (SW) are determined. The surface runoff is transformed into a flow at the specific crossection of the hydrographic net, through the linear direct-runoff tank (LR_d). The percolation (W_{perc}) is transformed through a system of reservoirs simulating a base flow. Total percolation from CATCH flows into the nonlinear resevoir (NLR_b). One output (Q_b^{slow}) simulates slow-base flow and goes/discharges directly into the coresponding karst aquifer (KI), and another goes into the linear reservir (LR_b) where it is additionaly transformed simulating fast-base flow and goes also into the coresponding karst aquifer (KI). More detailed mathematical description of this process

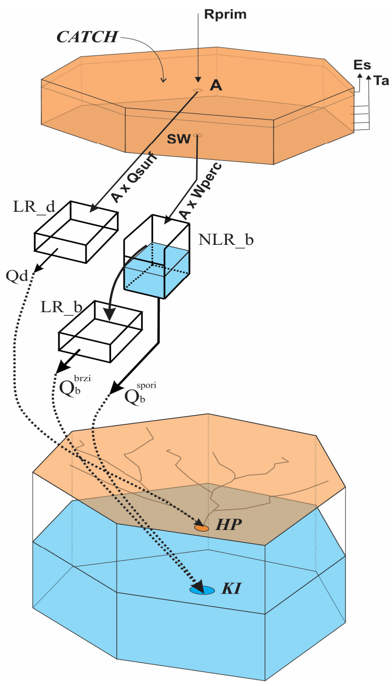

Fig 1. Components of vertical water balance

is presented in other papers and reports (Jaćimović et al, 2015, Water Management Institute Bijeljina, 2015).

The horizontal water balance calculation is based on the assumed hydraulic links by which the nodes of the system are connected. The nodes of the system represent the karst poljes, reservoirs and the karst aquifers, while hydraulic links connect, for example, the karst polje and the karst aquifers through the sinking zones. This is achieved by using the general hydraulic expression:

$$Q = C_1\sqrt{2g(\Pi - Z_1)} + C_2\sqrt{2g(\Pi - Z'_1)} \quad (1)$$

where: Π is the water level, Z_1 - the level at the control section and Z'_1 - characteristic level at which there is a change in the flow conditions.

It is important to note that the coefficients in the preceding equation have a physical meaning. For example, under pressure conditions, the coefficients C_1 and C_2 can be expressed as:

$$C_1=C_{q1}\,A_1 \quad (2)$$

$$C_2=C_{q2}\,A_2 \quad (3)$$

where A is the hydraulically representative surface of the cross-section of the conductor, C_q so-called. the flow coefficient, which depends on the hydraulic resistance along the conductors between the locations where the Π and the Z_1 are defined.

It should be noted that the piezometer level in equation (1) can represent the state of the level of groundwater at an arbitrary place of the karst reservoir. The change of the location implies correction of the C_1 and C_2 coefficients, since the location of the piezometer level depends on the hydraulic losses along the conductor, and therefore the flow coefficients.

The equation (1) assumes the possible influence of the level in the downstream reservoir to the capacity of the sink, in the case of a pressurized flow. This way it is possible to simulate the estavelle. Namely, when the downstream level exceeds the level in the polje, there is a change in the direction of flow. Naturally, in this case it is the pressurized flow, where it is assumed that the hydraulic resistance along the flow is the same in both directions. In other words, the same pressure coefficients apply, regardless of the direction of flow.

The horizontal water balance is completed by iterative numerical solution of the balance equation for each node in the system.

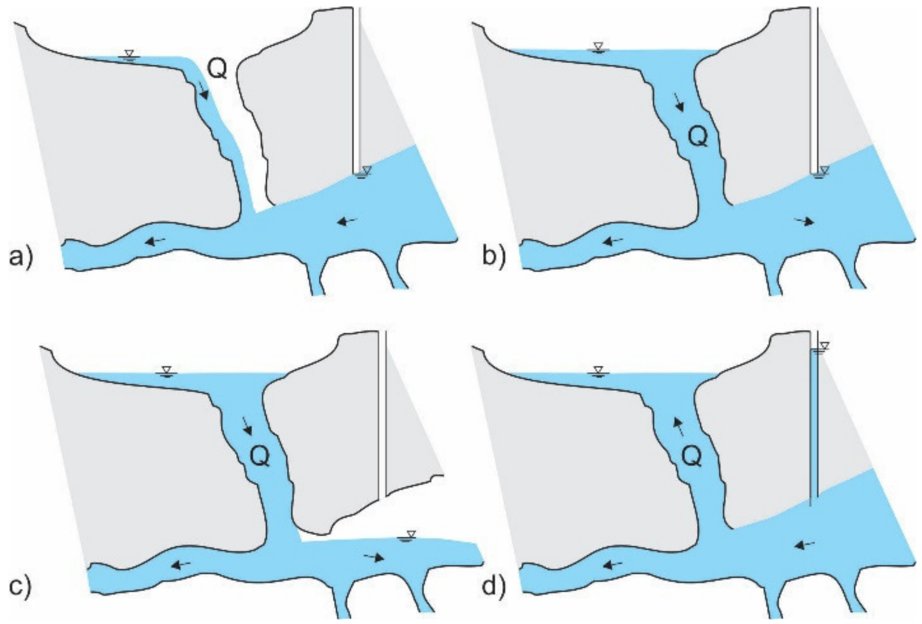

Fig. 2. Schematic representation of the simulated flow conditions in the case of the sink: a) overflow-weir flow, b) pressurized flow under the influence of the downstream level, c) pressurized flow without influence of the downstream level, d) – opposite flow direction

Dabarsko polje and the Bregava river basin

Study area is highly karstified catchment area of Bregava River spring zone in Eastern Herzegovina (Fig. 1). It includes parts of the mountain massifs of Hrgud and Sitnica and the Dabarsko Polje with sub-catchments of the Trusinsko and Lukavačko Polje. The spring zone of the river Bregava includes the area between the permanent Spring Bitunja at 130 m a.s.l. and the periodical springs of Mali Suhavići and Veliki Suhavići at 195 m a.s.l. Figure 1 shows a simplified hydrogeological map of the catchment area of Bregava spring zone. The flows are measured at the gauging station Do, a few kilometers downstream from the spring zone. Basic characteristics of the flow of the Bregava River: $Q_{min} \approx 0.40$ m^3/s; $Q_{max} = 59$ m^3/s; $Q_{sr} = 17.5$ m^3/s. In the drought year 2003, the minimal flow was measured $Q_{min} = 380$ l/s. In that period flow of 43 l/s sink into the Ponikva Ponor in the Dabarsko Polje (August 13, 2003).

Total catchment area is estimated at approximately 396 km^2. It can be divided into two parts: direct and indirect catchment areas. Direct catchment area includes parts of the mountain massifs of Hrgud and Sitnica. Its area is estimeted at approximately 218 km^2. Water from this area flows directly toward the Bregava Spring zone as underground water flow.

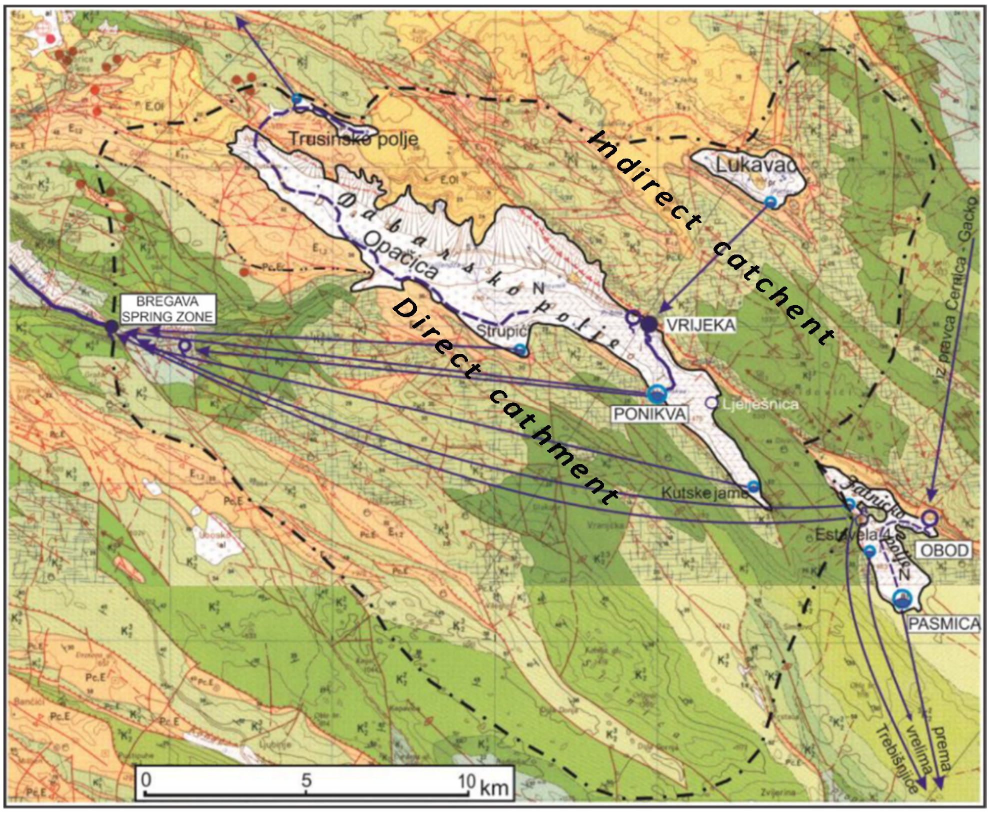

Fig. 3. Map of the the Bregava river basin with significant sinks, spring zones, estavelle and confirmed hydraulic links (Jaćimović et al, 2015)

Indirect catchment area is catchment area of Dabarsko Polje, with estimated area of approximately 178 km². Water from this catchment first appears in Dabarsko Polje, flows through polje, and then sinks and flows as underground flow to Bregava Spring zone. The watersheds of the catchment area include two bifurcation zones: Trusinsko and Fatničko polje. While the bifurcation zone of the Trusinsko Polje has limited/small significance for the water balance of the Dabarsko Polje, the bifurcation zone of the Fatničko polje in some hydrological conditions can be significant for water balance of the Bregava springs. Fatničko Polje is a part of Trebišnjica River catchment area. But, in flood periods when water level in Fatničko Polje is higher than 671 m a.s.l, bifurcation zone activates and a part of water flows toward the Bregava Springs.

The Dabarsko Polje (Fig. 1) was formed along the regional reverse fault with slope of 60º to 70º in the direction of north-east. The northern edge of the polje consists of limestones and sediments of Promina Formation, and the southern edge is formed of karstified limestone Cretaceous age. There is a deep hydrogeological barrier of impervious Tertiary sediments beneath the Dabarsko Polje (with depths between 200 and 400 m). It intersects the underground water paths, and water appears in springs located along north-east edge of the Polje. Water flows across the Polje and sinks into ponors situated on the south-west edge. The most important and the only permanent is the Vrijeka Spring, with discharges form 100-150 l/s in dry periods (with absolute minimum of 43 l/s) to 25 m^3/s in flood periods. Water flows as Vrijeka River, 2.5 km long, to the Ponor Ponikve, where it sinks and appears on the Bitunja Spring. Beside the Ponor Ponikva water from Dabarsko Polje discharges through the ponor Kutske Jame, ponor zone Stupići and Ljelješnica Estavelle. It has been established, by tracer test, the water from Dabarsko Polje discharges at Bregava Springs. Possibility for direct connection between Dabarsko Polje and Hutovo Blato can't be excluded. However, if exist this connection is negligible and without influence on general water regime.

Model application

The 3Dnet-HET model was firstly calibrated for a period of nine years, 1.1.1972. - 31.12.1980. During this period, the hydraulic tunnel between the Dabarsko and Fatničko poljes, as well as the tunnel between the Fatničko Polje and the Bileća reservoir did not exist, i.e. this represents the natural state of the catchment.

Considering the global water balance in the analyzed part of the basin, the obtained runoff coefficient was 0.88, that is, only about 12% of water is lost to evapotranspiration processes.

For the evaluation of the quality of the model, i.e. the agreement of the simulated values obtained by the hydrological modeling, the linear correlation coefficient and the Nash-Sutcliffe coefficient were used. Two data sets were compared with the observed values: the river Bregava discharges, and the water levels in the Dabarsko Polje.

The obtained values of the correlation coefficient for the simulated period of nine years amount to 0.87 for the flows in the river Bregava and 0.81 for the levels in the Dabarsko Polje. At the same time, the value of the Nash-Sutcliffe coefficient is 0.74, which indicates a very good agreement between the results of the model and the observed values. Another indicator of model performances is difference of the total volume of water flowing on the gauging station. By comparing the mean values of measured and simulated flows of Bregava River for the analyzed period, the difference was less than 1.7% ($Q_{measured}$= 18.36 m^3/s, Q_{model}= 18.64 m^3/s).

The comparison of the flow duration curves at the river Bregava obtained on the base of measured and simulated data are shown in Figure 4. Curves are calculated for the same period (1972 – 1980), and there is a very good agreement between them, which indicates that all physical processes are adequately simulated in the model. The water level curve in Dabarsko Polje also shows very good agreement with the duration curve of the observed values.

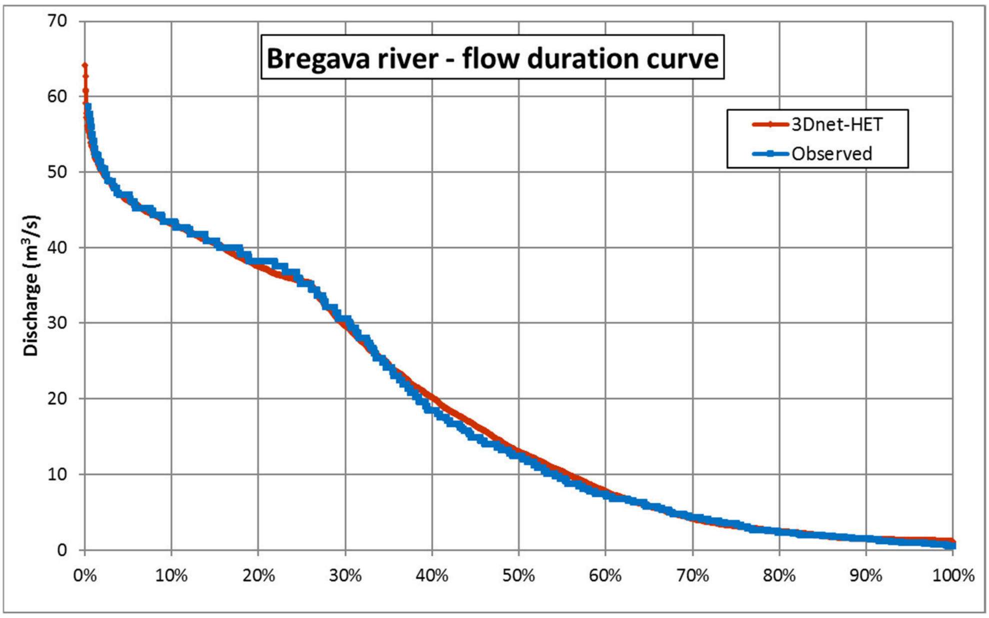

Fig. 4. Flow duration curve comparison of modeled and observed data sets for the period 1972. - 1980. year

Obtained model is utilized for simulation of the 50 years hydrologic period (1961-2014) for natural conditions. Figure 5 reveals the subcatchment partition in the total discharge of the Dabarsko Polje. Namely, the direct runoff to Dabarsko Polje is very similar to the discharge of the spring Vrijeka. This is important result in regard of considered possibility to transfer the water toward the Trebišnjica river basin. This will be a challenging task in the future, since the most of runoff occur during the short period of time, as shown in Figure 5.

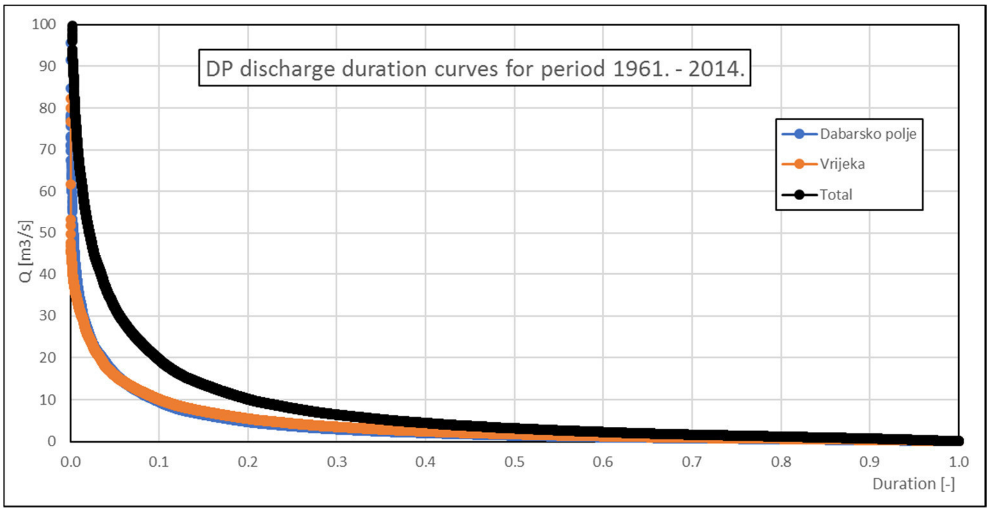

Fig. 5. Discharge duration curve for the Dabarsko polje.
Contributionof the spring Vrijeka versus direct runoff.

Conclusions

The application of distributed hydrological models, based on the physical laws of precipitation transformation, is possible even for the karst basins. The precondition for this is the existence of quality observations data, which includes precipitation, discharges, and especially the water levels in the karst aquifers. We believe that such models provide more reliable forecasts of the discharges in altered (planned) conditions in the basin, compared to the frequently used statistical models. In this study, application of developed hydrological model 3Dnet-HET provided better insight into the components of water balance of the Dabarsko polje karst polje. This may be of great importance considering the goals of the water management system "Gornji horizonti", which is in the construction phase.

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PRELIMINARY CHARACTERIZATION OF SELJAŠNICA KARST AQUIFER (SW SERBIA) BASED ON RECESSION CURVE ANALYSIS

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Abstract: Identification of karst aquifer characteristics as well as the features of karst rock massif can be performed by analyzing a karst spring hydrograph. Behavior of karst aquifer discharging in recession conditions can give relevant data on the character of a karst hydrogeological system. Such an approach has been applied to the example of the Seljašnica karst aquifer, which is part of a large karst system, the Babine karst plateau (located in SW Serbia). Recession analysis of the spring hydrograph was carried out for 2015, 2016 and 2017 by using the Maillet's equation. The analysis has shown the existence of 4 micro-regimes of discharging in 2015, 2 micro-regimes in 2016, and 3 micro-regimes in 2017. These results prove the existence of dual porosity of karst aquifer system, and also indicate the existence of two dominant karst channels, probably at different levels, that react on the recharge process with different time-delay.

Key words: karst, aquifer characterization, recession curve, Serbia

Introduction

Understanding the characteristics of a karst hydrogeological system is essential for the utilization and protection of karst groundwater in a sustainable way (Stevanović, 2015). Relevant data of karst aquifer characteristics can be obtained by analysing a karst spring hydrograph. Karst springs are considered to be one of the most important hydrogeological features in a karst hydrogeological system, mostly because they represent the only visible part of a karst aquifer. Therefore, it is important to continuously measure the karst spring discharge in order to determine the geometry and hydraulic features of a karst aquifer based on hydrograph and recession curve analysis (Bonacci, 1993; Fiorillo, 2014). Such an approach has been applied to the Seljašnica karst aquifer, which is part of a larger karst system - the Babine karst plateau (located in SW Serbia) that belongs to the Dinarides. This karst plateau (and aquifer system) is located at the very border with Montenegro (probably having a transboundary character) and is drained by three large karst springs: Seljašnica and Bučje in Serbia and Breznica in Montenegro (Fig. 1). The plateau is a fluvial relict formed over the thick deposits of Triassic limestones. The thickness of the limestones varies from 150 to 750 m, in some parts possibly up to 1200 m, as a bedrock of the ophiolites of Jurassic age. Numerous karst features can be recognized, such as sinkholes, dry and blind valleys that testify to the formerly well-developed river network. Some ponors and small caves exist as well. The karst aquifer of Seljašnica was formed in the carbonate rocks of Triassic age. The recharge process of the karst aquifer is primarily dependent on precipitation regime (effective rainfalls and melted show). In bare karst areas, the karst aquifer is being recharged by the direct infiltration of atmospheric waters, while the aquifer can be recharged by the sinking of surface streams formed on ophiolites and young volcanic rocks (allogenic recharge). This can be seen in Fig. 2, where a comparative diagram of the discharge hydrograph for the Seljašnica karst spring (from May 2015 to December 2017), rainfall, snow and temperature value (from May 2015 to June 2017) from the nearest gauge station is shown. The comparative diagram (Fig. 2) proves the relationship between the precipitation and the spring discharge, showing that the intensive rain events caused the highest discharge values. Also, show melting caused intensive recharge of karst aquifer in spring-time of each year.

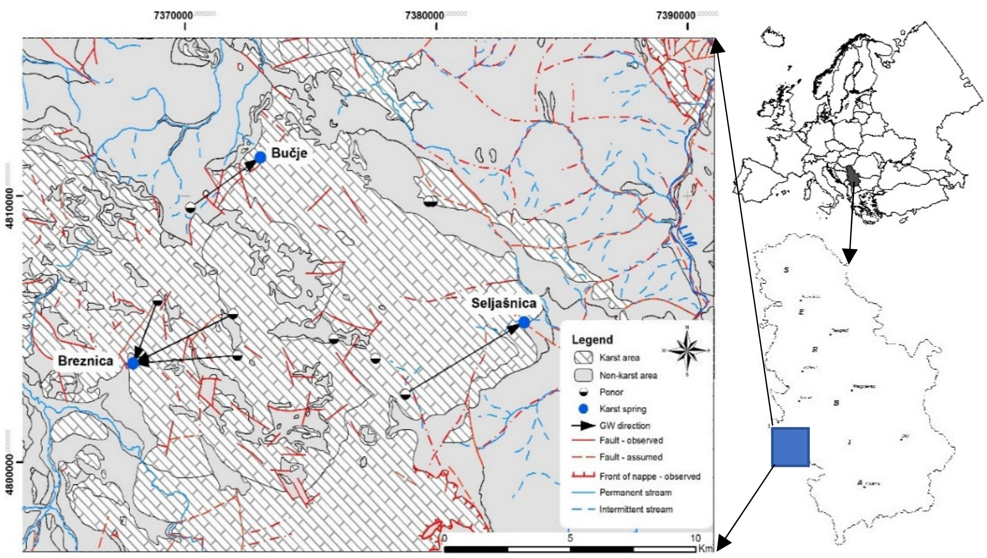

Fig. 1. Location and a simplified hydrogeological map of the Babine karst plateau

Methodology

As stated above, the characteristics of a karst aquifer may be properly evaluated by analyzing the behavior of the karst aquifer during different conditions within a hydrologic year. To do so, systematic records of spring discharge need to be collected. In the case of the Babine karst plateau, a recession analysis of the spring hydrograph has been applied to the Seljašnica karst aquifer only, given that the spring discharge has been measured at the Seljašnica karst spring since May 2015. Even though there are several methods for the analysis of the recession curve (Bonacci, 1993; Fiorillo, 2014), the recession analysis of this karst aquifer was carried out for 2015, 2016 and 2017 by using the Maillet's exponential equation (1):

$$Q_t = Q_0 e^{-\alpha(t-t_0)} \quad (1)$$

Where:
Q_t – spring discharge (m³/s) in period t-t_0
Q_0 – spring discharge (m³/s) in period t_0
t_0– the beginning of the recession period
t – the end of the recession period
α – recession coefficient

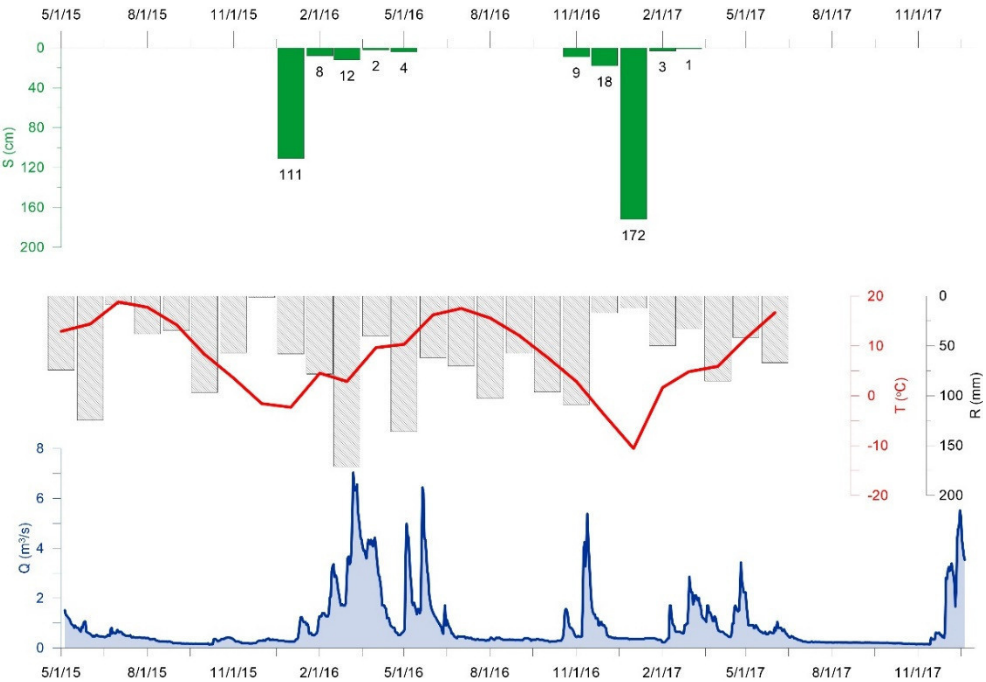

Fig. 2. Comparative diagram of spring discharge hydrograph of Seljašnica karst spring (from May 2015 to December 2017) and rainfall, snow and temperature values (from May 2015 to June 2017) obtained from local gauge station

Results and discussion

The recession curve analysis was carried out for the recession periods in 2015, 2016 and 2017. Looking at the each of hydrographs (Fig. 3), it can be observed that the recession periods lasted for 98, 120 and 144 days in 2015, 2016 and 2017, respectively. Table 1 shows the recession coefficients and duration of each micro-regime of discharging. When it comes to 2015, there were 4 micro-regimes of discharging during the recession period. The recession coefficients of the order of 10^{-2} (α_1 and α_3) indicate faster groundwater circulation and discharging through the spring, probably by activating larger karst conduits, while the recession coefficients of the order of 10^{-3} (α_2 and α_4) represent slower base outflow from secondary pores or matrix rock. The assumption is that there are two discharging cycles with one faster and one slower discharge, probably caused by groundwater level at a given moment, indicating a specific way of discharge of this aquifer. The saturation of the karst aquifer during the recession period causes the beginning of rapid discharge, most likely due to the transmission of pressure throughout the system, after which the system re-enters the period of slow discharge. When it comes to 2016 the recession period lasted almost four months (120 days) with just two micro-regimes of discharging. The first micro-regime lasted 10 days with recession coefficient of the order of 10^{-2} that indicates rapid discharging of large karst conduits. After that period, the karst spring discharge entered the very long recession micro-period (110 days) where only baseflow from matrix porosity was discharging. This can be explained by huge spring discharge rate in springtime ($Q = 7\ m^3/s$), when the largest amount of dynamic reserves discharged throughout the spring, while groundwater level in the recession period was below the main karst conduits.

Almost the same situation was in 2017, when 3 micro-regimes occurred. As was the case in previous years, the first micro-regime of discharge in 2017 lasted 14 days, during which the discharge of dynamic reserves was very rapid. After that period, karst hydrogeological system started discharging slowly with 2 micro-regimes with duration of 87 and 43 days, respectively. The third micro-regime of discharging may have been caused by the removal of suspended materials from pores (clay, sand, etc.) which enabled faster circulation of the karst groundwater through the matrix and channels. Another explanation of the third micro-regime can be given based on the maximum discharge rate in the springtime, which was not as high as the discharge rate in the previous year. That fact implies that dynamic reserves were stable up to 101st day of the recession period, after that the groundwater level dropped below the dominant channel and karst groundwater discharged only as baseflow from matrix rock.

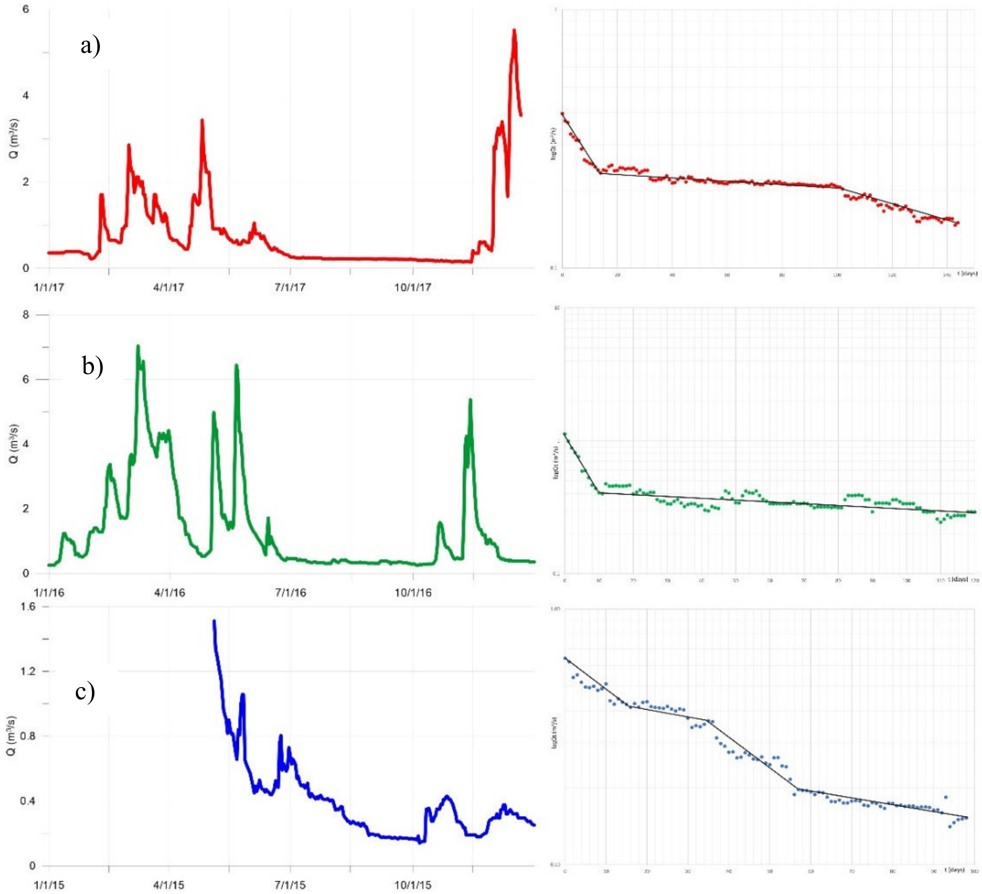

Fig. 3. Karst spring hydrograph and recession curves of the Seljašnica karst spring for 2017 (a), 2016 (b) and 2015 (c)

Considering that each year has several micro-regimes of discharging, the Maillet's equation (1) can be decomposed into the sum of a set of micro-regimes of discharging, which gives the final equation that represent the entire recession period. The equations for each year are:

$$2015\text{: } Q_t = 0{,}6419e^{-0{,}027624t} + 0{,}4126e^{-0{,}006342t} + 0{,}3657e^{-0{,}028161t} + 0{,}1524e^{-0{,}006229t} \quad (2)$$

$$2016\text{: } Q_t = 1{,}1276e^{-0{,}102144t} + 0{,}40604e^{-0{,}003036t} \quad (3)$$

$$2017\text{: } Q_t = 0{,}3962e^{-0{,}037725t} + 0{,}2336e^{-0{,}001474t} + 0{,}2055e^{-0{,}007354t} \quad (4)$$

Table 1. Recession coefficients for the Seljašnica karst aquifer in 2015, 2016 and 2017

Year	Recession coefficient (α)		Duration of micro-regimes (days)
2015	α_1	0,027624	16
	α_2	0,006342	19
	α_3	0,0238161	22
	α_4	0,006229	41
		Σ	**98**
2016	α_1	0,102144	10
	α_2	0,003036	110
		Σ	**120**
2017	α_1	0,037725	14
	α_2	0,001474	87
	α_3	0,007354	43
		Σ	**144**

Further discussion can be made about the existence of 4 micro-regimes of discharging in recession period in 2015. A possible explanation could be based on rainfall regime, mostly because 2015 is considered to be a wet year. It is very probable that dynamic reserves within karst system were very large, and that discharging during the recession period happened through the main karst conduits. Assumption is that the first conduit is on a higher elevation than the second one and drains higher parts of aquifer. Afterwards, as groundwater level goes down, the first conduit becomes dry and matrix porosity overtakes groundwater circulation and discharge. This was the case with the first two micro-regimes of discharge. The third and the fourth micro-regimes of discharge during the recession period can be explained the same way: groundwater level continuously goes down until it reaches the second karst conduit (on lower elevation) which is now dominant in the discharging process. The duration of the third micro-regime is longer because of position of the conduit and the amount of groundwater. At the end, when groundwater level drops below the second karst conduit, matrix porosity overtakes the karst groundwater and distribute it to the spring. Duration of that period is the longest, which lasts until the recharge process starts again. Based on this example, we deduce that this aquifer is actually a dual porosity system, which is very often the case in karst hydrogeological system (Goldscheider, 2015). The recession conditions in 2016 and 2017 were different, probably because the amount of effective rainfalls regime was not enough to recharge the karst hydrogeological system sufficiently to activate the higher karst channel. It is more likely that karst groundwater was discharged by the lower karst conduit and matrix rock beneath, after the conduit dried out. This also explains the longer recession period in 2016 and 2017 than in 2015. The arguments above also explain the difference in the order of magnitude of recession coefficient in 2015 and 2017, where the third recession coefficient is higher than previous ones. Some similar examples where the increase of recession coefficient happens during the recession period were discussed by Bonacci, 1993.

Conclusion

Preliminary characterization of the Seljašnica karst aquifer is based on the recession curve analysis, that was carried out for 2015, 2016 and 2017. First results show that the Seljašnica karst aquifers is a dual porosity karst system with two dominant karst conduits which are the main drainage channels of this karst system. These tectonically predisposed conduits distribute the largest amount of groundwater and feed the Seljašnica karst spring. During the recession period, when the groundwater level drops below the elevation of the conduits (which are dry at that moment), the spring discharge occurs only as baseflow from the matrix porosity. The next step in order to characterize this karst hydrogeological system will be the identification of relationship between discharge and rainfalls by applying stochastic modeling techniques like autocorrelation, cross-correlation, spectral analysis and establishing autocrossregressive model for simulating daily discharge rates of this karst aquifer system. Also, a further step will include the karst groundwater budget calculation and more precise delineation of the catchment area, bearing in mind the probable transboundary character of this karst aquifer.

Acknowledgment

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THE SPECIFIC ROLE OF KARST AQUIFERS IN THE HYDROGEOLOGICAL SECTIONS OF RIVER BASIN MANAGEMENT PLANS

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Abstract: Karst can accumulate significant amounts of drinking water and, as such, needs to be properly protected. To do so, it is necessary to assess all potential threats that may have an impact on groundwater quality and quantity deterioration. An approach suggested by EU involves promotion of water protection and sustainable use of surface water and groundwater within the River Basin Management Plans (RBMP) in order to estimate the pressures on water quality and quantity. Such plans have been prepared in most European countries, and this paper discusses case examples from Bosnia & Herzegovina and Serbia in the Danube and Sava River basins. The above documents confirmed the great potential of karst aquifers in both countries as regards groundwater quantity and relatively low pressures on groundwater quality. The latter is mostly due to low population density in hilly karstic areas and underdeveloped industry and agriculture.

Key words: karst aquifer, RBMP, WFD, water management

Introduction

Managing the water issues in a sustainable way has been a priority task, particularly in the last decades of the 20th century. Many conventions, protocols and agreements have been signed at all levels (from international to local) with the aim of regulating water management issues and considering mostly rational and balanced utilisation of surface and groundwater resources and their protection from pollution (Stevanović & Marinović, 2016). The most important legislation document is the Water Framework Directive (WFD), which has been adopted by the European Union (EU) in 2000 with the aim to preserve, protect and improve the environment and the quality of water by also promoting reasonable and rational use of natural resources. WFD suggests the creation of Programmes of Measures (PoM) and River Basin Management Plans (RBMP) for larger and smaller river basins alike, with a strong support to international coordination to achieve the above objectives. This implies the preparation of RBMPs for the largest river basins in a particular region as the first step, to be followed by the creation of several RBMPs for smaller, inner river basins (sub-catchments). Such a hierarchical approach has been applied in the Balkan region, where the first step was the creation of the Danube RMBP (coordinated by ICPDR, 2009) and Sava RBMP (coordinated by ISRBC, 2013) while in recent years all the countries of the region started preparing RBMPs at the national level. The current situation is as follows: Bosnia & Herzegovina (B&H) (non-EU member), Slovenia and Croatia (EU members) have mostly completed their national RBMPs for the period 2016-2021, Serbia has prepared the document only for the pilot areas, while Montenegro is currently in the process of preparing its RMBPs.

Methodology

Each RBMP includes a section pertaining to groundwater, which includes an analysis of the current exploitation of water resources, possible pressures on the groundwater quality and quantity, the current monitoring network and measures to maintain or remedy the current chemical status, as well as long-term sustainable use of water resources including measures for protection of dependent ecosystems and safe water management in designated protected areas. Such an approach is not always easy to implement when it comes to karst aquifers, considering their high vulnerability, problems of catchment delineation and water balancing. Karst aquifers are of particular importance for the countries of former Yugoslavia (YU), considering the fact that almost one third of the total former YU area is covered by karst features (Herak, 1972) and that a large percentage of the population, including citizens of three capital cities (Sarajevo, Skopje and Podgorica), use karst groundwater for drinking. Therefore, in water strategies and master plans special attention ought to be paid to karst groundwater.

The very first step in the hydrogeological analysis within the RBMPs is the delineation of groundwater bodies. In the case of karst aquifers, it is often difficult to precisely determine the boundaries of a karst spring catchment area, which usually comprises autogenic and allogenic (attached) aquifer recharge zones (Stevanović et al, 2015a). This is of particular interest, especially for karst groundwater reserves and budget calculation. In the groundwater bodies' delineation process the scale of RBMP needs to be taken into account, as it directly determines the size of each groundwater body. Although WFD recommends characterisation (quantitative and chemical status) of each water body that supplies more than 50 people and whose abstraction is larger than 10 m^3/day, in the case of larger basins their grouping is absolutely required. This can be observed in the example of the Danube RBMP, where only transboundary groundwater bodies larger than 1,000 km^2 were considered, while delineation of groundwater bodies was done in greater detail in the national RBMP of each country that belongs to the Danube River basin. In this case, the so-called scale effect, which depends on the size of the concerned territory, should be applied. The WFD has also set forth a logical concept "from the larger to the smaller river basin", and thus the plan for larger basins must contain more generalised data, while the degree of detail increases with the transition to smaller river basins. The next step in the hydrogeological section of RBMP is the conceptualisation of each groundwater body in order to characterise it. This step is essential for any further analysis, implementation of water management measures, and the promotion of a sustainable development concept. Several issues that must be evaluated to develop a proper conceptual model for each delineated groundwater (GW) body, particularly in karst, are shown in Figure 1.

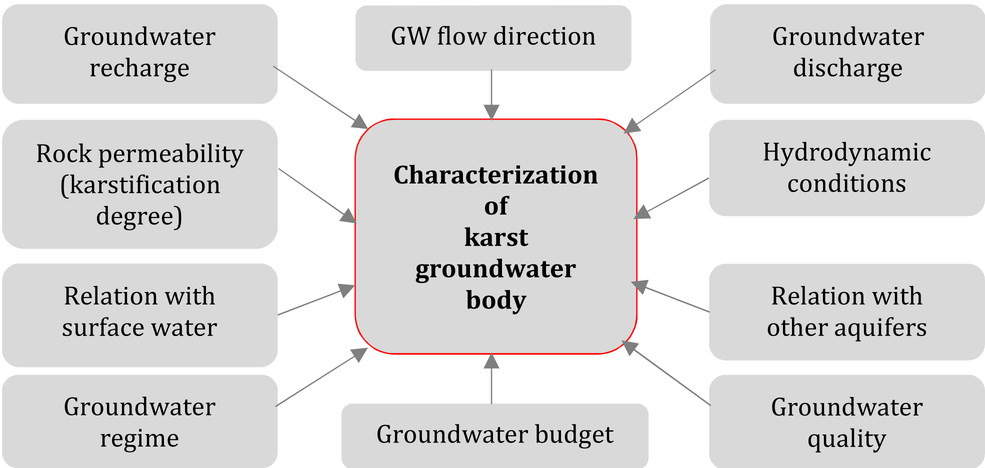


Fig. 1. A conceptual model for the characterisation of a karst groundwater body within RBMP

One of the main tasks of RBMP is to define the pressures on groundwater quantity and quality. This is especially important in karst, considering the high intrinsic vulnerability of karst aquifers and extensive usage of karst groundwater for drinking in daily life, particularly in the ex YU region. The pressures on groundwater quantity could be suitably assessed as a ratio of totally available or renewable groundwater resources and total water demands. There are several concepts that are used to estimate the pressures on groundwater quantity (WFD, CIS 2007; UK TAG, 2005), but experience has shown that all of them are in line, providing almost the same final score for pressures on studied groundwater bodies (Table 1).

Besides these concepts, it should be stated that methodology for groundwater budgeting, which is the main prerequisite for determining the pressures on GW quantity, is different in the case of different aquifer types. Karst groundwater budgeting depends on the ratio of input parameters (recharge from precipitation, surface and subsurface inflow) and output parameters (surface and subsurface outflow, evapotranspiration, spring discharge, exploitation), and the calculation needs to be done for at least one – average – hydrologic cycle (Stevanovic, 2015b). Also, the fact that the budget calculation is done almost always based on historical data because new monitoring network is rarely implemented during the creation of the RBMP also happens to be important.

Table 1. Different concepts of estimation of the pressures on karst GW quantity within RBMPs

Current extraction rate and demands of water-dependent ecosystems Vs. Renewable groundwater reserves	< 33 %	33 – 66 %	>66 %
	No pressure	**Potentially under pressure**	**Under pressure**
Current exploitation rate Vs. Total amount of infiltrated water	< 15 %	15 – 30 %	> 30 %
	No pressure	**Potentially under pressure**	**Under pressure**

An assessment of the pressures on groundwater quality can be done based on numerous historical analyses, but at a regional scale it can be based on groundwater vulnerability, hazard and risk map. As regards the Vulnerability Map, there are several well-known methods for determination of vulnerability in karst, such as EPIK, DRASTIC, COP and so on, but it is not rare to also see new methods that were developed and implemented to achieve the same purpose. Hazard maps can be prepared based on punctual and diffuse pollutants, while the combination of the Vulnerability and Hazard Maps results in a Risk Map. Finally, by introducing an adequate grading system of risks (Table 2), the final maps may show the level of risk for each GW body, based on which pressures on groundwater quality can be assessed (Stevanović & Marinović, 2016).

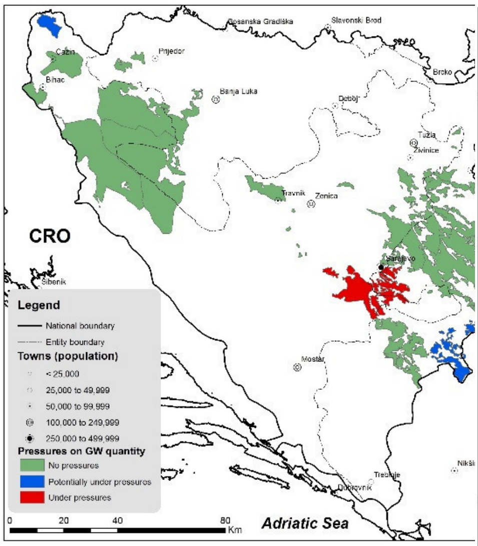
Table 2. Grading system of groundwater risks against pollutants used to assess the pressures on karst groundwater quality

No pressure	No risk	Very low risk	Low risk
Potentially under pressure	Moderate risk		
Under pressure	High risk	Very high risk	

Special attention should be paid to karst aquifers when it comes to determination of vulnerability, hazard and risk, as a medium such as karst is very sensitive to pollution because of its very rapid horizontal and vertical propagation of fluids (i.e. pollutants), turbulent flows and low attenuation capacity.

Case Studies

The above presented methodology for karst groundwater bodies' delineation and estimation of the pressures on karst groundwater quantity and quality was implemented in the Sava River basin in Bosnia & Herzegovina (B&H) and the Danube River basin in Serbia. Figure 2 shows only karst (group of) groundwater bodies delineated in B&H and in Serbia.



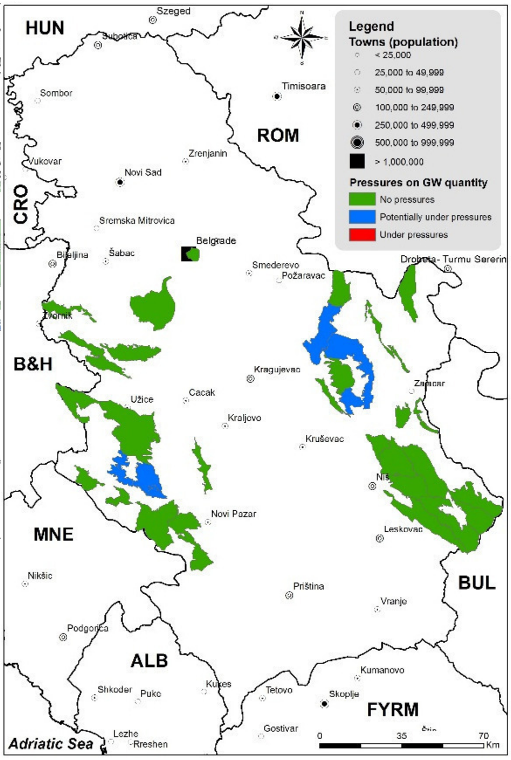


Fig. 2. Pressures on karst groundwater quantity in karst GW bodies in B&H (left, according to ASRB, 2016; PIVS, 2016; GBD, 2016, modified); and in Serbia (right, according to the Official Gazette (2011), modified)

There are 13 karst groups of GW bodies that have been delineated in B&H, with the average surface of 630.8 km^2, while 34 karst GW bodies have been delineated in Serbia with the average surface of 292.3 km^2. The total surface of karst groundwater bodies in B&H is 8,201.2 km^2, which represents 21.4% of the entire Sava River basin in B&H, while the total surface of karst groundwater bodies in Serbia is 9,950.1 km^2, i.e. 12.2% of the entire Danube River basin in Serbia. They were all determined based on (hydro)geological maps, tracing tests, karst groundwater flow direction and hydrogeological watersheds. The pressure on groundwater quantity was assessed based on both approaches from Table 1, showing the same results (Fig. 2). According to these concepts, in B&H 2 karst GW bodies were found to belong in the category Potentially under pressure, only one is actually under pressure, while the rest are free of pressure on groundwater quantity (Fig. 2). In Serbia, 6 GW bodies were found to belong in the category Potentially under pressure, while the rest are free of pressure on GW quantity (Fig. 2). Pressures on groundwater quality were estimated based on the Risk Map, which is the result of the compilation of the Vulnerability and Hazard Maps. The new methods for vulnerability assessment have been applied in both B&H and Serbia. The first regional Vulnerability Map was created in Serbia by applying the IZDAN method (Milanović S. et al, 2010), while the vulnerability assessment in B&H was conducted by applying the newly created SODA method (Stevanović et al, 2015a) which combines several factors such as slope, overlying layers, depth to the GW table and aquifer types. Based on the above criteria, almost all karst groundwater bodies (in both countries) were found to belong in the category No pressure, with the exception of one karst GW body in Serbia that is potentially under pressure. Even though karst happens to be a very vulnerable medium, most of karst GW bodies from the studied cases are without pressures on groundwater chemistry (quality), mostly because of the absence of agriculture and the low population density in areas that are mostly hilly and mountainous.

Conclusion

Karst aquifers in the former Yugoslav countries have a great potential for actual and further groundwater exploitation, but they need to be properly protected from pollution. This objective can be achieved by creating and thoroughly implementing River Basin Management Plans (RBMPs), as suggested by EU WFD. The analyses included in the documents concerning the Sava and Danube River basins in B&H and Serbia show relatively low pressures on karst groundwater quantity, as in most of the studied karst groundwater bodies utilisation of karst groundwater does not exceed one third of the total renewable karst groundwater reserves. The pressures on GW quality were found to be low to moderate as a result of low population density, low level of industrialisation, and not much agricultural activity in the studied catchments. Such findings certainly do not exclude any preventive measures that will maintain such groundwater quantity and chemistry status. EU WFD (Annex VI) suggests the creation of Programme of Measures, to be incorporated in every RBMP. The measures could include, for instance, the issuance of water permits and concessions to persons or legal entities, determining how much water may be extracted within a specified time period. Several other measures, such as the "polluter pays" principle or the treatment of pollutants at their source, may also help achieve a good groundwater chemical status for GW bodies that are currently under threat.

Acknowledgment

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REGULATION AND UTILIZATION OF FLOOD WATER OF KARST POLJE – EXAMPLE OF GATAČKO POLJE, EASTERN HERZEGOVINA

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Abstract: In general, karst is known as extreme environment for construction of large structures. The average precipitation of karst poljes at Dinaric region of the Eastern Herzegovina for a wet year is about 2450 mm. Daily precipitation can be more than 250 mm. Due to prevailing underground drainage and limited dewatering capacity of ponors the floods are frequent. Only agricultural land is in the karst poljes, which remain flooded from 150 to 250 days in average per year. The population remains low as these difficult living conditions have driven people out of this region for many decades. Possibilities for socio-economic developments are poor. One of these poljes the Gatačko Polje is situated at the highest elevation of the Eastern Herzegovina. Uneven water regime of polje is typical for regions with deep and high developed karst. Sometimes floods are disastrous particularly for infrastructure. To change inconvenient natural water regime a few possible options are analyzed.
In article are presented, in very general, properties of natural regime of the Gatačko Polje, including some hydrological and hydrogeological specificities. Many decades behind two mutually coupled questions were analyzed: possibility to transfer the part water from the Gatačko Polje catchment to be used at the Multipurpose Hydrosystem Trebišnjica for power production, irrigation, water supply and other secondary benefits, and at the same time, to protect infrastructure, particularly to prevent disastrous effect on the Thermal Power Plant.

Key words: Karst polje, ponor, flood protection, management of reservoirs, Mušnica River

GENERAL SETTINGS

The drainage area of the Gatačko polje belongs to the uppermost cascade of the large Trebišnjica catchment area. This area is situated between the drainage basins of the Neretva, Drina and Zeta rivers. The Neogene sedimentation trench of the Gatačko Polje has been developed along the steep dislocations that follow Dinaric direction and transverse fractures. New tectonic movement had a pivotal role in predisposing and developing the karstification process. The capacity of karst corrosion and erosion abruptly increased with the rising of the northern tectonic blocks. As consequence of these processes the surface river net was disorganized, and underground drainage system has been developed.

The Gatačko Polje lost the surface drainage, particularly in direction of west, toward the Zalomka River. At the level of the Gatačko polje two independent infiltration zones have been formed under the influence of these two erosion bases (Milanović P, 2006). Evolution of this part of the karst aquifer moved in two directions, eastward toward the Piva Spring and southward toward the Trebišnjica Springs. The most concentrated infiltration zones were created along the south-east border of the Malo Gatačko Polje. The preferential sinking zone and groundwater flow was predisposed by the most important transverse fault zone of north-south direction between the Malo Gatačko Polje and the Cerničko Polje. The huge swallow-hole zone with massive swallowing capacity Jasikovac and Vranjača has been developed.

Total surface of Gatačko Polje is about 37.6 km^2, and its elevation is between 936 and 950 m a.s.l. It consists of two geomorphologicaly and hydrogeologicaly interconnected units: Gatačko Polje itself (31.83 km^2) and Malo Gatačko Polje (5.77 km^2), Fig. 1. Average annual precipitation is 1756 mm, with minimal annual values of 918 mm and maximal 2513 mm. The main stream of the Gatačko Polje is the Mušnica River, formed from three streams Vrba, Ulinjski and Jasenički stream. Its main tributaries are Gračanica and Gojkovića (Žarovića) stream. The Mušnica River flows through Gatačko Polje to Malo Gatačko Polje where it sinks in numerous ponors from Srđevići Ponor to Šabanov Ponor and the sinking zones Jasikovac/Vranjača (Fig. 2). Further, water flows as groundwater to Trebišnjica springs.

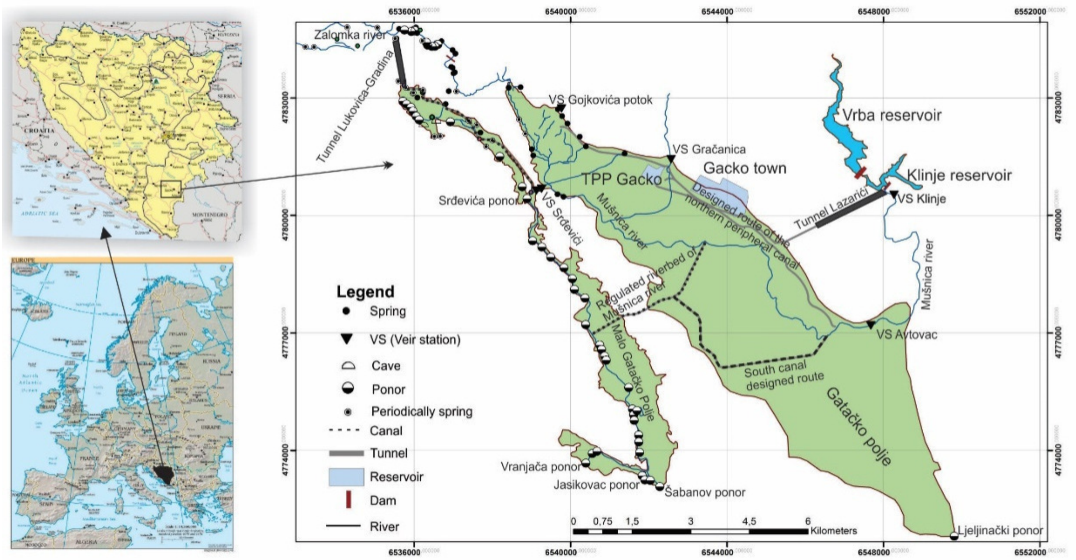

Fig. 1. Geographical position and schematic map of wider area of Gatačko Polje with main hydrotechnical constructions

There are 6 gauging stations in the Gatačko Polje with average annual flow values calculated for monitored data: VS Vrba (1949-1975) - 0.92 m^3/s, VS Klinje (calculated on the base of correlation with VS Vrba and VS Avtovac) 3.11 m^3/s, VS Avtovac (1962-1982) - 4.514 m^3/s, VS Gračanica (1947-1995) - 1.746 m^3/s, VS Gojkovića Most (1975-2001) – 0.415 m^3/s, VS Srđevići (1947-2014) - 8.06 m^3/s.

Natural regimes of water flows in the Gatačko Polje have been slightly changed after 1898, when Klinje Dam was built to provide water for irrigation. It has a water storage reservoir of only $1.73 \cdot 10^6$ m^3, with regular water level 1027 m a.s.l. Significant change of the water regimes in the Gatačko Polje have been registered after 1982, when dam Vrba was built, for the needs of technical water supplying for Thermal Power Plant Gacko (TPP Gacko). It is located upstream from the Klinje reservoir. Volume of water storage reservoir is $14.6 \cdot 10^6$ m^3, and regular water level 1062.5 m a.s.l. Reservoirs Vrba and Klinje works together - water from the Vrba reservoir is complementing the Klinje reservoir, from which water flows through the 6150 m long pipeline. First section of pipeline is constructed in the tunnel Lazarići (2920 m), and remaining part is realized as underground pipeline to the TPP Gacko.

PONORS AND PONOR ZONES IN GATAČKO POLJE

Natural dewatering of Gatačko Polje is possible only through the ponors and underground flows. The largest amount of water disappears through number of ponors developed along the contact impervious sediments/limestone, between the Srdjevići Ponor and the last one the Šabanov Ponor at the lowest, south/west section of Malo Gatačko Polje. The total recharge capacity, in the case of maximum flood, is approximately 160 m^3/s (Fig. 2).

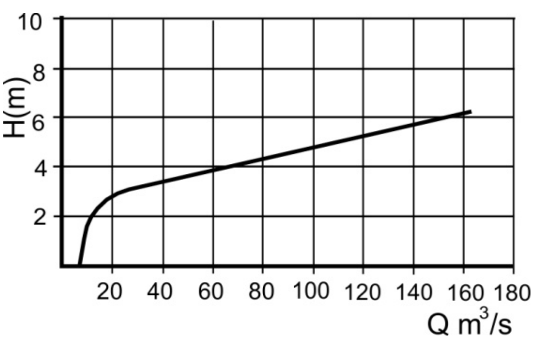

Fig. 2. Gatačko Polje. Summarized capacity of ponors in Malo Gatačko Polje, based on data at Srdjevići weir.

The largest infiltration zone developed along the southern perimeter of the Malo Gatačko Polje is ponor zone Jasikovac/Vranjača (Fig. 3). This ponor zone consists of number of huge shafts at elevation between 920 - 935 m. The total capacity of that zone is probably more than 60% of the total capacity of the Malo Gatačko Polje. The closest hydrologic station to this ponor zone is at the same time the lowest point, Šabanov Ponor at Malo Kulsko Polje, 924.90 m a.s.l. (personal communication Supić R, 2016). It is about 4 m lower than elevation of the closest Mušnica river bottom (929.03 m). Between Mušnica River bed and Jasikovica/Vranjača ponor zone is natural ridge at least 5 m higher (approximate elevation 925 m) than Mušnica river bed and about 9 m higher than Šabanov ponor.

Because the swallowing capacity of the Šabanov Ponor is small, it becomes "suffocate" very fast and flood level in front of the ponor increases fast. When flood rise up to the level to overflow natural ridge the ponor zone Jasikovica/Vranjača becomes active.

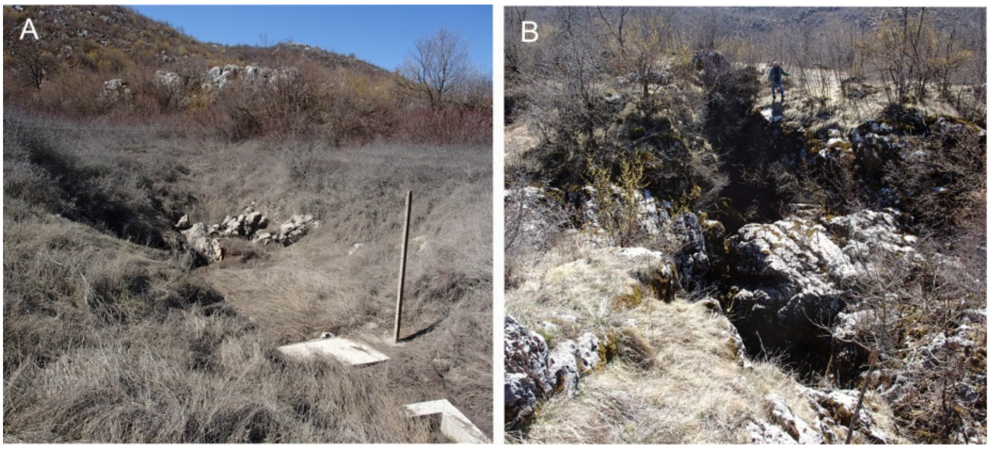

Fig. 3. Gatačko Polje. A. Šabanov ponor, B. One of Jasikovac ponors

According earlier opinion, the Srđevići Ponor has been declared as the largest ponor in the Malo Gatačko Polje. However, according the new findings this opinion needs to be revised. Usually, due to its prevailing hydrogeological function Srdjevići are declared as ponor. However, in the case of precipitation more than 100 mm/24 h at area of the Bjelasnica Mountain and abrupt saturation of aquifer Srdjević becomes estavelle until piezometric line is higher than surface water.

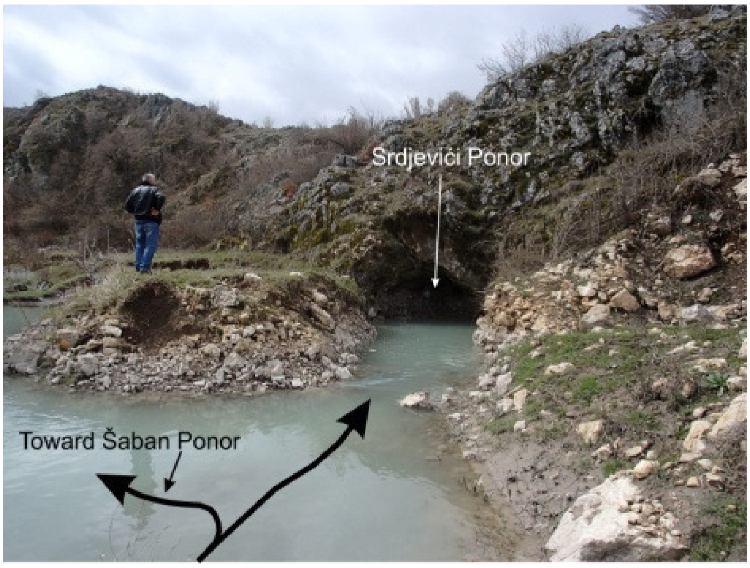

Fig.4. Gatačko Polje. Mušnica River. Branch toward the Srdjevići Ponor

Only a small area of the south-eastern part of Gatačko Polje belongs to the Piva River catchment area. Negligible amount of water (less than 5%) sinks into the Ljeljinački Ponor and flows toward the Piva Spring (Fig. 1).

GENERAL CONCLUSIONS

For the thermo-power structures flood waters are particularly risky. Fast concentration of flood waves is common in Dinaric karst region, with high maximal flows. Return period of flood water of 1% (once per 100 years) are estimated to be: VS Vrba - 123 m^3/s, VS Klinje - 264 m^3/s, VS Avtovac - 283 m^3/s, VS Gračanica - 131 m^3/s, VS Gojkovića Most - 49 m^3/s, VS Srđevići - 387 m^3/s.

Drainage capacities of ponors in the Malo Gatačko Polje are limited, with maximal swallowing capacities of approximately 160 m^3/s (Fig. 2). In the period of high water flows, when flows in Mušnica River is higher than swallowing capacities of the ponors, the Malo Gatačko Polje floods and acts as natural retention.

An example is the large flood occurred in 1975. Flow measured at the Srdjevići hydrologic station was app. 600 m^3/s. The flood wave provoked damages at the Klinje Dam (Fig. 5).

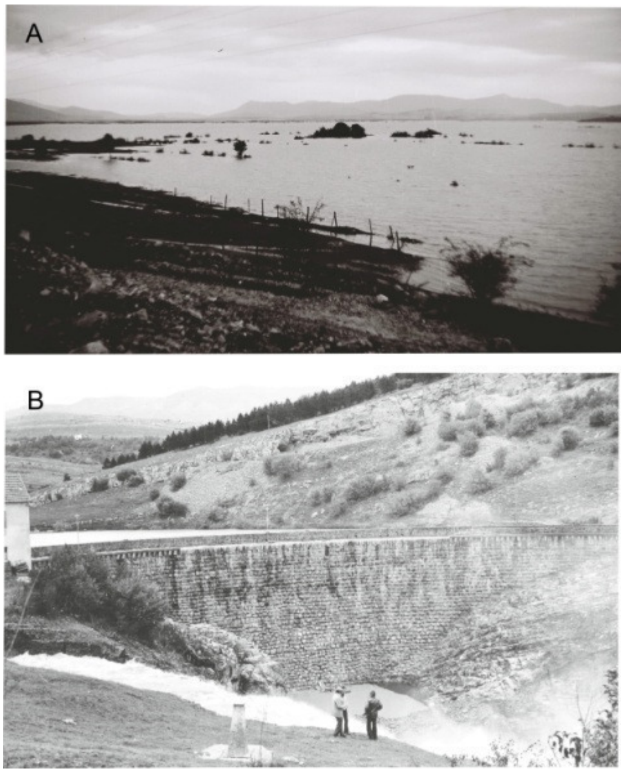

Fig. 5. A) Gatačko Polje. Flood 1975. B) Klinje dam, the day after flood 1975.

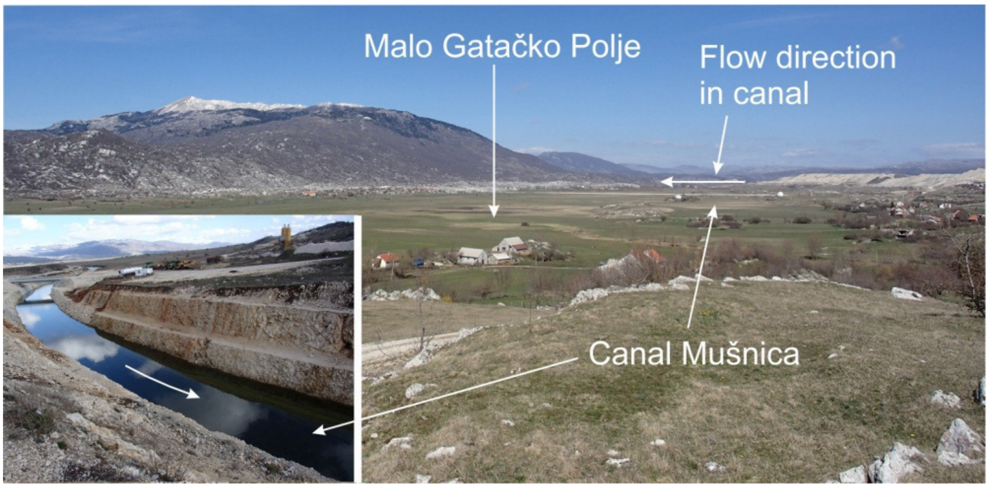

Fig. 6. Gatačko Polje. Re-routing canal of Mušnica river bed

After intensive rain of 280 mm in three days disastrous flood occurred in October 1998. (limnigraph Srdjevići – 498 m^3/s). Open coal mine was flooded and heavily damaged. To prevent such events, different protection measures have already been undertaken: re-routing sections of the Mušnica River and defining the optimal management rules in flood periods for Vrba and Klinje reservoirs.

Effects of reservoirs to mitigate the flood waves are analyzed in detail in Dašić et al., 2016. The conclusions show that reservoirs, even are of small volume, can have considerable influence to mitigate huge water waves if management procedure is optimal.

Due to great importance of thermal-power potential situated in the Gatačko Polje, and need to be protected against floods, and to take advantage of considerable hydro-power potential the concept of water conveyance at two directions is developed.

To protect the thermal-power structures and facilities, the re-routing part of Mušnica in direction of the Malo Gatačko Polje has been already done (Study of water resources management, 2015). The re-routing canal crosses the limestone ridge to be connected with the Mušnica river bed in the Malo Gatačko Polje (Figures 1 and 6). However, influence of these structures on flood regime in the lower part of polje is not expected. To decrease the flood time of the Malo Gatačko Polje the connecting canal between river bed at elevation 929 m and ponor zone Jasikovac/Vranjača should be constructed. According this solution, the part of water belonging to the Gatačko Polje catchment will travel, mostly, as underground flows in direction of the Trebišnjica Springs.

As the water at elevation of about 1000 m a.s.l. contain a huge hydro-power potential, the concept of the Multipurpose Hydrosystem Trebišnjica System – Upper Horizons, includes transfer the part of flood waters from the Trebišnjica catchment into the Zalomka Reservoir. On this way each cubic meter of transferred water can be used for different purposes from elevation 1000 m to the sea level. According this concept the complex conveyance structure is foreseen (Fig. 7). This structure consists of pumping facilities in front of the Srdjevići Ponor; derivation canal along the Lukovice valley; and tunnel Lukovice – Gradina (Zalomka Reservoir).

To overcome difference of 22 m between the Srdjevići Ponor and canal entrance the pumping facilities are needed. Due to complex geological structure (reverse regional fault) the hydrogeological properties along the route of conveyance system was carefuly investigated (Study of detailed geological research for the main project needs of "Nevesinje" HPP, 2016). Number of ponors and caves were investigated. One of important problems is frequent floods of the Lukovice valley. Protection of arable land against floods is one of secondary benefits of the conveyance system (Milanović S, 2015).

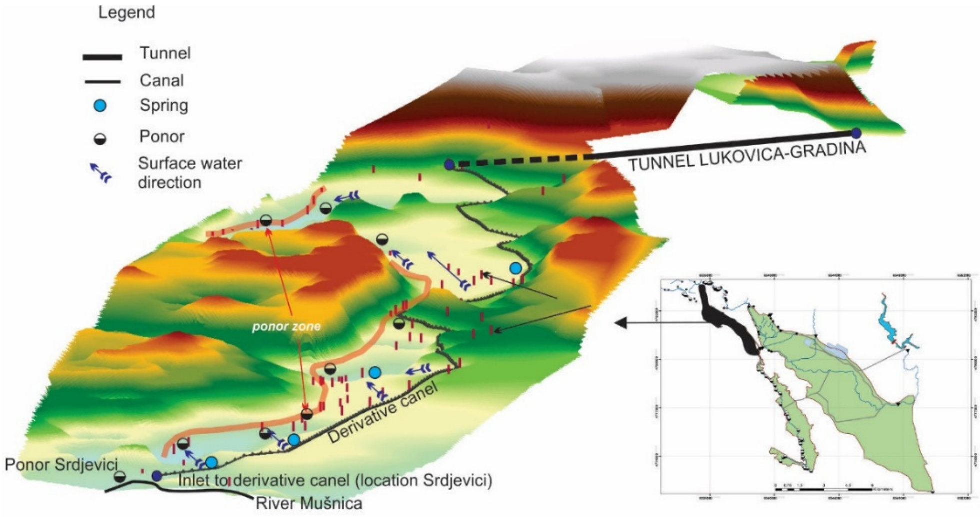

Fig. 7. Conveyance structures for water transfer from Gatačko Polje to the Gradina (Zalomka Reservoir)

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USING EPIK METHODS IN THE ASSESSMENT OF GROUNDWATER VULNERABILITY OF CATCHMENT OF THE NIKŠIĆKO POLJE

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Abstract: In the last decades, we have witnessed the problem of the protection of groundwater resources, and as a result, a number of methods have been developed for assessment of groundwater vulnerability. The maps of the groundwater vulnerability, which are very important bases in determining the zone of sanitary protection of drinking water sources, and play an important role in spatial planning, are presented using these methods. The quality of the obtained map of groundwater vulnerability depends on the choice of the method for assessment of groundwater vulnerability. The paper presents the use of the EPIK method in the assessment of groundwater vulnerability of the catchment Nikšić Polje. The geological and hydrogeological complexity of the terrain, as well as the degree of area research, justified the selection of a method that is very suitable when performing the assessment of groundwater vulnerability of large areas.

Key words: Nikšić Polje, groundwater, karst, groundwater vulnerability, EPIK

Introduction

The assessment of groundwater vulnerability is applicable to all types of aquifers, but the most complex hydrogeological relationships are present in terrains with karst porosity, and therefore special methods have been developed in assessment of groundwater vulnerability of exclusively related to the karst terrains. One of these methods is the EPIK method, which takes into account the specific structure of the karst aquifer, and as such has found the widest implementation. The EPIK method requires preparation of special maps that show the impact of analyzed parameters to the overall of groundwater vulnerability. The issue with groundwater protection is mostly present in karst terrains, to which the catchment area of the Nikšić Polje belongs.

Nikšić Polje is the largest karst polje in Montenegro with an area of 66 km^2 (Fig. 1). The catchment area of the Nikšić Polje belongs to a typical holokarst, because it has all forms of karst hydrography with about 300 springs, 886 ponors, 3 reservoirs, a sinking river, a large number of estavelles, river flows, karst valleys, dolines, etc.

The catchment area of the Nikšić Polje belongs to the outer Dinarides and is characterized by geological diversity, since the rocks of the Paleozoic, Mesozoic and Cenosoic ages are present in the geological structure of the terrain. The most prevalent are the carbonate rocks of Cretaceous age, represented by karstified limestone, dolomite limestone and, to a lesser extent, dolomites, which make up the margin of the polje and its paleorelief. In the polje itself, fluvioglacial, limnoglacial and alluvial sediments are represented by various sands, gravels, sandy clays and clays.

The hydrogeological catchment of the Nikšić Polje occupies an area of 864.4 km^2 and is smaller than a topographical catchment of 1,004.4 km^2 (Vlahović V, 1975). On the catchment area of the Nikšić Polje, there are the intergranularly, karstic, karst-fracturing and fracturing types of aquifer, as well as conditionally insignificant aquifers. The most abundant is the karstic type aquifer which was formed within the carbonate rocks of the Mesozoic age. The intergranular type is formed within the fluvioglacial and alluvial sediments of the polje itself, while conditionally insignificant aquifers are mainly represented within the limnoglacial sediments of the southern and western part of the polje.

Methodology mapping of groundwater vulnerabilities using EPIK method
Assessment of groundwater vulnerability by EPIK method is done through a protection index calculated on the basis of four factors that form the acronym: **E**pikarst; **P**rotective cover; **I**nfiltration Condition and **K**arst network development.

The protection index F is calculated for each field in the investigated area through the equation in which all four parameters are identified as the variable, with its value ranging from 9-34. Each of the parameters contains classes that have a certain weight value, with the smallest value indicating the highest sensitivity to pollution (table 1).

Table 1. Standard values for EPIK parameters (Doerfliger N, & Zwahlen F, 1997)

Parameter	E			P				I				K		
Class	E_1	E_2	E_3	P_1	P_2	P_3	P_4	I_1	I_2	I_3	I_4	K_1	K_2	K_3
Value	1	3	4	1	2	3	4	1	2	3	4	1	2	3

The total protection index F is calculated according to the equation: $F=\alpha E + \beta P + \gamma I + \delta K$, where the coefficients α, β, γ and δ take values 3, 1, 3 and 2, respectively (Doerfliger N, & Zwahlen F, 1997).

Creating a map of E factor

The first acronym E represents the development of the epikarst. To determine the development of Epikarst as substrates, the following bases were used: Geological Maps at scale 1:100,000, Topographic maps at scale 1:25,000, satellite images and Digital elevation model of terrain which was done using Slope analysis.

Firstly, the distribution of carbonate rocks was determined by the analysis of geological maps, and then by analyzing topographic maps and satellite images in correlation with the elevation model of the terrain of a certain epikarstic zone. The class E_1 includes the terrains of the developed epikarst, that is, zone of dolines and open karst. ,The terrains built of pure limestone covered with low vegetation, as well as terrains made of carbonate rocks with admixtures but without vegetation cover, are assigned to Class E_2. Class E_3 are terrains that do not build carbonate rocks (Fig. 1).

Creating a map of P factor

The protective cover is shown on the map of the P factor, whereby the following was used as basis for its preparation: Pedological maps at scale 1:50,000, Map of vegetation at scale 1:100,000 and satellite images.

On the pedological map, the areas were determined based on the type and thickness of the soil, and then, the division of P factor into 4 classes (P_1, P_2, P_3, P_4) was made on the basis of composition of vegetation and satellite images. Terrains built of karstified limestone with no soil cover, or soil cover less than 20 cm thickness, on which there is no vegetation or is present in the form of low vegetation and macchia, are classified into class P_1.

The land that is present on terrains built of dolomite rock and flysch creations are classified into P_2 class. The power of these lands is over 20 cm. These terrains are covered with dense forests (hilly areas) and meadows (plain areas).

Terrains built of alluvial and glacial sediments within which the clay component is present, and whose total thickness is more than 1 m, is classified into P_3 class. From the aspect of vegetation, these terrains are characterized as meadows and pastures. The terrains built of waterproof clays over 2 m thickness with the presence of vegetation cover are classified into class P_4.

Creating a map of I factor

Infiltration conditions are a parameter that cannot be directly measured in the terrain, but is calculated indirectly through other factors on which it depends. Therefore, the following substrates were analyzed in order to determine factor I: Hydrogeological map at scale 1:100,000; Topographic maps at scale 1:25,000; Map of vegetation at scale 1:100.000; Digital elevation model of terrain; Map of slope of terrain and Satellite images.

For the calculation of this factor, firstly the areas that belong to the areas of catchment ponors and ponors flows were identified using topographic maps and shaded reliefs derived from the DEM model using the terrain analysis of the slope, so-called Slope analysis. Parts of the terrain that are out of the catchment ponors and ponors flows are divided in two classes. Terrains in which the karst aquifer is developed, as well as terrains that are not built from carbonate rocks, belonging to the catchment of karstic springs or streams passing through the karstic terrain, are classified into class I_3. The rest of the terrain outside the catchment ponors and ponors flows are classified into class I_4.

Terrains belonging to the catchment of ponors and ponor flows are classified in a different way. The class I_1 comprises zones that are located directly around the ponors and ponors flows, as well as groups of dolines in which the infiltration of surface water is present.

The remaining part of the catchment is classified according to the roughness and slope of the terrain. In the instruction for the EPIK method, the boundaries of terrain slopes in forest areas are not defined, therefore a limit value of 35% is proposed for these areas by some authors who have previously applied this method (Iurkiewicz A, et al, 2005). Thus, class I_2 includes forest areas with a slope of terrain >35% and meadows, pastures and arable lands with a slope >25%, while class I_3 includes forested areas with a slope of terrain <35% and meadows, pastures and arable areas with a slope <25% (Fig. 1).

Based on the previously presented criteria, I parameter is classified in such manner that the ponors zones along the Budoš fault and the riverbed of Zeta and Gračanica are classified into I_1 class. Terrains with a slope of over 25% along the Nikšićka Župa, the spring zone of the Donja Zeta and the mountain massifs around Nikšić Polje are classified into class I_2. Class I_3 includes the remaining terrain belonging to the catchment area of the Nikšić Polje, and the terrains located outside the catchment are classified in class I_4.

Creating a map of K factor

As a base for analysis of the degree of karstification, i.e. mapping of the K factor, Basic Geological and Hydrogeological Map at scale 1:100,000, as well as the results of hydrogeological and engineering-geological explorations in this area, which are mostly performed in the design of hydropower system of HPP "Perućica", were used. This primarily refers to the groundwater tracing, exploration drilling and the production of grout curtains in the area of reservoirs Slano, Krupac and Vrtac.

Karstic systems with groundwater speeds exceeding 15 m/h can be considered as systems with a developed network of karst canals (Doerfliger N, & Zwahlen F, 1997). The performed experiments of groundwater tracing in the Nikšić Polje (Vlahović V, 1975; Radulović M, 1992; Vlahović M, 2005) have shown that the groundwater velocity ranges from 6.084-505.764 m/h (v_{sr}=102.276 m/h) indicating the presence of a highly developed network of karst canals. Also, the karst terrains of the Nikšić Polje are drained through a smaller number of karst springs, which is an additional indicator of the presence of privileged directions of groundwater movements, i.e. karst canals of considerable dimensions.

Based on the previously described analysis, the degree of karstification is divided into three classes (K_1, K_2, K_3) (Fig. 1). Class K_1 belongs to the limestone of the Mesozoic (mostly Cretaceous) age with the characteristic presence of the zone of the dolines and wide cracks, which were transformed by the process of karstification into karsts canals, caverns and caves. the carbonate rocks of the Jurassic and Triassic ages, in which the dolomite is more represented than limestone, are classified into class K_2, while the K_3 classes are assigned to other rock that construct the terrain (non-karst).

Assessment of groundwater vulnerability of the Nikšić Polje catchment

After creating a map of all factors, for each point in the catchment area of the Nikšić Polje, a protection index was calculated based on the size of which four classes of groundwater vulnerability were distinguished: very high, high, medium and low (Fig. 1).

The largest part of the Nikšićko Polje catchment area is classified into terrain with very high groundwater vulnerability (about 76%). These are terrains built of carbonate rocks in which the karstic aquifer has been developed with the evident development of the epikarst and the presence of a large number of ponors, ponors streams, estavelles, dolines and caves, with very intensive infiltration of surface waters. Parts of the Nikšić Polje catchment area that are made of carbonate rocks with admixtures and in which there is no dominant distinction of karstification, and on which there is no vegetation cover, are characterized as terrain with high groundwater vulnerability (about 11%).

The medium groundwater vulnerability includes parts of the terrain in which there are intergranular aquifers with significant soil and vegetation cover. This is the plain field of the polje and valleys of the Nikšićka Župa, which occupy about 11% of the surface of the Nikšić Polje catchment.

The low groundwater vulnerability is present in conditionally insignificant aquifers where epikarst is not developed, the soil cover provides good protection, and the infiltration of surface water is predominantly diffuse. These terrains are located on the periphery of the catchment area of the Nikšić Polje and occupy about 2% of the catchment surface (Fig 1).

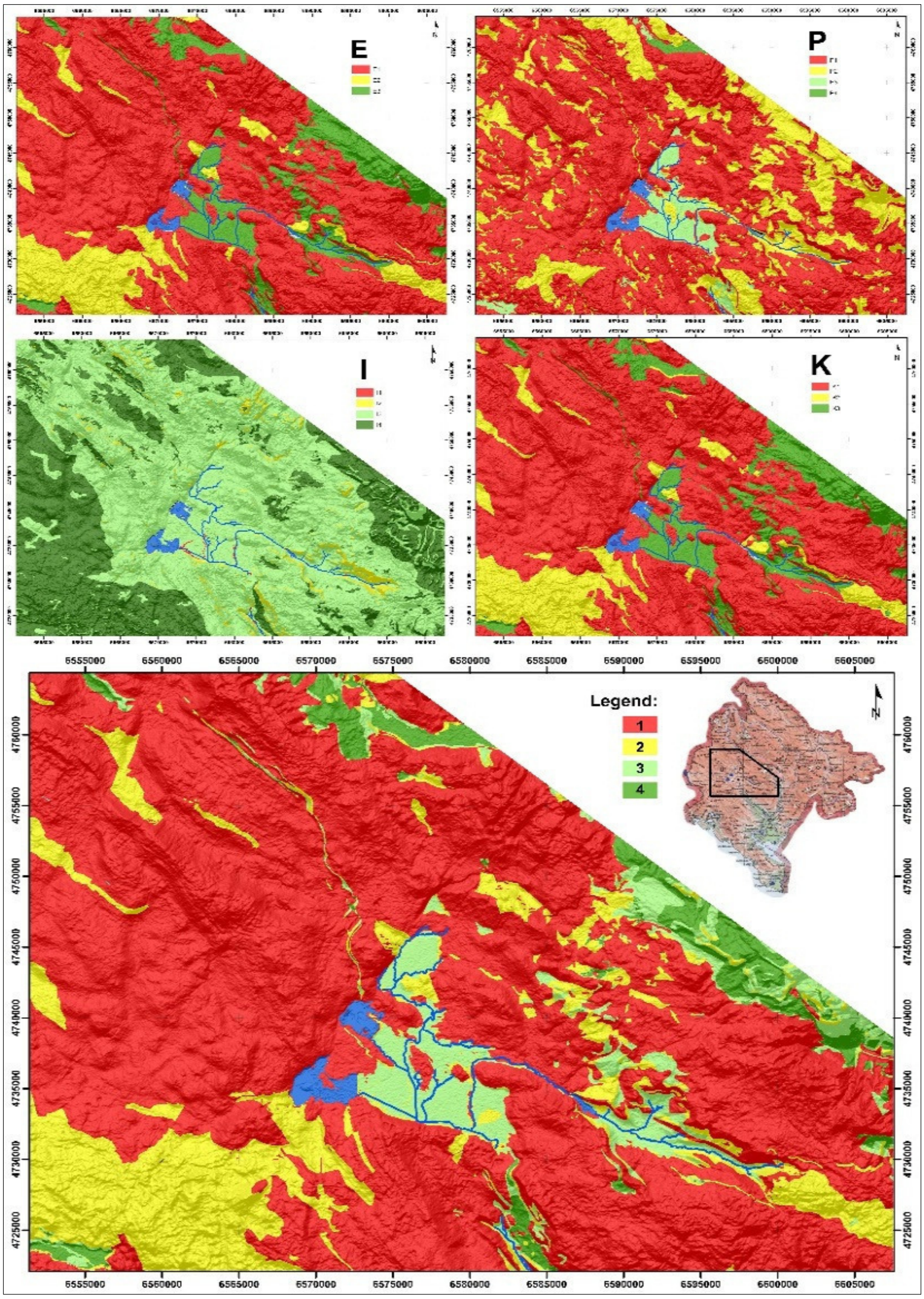

Figure 1. EPIK map of groundwater vulnerability of the Nikšić Polje catchment area Legend of vulnerability: 1-very high, 2-high, 3-medium, 4-low (Mrvaljević V, 2015)

Conclusion

The biggest impact on the assessment of groundwater vulnerability are factors E and K, i.e. development of epikarst and network karst canals. On the map of groundwater vulnerability of the Nikšić Polje, the direct dependence of the distribution classes of groundwater vulnerability from the distribution of the karst aquifers can be observed.

Map of the groundwater vulnerability has shown that the largest part of catchment of the Nikšić Polje (about 86%) is characterized by very high and high groundwater vulnerability. This practically means that groundwater in these parts of the basin can be easily polluted in case of pollutant release on the surface of the terrain.

In order to ensure a satisfactory groundwater quality in the Nikšić Polje catchment area at a long-term level, it is necessary, during their protection, to take into consideration the situation and the results obtained by developing a map of the groundwater vulnerability. For this purpose, the EPIK method proved to be very applicable for the development map of vulnerability.

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EXPLORATION DRIVEN GROUNDWATER MANAGEMENT PLAN FOR KARST DOMINATED SMALL ISOLATED GEOLOGICAL BASIN OF CENTRAL INDIAN CRATON.

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Abstract The rocks of Mesoproterozoic Indravati Group in Indravati Basin cover ~5600 km^2 area in central Indian Craton, consists of consolidated, un-metamorphosed, mildly deformed, arenaceous-calcareous-argillo-calcareous sedimentary sequence of about 600 m thickness laying over the crystalline basement. The karstic calcareous and argillo-calcareous rocks of Kanger and Jagdalpur Formations out of four formations of the basin forms potential aquifer of phreatic to semi confined nature. Groundwater exploration in the basin is restricted to 180 m depth deploying DTH drilling rigs. Total 45 exploratory wells were drilled covering all four formations. The results reveal a maximum 40 l/s drill time discharge from the cavernous rocks within 70 m depth range. The argillo-arenaceous rock of Cherakur Formation and the arenaceous Tiratgarh Formation in general, except along the major Sirisguda fault line are poor aquifer. Groundwater quality within the basin remains very good and meets all quality standards.

Providing safe drinking water within a large geographical area covered by Cherakur and Tiratgarh Formations (~2000 km^2) of the basin is a major challenge in this tribal belt. Groundwater can be the only economically viable alternative source of the water in the area. Based on the exploration within basin, some sustainable, low discharge, vital water sources have been identified for providing safe drinking water. Further, the higher potential zones delineated within karstic aquifer area can be utilized gainfully for developing irrigation potential at micro level to improve the socio-economic condition of this socially agitated (naxal effected) area.

Key words: Groundwater exploration, Indravati Group, Karstic aquifer, Chhattisgarh, India

Introduction

A group of isolated Mesoproterozoic intra-cratonic geological basin occupies large area of Central Indian Craton in Peninsular India (Ramakrishnan, 1987, Sarbani Patranabish Deb et al 2007). Consolidated, unmetamorphosed, nearly horizontal sedimentary rocks of these basins having secondary porosity much dominated over primary. The Indravati Basin of Bastar district, Chhattisgarh State and adjoining Orissa State forms the study area of the present paper (Fig.

1). This nearly 5600 km² remote area of India is part of an important anthropological belt of aboriginal-tribal habitat and is lying in economically backward region and effected by naxal movement of socially agitated people. The triangular shape Indravati Basin forms parts of the Bastar plateau and is having a general elevation between 500 m 700 m above mean sea level. The area is blessed with high annual normal rainfall of about 1500 mm and is drained by Indravati and Kanger Rivers of the Godavari River system. The basin fringe to the Easternghat Mobile belt in its SE part and having faulted boundaries in NE, south, SE and western margin. Ramakrishnan (1987) have given the complete stratigraphic sequence for the basin and divided the 600m thick Indravati Group into four formations. These are namely Tiratgarh, Cherakur, Kanger and Jagdalpur formations in ascending order (Fig. 1). The basin is unconformable lying over the unclassified crystalline basement rocks of Archeaean age. Kimberlite clan rocks of 1050 Ma (Mainkar et al 2004) intruded up to the base of Kanger Formation, have divided the group in to upper and lower half. The terminal Birsaguda Tuff (1000 Ma) restricts the age of the sequence to Mesoproterozoic period (Mukherjee et al 2012). The lower part is largely arenaceous and argillo-arenaceous whereas the upper part is mainly calcareous and argillo-calcareous in character. Numerous faults have interrupted the sequence within the basin. The Sirisguda normal fault traverse E-W basin wide has dislocated the formation in regional scale (Fig. 1). The structurally controlled geomorphology result of series of normal fault in the west and SW part of basin is superimposed by the reworking of drainage system. The present slop in south western part of basin is towards north against the prevailing strata dip (due to fault in the SW part of basin). However, the formations are in general having horizontal to low dipping strata within the basin.

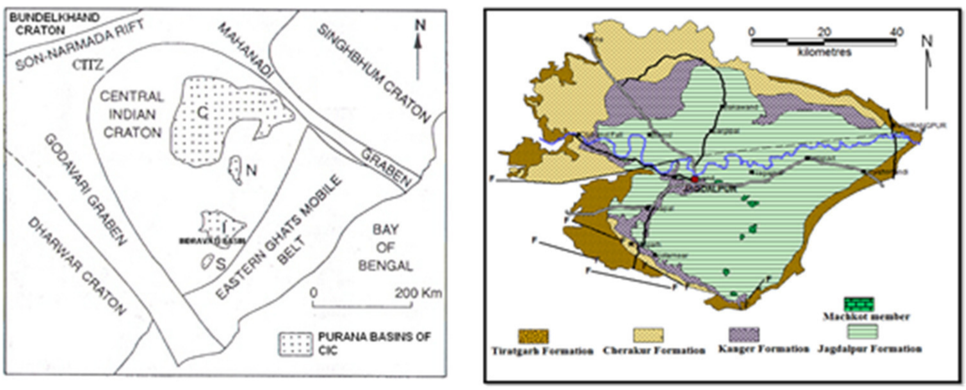

Fig 1. Location and Geological Map of Indravati Basin of central Indian Craton. (Note C=Chhattisgarh basin, I=Indravati basin, N=Nawagarh basin, S= Sukma basin)

Not much work has been carried out in the remotely located Indravati basin. Preliminary reporting of groundwater exploration carried out by Central Ground Water Board (CGWB) is available in published and unpublished form. According to Das (2014) groundwater exploration lays the foundation of scientific groundwater exploitation and conservation. But locating groundwater in the hard rock is still a puzzle despite the fact that hydrogeological investigations combined with space science and traditional geophysical methods have narrowed down the uncertainty. Thus, first time a comprehensive reporting of groundwater exploration is presented in this paper for the entire basin covering all geological formations to propose a groundwater management plan.

Methodology

Groundwater exploration covering entire basin was carried out by CGWB, Raipur between year 1994 and 2004 in phased manner. In the first phase 20 wells were drilled during 1994 -1998 where as in the second phase 18 more wells were drilled during 2004. Apart from these 3 wells were also drilled in Orissa (Fig. 2). The maximum drilling depth obtained was 184 m deploying DTH rig with rotary combination. The groundwater exploration within the basin was primarily initiated based on the findings of systematic hydrogeological investigations of CGWB on 1:53000 scale (completed by 1992) and detailed study prior to exploration. Sites for exploratory wells were selected adopting multi-disciplinary site selection procedure, where hydrogeological studies were followed by geophysical investigations. The priority areas were identified based on the needs of provincial state government water supply agencies. The successful wells were handed over to local administration for further use. The groundwater exploration involves the following steps apart from systematic hydrogeological studies.

1. Micro level hydrogeological study
2. Surface geophysical investigations for pin pointing of sites
3. Water well drilling, design and acquisition of data
4. Well development, well logging, pumping test and water quality analysis
5. Data compilation, analysis and reporting.

However, the process of site selection criteria is constrained due to compromise made on account of social (i) and administrative reasons (ii) the coverage of entire basis which reflects on the rate of success of getting water.

Results & Discussions

Exploration in Indravati Basin reveals geological, geophysical, hydrogeological and hydrogeochemical inferences which helped in solving groundwater related challenges in this tribal belt. Groundwater flow in karst aquifers is often characterized by strong variability of flow dynamics in response to different hydrologic conditions within a short time period (Ravbar, 2013). Groundwater forms the principal source of safe drinking water and at the same time provides support to the Kharif (monsoonal) crop irrigation in absence of canal irrigation system in the area. Formation wise information gathered in time & space can be used for planning water use for water and food security.

Geological Inference of Exploration

Plotting of exploration data on GIS environ found that the Tiratgarh sandstone is prismatic in its geometry. The thickness of this sandstone gradually reduces from 127 m (Karanji) to 5 m (Kumrawand) from basin margin to its center (Fig. 3). The maximum thickness in of this formation is found 127 m against the earlier reported 50 – 60 m (Ramakrishna, 1987). The thickness of Tiratgarh Formation is comparatively less in northern part then that of southern and western part within the basin. The Cherakur Formation also having prismatic geometry and found as thick as 86 m at Jaibel and reduces to 25 m at Kumrawand and 26 m at Pandripani. Interestingly in the southern part of basin at subsurface of Lohandiglida and Maulibhata Cherakur Formation is found absent below Kanger Formation. The thickness of Cherakur Formations is found higher in northern part of the basin. Even in partial penetration it is 86 m which is again higher than earlier know thickness 50-60 m for this formation (Ramakrishnan 1987). The Kanger Formation is having a white cherty limestone unit at its base in large part of the basin, this is reported first time. The thickness of this cherty limestone unit varies from 15 to 25 m and is observed in at list five bore holes. However, at several other places it is also found missing. At Tokapal, Tiratgarh sandstone is encountered at 113 m depth below Kimberlitic clan rock. Based on the thickness of Kanger & Jagalpur formations it is inferred that the depo-center for Kanger and Jagdalpur Formation in the basin is not the same but changed. The basin is also having evidence of syn-sedimentation slip to accommodate thicker sediment fill at center (Fig. 3). The formational contracts of Jagdalpur to Kanger and Kanger to Cherakur and Cherkur to Tiratgarh are found sharp in lithological level. A thin (1.5 m thick) orthoquartzite lance is found within Jagdalpur Formation at Baylabazarpara of Jagdalpur at a depth of 30 m. Terminal Tuffaceous porcellanite beds (1000 Ma, U-Pb magmatic zircon LA MC-ICPMS age, Mukherjee et al ,2012) are found around Birshguda- Markel within Jagdalpur Formation (Fig. 3).

The systematic recording and compilation of lithology during the exploration provides valuable information regarding the geological nature of various formations including their variation in thickness and position (Table 1).

However detailed petrology is beyond the scope of this study. To assist the groundwater exploration program, the surface resistivity investigations have been conducted in the basin to obtain the subsurface hydrogeological information to pin point the exploratory borehole site. Electrical Resistivity methods are also used in estimation of overburden thickness, delineation of basement topography, characterization of lithology, delineation of fractures/joints.

Table 1. Lithology, area and thickness of various formations of Indravati Group

Formation	Thickness reported earlier	Lithology	Observed Thickness	Area occupied
Jagdalpur	200-250 m	Shale -dolomite	200-250 m	3014 km^2
Kanger	150-200 m	Limestone-shale	>150 m	622 km^2
Cherakur	50-60 m	Shale - sandstone	>86 m	1175 km^2
Tiratgarh	50-60 m	Quartz arenite	>127 m	793 km^2

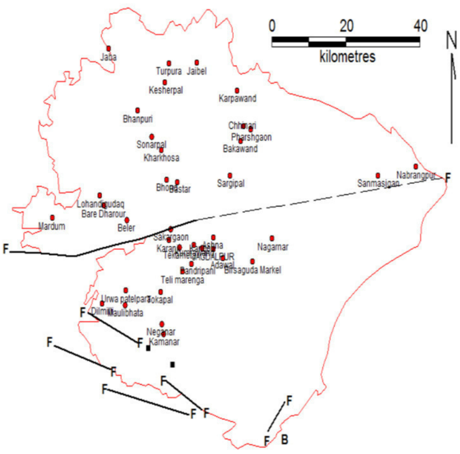

Fig. 2. Location of exploratory wells in Indravati Basin

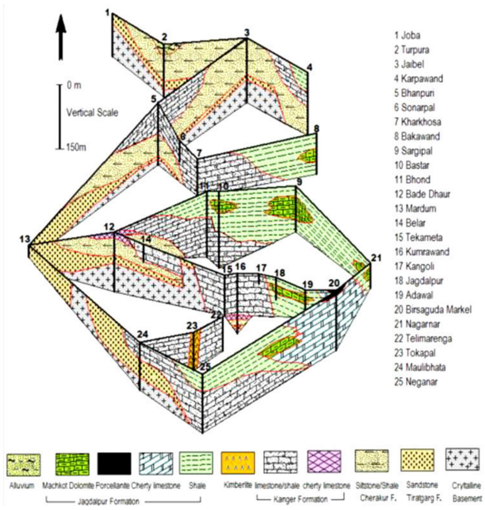

Fig. 3. Fence diagram of Indravati basin

Hydrogeological Inference of Exploration

The ground water exploration in Indravati basin has revealed the aquifer geometry of the basin, its water bearing potential and aquifer parameters (Table 2). It is provided in sites for sustainable resource management for the basin area. It helped in establishing the overall chemical quality of ground water and in understanding the specific drilling requirements for the basin and carbonate aquifer in general. The results of exploration is especially important for solving the drinking water augmentation problems in rural area of this tribal belt where due to low population density and remote isolated locations no other alternative source of water then providing ground water is viable for safe drinking water. The hydrogeological inference of exploration is discussed formation wise for the basin area.

Tiratgarh Formation

The ground water potential and water bearing capacity within Tiratgarh sandstone were explored through drilling of eleven exploratory wells. Four were drilled directly on this sandstone and another 7 well encounter Titatgarh Formation at depth. Except two wells drilled either side of the major Sirisguda fault plain, in all other wells tapping sand stone have yielded less than 1 l/s discharge. The Lohandiguda and Karanji well near the fault have 6 and 5 l/s discharge at 84 and 136 m depth respectively in Tiratgarh sand stone below Kanger lime stone. Dug wells in this formation tap water from weathered zone which is restricted to top 10 to 15 m only. Bedding plains and surface joints helps getting some water to the dug wells.

Table –2. Silent features of exploration in Indravati Group

Formations	No of Wells drilled on the Formation	In number of wells the Formation encountered	Water bearing zones struck between (m)	Drill time discharge range (l/s)	Range of SWL (m bgl) /Draw down (m)	Transmis ivity m^2/day	Specific Capacity m^3/min/ m
Jagdalpur	14	14	5-66	0.5-40	7-16 /1.72-19	5- 395	0.022-1.39
Kanger	14	21	9-74	0-35	2.5-30 / 1.6-20.2	28-679	1.008-1.31
Cherakur	3	11	nil	0.01	-	-	-
Tiratgarh	4	12	23-136	0-8	12.10/ 28.36	29-63	0.007-0.018

Contact zone of Tiratgarh sand stone with basement crystalline at Joba (in the northern part of basin margin. Fig 2) have yielded nearly 1 l/s of water at a depth of 17 m. Similarly, at Jaibel the contact at depth of 96 m have yielded 0.13 l/s water whereas at Pandripani contact at 15 m depth have seepage only but at Maulibhate toward western margin of basin the contact at 93 m have nearly 1 l/s discharge. The basement below Tiratgarh sandstone at several places within 80 m depth (from contact) has yielded 2 to 15 l/s of water, where the thickness of cover sediments is found within 60 to 70m. Such as at Kesherpal at a depth of 143 m (where cover is 68 m thick), Urba at depth of 126 m (cover is 58 m) and at Joba at depth of 34 m (cover in 17 m). However, no yield was found when thickness of cover sediments is higher such as at Bade Dhaur (cover in 86 m) Jaibel (cover is 86 m) Maulibhata (cover 93 m) and Turpura (cover is 121

m) and so on. Transmissivity of three wells with more than 3 l/s yield within Tiratgarh Formation ranges from 29 to 63 m^2/day whereas the specific capacity varies from 0.007 to 0.018 m^3/min/m. The orthoquartzites of Tiratgarh Formation along with its silica cement in un-weathered part are forming very hard mass and possess very high rate of bit loss. Due to this character of Tiratgarh sandstone commercial drilling firms avoid penetrating the Tiratgarh Formation during the drilling for state government or private owner. Below Tiratgarh sandstone low water bearing zone exists in basement crystalline.

Cherakur Formation

Exploration in this formation reveals that the shale and silty-shale forms aquiclude or aquitard. Three sites were located on Cherakur shale and another 8 wells encounter Cherakur Formation, none have yielded any water and are dry or having seepage only. Dug wells occasionally are having some water in this formation. Square shape small dug wells are constructed within this formation using surface joints and bedding plain as at Chitrakot.

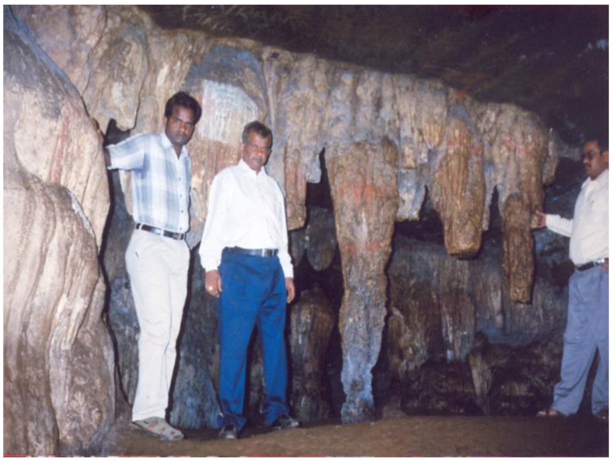

Fig. 4. Panoramic view of Kotamsar cave interior

Kanger Formation

To explore the water bearing property 14 wells were drilled on Kanger limestone. Another 7 wells had penetrated through this formation at sub surface below Jagdalpur Formation. The highest discharge obtained in this formation is (below Jagdalpur Fm) at Nagarnar where 35 l/s water obtained at depth of 46 m. The same discharge at same depth is also obtained in observation well drilling at a distance of 50 m from main well and this well is used to obtain the aquifer parameters. At Telimarenga 18 l/s discharge is obtained between 65 and 67 m depth in Kanger Fm. However, in general the discharge in this formation varies from 4 to 15 l/s in successful wells where cavernous zone encounter, but where bore hole miss the cavity there the wells are either dry or having very low yield only up to 15 lpm. At cavernous zone of Kamanar deeper water level of 23 m obtained. The Kanger shales are not good aquifer and having very negligible yield. The Kanger limestone overlies the Cherakur Formation or occurs directly on Tiratgarh sandstone therefore once cavity is missed within limestone then there exist little chance of getting water at depth in that location (exceptionally at Lohandiguda water taped from Tiratgarh below Kanger). Mammoth caves are found within this formation along the southern margin of the basin, where faults have played vital role in development of series of caves. These caves are having subsurface ephemeral drainage with perennial pool of water and are full of cave structures (Fig. 4). This cavernous limestone aquifer is one of the most important aquifers in Indravati basin. Out of 21 bore holes encounter this formation 15 have yielded more than 3 l/s of water where the transmissivity varies from 5 to 679 m2/day and specific capability varies from 1 to 1.31 m3/min/m. The sticky clay filled cavernous zone and repeated cavernous zones create hindrance to drilling operation. At Balenga due to repeated cavernous zone (at 25 and 39 m depth) filled with yellow clay drilling has to be suspended. Putting casing through cover zone is troublesome at several occasion. State government have utilized hydro-fracturing technique to improve the yield of low discharge wells, got limited success in this formation.

Jagdalpur Formation

14 well were drilled on rocks of Jagdalpur Formation out of which 7 wells have more than 3 l/s of discharge (Fig. 5). This is the most important aquifer within Indravati basin. The maximum discharge obtained was 40 l/s in Sargipal at a depth of 68m where due to cavernous zone water level remains deep, at nearly 15 m bgl. At Bakawand 19 l/s discharge is obtained at depth 25m. The higher discharge wells in this formation ranges generally between 3 and 10 l/s. The water bearing cavernous zone within Jagdalpur formation is invariably associated with silt size dolomite which many a time show spongy nature and lower density with stromatolitic column structures. The Jagdalpur shale without carbonates having only low discharge up to 3 l/s whereas the porcellanatic Jagdalpur limestone as found at Birsaguda Markel are devoid of cavernous zone and water. Dug wells in Jagdalpur Formation are taping the weathered zone and shallow cavernous zone down to 12-15 m. Since the Jagdalpur Fm overlies Kanger Fm therefore even if cavernous zone of Jagdalpur Formation is missed

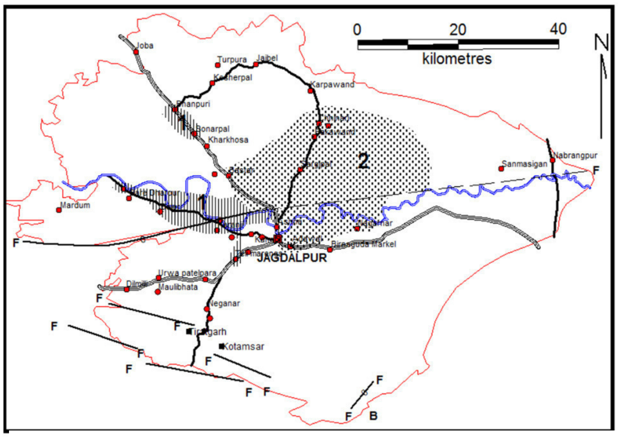

Fig. 5 Delineation of high yielding zone in Indravati basin. Note the zone 1 having yield up to 10 l/s and zone 2 up to 20 l/s potential.

in any well it may target fracture or cavernous zone in Kanger Formation below. Such as obtained in Nagarnar at 48 m depth (35 l/s). However, at few locations such in Neganar, Chidpal, Kurpawand well encounter both Jagdalpur and Karger Formation but missed the cavernous zone and fracture down to 150 m depth and remained dry.

Aquifer parameters: The cavernous dolomite/shale of Jagdalpur Formation, where discharge of more than 3 l/s were obtained the transmissivity varies from 36 to 395 m^2/day and specific capacity ranges from 0.022 to 1.39 m^3/min/m. Drilling constrains: The re-crystalline dolomite with silt size gains behave like loose collapsible formation and need DTH -rotary combination rig for drilling and constructing well at these locations. Such successful wells were constructed at Asna, Jagdalpur, Nagarnar. However, at Pharashgaon, Chinhar and Sarakrgaon due to non-availability of DTH-rotary combination rig the wells were not constructed successfully taping the available discharge.

Geochemical inferences of Exploration

Chemical analysis of ground water samples collected during drilling and pumping test show the ion load is relatively low in this geological basin where EC ranges from 26-625 μS/cm (Table 3), except at Bhand where EC is found 1154 μS/cm. All the major ion concentrations are well within the prescribed BIS drinking water standard. However, sporadic higher iron concentration (>1.5 mg/l) is observed specially in the area occupied by Cherakur and Tiratgarh Formation. The ground water is found moderate to weakly basic and HCO_3 type. Graphical plots of analytical data show water are suitable for all crop type.

Table –3. Ground Water quality in rocks of Indravati Group

Formations	pH	EC	Ca	Mg	HCO_3	Cl	TH	Na	K
Jagdalpur	7.1-8.1	83-620	10-68	3-66	43-268	7-116	35-270	6-12	0.2-0.6
Kanger	7.9-8.1	186-1156	24-36	5-22	98-750	4-57	80-405	13-86	0.2-20
Cherakur	7.8-8.0	304-318	16-52	3.6-5	146-213	60-145	65-145	17-42	0.2-5.5
Tiratgarh	7.7-8.1	26-625	28-56	10-21	122-342	7-73	110-225	28	0.2-3.1

Conclusion

The ground water exploration in Indravati basin has revealed firsthand information about the aquifer geometry, its water bearing potential and aquifer parameters of the basin. It has provided in sites for sustainable resource management for the basin area. It also helped in identifying the overall chemical quality of ground water and understanding specific drilling requirements for the basin and carbonate aquifers in general. Augmentation of drinking water within area covered by Cherakur and Tiratgarh Formations (>1900 km^2) is a major challenge in this tribal belt. The thickness of these formations was found nearly double than what is known earlier. Based on the results of exploration within these formations, some low discharge zones were identified which can be useful to provide safe drinking water.

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THE ROLE OF KARST IN REDISTRIBUTION OF WATER RESOURCES: VODENIČKA RIVER BASIN, STARA PLANINA - SERBIA

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Abstract:
Located on the slopes of mountain Stara planina in Eastern Serbia, Visok kraj is an area characterized by attractive geological, geomorphological and hydrogeological phenomena. The aim of this study was to emphasize the role of karst in the spatial redistribution of water resources in this area. Vodenička River is the right tributary of Visočica, and it can be considered as a typical watercourse for the study of this phenomena. Upstream from the Middle Triassic carbonate complex, Vodenička River is a perennial watercourse. Due to the capacity of sinkholes and sink zones within this carbonate complex, downgradient from this zone Vodenička River is a non-perennial watercourse, which completely dries up during the recession period. It seems reasonable to assume that subsurface infiltration of Vodenička River from this zone is directed towards the spring Jelovičko vrelo.

Key words: karst, non-perennial watercourse, Vodenička River

Introduction

The study area is located in Eastern Serbia, on the southwestern slopes of mountain Stara planina. This geographical area, from Zavojsko Lake (West) to the border with Bulgaria (East), is known as Visok kraj. The entire area is characterized by attractive geological, geomorphological and hydrogeological phenomena. The study area belongs to the central part of Visok kraj. It extends from the Vodenička River (East) to the spring Jelovičko vrelo (West). The aim of this study was to emphasize the role of karst in the spatial redistribution of water resources in this area. Visočica River represents the main watercourse in Visok kraj. Vodenička River is the right tributary of Visočica and it can be considered as a typical watercourse for the study of this phenomena. The study was conducted in 2016.

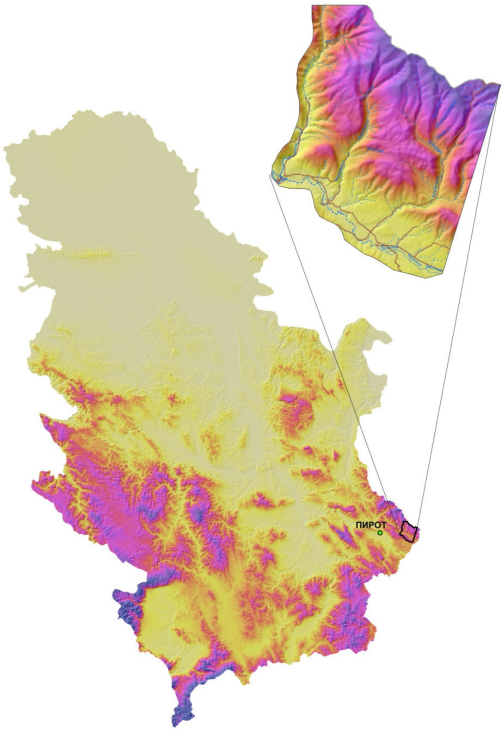

Fig. 1. Geographical position of the study area

Materials and methods

For the purpose of this study, geological, geomorphological and hydrogeological characteristics of Vodenička River catchment basin have been studied. Thus, data from published materials and public data sources were combined with field research. These field research activities have primarily included the reconnaissance survey of Vodenička River catchment basin. Where necessary, detailed geological and hydrogeological mapping was performed. For this purpose, Basic Geological Map (1: 100 000 scale), sheets Pirot (K 34-34) and Belogradčik (K 34-22) with a textual explanation, unpublished sheets of these maps (1: 25 000 scale) and 1:25 000 scale topographic maps have been used.

Results and discussion

The study area is made of Paleozoic, Mesozoic and Quarternary formations (Fig. 2). According to the Anđelković et al. (1977), Palaeozoic is dominantly represented by Riphean-Cambrian crystalline schist. Mesozoic is made of several lithostratigraphic units ranging from Lower Triassic to Lower Cretaceous. Thus, Mesozoic is represented by sediments of the Lower Triassic -

T_1 (sandstones, conglomerates), Middle Triassic - T_2 (limestones, dolomites), Triassic and Jurassic - T,J (claystones, sandstones, limestones, dolomites), Lower Jurassic $J_{1,2}$ (sandstones, claystones, conglomerates, sandy limestones), Upper Jurassic J_3^3 (limestones and marly limestones) and Lower Cretaceous - $K_1^{1,2}$ (limestones, marls, sandstones). Quaternary formations consist of terrace deposits - t.

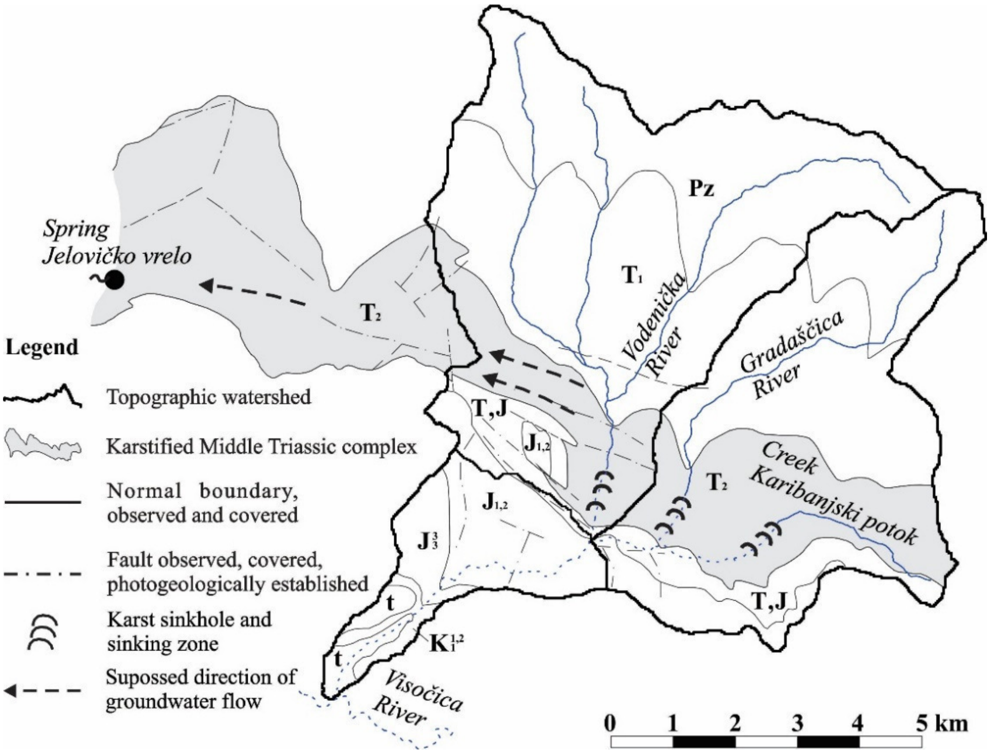

Fig. 2. Simplified geological and hydrogeological scheme of the study area

Within the study area, following types of the aquifer have been formed: fissure-karstic aquifers within Middle Triassic and Upper Jurassic sediments, and intergranular aquifer within Quaternary sediments. The aquifer formed within carbonate Middle Triassic complex can be considered as particularly important for this study. According to Krstić et al. (1974) and Anđelković et al. (1977), this complex is characterized by the shift of fissured and intensively karstified limestones, with significantly less karstified dolomites, dolomite limestones, and lumpy limestones. The intensive karstification of these sediments is confirmed by the development of typical surface and underground karst phenomena: springs, sinkholes, sinking zones, caverns, and caves. The infiltration of surface water can be considered as the main source of recharge for the aquifer formed within this carbonate complex. The rainfall infiltration can be considered as a secondary source of aquifer recharge. The other geological formations within the study area are characterized by a negligible subsurface runoff. These sediments represent a barrier to the flow movement of groundwater accumulated within Middle Triassic complex.

Upstream from the Middle Triassic complex, Vodenička River topographic catchment basin is a wide shaped area. Downstream from this carbonate complex the catchment area narrows. The source zone of Vodenička River is located on the cliff of Stara Planina anticline. This zone is characterized by a significant amount of precipitation. It is made of Riphean-Cambrian formations, characterized by the existence of local fissured aquifers. These aquifers drain through numerous springs with limited discharge. Due to the limited subsurface infiltration, Vodenička River in this zone is a perennial watercourse, with a constant flow during the entire year. By its downgradient movement, Vodenička River enters the zone of karstified Middle Triassic formations. Due to the intensive karstification of these sediments, the riverbed of Vodenička River in this zone is characterized by the existence of sinkholes and sinking zones (Fig. 3). The length of these sinking zones is estimated to few decades of meters.

Fig. 3. The sinking zone of Vodenička River

The infiltration of Vodenička River water due to the sinking occurs during the entire year, but during the recession period, it leads to the complete dry up of this watercourse. Downstream from this zone, up to its confluence with Visočica, Vodenička River is a non-perennial watercourse. Due to the hydrogeological characteristics of Lower Triassic and Upper Jurassic sediments, which represent a barrier to the groundwater flow movement, it is reasonable to assume that the sinking waters of Vodenička River are directed towards the Jelovičko vrelo spring (Nikić, 2003).

Fig.4. Spring Jelovičko vrelo

According to Milanović and Vasić (2015), Jelovičko vrelo is a typical ascending siphonal spring. Although the maximum discharge of the spring is about 4 m^3/s, during recession period the occurrence of no flow from the spring opening was recorded up to 2 days (Cvijić, 1926; Čubrilović, 1990). This redistribution of water from the Vodenička River catchment basin to the spring Jelovičko vrelo is also characteristic for other right tributaries of Visočica River. According to Nikić et al (2016), the water redistribution from Visočica to the Dojkinačka River the catchment basin represents a hydrogeological specificity of the entire area of Visok kraj.

Conclusions

The hydrogeological conditions of Visok kraj lead to the spatial redistribution of water resources in this area. Vodenička River can be considered as a typical watercourse for the study of this phenomena. Its source zone is located on the cliff of Stara Planina anticline, characterized by a significant amount of precipitation. This allogenic watercourse has a constant flow during the flood period, while during the recession period is characterized by the shift of sections with and without flow. Similarly to other right tributaries of Visočica, Vodenička River is a perennial watercourse upstream from the zone of Middle Triassic carbonate complex. Due to the capacity of sinkholes and sink zones within this carbonate complex, downstream from this zone, Vodenička River is a non-perennial watercourse, which completely dries up during the recession period. Considering the hydrogeological features of the study area, it seems reasonable to assume that subsurface infiltration of Vodenička River from this zone is directed towards the spring Jelovičko vrelo. This redistribution of water towards the spring Jelovičko vrelo is also characteristic for other right tributaries of Visočica in Visok kraj.

Acknowledgements

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HEAD AND TEMPERATURE CHANGES INDUCED BY EARTH-TIDE IN FELIX - 1 MAI – ORADEA THERMAL AQUIFER (BIHOR, ROMANIA)

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Abstract: Head of karstic confined thermal aquifer in Felix-1 Mai and Oradea areas present oscillations of up to 20 cm generated by the earth – tides. Their main components were identified by processing of the time hourly series of the piezometric surface levels. The temperature series values depict harmonic frequencies too. The shape and amplitude of the harmonic oscillations is strongly altered by the unevenness of the piezometric surface generated by the exploitation of the aquifers.

Key words: Earth-tide, piezometric surface, thermal aquifer, Felix- 1 Mai - Oradea, Romania

Introduction

The earth tides are produced by the gravitational attraction forces of the Moon and the Sun on the Earth. They occur as rythmic rises and falls of the earth surface.

The amplitude of the gravitational forces is periodical with the time, like the movement of the celestial bodies which it generates. This results in the presence of a high tidal potential, the earth surface oscillations forming a sum of sinusoids (harmonic) with different frequencies and phases called tidal constituents or components, (Agnew, 2005). The frequency of the earth tides is identical for the whole terrestrial globe, but their amplitude and phase being specific to each place on the Earth. Five tidal components (M2, S2, N2, K1 and O1) totalize 95% of the tidal potential (Hsieh et al, 1988, Melchior, 1964, table 1).

The oscillation of the Earth induced by tides presents components with a period of almost 12 hours highlighting the semi-diurnal character. They are mainly lunar (M2 and N2).

The gravitational attraction forces exercised on the Earth's crust show varyable rythmic intensities and produce fluctuations of the water pressure in the pores and fissures of the aquifers represented by variations of the levels/flow-rates in wells, (Merritt, 2004).

Similar short-term oscillations of the aquifer surfaces are also produced by the daily cyclic variations of the atmospheric pressure, (Spane, 2002).

Table 1. Harmonic components of tides, after Wilhelm et al., 1997, Merritt, 2004 and NOAA Tides Online. (Tva-tipical vertical amplitude; Cr- coefficient ratio, m=100)

	Symbol	Angular Freq. (rad/hr)	Frequency, cycles/day	Period, (hours)	Tva, mm	Cr	Description
Semi-diurnal	M2	0,50586804	1,93227356	12,420602	108	100	Main lunar semidiurnal
	S2	0,52359878	2,0	12,0	25,05	46,6	Main solar semidiurnal
	N2	0,49636693	1,89598199	12,658348	10,31	19,2	Lunar elliptic
	K2	0,5250322	2,0055152	11,967	6,082	11,97	Solar-lunar semidiurnal
Diurnal	K1	0,26251618	1,00273794	23,934469	32,01	23,93	Lunar-solar diurnal
	O1	0,24335189	0,92953574	25,381934	22,05	25,82	Main lunar diurnal
	P1	0,2610825	0,9972575	24,066	10,36	25,0	Main lunar diurnal

Thermal Reservoir

The thermal water reservoir of Felix-1 Mai, is situated in the Western side of Apuseni Mountains at the crossing point of Galbena crustal faults system with the fracture system along which Panonic Basin subsidence occurred (I. ORĂŞEANU, 2015, 2016). The thermal groundwater are hosted in Lower Cretaceous (Lower Aptian - Neocomian) fissured and karstified limestones covered locally by calcareous mudstones (Aptian) and by Pliocene sandstones and sands of 20-128m thick over the entire area. Sarmatian sandy conglomerates are present in the lowered compartments.

The thermal aquifer is confined and opened by wells up to depths of 25-650m. The water temperature is ranging between 32,1- 47,1^{o}C. The waters are ascensional through the wells and the piezometric level is situated close to the topographic surface (average level 155m). In some wells the aquifer is arthesian. The aquifer is of fissure – karstic type with drainage axes along the fracture planes. It has high transmissivity, the drawdowns of the piezometric surface produced by the pumping wells are rapidly transmitted and blurred in the whole aquifer mass.

In the Lower Triassic dolomites and limestones of Oradea town area there is located a hyperthermal aquifer opened through several wells and exploited to be used for heating the dwellings. The aquifer is intercepted at an average depth of 2,000 m while its hydrodynamic relations with the Upper Cretaceous aquifer from Felix-1 Mai are not entirely clarified.

Water level monitoring

Between 2014-2017 the Romanian Association of Hydrogeologists conducted studies within Felix -1 Mai zone funded by the National Agency for Mineral Resources, the water level monitoring constituting a part of this program.

The piezometric surface of the thermal aquifer of Felix-1 Mai zone depicts a complexe dynamics generated by natural recharge – discharge hydrologic cycles and by anthropic exploitation, proceses developed on long term (I. Orăşeanu, F. Malancu, 2017). The surface exibit as well hourly variations induced by the earth tides, short time fluctuations that make the object of the present paper.

The evolution of the thermal aquifer surface level was monitored by placing pressure sensors at most of the wells of Felix-1 Mai zone, in the preservation wells 1730 Cihei, 1715 Oradea and 1720 Sânandrei (Fig. 1). The records were carried out at hourly interval.

In all wells of Felix-1 Mai zone (Cretaceous collector) and from Oradea zone (Traissic collector), the short term trend of the piezometric surface show rythmic semi-diurnal oscillations with amplitudes up to 20 cm, (Fig. 2), with maximum values during the periods of New Moon and Full Moon and minimum values during the first and last quarter. Their allure is altered by the thermal water exploitation (Fig. 3).

The hourly series of the water levels were corrected to remove the barometric loading and analyzed using Fast Fourier Transform highlighting the main components of the tides, their periodicity and amplitude (Table 2).

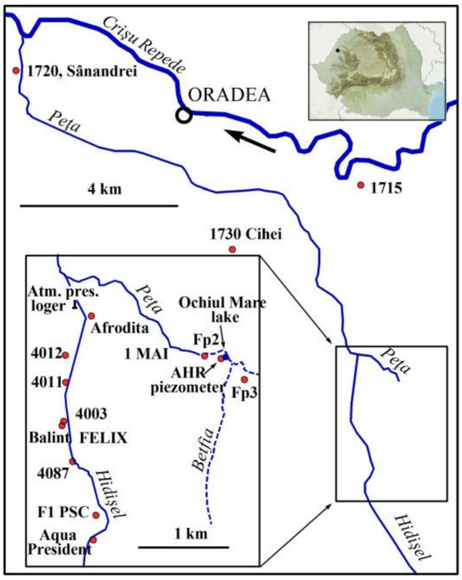


Fig. 1. Location of the monitored wells

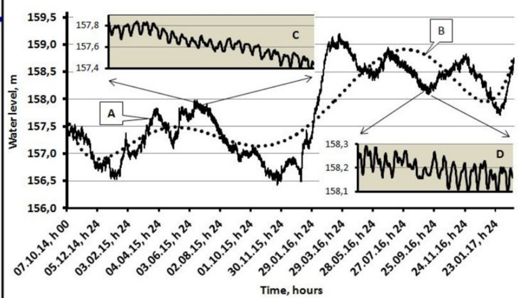


Fig. 2. Evolution of the piezometric surface level of the thermal aquifer in Afrodita well between 2014-2017, (A). Polynomial trendline, order 6, (B). Oscilation of water surface induced by tides: 10-31.07.2015 period, (C) and 01-16.09.2016 period, (D).

The atmospheric pressure was monitored with a sensor (absolute gauge transducer) located in 1 Mai resort. Its density spectrum for a 2 year period indicate two maximum values with periodicities of 24,016 and 12 hours attributed to the solar components S1 and S2, (table 2). The components of the atmospheric pressure S1 and S2 have frequencies identical with K1 and S2 components of earth tides.

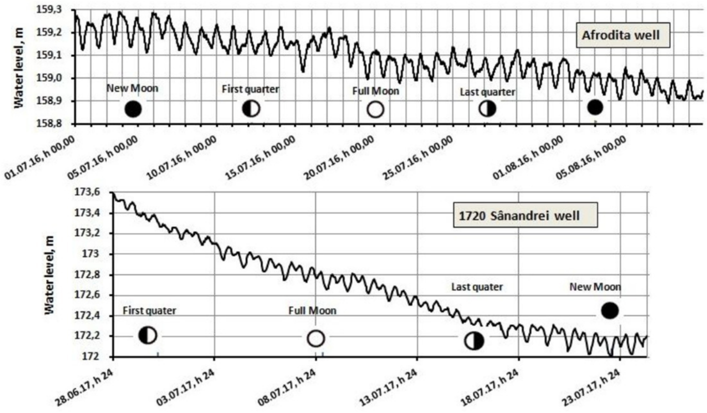


Fig. 3. Evolution of piezometric level in Afrodita and in 1720 Sânandrei wells. The amplitude of the oscillations of the level is influenced by the Moon phases

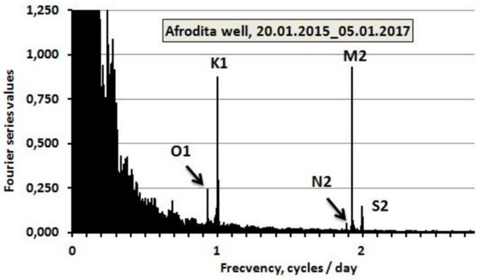
The periodograms of the harmonic frequencies elaborated for the hourly series of piezometric surface levels measured in Afrodita and Cihei wells indicate the complete view of the tide constituents being highlighted by the large value of the Fourier M2 and K1 components amplitude (table 2, fig. 4 and 5).

The tidal oscillations of the thermal aquifer surface are also visible in Ochiul Mare lake which is connected to it through a fissure providing a permanent recharge – drainage relationship with the aquifer (table 2). It represents a piezometer of the thermal aquifer.

Tablel 2. Principal tide constituents of Felix-1 Mai-Oradea thermal aquifer head.

Site	Symbol	Angular freq. (rad/hr)	Frequency, (cycles/day)	Period (hours)	Ampl.
Baro. pres. (20.01.2015-28.01.2017)	S1	0,26162214	0,999333777	24,016	1567,372
		0,26197664	1,000917508	23,978	767,608
	S2	0,52359878	2,00000000	12,000	1699,576
Afrodita well (20.01.2015-05.01.2017)	M2	0,50581250	1,93205603	12,422	0,933
		0,50500000	1,930657228	12,431	0,358
	K1	0,26204304	1,000917508	23,978	0,877
		0,26240851	1,002338791	23,944	0,629
		0,26167756	0,999541877	24,011	0,620
	O1	0,24376946	0,931134821	25,775	0,244
	S2	0,52372060	2,000500125	11,997	0,150
	N2	0,49631024	1,895734597	12,660	0,054
1730 Cihei well (20.01.2015-05.01.2017)	M2	0,50584223	1,932211577	12,421	2,220
	K1	0,26257459	1,002967111	23,929	0,981
	S2	0,52374504	2,000500125	11,997	0,570
	O1	0,24326764	0,92922410	25,828	0,395
	N2	0,49636427	1,89597184	12,658	0,072
Afrodita well (1-27.12.2014)	K1	0,26200000	1,00000000	24,000	0,042
	M2	0,50400000	1,92585460	12,462	0,048

Site	Symbol	Angular freq. (rad/hr)	Frequency, (cycles/day)	Period (hours)	Ampl.
AHR Piezometre (17.05.2015-03.08.2016)	K1	0,26253852	1,002823264	23,932	3,074
		0,26194721	1,000564653	23,986	1,764
	M2	0,50556404	1,931112366	12,428	0,723
		0,50615534	1,933370977	12,414	0,813
	S2	0,52364792	2,000187705	11,999	0,233
		0,52330312	1,998870695	12,007	0,195
Ochiul Mare lake (11.09.2014-21.04.2016)	K1	0,26275712	1,003658274	23,913	3,233
		0,26185573	1,000215193	23,995	2,492
		0,26230642	1,001936733	23,954	2,285
		0,26320782	1,005379815	23,872	1,599
	M2	0,50564725	1,931430211	12,426	0,318
		0,50609791	1,933151628	12,415	0,218
	S2	0,52277255	1,99684407	12,019	0,261
		0,52457522	2,00372974	11,978	0,365
1720 Sânandrei well, (22.06-25.07.2017)	K1	0,26179939	1,00000000	24,00	4756,3
	M2	0,50670849	1,93548387	12,40	9605,1
	S2	0,52359878	2,00000000	12,00	2056,8



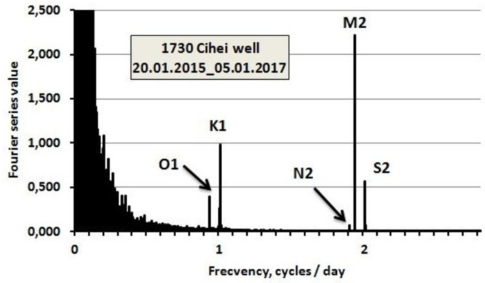


Fig. 4 and Fig. 5. Periodogram of harmonic frequencies present in head data of Afrodita and 1730 Cihei wells.

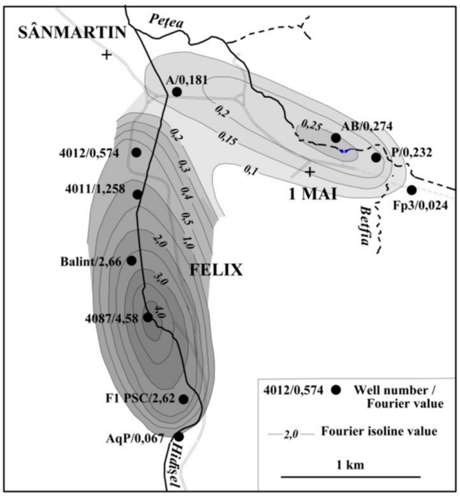


Fig. 6. Area variation of the Fourier amplitude of the M2 earth-tidal component

In fig. 6 there is shown the area variation of the Fourier amplitude of M2 tidal constituent calculated for the interval between 16.06-13.09.2015, when we took advantage of the datalogger records at all the monitored wells of Felix -1 Mai area It is revealed the presence of the maximum values along the alignment of F1 PSC-4087-Balint wells, equivalent to the maximum thermal water pathway outflow.

The exploitation of the thermal aquifer from Felix-1 Mai is carried out with varyable weekly intensities required by the number of tourists. The minimum levels of the piezometric levels are recorded in the wells at the end of each week, when the tourists inflow is maximum and the exploitation of the thermal aquifer reaches the highest values. The weekly cyclicality of the intensity of the exploitation of the wells, (Fig. 7), is well revealed by the spectrum of the harmonic components of the oscillations of the piezometric level of the thermal aquifer at Afrodita well (Fig. 8, left).

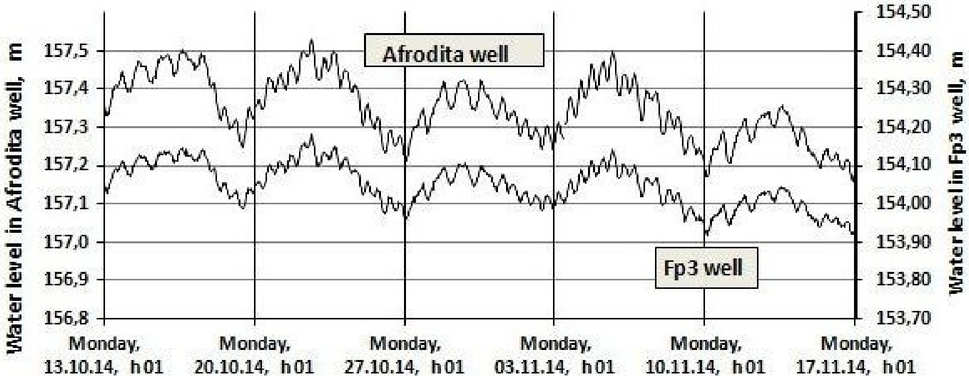


Fig. 7. Weekly evolution of the thermal aquifer level of Felix -1 Mai zone revealed at Afrodita and Fp3 wells

The piezometric surface of the thermal aquifer opened through the well 1720 Sânandrei is embroided by oscillating movement caused by the tides with amplitudes of up to 20 cm (fig. 3), the harmonic component spectrum being dominated by the mainly lunar semi-diurnal component M2 (fig. 8, right and table 2).

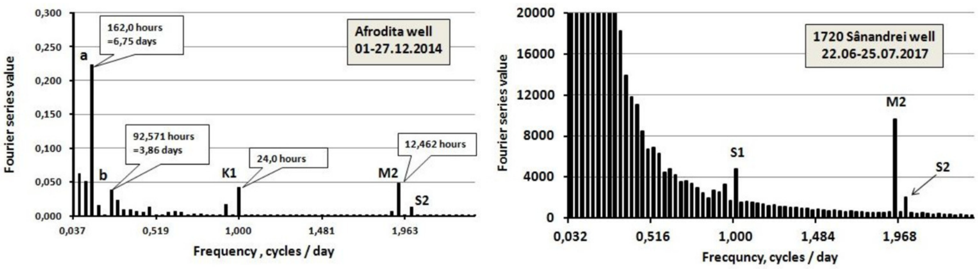


Fig 8. Periodogram of harmonic frequencies present in heads data of Afrodita and 1720 Sânandrei wells

Water temperature

The real temperature of the thermal water is recorded by sensors during the well exploitation. The intense pumping periods revealed by the lowering of the dynamic level of water in the wells are accompanied by the increase of their temperature. The fig. 9 presents the evolution of the previously mentioned parameters at well 4011. The weekly variation cuve of the temperature is „parasitized” by small semi-diurnal oscillations caused by the tides.

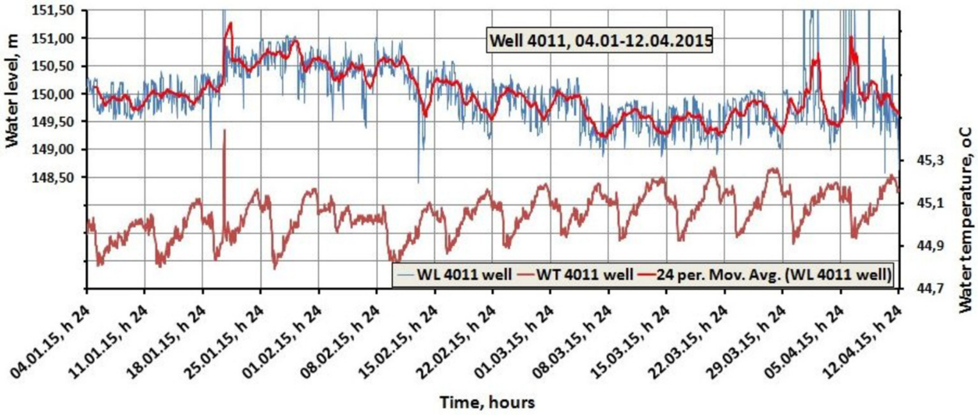


Fig. 9. Evolution of the piezometric level and temperature of the pumped water of the well 4011 during the period January –April 2015

The processing of the hourly temporary series of levels and the temperatures recorded at well 4011 throughout its exploitation provide information about the presence of some periodicities in their development. The periodicities are revealed both in the oscillations of the piezometric surface levels (fig. 10, left) and in those of the water temperature, (fig. 10, right). There are observed the weekly, semi-weekly and 8 hours periodicities generated by the exploitation program of the neighbouring wells and the presence of the tidal lunar-solar diurnal K1 and mainly solar semi-diurnal S2 and P1.

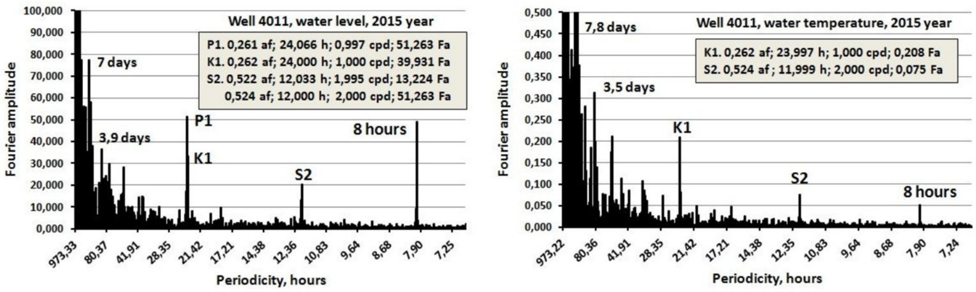


Fig. 10. Periodogram of harmonic frequencies present in the head (left) and water temperature (right) data of 4011 well in 2015 year interval.(af=angular frequency in rad/hour; h=period in hours; cpd= frequency in cycles per day; Fa=Fourier amplitude.

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Astronomical observatory "Amiral Vasile Urseanu" Bucharest, http://www.astro-urseanu.ro/index.html, Moon phases.

COMPARISON BETWEEN SOME KARST SYSTEMS IN SOUTHERN ITALY TYPIFIED BY DIFFERENT HYDROLOGICAL BEHAVIOR

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Abstract

This short paper aims to provide an analytical approach to pinpoint the recharge processes evaluated for some karst massifs of southern Italy. The assessment of annual mean recharge for thirty-year period (1971 – 1999) was carried out for Terminio, Cervialto, Matese and Alburni massifs. The annual scale groundwater recharge analysis starts from regression of annual mean values of different ground-elevated rain gauges and thermometers. The estimation takes into account the presence of wide endorheic areas (for Matese, Terminio and Cervialto massifs), distinguished from the rest of the catchment, characterized by the "open areas". For the Alburni karst massif the recharge phenomenon is chiefly controlled by summit karst plateau considered as unique closed depression; geomorphological and hydrological analysis carried out on plateau, proves that it represents the predominant recharge area feeding basal karst springs.

Key words: groundwater recharge**,** karst aquifer, karst plateau, southern Italy

1. Introduction

This paper highlights the main results obtained by the analysis of annual groundwater recharge, carried out on some hydrogeological catchments in southern Italy. The hydrological analysis focused on the assessment of parameters which define annual groundwater recharge, each one was implemented using GIS tools to enhance the model proposed by Fiorillo et al., 2015. The topic appears very interesting because the annual scale recharge model provides a useful tool to compare long-term aquifer recharge for some karst aquifers affected by similar geomorphological and geological features.

2. Geological and hydrogeological features

Figure 1 depicts a hydrogeological sketch of southern Italy pointing out the main karst systems in southern Apennines. The Alburno massif is formed by Mesozoic calcareous series (Jurassic - Cretaceous) and belongs to Alburno-Cervati Unit (Patacca and Scandone, 2007). It is characterized by a monoclinal structural assessment, gently dipping toward SW, and it is interested by several fault systems. This massif is bounded by flysch sequence constituted by argillaceous and sandstone series (Burdigalian –Serravallian). The other karst massifs considered in this study, are the Matese and Picentini mountains (in the matter in question Terminio and Cervialto massifs). The above-mentioned massifs are mainly formed by Mesozoic carbonate sequences and are characterized by a high-elevated reliefs, bounded by faults or flysch sequences.

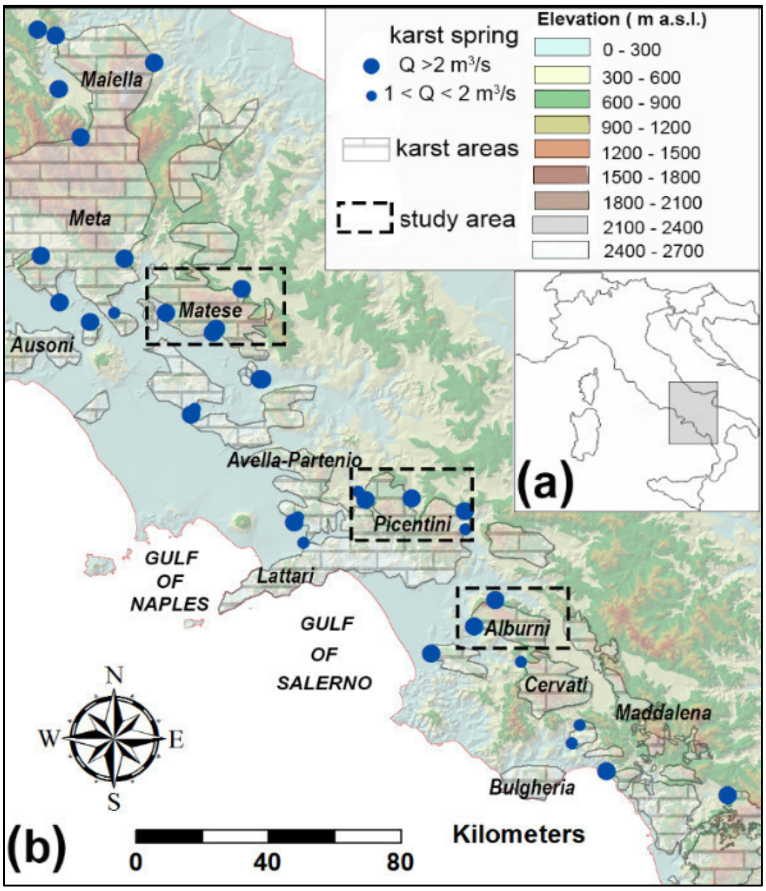

Fig. 1. a) Italian peninsula; b) Main karst areas in southern Italy and main karst springs, with location of Alburni, Matese and Picentini massifs (black rectangle drawn with dashed line).

These karst massifs are affected by wide endorheic zones, connected to tectonic activity during Pliocene-Pleistocene, when a general uplift by normal faults occurred, with formation of graben zones. Fiorillo et al. 2015 described the endorheic areas formation, which constitute the most important recharge areas of karst massifs of central-southern Italy and have also an important role in the groundwater protection.

3. Hydrological analysis

Rain gauge and thermometers data collected on thirty years allowed finding out a relevant correlation between the catchment elevation, annual mean rainfall and air temperature. Very reliable statistical correlations were found considering regression line of annual mean rainfall (**R^2 =0.94**) and annual mean temperature (**R^2 = 0.93**) for Picentini massif (Fiorillo et al.2015); also for Matese massif strong correlations about rainfall vs ground-elevation (**R^2 = 0.94**) and temperature vs ground-elevation (**R^2 = 0.92**) were founds (Fiorillo & Pagnozzi, 2015) while for Alburni karst massif statistical correlation index was lower than Picentini and Matese ones (**R^2 = 0.56**); rainfall vs ground-elevation; (**R^2=0.63)**, temperature vs ground elevation. Then the annual groundwater recharge model was applied, considering total meteoric afflux, actual evapotranspiration, effective meteoric afflux (fig.2). These amounts are implemented in a GIS environment; the groundwater recharge model is decribed by Fiorillo et al 2015 and Pagnozzi et al. 2017. In endorheic areas, A_E, as the runoff cannot escape, the recharge amount, *R,* can be considered equal to effective afflux, F_{eff}:

$$(R)_{A_E} = (F_{eff})_{A_E} \quad (1)$$

The model assumes that all the amount of the recharge reaches the basal water table, even if the vadose zone could be formed by portion of saturated zones, characterized by leakage, and contributing the percolation of vadose zone; suspended springs can be also taken into account. Recharge can be expressed in term of fraction of the effective afflux, providing the effective recharge coefficient, C_R *for different zones of catchment area (endorheic areas,* A_E*, open areas,* A_O*, total catchment area,* A_C*):*

$$(C_R)_{A_E} = 1 ; \quad (C_R)_{A_O} = \frac{(R)_{A_O}}{(F_{eff})_{A_O}} ; \quad (C_R)_{Ac} = \frac{(R)_{Ac}}{(F_{eff})_{A_c}} \quad (2)$$

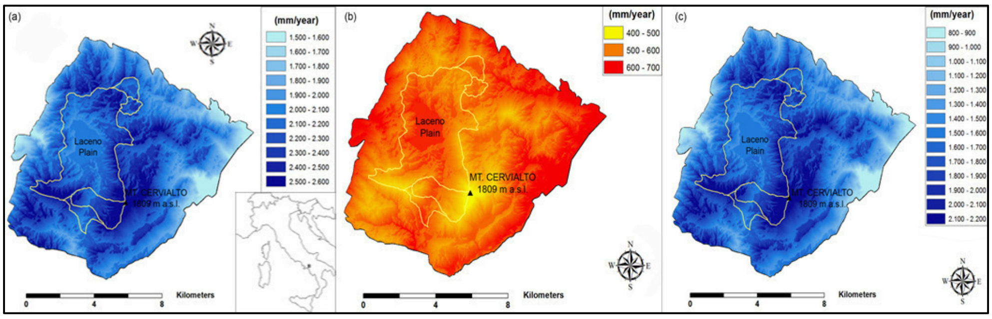

Fig. 2 - a) Total rainfall, b) actual evapotranspiration, c) effective rainfall distribution for Cervialto catchment; endorheic areas are marked by yellow line (from Pagnozzi et al. 2017).

4. Outcomes

Table 1 shows main results obtained by groundwater recharge analysis of study areas. The simulation model, applied to the northern sector of the Picentini mountains then extended to Matese massif, points out the similar recharge coefficient obtained for open areas of catchment; **0,66** for Cervialto and Matese, **0,67** for Terminio (Fiorillo et al., 2015; Fiorillo & Pagnozzi 2015) comparables with other groundwater recharge models provided by literature (Allocca et al. 2014). The annual scale recharge model analysis allows assessing runoff amount and the endorheic areas contribution to spring discharge (Fiorillo et al., 2015). Hydrological analysis carried out for Alburni karst system provides an annual mean discharge quantified as **233,3 m^3 x 10^6**.The fundamental role of karst plateau (internal runoff area) is highlighted by effective contribute to spring discharge value (**C_s= 0.54**) higher than open area one (**C_s=0.46**). For the open area, the analysis has provided a high effective recharge coefficient (**C_R = 0.91**), and the annual runoff amount is **13.4 m^{3}x 10^6** (Table 1). For Matese Terminio and Cervialto massifs comparable values of recharge coefficient along the slopes of open areas, $(C_R)_{Ao}$ were founds (Fiorillo et al. 2015; Fiorillo & Pagnozzi, 2015), while different recharge coefficient (**C_R=0.91**) for Alburni massif points out a different slope distribution for external area. This means that the runoff coefficient, C_{RO} (Fiorillo et, 2015), along the steep slopes of open areas of the Alburni massif would be only **0.09** (C_{RO}=1-C_R). The low value of C_{RO} for the Alburni massif can be explained by the lower ground elevation of the open areas (Table 1) but can also suggest possible unknown groundwater amount towards Tanagro river along the northern boundary. The groundwater recharge model proposed represent a useful tool to plan the supply of water resources, especially during drought period as 2016/17 hydrological year where the recharge volume of Cervialto massif is only **70 m^3 x 10^6** while the estimated annual mean recharge of this aquifer in normal hydrological conditions is **124 m^3 x 10^6** (Pagnozzi et al.2017).

5. Discussion

The annual scale recharge model proposed in this research paper needs the assessment of some fundamental hydrological parameters. GIS tools allow considering an overview of spatial distribution of the actual evapotranspiration and rainfall in the catchment, and relative quantification. Hydrological analysis carried out defining annual recharge allows a detailed assessment of several parameters included in the model. To explain the different hydrological response of the Alburni massif (table 1), is fundamental to take into account other geomorphological data and karst landforms as the several sinkholes and dolines affecting plateau surface (Cafaro et al. 2016) in order to better define the recharge phenomena. However, while for the Terminio, Cervialto and Matese springs, discharge measurements for long time periods are available, for the basal springs of Alburni massif, only sporadic discharge measurements are usable (Celico et al. 1994; Santangelo & Santo 1997; Ducci 2007), especially for the Tanagro group springs which constitutes the major outlet; this poor dataset doesn't allow to fully understand the recharge phenomenon for Alburni system, which is more complex to estimate respect to other karst massifs argued in this research. To assess the recharge coefficient proposed in this paper is fundamental the knowledge of external runoff amount, even if it can't be always accurately estimated in catchment areas not completely guaranteed by an extended hydrogeological monitoring network.

6. Conclusions

To assess the recharge of some karst massifs in southern Apennines (Terminio, Cervialto, Matese and Alburni massif), a specific procedure has been used concerning the assessment of annual scale recharge model. As the latter are typical features of karst environment, the annual model is focused on karst aquifers, assuming that no-flow boundary occurs towards impervious terrains. Recharge coefficient found in Cervialto annual hydrological analysis is similar to Matese one because two massifs have comparable topographical features (Fiorillo & Pagnozzi, 2015). Therefore, the models proposed could be applied for other karst massifs characterized by similar hydrogeological and morphological framework. In Alburni massif the hydrological analysis shows that the ground-elevated flat area play an important role in karst aquifer hydrological behavior, being the hydrogeological structure that mainly contribute to basal springs discharge; for this reason, because on the plateau the predominant kind of recharge is that provided by concentrate infiltration it could be mainly vulnerable to water contamination risk (Stevanovic 2015), overall considering that some karst landforms can be considered as preferential vehicles for a generic polluting (Gutierrez et al. 2014).

Table 1 Summary of hydrological parameters obtained by annual groundwater recharge analysis for Alburni, Cervialto, Terminio and Matese massifs; F, Afflux; F_{eff}, effective afflux; RO, runoff; Q_P, pumped water; C_R, effective recharge coefficient; C'_R ,total recharge coefficient; C_s, effective contribution to spring discharge.

	Area	Mean eleva. (m asl)	Km^2	F $(m^3x10^6)/y$	F_{eff} $(m^3x10^6)/y$	RO (m^3x10^6)	Q_p $(m^3x10^6)/y$	R $(m^3x10^6)/y$	C_R	C'	C_s
ALBURNI	Plateau area	1124,5	111,5	180,3	122,8	0,0	0,0	122,8	1,00	0,68	0,532
	Open areas	828,2	151,3	207,9	121,3	13,4	0,0	108,0	**0,91**	0,52	0,468
	Total catch.	953,9	262,8	388,2	244,1	13,4	0,0	230,7	0,95	0,59	1,000
CERVIALTO	Closed areas	1249,3	27	58	44	0,0	0,0	44	1,00	0,76	0,343
	Open areas	1153,9	83	172,4	128,3	43,8	0,0	84,5	**0,66**	0,49	0,657
	Total catch.	1176,4	110	230,4	172,3	43,8	0,0	128,5	0,75	0,56	1,000
TERMINIO	Closed areas	959,1	68,6	132,1	93,1	0,0	6,3	86,8	0,93	0,66	0,509
	Open areas	934,9	94,3	180,2	125,0	41,4	0,0	83,7	**0,67**	0,46	0,491
	Total catch.	944,5	162,9	312,3	218,1	41,4	6,3	176,8	0,81	0,57	1,000
MATESE	Closed areas	1229,3	123,8	221,8	162,5	0,0	42,2	0,0	0,78	0,57	0,276
	Open areas	919,8	427,7	701,2	476,4	162,0	0	162,0	**0,66**	0,45	0,724
	Total catch.	988,8	551,5	923,0	638,9	162,0	42,2	162,0	0,69	0,48	1,000

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GIS DATABASE OF TRACER TESTS CARRIED OUT IN THE SLOVENIAN KARST

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Abstract: Tracing using artificial tracers is an extremely valuable research method for studying the karst aquifers and an essential tool for the process of management of karst water resources. In Slovenia, where approximately one half of the population is supplied with drinking water from karst aquifers, more than 200 tracer tests have been carried out since the end of the 19th century. As the results are often hard to find in published and unpublished reports, in the project described they were compiled systematically and structured in a GIS database. An important and innovative achievement is the fact that the database will be freely available on the website of the Slovenian Environment Agency.

Key words: karst, tracer test, GIS database, Slovenia.

Introduction

In karst aquifers, tracing using artificial tracers is an extremely valuable research method for studying the characteristics of groundwater flow and solute transport (e.g., Benischke et al., 2007; Goldscheider et al., 2008; Kogovsek & Petric, 2014). The most common usages are the characterization of groundwater flow directions and velocities, the delineation of catchment areas, and the identification of contamination sources. It is an essential tool for the process of management of karst water resources, which are in many parts of the world a highly valuable source of drinking water.
Dissemination of the results is very important as it helps to build upon previous findings and sometimes limits unnecessary repetitions of tracer tests. For these reasons the results should be available to other experts involved in the research of karst aquifers and in the process of management of karst water resources in the area. One possible way is by publishing in the scientific and professional literature, the other by reporting on expert meetings and public presentations. Still, the results of numerous tracer tests remain hidden as unpublished reports in archives of various institutions. Also, the literature describing the tracer tests and their results is often hard to find due to a great number of various journals. Although this becomes easier with the possibility of searching by keywords in on-line journals, still the process of surveying and evaluation of data remains a

time-consuming process. A step further is a shared database of tracer tests, which compiles the results of previous tracer tests systematically and in a form that enables fast and easy data access.

In Slovenia, karst covers around 43 % of the total area of 20,273 km^2; approximately one half of the population uses karst aquifers for water supply (Gams, 2003). Traditional use of tracer tests in the Slovenian karst dates back to the end of the 19th century (Müller, 1891). Since then more than 200 tracer tests have been performed. Even today tracer tests remain an important tool for better understanding of the functioning of karst aquifers. They are especially useful for solving specific environmental or engineering problems and are also increasingly recognized by administrative and management bodies (e.g. Slovenian Environment Agency, water supply companies, managers of landfills) as being useful for management of karst water resources.

Based on the above discussed facts, an initiative for formation and maintenance of a tracer tests database has been forwarded recently by the Karst Research Institute to the Environment Agency, which is the administrator of such databases (e.g. meteorological, hydrological, and water quality data; mostly freely accessible on the web) in Slovenia.
The proposal was accepted and in January 2018 the database was delivered to the Environment Agency. Available data about the tracer tests and their results have been searched, critically examined and evaluated, properly edited and transformed into an independent GIS database. Now it is tested and adapted to the standard conditions of the Agency, and in due time it will be freely accessible on its website
http://gis.arso.gov.si/atlasokolja/profile.aspx?id=Atlas_Okolja_AXL@Arso&culture=en-US.

Description of the database

In the recent years, the available data about the tracer tests carried out in the Slovenian karst has been collected at the Karst Research Institute from various sources including scientific and professional journals, and unpublished reports found in archives of various institutions (Petrič, 2009). For the above-mentioned project, these sources were evaluated and supplemented with new data, which was then sorted chronologically in an Excel database. The database contains specific details of each tracer test, it has altogether 38 columns with parameters described below:

- serial number of the tracer test (in chronological order);
- code and name of the groundwater body of the injection point;
- date of injection, name and coordinates (Y, X, Z) of the injection point, and the type of input (e.g., sinking stream, fissure, borehole);

- type and quantity of injected tracer;
- hydrological conditions in the time of tracing;
- names, coordinates (Y, X, Z) and description of the type of output site (e.g., spring, cave stream, drip);
- code of the groundwater body of the sampling points;
- type of groundwater connection (main, secondary, uncertain, no connection);
- maximum tracer concentration observed at the sampling point;
- peak and dominant apparent flow velocity;
- tracer recovery and duration of sampling;
- operator of the tracer test;
- purpose of the tracer test and wider area of the research;
- citation of the source of information (published and unpublished);
- additional comments about the tracer tests and evaluation of its results.

These basic parameters are the main attributes of a GIS database. With the use of the ArcGIS software, three data layers were formed in the shape format (.shp):

- injection points (points),
- sampling points (points),
- groundwater connections (lines).

The layer "groundwater connections" represents vector data in the direction from the injection point to the sampling point. Some selected parameters from the Excel database (describing the tracer test and its results) were attributed to each layer, and in the GIS database they are shown by clicking an individual element of the layer. Individual points and lines can often include information for several tracer tests carried out at this location in different periods.

An important part of the database are the sources of used data (e.g., articles, books, reports), which are attached as pdf files for 70% of the tracer tests included in the base (94% for tests carried out after 1990). By clicking the reference, the user can open the attached pdf document and obtain more detailed information on the performance and results of the tracing.

The final GIS database of the tracer tests will be soon freely available at the web as a special layer in the Environmental Atlas of Slovenia. This is an online service that allows the access of spatial data (e.g., water, nature, weather, earthquakes, environmental protection) to the general public via the Internet using a web browser.

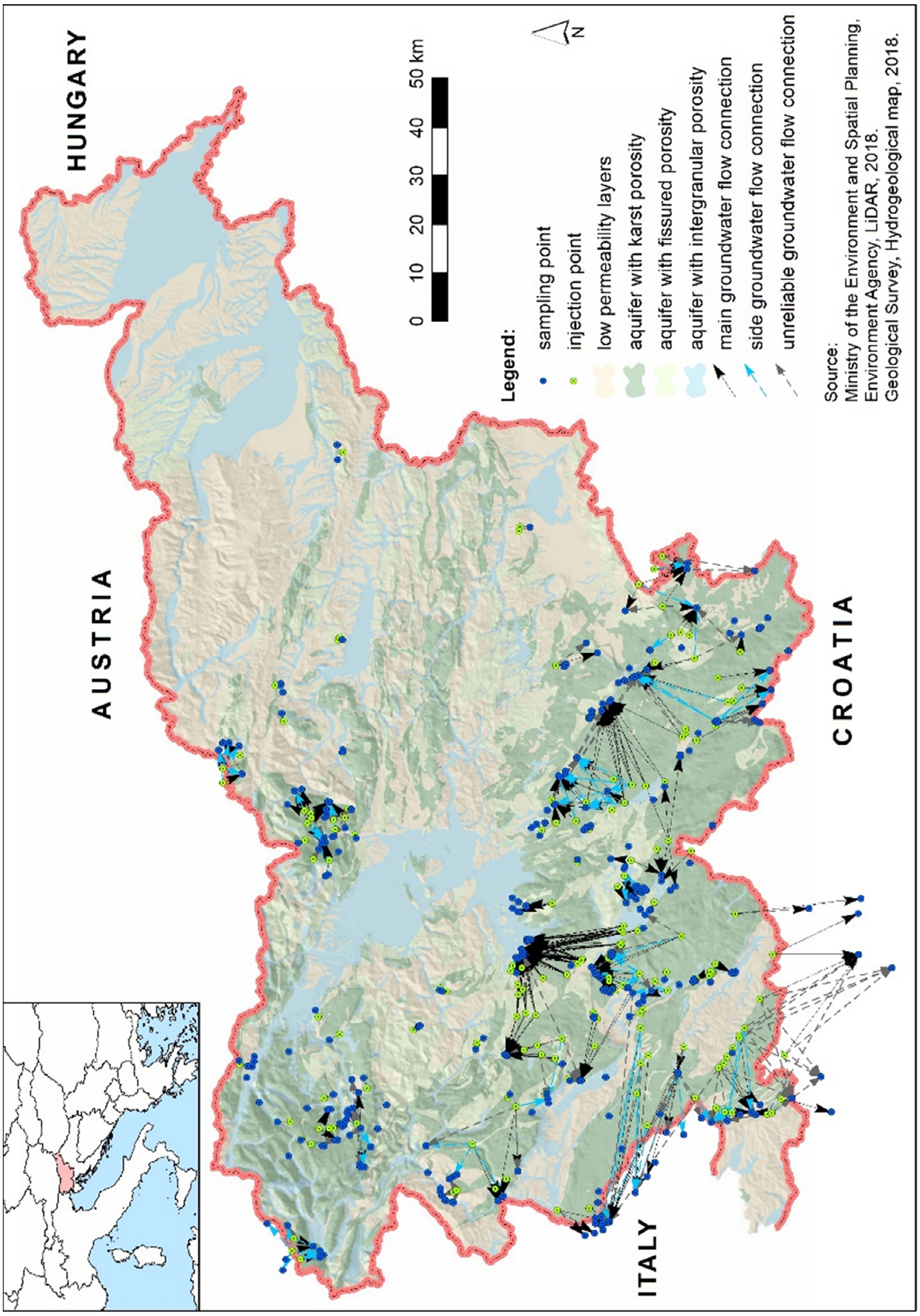

Fig. 1. The elements of the GIS database of tracer tests on the hydrogeological map of Slovenia.

Of course, within the framework of this project, due to time and financial constraints, it was not possible to find the reports of all tracer tests carried out in the Slovenian karst. Additionally, tracer tests will be carried out also in the future, so the database will need to be constantly maintained and updated.

Of the total of 200 tracer tests included at the moment in the database (Fig. 1), 159 are tracer tests with one injection point and one type of tracer used, 5 are multi-tracer tests with one injection point and several tracers used, and 36 are multi-tracer tests with several injection points (maximum 10) and several different tracers used simultaneously. If these multi-tracer tests are considered separately, 267 injections are included.

The organization of data into the database also facilitates the execution of various comparisons and statistical analyses. It is interesting to compare the number of tracer tests carried out in different periods of time (Fig. 2). The number of tracer tests carried out before World War I (almost 2 tests per year) is relatively high. In the following period this number decreased significantly. After 1960, the use of tracer tests increased again and was the most intensive during the decade between 1986 and 1995 (more than 4 per year), when surveys for the regulation of drinking water supply were dominant. In the last twenty years, the number of tracer tests has been declining.

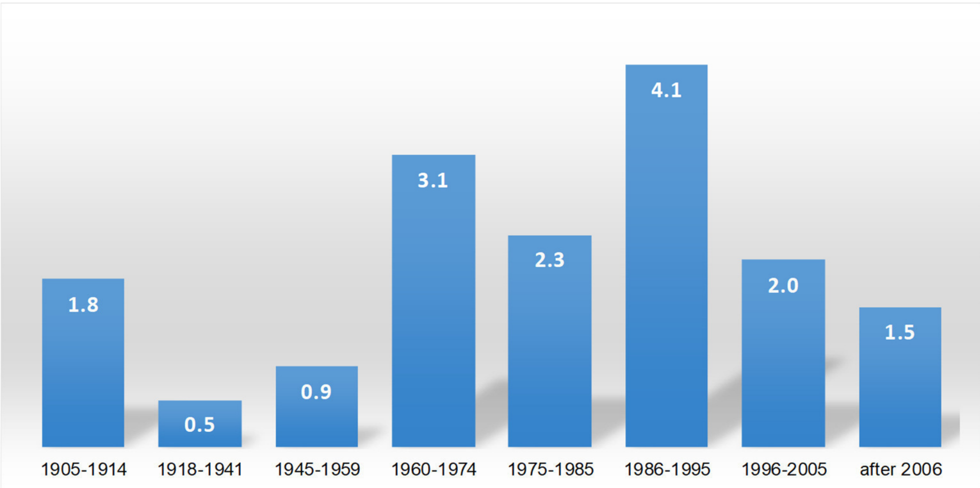

Fig. 2. Average yearly number of tracer tests carried out during the selected time intervals (due to the selection of periods according to the historical events, their duration differs).

Conclusions

A GIS database of tracer tests carried out in the Slovenian karst was compiled. An important and innovative achievement is the fact that the database will be freely available on the website of the Slovenian Environment Agency. This will facilitate the access to information on groundwater flow and solute transport in karst for researchers and those involved in developing, adopting, implementing and evaluating environmental policy, as well as for the general public. For example, it will be very useful in the process of integrated management of karst water resources, and especially in cases where there is an imminent danger of pollution, which require a fast and accurate response.

At the moment the results of 200 tracer tests are included. Some of them, especially those from earlier years, should be used in further studies with a certain degree of caution, as the tracer tests greatly differ in their basic purpose, approach and accuracy of performance. An important part of the database are therefore the sources of used data (e.g., articles, books, reports), which are attached as pdf files. By reading these reports the users can obtain more detailed information on the performance and results of the tracing, thus assessing the quality and usefulness of the data in the database. And for the future, it is important to maintain and update this database regularly with new information.

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INTRINSIC GROUNDWATER VULNERABILITY ASSESSMENT OF SUVA PLANINA MT. (SE SERBIA)

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Abstract: Suva planina Mountain is one of greater and highest karst massifs in South-East Serbia. Almost all karst features are developed, but due to a steep slope neither many dolines, nor large karst caves are present (Petrović, 2014). Several large springs at the foothill of the mountain that have been captured for water supply, are result of developed karstic process. Although, the catchment areas of springs are not populated and there is no industry, beside grazing and forestry, some limits for human impact have to be enacted. According to the available data, the present work is an approach that uses the GIS-overlay spatial modeling technique in performing the groundwater vulnerability assessment of of Suva planina Mt. Maps of intrinsic vulnerability, designed by three multiparameter methods for vulnerability mapping (EPIK, PI, COP), for Suva planina Mt. show existence of 4 classes of vulnerability, but in slightly different arrangement and distribution. Based on these maps a proposal for defining the sanitary protection zones of the groundwater sources in the foothill of Suva planina Mt will be made.

Key words: karst aquifer, intrinsic vulnerability, EPIK, PI, COP

Introduction

Water pollution of karst aquifer which is open and very permeable is major constrain in local water management. Preventive measures are the basis for the sustainable management of this precious natural resource (Živanović, 2011). An assortment of groundwater vulnerability assessment methods has been developed as the necessary basis for implementing preventive measures. Vulnerability maps have become essential tool for groundwater protection and environmental management (Vías et al, 2005). Groundwater vulnerability maps synthesize the relevant lithological, pedological, hydrogeological, meteorological, hydrological and geomorphological information and support decision making in environmental management, land use and water management and aid communication between hydrogeologists and decision makers (Witkowski et al. 2007). Due to special characteristics of karst systems it is much more difficult to define the recharge conditions and predict measures for karst water protection, thus, application of vulnerability mapping is the most important in deciding the sanitary protection zones of karst ground water sources. Intrinsic vulnerability only considers the hydrogeological properties of the system whilst specific vulnerability considers, in addition, the specific interactions with particular contaminants (Zwahlen, 2004). EPIK is the first method of vulnerability mapping which was designed to assess karst water vulnerability (Doerfliger et al, 1999). PI (Goldscheider et al, 2000) and COP (Vías et al, 2006) are modern versions of EPIK method which involve more parameters and sub parameters, and because of this fact more detailed maps can be created.

Study area

Suva planina Mt. lies 250 km SE from Belgrade (Fig. 1), generally oriented in the NW-SE direction. The Nišava River borders Suva planina Mt., from the north and the north-west, the Koritnička R. forms the eastern border, and the southern and south-eastern borders are formed by the Lužnička R. Geological setting of Suva planina Mt. is very complex due to multiple thrusting and faulting that happened during the Caledonian Orogeny, the Hercynian orogeny and finally the Alpine orogeny. Faulting caused creation of plunging anticline of Suva planina Mt., and longitudinal structure of Lužnica regional fault with NW-SE direction where older rocks are in the core of fold. Aquifer have been created mainly in cracked and karstified carbonate rocks of Jurassic and Cretaceous period (Fig. 2). Faulting also, caused creation of groundwater flows within karst massif that have radial direction from Suva planina Mt. anticline axis toward its limbs. However, afterward karstification contributed to changing of predominant groundwater flow directions and quantities of water discharged through observed springs (Petrović, 2014).

The most of karst springs are formed as a result of contact of karstified Jurassic and Cretaceous limestone with impermeable sediments of Neogene period (Fig. 2). Karst springs that drain Suva Planina Mt. and have significant yield are: Mokra, Divljana, Gornja Koritnica, Vrelo, Bežište (on the eastern side), Ljuberađa (on the south side), Ropot, Laznica, Sopotnica, Gornji Dušnik (on the west side), Ostrovica, Vrgudinac, Golemo vrelo, Bojanine Vode (on the north side), and Rakoš česma (on Suva Planina Mt. itself).

Fig. 1. Geographical position of Suva planina Mt.

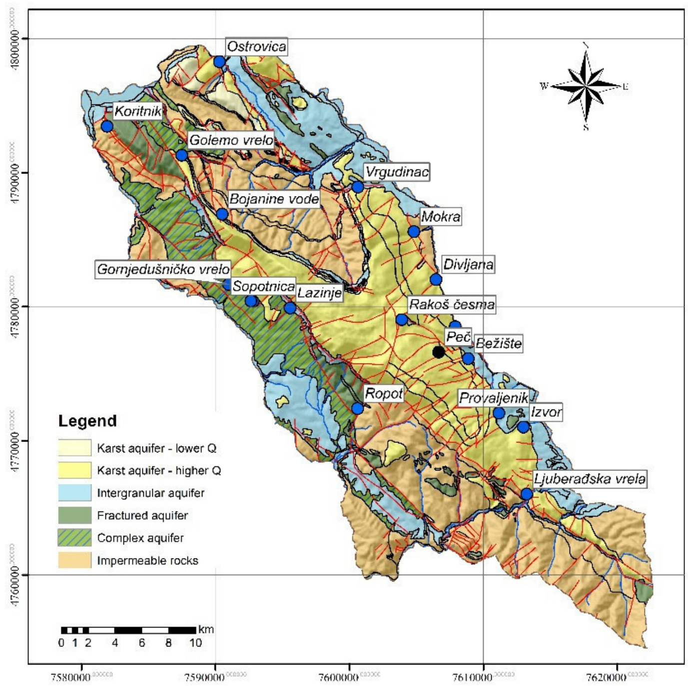

Fig. 2. Hydrogeological setting of the research area, with karstic springs (according to Basic geological map of SFRJ; Dimitrijević et al, 1980)

Methods

EPIK method, name is an acronym for Epikarst (E), Protective cover (P), Infiltration conditions (I) and Karst network development (K), is a multi-attribute weighting-rating method (overlay and index method) that assesses the groundwater sensitivity of karst terrain. A multiplier, reflecting a relative importance weighting, is assigned to each attribute. The acronym PI stands for the two factors protective cover (P factor) and the infiltration conditions (I factor). The PI method is a combined GIS-based approach to mapping groundwater vulnerability for all types of aquifers but with special consideration of karst. It is based on a source-pathway-target model, pathway includes everything between the ground surface and the groundwater table. The COP acronym comes from the three initials of the factors used: flow **C**oncentration, **O**verlying layers and **P**recipitation The conceptual basis of this method, is to assess the natural protection of groundwater (O factor) determined by the properties of overlying soils and the unsaturated zone, and also to estimate how this protection can be modified by the infiltration process – diffuse or concentrated – (C factor) and the climatic conditions (P factor – precipitation).

To determine required parameters for application of the vulnerability mapping for the research area a detailed geological survey was carried out, and data of lithology, karst features, precipitation, vegetation and soil cover, were gathered from different sources. The raw data were processed and used to generate the thematic layers. Thematic layers for each hydrogeological parameter were generated using ArcGIS software. Maps decided areas which are more likely than others to become contaminated. However, results will lead to better decision-making and more appropriate selection for the groundwater protection zones that need special management to maintain their sustainability for future use. A superimposed geographic information system (GIS) layers were built-up to include all the decisive parameters or criteria that have been suggested by authors for the groundwater vulnerability mapping. The GIS-based models were developed for generating the aquifer vulnerability maps of Suva planina Mt. (Fig. 3). Maps reflect the aquifer's inherent capacity to become contaminated and represents the range of the vulnerability indices.

Results and discussion

Abovementioned methods have been used to evaluate the groundwater vulnerability of Suva planina Mt. and to calculate vulnerability indexes and to produce vulnerability maps, with ranges of four intervals, from "very high" to "low".

The map obtained by the EPIK method (Fig. 3a) shows a range from "very high" to "low" vulnerability. Based on analysis of impact factors, the most influence on the final vulnerability index F, have parameters E and I. One can notice direct correlation of (hydro)geological setting of the research area with the vulnerability index. The "very high" and "high" vulnerability is related to highly karstified areas with well developed epikarst and significant number of dolines, and due to this effective precipitation is more rapid.

The PI vulnerability map (Fig. 3b) shows the intrinsic vulnerability and the natural protection of the uppermost aquifer. The map shows the spatial distribution of the protection factor π, which is obtained by multiplying the P and I factors. We can notice the smaller area of "Extreme" (Very High) vulnerability and they are related to the existence of dolines. Dolines serve as an indicator for extensively developed epikarst and for a low degree of protection provided by the unsaturated karstic bedrock. "High" and "Medium" vulnerability areas in this case coincide with the rest of karstified terrain. However, "Medium" vulnerability prevails due to high depth to groundwater level and presence of clayish soil, especially in the eastern slope of Suva planina Mt. The rest of the area is characterized as "Low" vulnerable as it is non-karst area, consist of impermeable Paleozoik and Neogen rocks, and alluvial deposits (gravel, send clay).

The factors of the COP method have been combined to evaluate the intrinsic groundwater vulnerability. The final numerical representations of the C, O and P factors are multiplied, because each one is considered to impact on the assessment of karst aquifer vulnerability. The vulnerability map that results from COP method (Fig. 3c), compared to other two methods, has more "Very High" vulnerability area. The reason for that is low protection provided to the aquifer by the physical properties and thickness of the layers above the saturated zone (O factor) and very high and high flow concentration (C factor). The P factor (precipitation) has small or no impact on the vulnerability due to almost the same value of this factor in the karstified area.

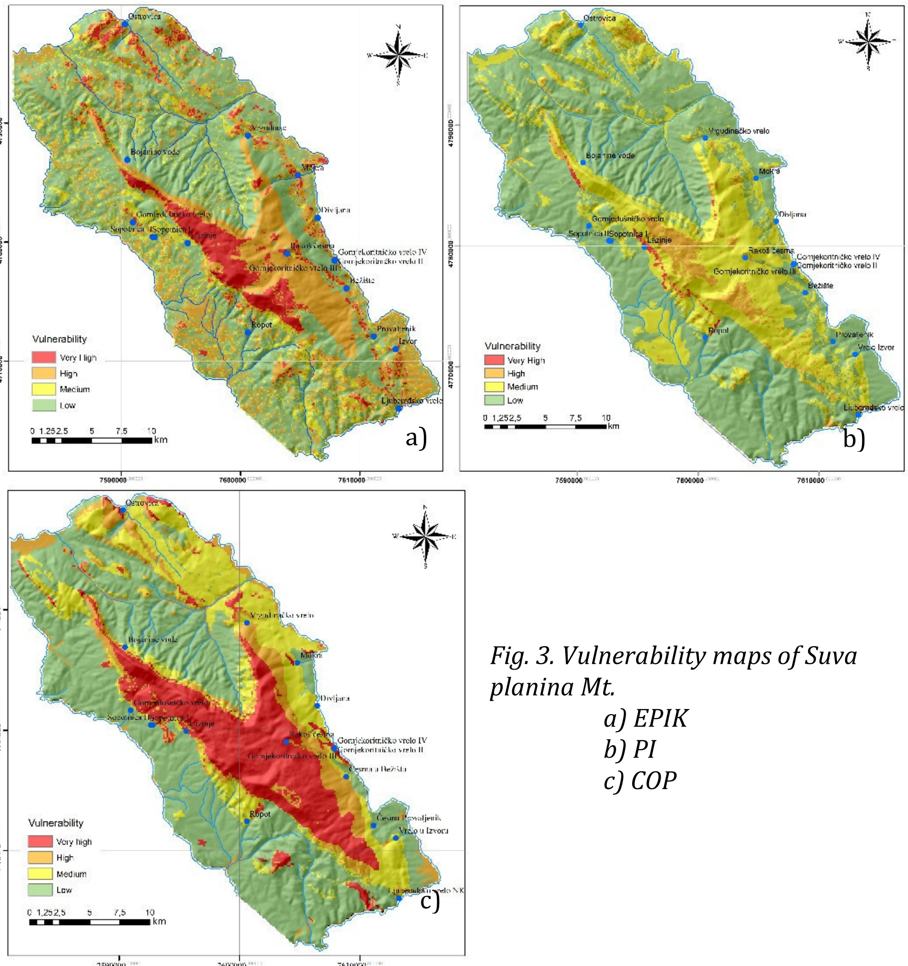

Fig. 3. Vulnerability maps of Suva planina Mt.
a) EPIK
b) PI
c) COP

Conclusion

The results of this study highlighted that the karstic test site shows aquifer vulnerability that ranges from low to very high (extreme). The highest contribution to vulnerability was due to karstic features such as dolines, in all three maps. The COP map has the greatest extension of "Very High" vulnerability area due to high presence of carbonate rocks on the surface, that produce low natural protection and concentrated flow in aforementioned dolines. The PI map shows that most of the area has "Medium" vulnerability due to high depth to groundwater level in karstified limestones and presence of clayish soil in wider area. Vulnerability map designed with EPIK method is "more balanced" compared to other, still "Very High" and "High" vulnerable portions of the terrain could be noticed. Based on these maps a proposal for defining the sanitary protection zones of the groundwater sources in the foothill of Suva planina Mt will be made. That new map should help in decision making considering water supply protection and in supporting sustainable development of this area, especially since the proclamation of one part of Suva planina Mt. as a special nature preserve.

Acknowledgment
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HYDROGEOLOGICAL POTENTIAL OF MIOCENE LIMESTONES OF SOUTHERN PART OF THE KOLUBARA COAL BASIN

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Abstract: Kolubara-Tamnava coal basen is of the major importance for the economy of the Republic of Serbia and is insufficiently explored in terms of groundwater resources. This is primarily referred to the resources of potentially high-quality drinking groundwater as well as to the potential reserves of thermomineral groundwater. The previous studies conducted in the exploration area revealed the occurrence of the Sarmatian limestones, which due to their fabric, are considered as good aquifer. These data indicate that the Sarmatian limestones were discovered during drilling exploration in the southern part of the Kolubara-Tamnava coal basin, in the proximity of Vreoci village. The article deals with the spatial distribution of a limestone formation based on stratigraphic correlation of drill cores data as well as the possibility to estimate the spatial distribution of groundwater body.

Key words: Miocen limestone, coal basin

Introduction

Miocene limestones are known from earlier as suitable environment for the aquifer development. It has been found that many sources in the wider surroundings of Belgrade, both active and those that are no longer in function, derive or derived from Badenian (i.e. “Lajtovački krečnjak”) or Sarmatian limestones. Within the Kolubara basin, as an important factor of the economy of the Republic of Serbia, geological research has been conducted for many years. Based on results of these explorations, stratigraphic differences of the northern and southern parts of the Kolubara basin were determined, as well as the kinematics of the neotectonic activity were performed based on morphostructural analysis of paleolandscape of the Badenian, Sarmatian, Pannonian, Pontian and Quaternary (Kezović, 2003). In the southeastern and eastern periphery of the Kolubara basin, the outcropping limestones of Miocene, predominantly Sarmatian age, were revealed; for example, surroundings of Ostružnica (Pećane), Sremčica, Barajevo, Sibnica, where these limestones are more or less karstified, while in the area of the southern productive (coal-bearing) part of the Kolubara Basin, Miocene limestones are overlaid with sediments of late Miocene age (Pannonian and Pontian). In this work, the analysis of the distribution of Miocene limestones and their hydrogeological characteristics in the territory of the southern part of the Kolubara basin was performed through synthesis of the previous results of exploratory drilling and the analysis of sampled groundwater.

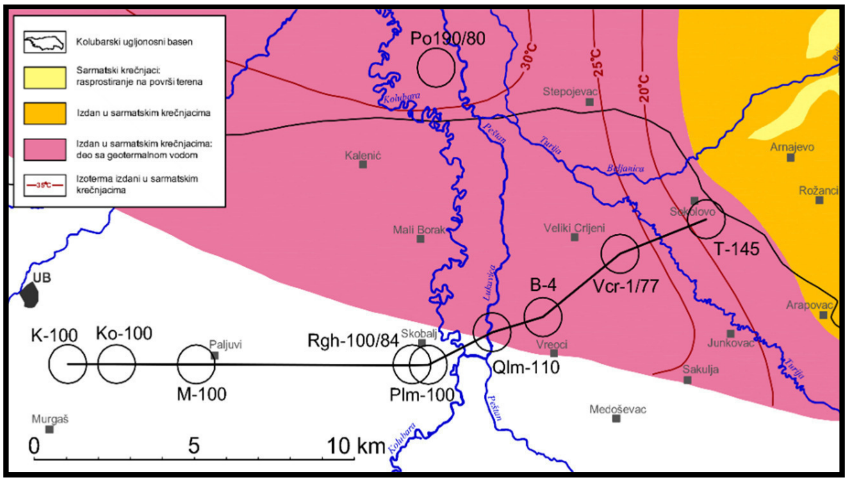


Figure 1 Modified map of distribution of Sarmatian limestone in the area of the Kolubara coal basin (taken from Milivojević, 2006) Black line is cross-section discussed in the text and part of it (between Qlm-110 and T-145) is given in Figure 2.

Results of previously performed geological exploration

In order to investigate the occurrence and spatial distribution of the Miocene limestones, the analysis of the results of previous geological exploration (i.e. exploratory drilling) was performed, whereby the presence of both the Badenian and Sarmatian limestones was singled out. The simplified hydrogeological map with the sites of drilling objects for which the processing of the available data has been made, is given in Figure 1, while the profile through the prospective area is given in Figure 2.

Badenian

Badenian limestones (i.e. Lajtovac) were revealed in the boreholes Vcr-1/77 (village of Veliki Crljeni) and T-145 (village of Arnajevo). In the Vcr-1/77 borehole, the Badenian limestone was determined in a depth range of 374-385 m (239-250 m of absolute height), interlayer with one meter thick marl. In the T-145 borehole, the Badenian limestones were recorded in an interval from 280m (164m absolute height) to the bottom of the well, i.e. depths of 294m.

Sarmatian

The Sarmatian limestones have a much larger distribution than Badenian ones and are found in boreholes M-100 (Paljuvi), Plm-100 (Skobalj), Qlm-110 (Vreoci), B-4 (Vreoci), Vcr-1/77 (Veliki Crljeni) and T-145 (Arnajevo). In the M-100 borehole, the Sarmatian limestone was found in the depth range of 232-327 m (239-201 m absolute height), in the Plm-100, in the depth range of 240-250 m (142-153 m absolute height), in Qlm-110 in depth range of 216-235 m (129-148 m absolute height), in the well B-4 in the depth range of 210-265 m (118-173 m absolute height), in Vcr-1/77 in the depth range of 318-362m (129-148 m absolute height) and in the borehole T-145 in the depth range of 206-266 m (90-150 m absolute height). The above facts indicate that the Sarmatian limestones are located in the central belt of the southern part of the Kolubara coal basin. The limestones occur in the altitude range of 205.9-362 m, where the shallowest one is ascertained in the borehole T-145. The largest thickness of these sediments was observed in the B-4 well, where they exceed 57 meters, and in the boreholeT-145 where limestones occur in two packages separated by marl, of which the shallows have a thickness of 20 meters, while deeper one of about 60 meters. The performed stratigraphic correlation of the cores shows great hypsometric differences in the spatial position of the Sarmatian limestones. Based on these observations, the large faulting is postulated to have occurred in the exploration area and there were strong differential movements of the separated blocks. They led to the creation of a complex structural fabric of Miocene deposits including Sarmatian limestones with the appearance of local tectonic trenches and horsts. For example, the terrain at which the Vcr-1/77 well is located is in a descending structure where the Sarmatian limestones are at about 70 meters deeper than those in the immediate surroundings.

By analyzing the profile of the wells, towards the west, it was found that the Sarmatian limestones pinch out and grade into other facies of the Sarmatian deposits (marls, alevrites). In addition, it has been noted that the thickness of the Sarmatian limestones decreases in that direction. The boreholes drilled southern of the analyzed profile are characterized by the lack of Sarmatian sediments as well as the Sarmatian limestones, since the sediments of the upper Miocene (Pannonian and Pontian) are deposited discordantly over Paleozoic-Mesozoic paleolandscape (e.g. Devonian shales). In this part of the southern periphery of the basin, Miocene transgression took place only in the upper Pannonian.

Hydrogeological characteristics of Sarmatian limestones

Aquifer in the Sarmatian limestones have relatively restricted distribution in the Kolubara coal basin, but its largest part lies in the eastern and southern parts (Figure 1). According to the hydrodynamic characteristics, an aquifer in the Sarmatian limestones in the area of the coal basin is under the pressure (i.e. confined aquifer) (Milivojević, 2006). The water of aquifer from this section, generally flows towards the west (Milivojević, 2006).

In the wider area of the Kolubara coal basin, that is, northeast of it, in the area of Barajevo-Manic-Sibnica, the Sarmatian limestones are directly exposed on the surface of the terrain, where the recharge of aquifer is mainly done by the infiltration of atmospheric waters. To the west, younger clay sediments prevent the recharging of aquifer. Discharging of water from the Sarmatian limestones is done in the valleys of the eastern tributaries of the Turija River, in the zones of contact of the Sarmatian limestone with Pannonian clay. In the southern part of the Kolubara coal basin, recharging of aquifer within the deeper Sarmatian limestones is not clear. However, the assumption is that its balance of water is well-balanced during the geological time that has passed since the time of its formation. The leakage from the confined aquifer is very little in natural conditions and is mostly carried out under the influence of the "thermolift", and to a lesser extent, under the influence of gravity or hydraulic gradient.

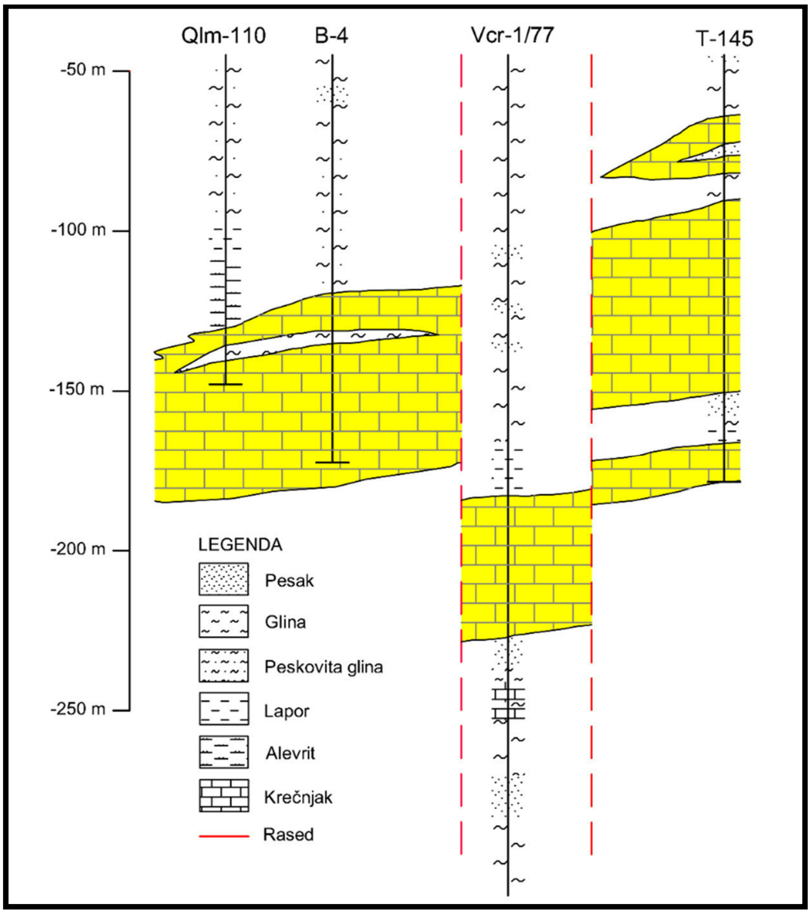
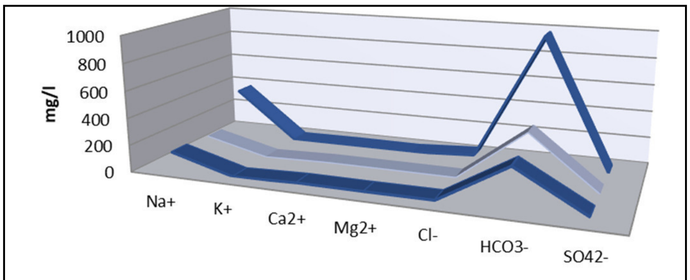


Figure 2 Cross-section through some drillholes as shown in Figure 1

Physical and chemical characteristics of ground waters in the Sarmatian limestone

The groundwater was sampled from the well B-4, from the borehole Qlm-110 (in the research area), and from the Po-190/80 borehole which is located north of study area but useful for data correlation. The water from these objects belongs to the hydrocarbonate-sodium group with temperatures up to 30.2 ° C, which is classified into water suitable for the exploitation of subgeothermal energy. This aquifer is characterized by chemical zonation, depending on the space, i.e. with departing from recharging zone, the mineralization gradually increases, as is the temperature. To the depth of about 250m, the quality of spring water is about the same as the quality of drinking water. The groundwater temperature measured in the Qlm-110 well is 28.2°C, the mineralization is 558 mg/l, while in the B-4 water temperature is 25°C and the mineralization is 550 mg/l.



	Na+	K+	Ca2+	Mg2+	Cl-	HCO3-	SO42-
B-4	132,3	1,8	15,5	13	13,50	305,00	30,00
Qlm-110	117,8	3	14	12,8	10,70	390,40	10,00
Po-190/80	370,00	2,50	5,50	2,30	29,60	972,00	0,20

Figure 3. Chemical composition of groundwater samples taken from well B-4 and borerhole Qlm-110 (Vreoci)

The measured water temperature sampled from the Po-190/80 well is 30.2°C, and the mineralization is 1.43 g/l. The groundwater from the well Po-190/80 belongs to the same type of water as the water from study area, but it is more mineralised and has higher temperature, which is probably the result of deeper burial of the Sarmatian limestones than at the investigative sites. This information is indicative and important due to the fact that in the research area in the tectonically lowered structure, drilled by the borehole Vcr-1/77 where the Sarmatian limestones are located at greater depth than in the surrounding (for about 70m from B-4), it can be assumed that the temperature of the underground water in them is probably higher than in B-4. The authors did not have the measured values of groundwater temperature for the other boreholes mentioned in this work. The water of the Sarmatian limestones were captured by the wells B-4 and B-5 at the location of Vreoci village, in the amount of approximately 8 l/s, the well Qlm-110 also has a yield of about 8 l/s, while the yield of the well Po-190/80 is 16,6 l /s. According to preliminary estimates (Milivojević, 2006) and data synthesis, the assumption is that in the perspective location, the production of exploitation wells of depth 300-450m can yield 10-20 l/s with a temperature of 30-38 °C. Based on the analysis of water from wells Qlm-110 and well B-4, it can be concluded that the lithological composition have not affected the chemical composition of groundwater, given the extremely high content of Na and the extremely low content of Ca (Figure 3). According to internal data for the exploitation of geothermal water, regardless of its chemical composition and temperature, it is necessary to produce boreholes at given locations of depths of 300-450 m. From them it is possible to obtain a yield of 10-20 l/s with a temperature of 30-38 °C.

Conclusion

Based on the analysis of earlier research results, it can be concluded that in the central belt of the southern part of the Kolubara basin, the Miocene limestones occur and may be potential aquifers that can be used in the future as a source of drinking water. The occurrence of Badenian and Sarmatian limestones are determined. The limestones of Badenian stage have considerably lesser distribution and have been revealed only in one borehole (Vcr-1/77) with a thickness of 12 meters. However, these sediments can be collectors of groundwater of exceptional quality, and especially in terms of balneological properties. The Sarmatian limestones have much larger thickness as well as distribution in relation to Badenian limestones. As previously mentioned, based on the analysis of the core of the wells, their thickness is locally up to 60 meters. In the wider surroundings of the study area, i.e. going towards the central part of the Kolubara coal basin, the limestones pinch out and grade into other facies of Sarmatian sediments (i.e. marl, clay, sand). In the very southern area of the Kolubara basin, the Sarmatian limestones are absent, as it has been noted that the sediments of the upper Miocene (Pannonian and Pontian) lie discordantly over the Paleozoic-Mesozoic paleolandscape. It was also found that the structural fabric of Miocene deposits in this part of the Kolubara basin is much more complex than it was previously known. This primarily relates to newly identified local neo-structures that were formed through differential movements of faulted and separated blocks, which positioned Sarmatian limestones at different altitudes. The distribution, thickness and position of the Sarmatian limestones as well as the known hydrogeological characteristics of these deposits, it can be concluded that the Miocene limestones, especially the Sarmatian ones, represent the unused hydrogeological potential of Serbia, which is worth further research.

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FIRST PRESENTATION OF MODIFIED POINT DILUTION TEST FOR ASSESSMENT OF GROUNDWATER FLUX IN KARST AQUIFERS

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Abstract: The aim of the research was to design an easily applicable test that can be used for the assessment of groundwater flux (velocity) in highly permeable karst aquifers. The modified point dilution test (MPDT) is based on the constant-rate injection of tracer solution in a borehole (or sub-vertical cave) and continuous measurement of tracer concentration in the same borehole. When the concentration is stabilized then the groundwater inflow in the borehole can be assessed on the basis of the known injection rate and measured concentrations (initial and stabilized). By the obtained inflow and known borehole cross-sectional area, the groundwater velocity under a natural hydraulic gradient can be assessed. The test was applied in well B1 (Lješanska Nahija, Montenegro). The obtained apparent groundwater velocity amounts to 1.71×10^{-4} m/s. The modified point dilution test (MPDT) provides satisfactory results only in highly permeable aquifers.

Key words: Modified point dilution test, groundwater velocity, borehole, karst aquifer

Introduction

The application of tracer dilution tests in boreholes began in the middle of the last century. The main goal of these tests is to assess groundwater velocity in the zone of a borehole. This paper suggests modifications to the well-known point dilution test (PDT), the application of which is based on the slug injection of tracer into a borehole (well) and continuous concentration measurements in the same borehole. A more rapid decrease in concentration indicates a higher inflow of groundwater into the borehole (higher groundwater velocity), and a slower decrease indicates the opposite (Drost et al. 1968; Freeze and Cherry 1979; Lamontagne et al. 2002; Van Tonder et al. 2002; Brouyère et al. 2008; Akoachere and Van Tonder 2011).

This paper presents a new approach to the application (and data processing) of PDT, so hereinafter it will be called a modified point dilution test (MPDT). The aim was to design a test that would overcome the shortcomings of classical PDT (Lamontagne et al. 2002; Akoachere and Van Tonder 2011) and at same time be easily applicable in karst terrains. Besides boreholes and wells, the MPDT can be applied in sub-vertical caves filled with groundwater, which are often difficult to access. For that reason, simple and portable equipment that does not require a power supply is suitable for this test.

Classical point dilution test (PDT)

The point dilution test (PDT) involves the injection of tracer into a borehole, its mixing with bore water, and continuous concentration measurement in the same borehole. The transit of groundwater through the borehole, thanks to its natural gradient, dissolves the tracer over the measured time. Faster dissolution indicates the more intensive transit of groundwater (higher inflow/outflow), i.e. it indicates a higher groundwater velocity (flux), and slower dissolution indicates the opposite. According to Freeze and Cherry (1979), the apparent groundwater velocity v* (average bulk velocity across the centre of the well bore) can be calculated by the following equation:

$$v^* = -\frac{W}{A \times t} ln(\frac{C_d}{C_s}) \quad (1)$$

where, W–volume of water contained in the borehole (or tested segment of borehole); A–cross sectional area of the water column in the borehole (or segment); C_s–tracer concentration at time t=0, C_d–tracer concentration at time t, t–time needed for the concentration to decrease from C_s to C_d.
The apparent groundwater velocity (v*) is different from the Darcy velocity (v_d) because the natural groundwater flow is disturbed by the existence of the borehole, which lends higher hydraulic conductivity to the zone. However, the Darcy velocity can be assessed by dividing v* with a borehole-distortion factor α (most often α=2) (Lamontagne et al. 2002; Van Tonder et al. 2002). Then, the average linear velocity (v_r) can be assessed by dividing v_d with the porosity of rocks (Freeze and Cherry 1979).
In order to achieve the uniform mixing of tracer within the tested borehole (or borehole segment), artificial mixing of bore water is required. The mixing is often carried out by mixers installed at the bottom of the tested segment or by establishing water recirculation using a pump (Freeze and Cherry 1979; Lamontagne et al. 2002). The perturbation of water caused by artificial mixing can affect the rate at which the tracer flows out from the well. Lamontagne et al. (2002) points that out precisely as the main technical difficulty in the classical PDT. Further, it is not always easy to achieve a homogeneous solution of tracer within a tested borehole. For these reasons, the PDT has been applied much less often in recent years. It is believed that the shortcomings of the PDT can be overcome by means of the modifications presented in the following section.

Modified point dilution test (MPDT)

The test for the assessment of groundwater inflow into a borehole proposed in this paper is an analogy of a technique which has long been used in hydrology

for measuring stream discharge, known as the salt dilution method with constant-rate injection (Moore, 2004).
The injection of the salt solution into a well should be carried out with a low constant injection rate (through a hose with a diameter up to 6 mm), and simultaneously the concentration (electrical conductivity) should be measured in the same well until its stabilization. This stabilization occurs when equilibrium between two flow rate components of different concentrations (injection rate and groundwater flow) is achieved (Fig. 1). Based on the known injection rate and measured concentrations in the well (initial and stabilized) the groundwater flow which enters the well under a natural hydraulic gradient can be assessed.

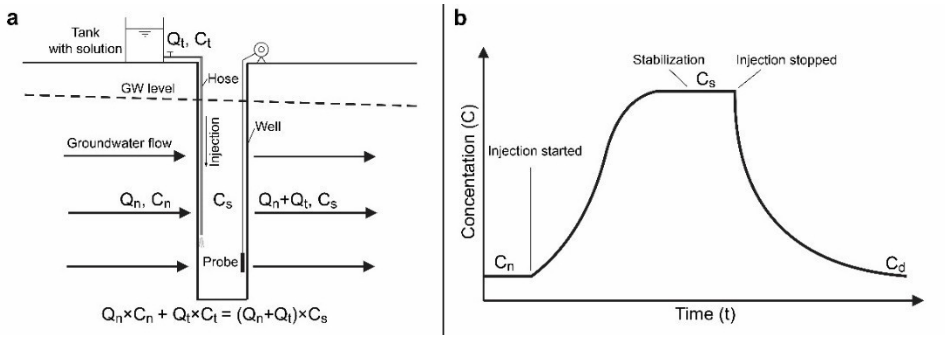

Fig. 1. a) Application of a constant rate-injection test for the assessment of groundwater inflow to a well; b) schematic diagram of the change in tracer concentration during the test

The assessment of groundwater flow into a well by MPDT is based on a water and tracer mass balance equation, i.e. on the mixing of two flow rate components with different concentrations (Fig. 1). By introducing values for the relative concentration (C_n=0; C_t=1), the mass balance equation can be expressed as:

$$Q_n = Q_t\left(\frac{1}{C_s} - 1\right) \quad (2)$$

where, C_n–initial (natural) concentration of tracer in groundwater; C_t–concentration of injection solution; C_s–stabilized concentration at the measuring point; Q_n–groundwater inflow in a well; Q_t–injection rate.
Since the relative concentration of salt (NaCl) in water relates in a linear way to electrical conductivity (EC), the relative concentration C_s can be expressed as C_s=a(EC_s - EC_n) (Moore 2004), where: a–is the slope of the relation between C and EC, EC_n–initial (natural) electrical conductivity of groundwater, EC_s–stabilized electrical conductivity in a well after a certain amount of time has passed since injection commenced. Then, from the Equation 2 follows:

$$Q_n = Q_t\left(\frac{1}{a(EC_s - EC_m)} - 1\right) \quad (3)$$

Through the assessed groundwater inflow (Q_n) to a well and a cross-sectional area of the well (A), the apparent groundwater velocity can be calculated (Lamontagne et al. 2002). Then, the Darcy velocity (v_d) and average linear velocity (v_r) in the zone of the well can be assessed (see previous section). If there are other boreholes in the surrounding area, the hydraulic gradient can be measured (i), and by means of Darcy's law the hydraulic conductivity can be assessed ($K = v_d / i$). In order to obtain data on the decrease in concentration, measurements should continue in the well after the process of injection has ceased. This data can be used for checking the constant-rate injection test by applying the classical data processing approach of PDT (Equation 1).
Equations for the assessment of a desired concentration in a recipient after tracer injection, and a detailed explanation of calibration (establishing a relation between relative concentration and electrical conductivity) are presented in Moore (2004). Also, a very useful flowchart for the estimation of a critical injection rate (the injection rate should be much lower than the critical injection rate), tracer injection duration, volume of tracer fluid, and mass of tracer injected, is presented in Brouyère et al. (2008). The MPDT gives satisfactory results only in highly permeable aquifers where such a limited injection rate cannot slow the inflow of groundwater in a well. For the quantification of groundwater velocity in less permeable rocks, the more complex and more accurate finite volume point dilution method (FVPDM) should be applied (Brouyère et al. 2008).

Application and results

The MPDT was applied in well B1 (Lješanska Nahija, Montenegro). An unconfined karst aquifer is present in this area. Groundwater recharge occurs through the infiltration of atmospheric water (mean annual precipitation is around 2,700 mm). The main discharge point of the karst aquifer is Kaludjerovo Oko Spring which is located 250 m southeast of the well. The well is 70 m deep and drilled through karstified limestone. The depth to groundwater level is around 26 m. The diameter of the installed pipe is 180 mm to a depth of 56 m, and 165 mm for the depth from 56 to 70 m. A well screen extends from 26 to 70 m. There are three piezometers around the well where the groundwater level was measured (Radulovic et al. 2017). The hydraulic gradient (i) established on the basis of this measurements is 0.007. The results of a pumping test from well B1 show that the pumping of 10 l/s caused a drawdown of 5 cm (Radulovic et al. 2017).

The MPDT was applied with the following equipment: probe for the measurement of electrical conductivity in boreholes (diver), graduated bottle filled with 27 l of water, 60 m long hose (diameter 6 mm), 5 kg of salt, stopwatch, rod for mixing the solution, equipment for calibration (1 l and 2 l graduated flasks, 1 l graduated cylinder, squirt bottle and five sterilized syringes of 10 ml). First, an 18.5% solution of sodium chloride was prepared (5 kg of NaCl was dissolved in 27 l of water). From this solution 10 ml was transferred to a 1 l flask for the purposes of calibration later on. Before the start of injection, the hose was lowered to a depth of 52 m, and a diver to 42 m. The injection of the solution lasted 1180 s (around 20 min). The constant injection rate was Q_t=0.023 l/s. After injection had ceased, the diver was kept in the well for another 1520 s (around 25 min) to measure the decrease in concentration. Then, calibration was carried out according to the explanation from Moore (2004). The slope of the established relation between C and EC was $a=2.45\times10^{-6}$. According to the data downloaded from the diver, a Conductivity-Time diagram was obtained (Fig. 2). The initial (natural) electrical conductivity of bore water before the injection was 275 μS/cm. From the diagram (Fig. 2) it can be seen that conductivity increased for the first 14 min of injection, after which it stabilized at 7,278 μS/cm on average, until the injection ceased. After injection ceased, the concentration began to decline, and in 1520 s (around 25 min) it decreased to 874 μS/cm.

Using the Equation 3, it has been calculated that the inflow in the well is Q_n=1.317 l/s. Given that the cross sectional area of the well is 7.71 m², the apparent groundwater velocity is $v^*=1.71\times10^{-4}$ m/s. The smoothly distributed data of the last part of the diagram (decrease in concentration; Fig. 2) indicate that continuous injection led to the homogenous mixing of tracer along the entire volume of bore water (V=0.808 m³). Such data can successfully be used for processing by means of the classical PDT approach (Equation 1). The apparent groundwater velocity obtained by this approach is $v^*=1.70\times10^{-4}$ m/s. Comparing the velocities, obtained through two different approaches applied to different data sets, it can be seen that almost identical values have been calculated.

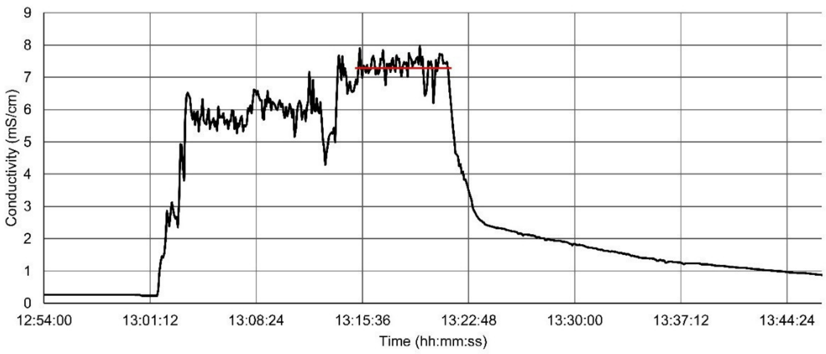

Fig. 2. Change in electrical conductivity during the test (the red line represents the EC_s value)

Conclusion

Based on the application of the MPDT and the checking of results, it has been concluded that the test can be used for the assessment of groundwater velocity (flux) in highly permeable kart aquifers. If the hydraulic gradient is known, the hydraulic conductivity can be assessed, but this value should be used with caution, bearing in mind the limitations of the Darcy law in karst aquifers (Kresic 2007; Stevanovic 2007). The MPDT can also be applied for the assessment of groundwater inflow in a sub-vertical cave filled by water, even where its dimensions are unknown (also, the filled volume of a cave could be assessed). Taking into account that the MPDT involves the assumption that the limited injection rate (through the hose 6 mm diameter) cannot slow the inflow of groundwater in a well, results should only be considered as assessed values. However, the aim of the research was to develop an easily applicable approach (involving simple equipment) that could be used for the assessment of groundwater velocity in highly permeable karst aquifers, which are often inaccessible with heavy equipment.

Acknowledgments I am extremely grateful to my friend Damjan Perošević, who helped with field work during the application of the test.

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HIGH WATERS STUDY OF A CLASSICAL KARST POLJE – AN EXAMPLE OF THE PLANINSKO POLJE, SW SLOVENIA

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Abstract: To gain information on basic hydrogeological behaviour of a classical karst polje high waters occurrence, statistical and time-series analyses of daily discharge and water level values have been performed. The study was done in the case of the Planinsko Polje, which represents an important area of confluence of karst waters from several contributing sub-catchments and an essential floodwater retention basin. Average and extreme annual and seasonal duration of high waters, and their amplitudes have been determined. The period of the greatest possibility of a high intensity event occurrence is the cold part of the year, tied to the mid-autumn rainfall peak, winter rains and snowmelting. The gained results improve the understanding of poljes' high waters occurrence and will contribute to a more careful land use planning and flood retention capacity evaluation. The needs for further studies have been identified.

Key words: karst polje, high water, flooding dynamics, time-series analyses, hydrogeological behaviour.

Introduction

Among the various questions regarding karst hydrogeology, flooding in karst poljes remains one of the least understood phenomenon and its dynamics the most difficult to predict. The occurrence of high waters is the result of fast rise of the karst water table and insufficient swallow capacities of underground conduits induced by very intensive rainfall or snowmelt events within a short period of time (Gams 1978, 2003; Ford & Williams 2007; Bonacci 2014). Not only is this occurrence related to hazard, at the same time it acts as a natural reservoir that buffers floodwater of the downstream areas.

The specific nature of groundwater flow has been proven to play an important role in flood genesis, with flooding directly linked to the structure and hydraulic properties of karst aquifers (White 1988; Gams 2003; Gabrovšek et al. 2018). Due to the rapid infiltration of water into the underground and predominantly subterranean water percolation through the unknown karst channels, the evaluation of water storage and transfer through karst aquifers are still a challenge, as well as forecasting flooding duration and intensity (Kovačič &

Ravbar 2010). Up-to-date studies and measures have mostly been related to civil engineering profession, for solving questions related to flooding or drought prevention, water supply and power generation. Several poljes have consequently been permanently modified (Milanović 2004). However, the origins of karst high waters are yet insufficiently understood in the frame of a possible intensification of exceptional hydrological events.

The present paper aims at basic characterisation of hydrogeological behaviour of a classical karst polje that has not been significantly influenced by human encroachments and can serve as a basis for further numerical and statistical studies investigating flooding dynamics. The study focuses on the Planinsko Polje as a case of a classical, i.e. sample karst polje. The polje is a significant confluence of karst waters from several contributing sub-catchments and an essential floodwater retention basin. The site-specific importance of the study was to assess the hydrogeological role of a particular karst polje in a wider regional context.

Study area

Planinsko Polje is situated in SW Slovenia. The polje receives autogenic recharge from the high karst plateaux of the Javorniki mountains (Fig. 1), drains allogenic catchment of the Pivka River basin on the west and a chain of karst poljes on the east (among which the Cerkniško Polje is the largest). In the south of the Planinsko Polje, water emerges in two large springs (Unica, Malenščica). The two watercourses join in the Unica River that crosses the polje and sinks on its northern and eastern edges. The water finally re-emerges at the outskirts of the Ljubljana Basin as Ljubljanica River. The polje extends over 10 km^2 at the elevations between 440 and 455 m asl.

The mean annual precipitation of the studied area (1981–2011) is estimated at about 1,500 mm (Ministry of the Environment 2017b). The mean daily discharge of the Unica River recorded at the Hasberg gauging station varies between one and 100 m^3/s, whereas the mean annual discharge is 21 m^3/s (Frantar 2008). More accurate measurements of maximum discharges are hampered by flood water. In addition to the Unica and Malenščica springs, it encompasses the Škratovka spring group as well (Fig. 4). Furthermore, several springs located below the mountain of the Planinska Gora recharge the polje with an estimated maximum capacity of $\sim$ 32 m^3/s (Gams 1980 and references therein). The Unica River starts to overflow when its discharge at the Hasberg gauging station exceeds 60 m^3/s; eastern ponors have the swallow capacity of $\sim$ 18 m^3/s and northern ponors $\sim$ 40 m^3/s (Šušteršič 2002; Blatnik et al. 2017 and references therein).

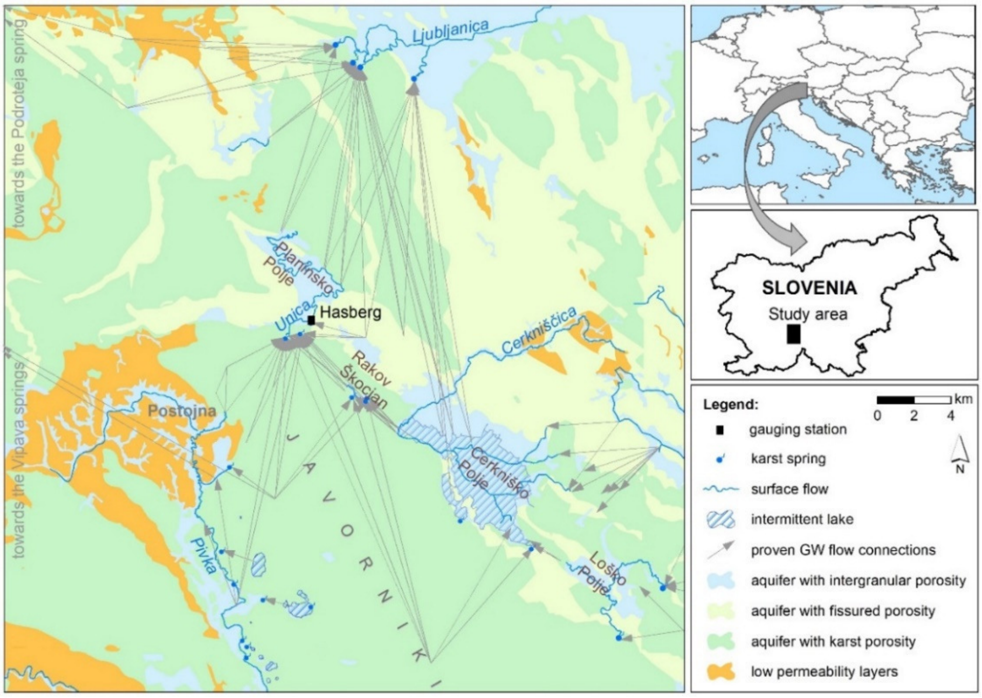

Fig. 1. Hydrogeological map of the study area showing hydrogeological units, karst poljes, springs, surface water, proven groundwater flow connections and gauging station location.

Although historical data are difficult to compare to current regular measurements, some extreme floods have previously been recorded in 1801, in 1851/52 when water level presumably reached an elevation between 456 and 458 m asl and in 1923 when water level reached 453.4 m asl. In 2014 water level reached 453.2 m asl (Gams 1980; Frantar & Ulaga 2015). Then the high waters extended over 10.3 km^2, more than forty houses and other facilities have been flooded.

Methods

Acquisition of relevant input data included daily discharge and water level values of the Unica River recorded at the Hasberg gauging station (Ministry of the Environment 2017a). The study focuses on the 60-year period between years 1954 and 2014. Relative water level data from the gauging station have been converted into elevations (in m asl). The high waters criteria of this study encompass situations when water level > 447 m asl and discharge > 60 m^3/s. Fundamental statistical and time-series analyses were employed including basic descriptive statistics of different variable time series, i.e., long-term, seasonal, and event comparative analysis.

Results

During the 1954–2014 period, high waters on the polje occurred on average 37.9 days per year. The longest periods the polje has been overflown was in 1960 (altogether 137 days) and in 2014 (altogether 126 days). High water levels are usually seasonal, tied to the mid-autumn rainfall peak, winter rains and snowmelting. Due to the influence of karst retention, the system's response to higher amount of precipitation is time-lagging for up to a month (Fig. 2). Significant is also the impact of evapotranspiration on aquifer recharge during the warm part of the year.

An event of high waters lasts on average for ten days, but can also be as long as 78 days, as it occurred in autumn and winter 2000/01. Yearly up to thirteen separate events of high waters can occur, but in the 60-year period on average 3.5 events occurred annually. These events differ in amplitude, duration and in water level increase or decrease dynamics (Fig. 3). On average, the water level of the events increased for 42.5 cm/day or 1.8 cm/h respectively. Similarly, the water level decreased on average for 10.8 cm/day or 0.45 cm/h respectively. The maximum increase of 210 cm/day or 8.8 cm/h respectively has been recorded at an event that occurred in October 1961. The maximum decrease of 43 cm/day or 1.79 cm/h respectively has been recorded at an event that occurred in November 1969.

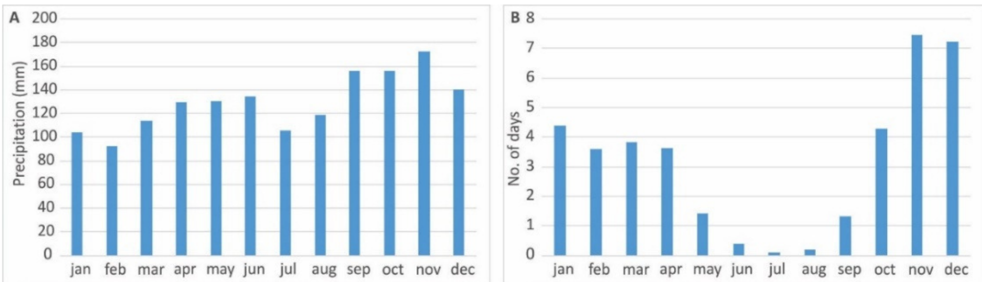

Fig. 2. Comparison of (A) average annual precipitation amount recorded at the Postojna rain gauge in the 1961–2014 period and (B) average number of days with high waters in the 1954–2014 period shows a primary peak of precipitation in November and the highest number of days with high waters in November and December.

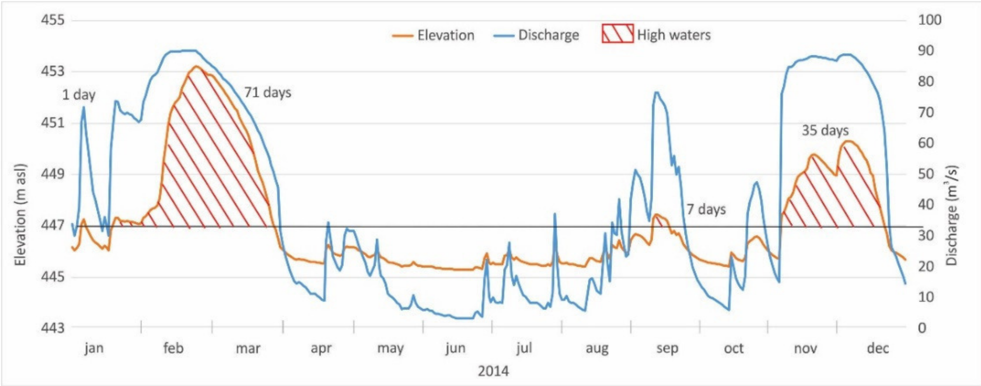

Fig. 3. Hydrograph showing high waters events of different dynamics as regards amplitude and duration. The year 2014 has been extreme in this respect.

The areas located up to 447.9 m asl are on average flooded up to 27.5 days annually, the areas in elevation up to 449.9 m asl are on average flooded 3.3 days annually and the areas higher than that are on average flooded 1.2 days annually or even less (Fig. 4). In the observed period, water level rose above 451 m asl only in years 1970, 1979, 1992, 2000, 2008, 2010 and in 2014. Only in 2014 water level rose above 452 m asl, when more than 70 million m^3 water has been retained in the polje (Frantar & Ulaga 2015).

The period of the greatest possibility of high water occurrence are November and December, when high waters last on average for 7.5 or 7.2 days respectively. Then the water level can increase up to 451 m asl. The same elevations can be reached also in April and May mainly due to the events in 1970 (water level stayed above 450 m asl for 22 days) and in 1975. Generally, duration of high water events in these months is shorter, on average between 3.8 or 3.6 days annually. However, the highest events occurred in February and March mainly due to the event of 2014, when the water level persisted above 452 m asl for 22 days. In September water level can reach 450 m asl. During the summer months (June – August), high water events last on average less than a day annually and do not surpass the elevation of 448 m asl, even if the most extensive event lasted 9 days (occurred in August 1977).

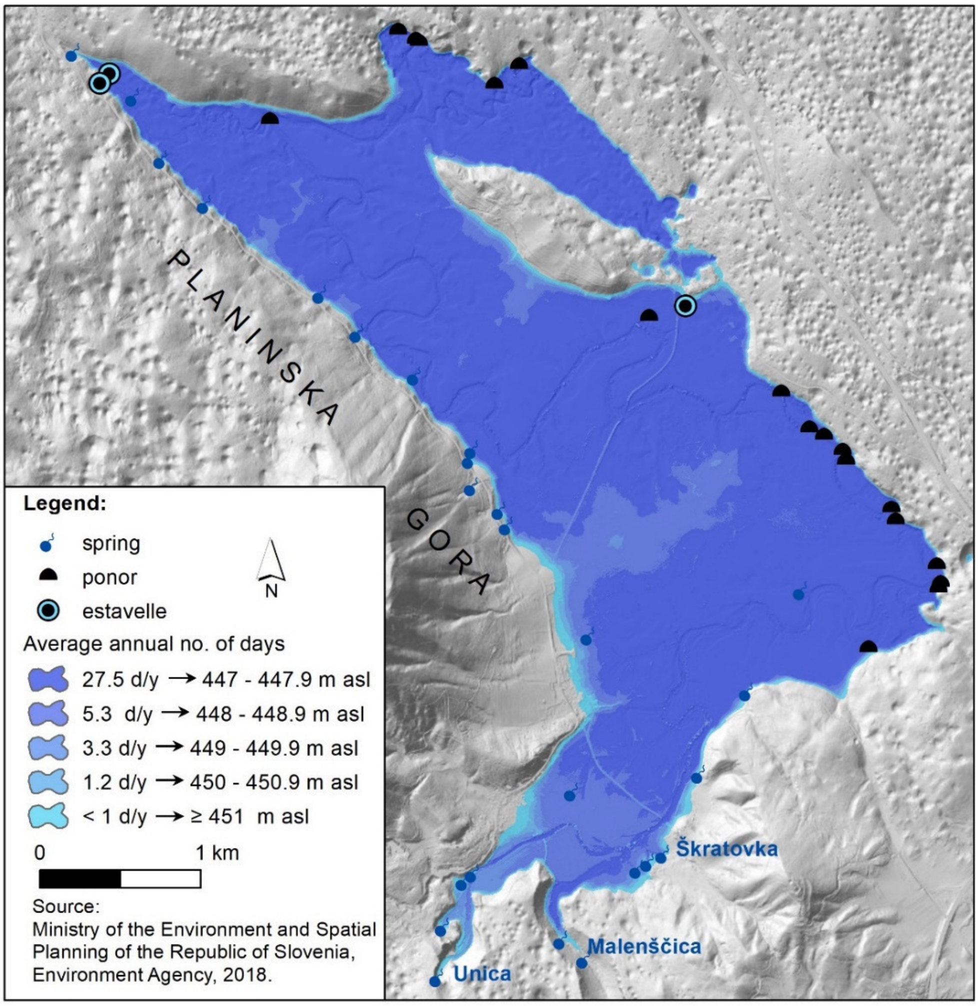

Fig. 4. Average annual duration of high waters on the Planinsko Polje and their extents.

Discussion and outlook

The study presents the preliminary results of the hydrogeological characteristics of a classical karst polje. The gained results will be useful for further numerical and statistical studies of karst poljes flooding dynamics, which will lead to a better understanding of their hydrogeological behaviour, flood hazard mitigation, evaluation of their buffering capacity and land use planning reconciliation.

However, the study has been made on basis of a single gauging station that is located close to the edge of an about 10 km^2 large polje with a relatively flat bottom. As this location is not representative for the whole polje (due its denivelation, additional springs located downstream of the station, etc.), an on-going research established a denser monitoring network. Continuous measurement of water level of 15 additional points on the polje and in the water active caves of its recharge and discharge areas has been set up. On these bases, detail study of the flooding dynamics will be possible. It's added value will represent a comprehensive determination of the factors influencing polje flooding and evaluation of their impact on the flood amplitude and duration.

Acknowledgement
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"MID HORIZONS" – POSSIBLE WAY OF WATER UTILIZATION FROM CERNIČKO POLJE AND GATAČKO POLJE IN HYDROENERGY PURPOSE

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Abstract: Utilization of water from Gatačko polje and Cerničko polje was considered in the early 60s, within the concept of the Hydro Power System Trebišnjica. Changes in the concept of the system development excluded utilization of water of these fields. On the other hand, the development of the system in last a few decades and real problems that occurred during it actualized this issue as very important. Problems related to water distribution and the efficiency of electricity production, in available hydro power plants situated in the Republic of Srpska, Federation of B&H and Croatia, request the higher level of cooperation in near future. The part of this solution is also control of the outflow from Cerničko polje toward lower fields, Fatničko polje and Dabarsko polje. It could be realized just after intensive geological and hydrological explorations and construction works, in the first order the construction of an appropriate dam and an embankment in Cerničko polje. The main goal of these actions is to prevent the underground flow from Cerničko polje toward the estavelle Obod in Fatničko polje during wet periods and in the same time to store and utilize water which in natural conditions goes unutilized within the system. It is concluded that after the construction of the dam and the embankment about 90 M m^3 of water should be stored in Cerničko polje and it makes energetic potential for production of 75 GWh in existing power plants. The reservoir of the above-mentioned volume would provide conditions for regular transfer of water from Dabarsko polje and the future hydropower plant Dabar toward downstream hydro power plants through the tunnel Dabarsko polje - Fatničko polje. It will provide additional increase in electricity production in the HPP Trebinje I and the HPP Dubrovnik, with significant financial effects.

Key words: Mid Horizons, water, storage, reservoir, electricity, Cerničko polje.

1. Introduction

For the first time water utilization from Gatačko and Cerničko polje was considered in the early 60s of the last century. The concept was based on water utilization from Gatačko filed in the power plant in Cerničko field, located in the northern edge of the field. The next step is to utilize the water accumulated in Cerničko polje in the power plant located in the northern edge of Fatničko polje. Water from Fatničko polje could be transferred by a hydro-technical tunnel to the HPP Bileća, together with water from Dabarsko polje and water from the

HPP Dabar. After the water reaches Bileća reservoir it would be utilized again in the HPP Trebinje I, the biggest one in the HPS Trebišnjica and further in the HPP Dubrovnik (Croatia) and the PHPP Čapljina.
But after the 60s of the last century this concept was not further considered, and it was practically left. The latest activities on the construction of the facilities within the project named „Upper Horizons" and some recent analyses provided from the experts of the HPS Trebišnjica triggered the idea again.
The topic has been actualized during the last months and this paper tries to support the idea about possible water utilization from the mentioned fields, within the whole management concept of the HPS Trebišnjica. Key questions regarding the utilisation considered in the paper are:

- geological and hydrogeological conditions of Cerničko polje related to water storage;
- regulation of swallow holes in the southern edge of the field related to water storage;
- possible volume of stored water for different top levels of the reservoir;
- the retardation of maximum inflows into Fatničko polje, allowing water transfer in efficient way;
- management of the stored water related to water management in Nevesinjesko polje, Dabarsko polje and Fatničko polje.

2. Geographical characteristics of Cerničko polje

Cerničko polje is one of the highest fields in the Eastern Herzegovina, Bosnia and Herzegovina, periodically flooded. Some basic information about this field are given in the Table 1.

Table 1. Basic information about Cerničko polje

Area	4.1 km^2
Field-floor Elevation	810 m - 850 m above sea level (m a.s.l.)
Length	4.0 km
Average width	1.0 km
Field Type	Closed karst field
Drainage system	Swallow holes

3. Geological and hydrogeological conditions in Cerničko polje related to water storage

In geological sense, the field floor consists of flysch sediments of the Paleocene-Eocene age. It is surrounded by the Cretaceous and the Jurassic limestone (Fig. 1). In the northern edge of the field the Palaeocene-Eocene flysch sediments are in the nape contact with limestone and in the normal one in the southern edge with the Middle Cretaceous limestone (Mirković et al., 1974).

On the southern edge of the field, close to the contact of impermeable flysch sediments and permeable Upper Cretaceous limestone, there are numerous swallow holes, which drain waters from the field. The most important are Ključki ponor (the westernmost point in the Fig. 1) and Jasovica (mid-point in the southern edge of the field in the Fig. 1) (Krunić et al., 2014).

The crucial thing regarding water storage is the selection of the reservoir top level, mostly depending on permeability of the Upper Cretaceous limestone in the southern edge of the field, because the contact of the Palaeocene, Eocene impermeable flysch sediments and the Cretaceous permeable limestone in the northern part of the field is lower than maximum considered level of the reservoir (855 or 860 m a.s.l.).

In thick-layered and massive limestone 22 ponors are identified along the southern edge of the field. The ponors Jasovica (815 m a.s.l.) and Ključki ponor (825 m a.s.l.) are primarily important regarding water storage.

In the zone of Jasovica ponor, within limestone of the Upper Cretaceous age, there are two different zones determined by detail geological mapping (Torbarov, 1967):

1. tectonized limestone appear west of the ponor Jasovica, toward the Paleocene, Eocene flysch sediments,
2. limestones are thick-layered and more compact on the east of the mentioned swallow hole.

Similar situation is in the southern edge of the polje around Ključki ponor.

1. very tectonized limestones appear in the final part of the Ključka river and south of Ključki ponor;
2. toward the east these zones stretch along about 1 km and compact limestone reclines on this zone. But after 1 km there is a zone of the Upper Cretaceous very tectonized limestone.

In the report from 1962 (Torbarov, 1967) it is emphasized that limestone, within these tectonized zones, are very intensively fissured. The fissures are generally orientated in two directions. The first one is the Dinaric direction and the second one is vertical on this first. The fissures generally have large slope angle. It is also possible to identify the third fissure family, so-called interlayer fissures, different from the previous two by smaller slope angle.

In geological/hydrogeological sense detail mapping and permeability test are necessary in the southern edge of the field in the zone of the Upper Cretaceous limestone, especially between Jasovica ponor and Ključki ponor in order to define necessary actions regarding ponors closing and water storage. More details will be considered in the next chapter.

4. Possible solutions for regulation of ponors in the southern edge in the aim of water storage

It is necessary to provide technical solutions and close the above-mentioned ponors in order to store water in Cerničko polje. In the northern part of the filed there are no necessary actions because the contact of the Paleocene, Eocene flysch and Cretaceous limestone is above proposed maximal level of stored water (855 or 860 m a.s.l.). There are two ways of the ponors regulation in the southern edge:

1. To decrease the reservoir maximal water level (above 855 m a.s.l.), practically on the contact of the Paleocene, Eocene and the Cretaceous sediments. But in this case, stored water is pointless, and reservoir would not be technically and economically justified.
2. To adopt 855 or 860 m a.s.l. as maximal water level in the reservoir, but with significant technical measures regarding water loss prevention.

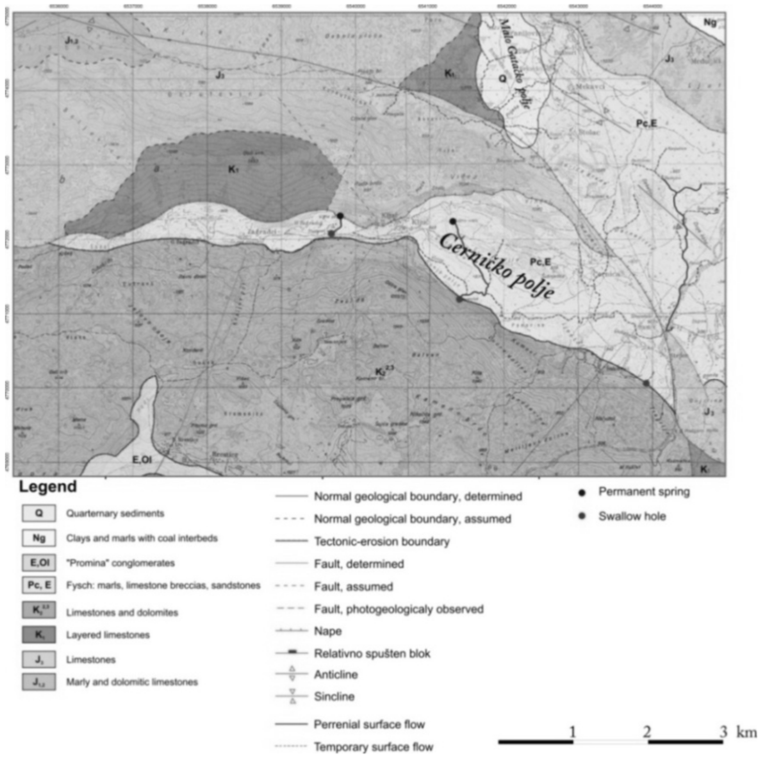

Fig. 1. Geological map of wider area of Cerničko polje

It is obvious that the second solution is the only acceptable.

Based on the results of the previous dye tests it is possible to conclude there are two separated, more or less concentrated, underground channel systems in the field:

a) the first one is toward Fatničko polje (and after that to Trebišnjica spring/Bileća reservoir) and

b) the second one is directly to the Trebišnjica river springs or indirectly, via Plane.

These two systems, or precisely the ponors connected to the systems, must be isolated from the future reservoir formed in Cerničko field. There is also important assumption that ponors in the eastern part of the field are connected to Ključki ponor. Of course, it must be proven by explorations.

If this assumption is valid, the solution will be simpler. In this case underground channels, that connect the ponors in the eastern part of the field with Ključki ponor, must be isolated by a slurry wall. The location of the wall should be probably between Jasovica ponor and Ključki ponor, closer to the second one. There are two possibilities for the isolation of Ključki ponor:

1) close the ponor by a dam, located near the ponor or

2) construct a dam in the narrowest part of the field, near Ključ village.

Jasovica ponor must be closed as well. An embankment must be constructed in the southern edge of the field, founded in the Paleocene, Eocene flysch sediments.

All mentioned assumptions have to be proven by explorations, before final solution proposal. The explorations must cover not less than:

- drilling in the southern edge of the field, bottom of the field (to determine the thickness of the Pc, E sediments) and in the zone of planned dams, with permeability tests and outfit of boreholes for groundwater level observation (conversion to piezometric boreholes),
- geophysical explorations (seismic and geoelectric), in order to determine flysch thickness, but also in the southern edge of the field to register underground flows and their position and to determine the erosion basis as well; refractive seismic exploration should be performed in the zone of the dams to determine the module of elasticity;
- dye tests should be performed in Jasovica ponor and some other smaller ponors, but dye also should be injected in the boreholes, after permeability measurements. The aim of the dye tests is determination of the connection of mentioned ponors and channels reached by boreholes with Ključki ponor;

5. Estimation of the ponors capacity and water storage in Cerničko polje

Data collection for estimation of the ponors capacity and water storage volume

In order to determine the capacity of the ponors if the field (Jolović et al., 2014), necessary topographic maps and the results of appropriate observations during the flood period were collected:

- a topographic map at scale of 1:25000 for determination the flood contours dependent on different flood levels, and
- measurements of water level drawdown in the field between December 6th and December 17th, 2010, during extreme flood event (Fig. 2).

Appropriate contours of flood water in the field, i.e. the levels 850, 840 and 830 m a.s.l., were drawn in order to determine stored water in the field and its changes during the time.

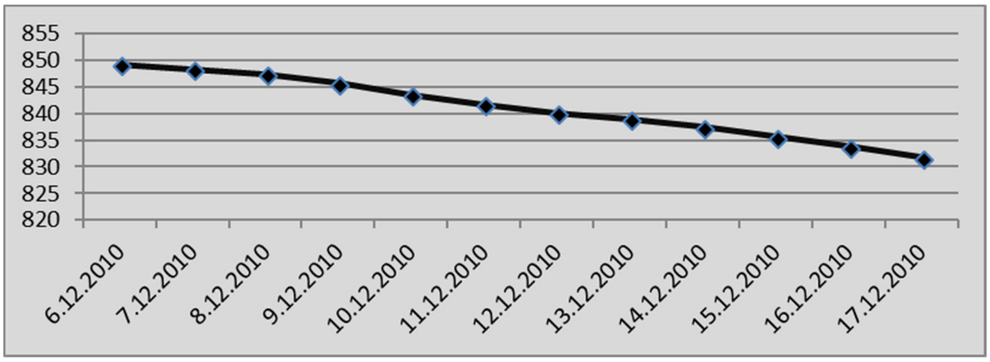

Fig. 2 Decreasing of the flood level in Cerničko polje, period 6-17/12/2010

The first one is close to maximal proposed for Cernica reservoir. The contours were digitalised and used by appropriate GIS tools to calculate the volume of stored water.

As the second key factor for the ponors capacity calculation, beside previously defined contours (and also areas and volumes) of the flood, there are the data about drawdown of flood vs. time collected by experts of the Hydro Power Company „Hidroelektrane na Trebišnjici“ (Fig. 2).

The data had been collected during the extreme flood event in December 2010.

Estimation of the ponors capacity

Flood level decreasing vs. time were also taken into account as the key factor for calculation of the ponors capacity if Cerničko polje (in the first order the capacity of Ključki ponor and Jasovica ponor) (Table 2).

Table 2. Flood drawdown vs. time in the field for the period 6-17/12/2010

Time (hour)	Flood level (m a.s.l.)
0	849,18
72	845,65
144	840,09
216	835,67
264	831,78

One measurement per day was provided, each day at the same time (10 AM). Taking into account that flood contours, which is possible to draw correctly in the topographic map 1:25000 (for calculation of the volume of stored water in different time steps), were not registered just in that moment (10 AM of the appropriate day) it was necessary to make some interpolations and extrapolations (but not more than 5%) to obtain the right time between two levels of decreasing (10 m).

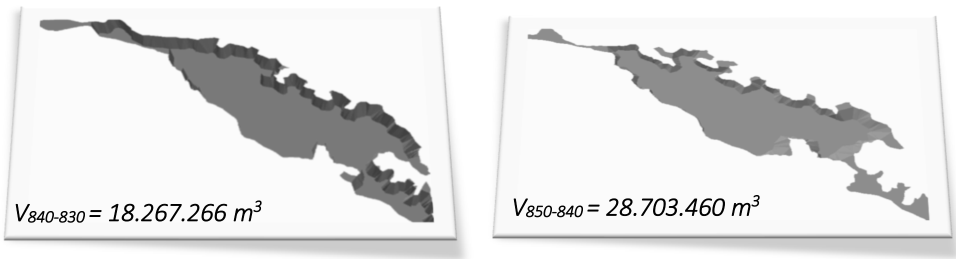

Fig. 3. Change of volume of the water for flood level decreasing from 850 to 840 m a.s.l. and from 840 to 830 m a.s.l.

The volume of water runoff in ponors of Cerničko polje, for flood level decreasing from 850 to 840 and 840 to 830 m are shown in the Figure 3. Two levels of decreasing were taken into account in order to estimate ponors capacity dependent on the different hydrostatic pressures.
In the Table 3 the volume of water infiltrated through ponors for two above-mentioned changes in the flood level in the field are shown (with equidistance of flood change e=10 m).

Based on the values given in the table above it is possible to define ponors capacities dependent on different flood levels (Table 4) and flood volume decreasing (Fig. 4).

Of course, it is necessary previously to define the time of level decreasing from 850 m a.s.l. to 840 m a.s.l., and from 840 m a.s.l. to 830 m a.s.l., using the above-mentioned appropriate interpolation and extrapolation (up to 5%).

Table 3. Flood volume decreasing for the flood level decreasing from 950 m a.s.l. to 940 m a.s.l. and 940 m a.s.l. to 930 m a.s.l.

Level decreasing (m a.s.l.)	Period	Hour	Decreasing of water volume (m^3)
850-840	06.12.2010.-12.12.2012.	153	28.70 x 10^6
840-830	12.12.2010.-18.12.2012.	154	18.27 x 10^6

Table 4: Cerničko polje ponors capacity for flood level decreasing from 850 to 830 m a.s.l.

Decreasing of flood level (m a.s.l.)	Period	t (s)	Swallow holes capacity (m^3/s)	Average capacity of swallow holes (m^3/s)
850-840	06.12.2010.-12.12.2012.	550800	52.11	42.54
840-830	12.12.2010.-18.12.2012.	554400	32.97	

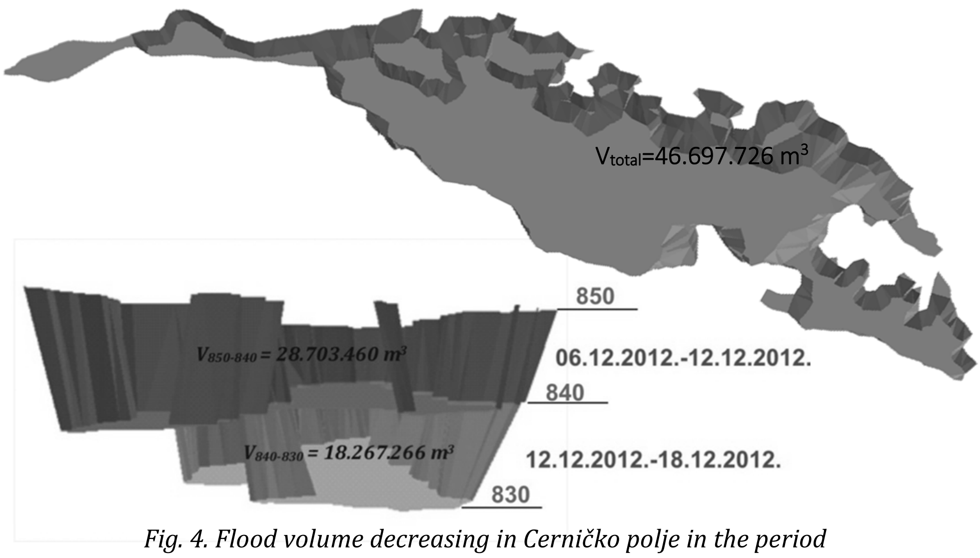

Fig. 4. Flood volume decreasing in Cerničko polje in the period 6/12/2012-18/12/2012 for flood level decreasing from 850 m a.s.l. to 830 m a.s.l.

Taking into account that Ključki ponor is in 825 m a.s.l., the fact that maximal reservoir level is 5 m higher than maximal flood level in the period 6-17/12/2010 (used for calculation) and calculation given above (Fig. 4) it is possible conclude that for e.g. reservoir level 855 m a.s.l. stored water should not be less than 60-65 M m^3.

6. Managing of water stored in Cerničko polje related to water regime in Nevesinjsko polje, Dabarsko polje and Fatničko polje

Water storage in Cerničko polje and its final utilisation in energetic purpose is directly dependant on water management in the Trebišnjica river basin and water transfer from the Neretva river basin to the Trebišnjica river basin (Fig. 5). Today, the only constructed hydrotechnical facility regulates water regime of the so-called "Uper Horizons" (upper karst fields of the Eastern Herzegovina) is the hydrotechnical tunnel between Dabarsko polje and Fatničko polje.
Total annual inflow in Dabarsko polje is about 236 M m^3 or 7.5 m^3/s and 630 M m^3/annualy or 20 m^3/s to Fatničko polje. The capacity of the ponors in Fatničko polje is about 47 m^3/s. About 90% of water from Fatničko polje belongs to the Trebišnica river basin, and about 10% to the Bregava (Neretva) river basin. Because 85% of total inflow to Dabarsko (200 M m^3/annually) is flood water, the transition of water to Fatničko polje by the tunnel 3.2 km long and maximal flow rate 35 m^3/s is considered, at the usual hydraulic conditions upstream and downstream and the current level of the tunnel lining construction.
Maximal flow rate can reach 50 m^3/s, even 90 m^3/s, in conditions of totally concrete covered tunnel and maximal flood in Dabarsko polje (Kam et al., 2012) and some other conditions provided in the hydro-power system Trebišnjica level. The tunnel was constructed in 1986. Taking into account that flood in Fatničko polje could have higher level than flood in Dabarsko polje, there is the tabular shutter constructed on the tunnel exit.
In accordance with the investment program and the permission/agreement from 1969, pass over of 6.8 m^3/s of water from Dabarsko polje to Fatničko polje is planned. Essentially, this water after construction of the second stage of the system – tunnels Dabar – Fatnica (finished in 1986) and Fatnica – Bileća (finished in 2007), should increase the production in the HPP Trebinje I and another downstream PP for about 160 M kWh.
To provide water storage in Dabarsko polje and water transition to Fatničko polje, the ponors Kuti i Ponikva should be closed. The shutter must be constructed in the biggest ponor Ponikva. It will be opened when water level on gauging station Ponikva falls down to 472 m a.s.l. (to allow flow toward the Bregava river during the dry period) and after water level in the field achieved 490 m a.s.l. (to prevent flood in the field above this level). Estavelle Kuti will be closed with a special type of shutter, to prevent swallowing and provide discharge, or in the other words, this estavelle will be converted into spring.
Most important implications of these measures are a longer flood period in the field and decreasing of discharge of the Bregava river. Because of all these facts,

it is necessary to maintain a permanent monitoring of ground and surface water levels hourly.

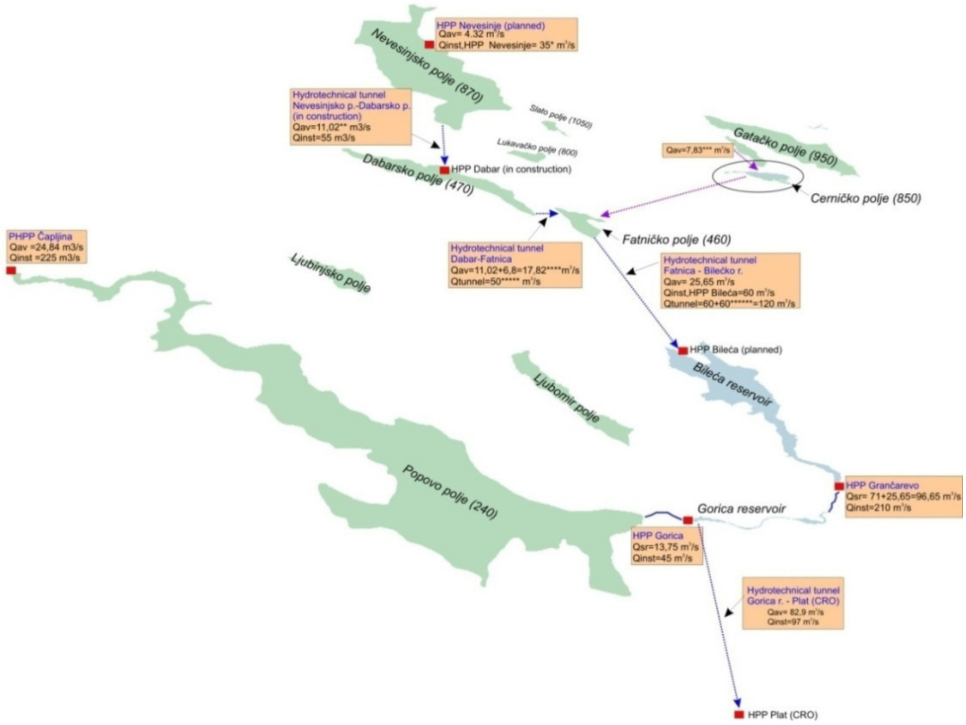

Figure 5: Distribution of karst fields in the Eastern Heryegovina and facilities of the hydrosystem Trebišnjica

*Remarks: *HPP Nevesinje will be realized in two phase (with reduction of installed power from 60 MW to 35MW), **In accordance with the Water Permit (1986), the maximum water that can be transposed are average perennial water (according to older data 12,6 m³/s or recent data 11,02 m³/s),***Average flow from Gatačko field (MP Srdjevići) without participation of own water of Cerničko field and part of the water that goes away directly to Trebišnjica springs or indirectly via Plane, ****Permitted translation of water from Dabarsko field (Water Permitt1986), *****Planned tunnel capacity(as first designed and with current capacity about 35 m³/s; it is increased only at maximum water differences in upstream and downstream poljes),******Circulation of overflow 60 m³/s(with concrete lining)*

Analyzed hydrological observations collected in the period 1956 – 1985 (before construction of the tunnel Dabar-Fatnica, Energoprojekt Beograd) and in the period 1986 – 1998 (after the construction, Elektroprojekt Zagreb) indicate inflow decrease in the Bileća reservoir of 7.4 m^3/s.
Furthermore, the calculation of the average discharge of the Bregava springs, after transfer of water from Dabarsko polje to Fatničko polje, based on numerous models, indicates decrease of average flow, from 17.7 m^3/s to 9.5 m^3/s. The data collected in the gauging station Stolac in 2013 did not confirm it. During the first half of the considered period the flow increased and in the

second half it was almost identical to the natural conditions (Fig. 6). Also, the data on electricity production on the HPP Grančarevo and HPP Dubrovnik in the periods 1957 – 1985 and 1986 – 2012 indicate decrease in the production (Fig. 7).

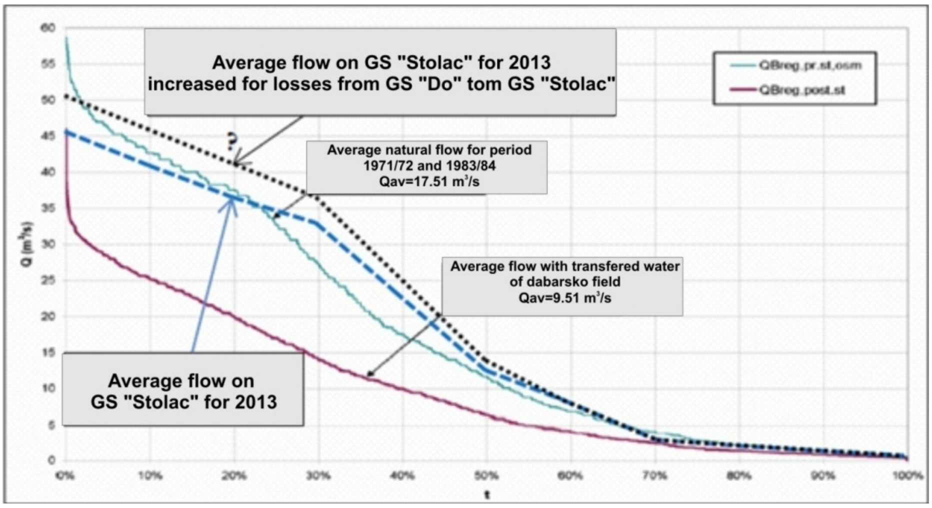

Fig. 6. Flow curve a) gauging station "Do" (uncovered tunnel Dabar-Fatnica) – period 1971-1984 (Water Management Institute Sarajevo), b) gauging station Stolac in 2013 (Hydrological Journal of FBIH), c) increased for losses from the GS Do to the GS Stolac

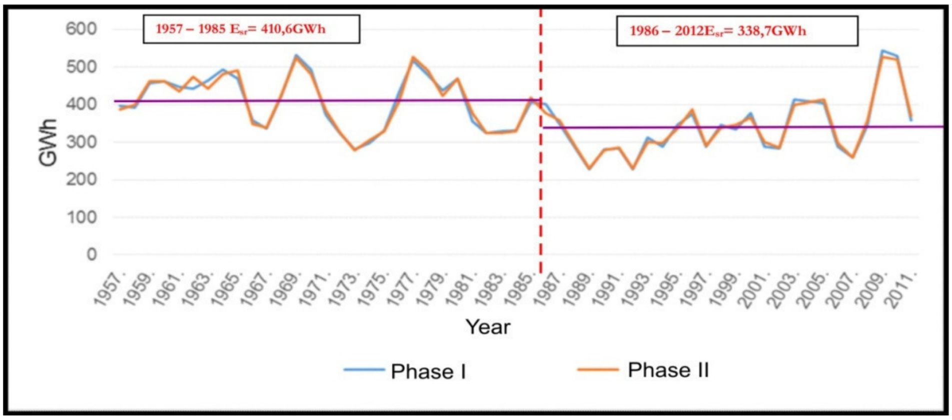

Fig. 7: Electricity production in the HPP Grančarevo in the periods 1957 – 1985 and 1986 – 2012, before and after the construction of the tunnel Dabar-Fatnica (Kam et al, 2012)

It practically means that planned effects of the hydrotechnical tunnel (increase electricity production in the above mentioned HPP accompanied with decrease in flows of the Bregava river) are not achieved despite the tunnel construction. However, water from the future reservoir "Pošćenje" in Nevesinjsko polje will be transferred to the HPP Dabar in the Dabarsko field. This water will be transported through the tunnel between these two fields to Dabarsko polje and after that to Fatničko polje (further to Bilećko reservoir). Planned average production in the HPP Dabar is 250 GWh. It practically means that additional 310 M m^3 of water could be expected in Dabarsko polje. Expected downstream effect is 265 GWh.

All this management aspects are in a very close relation with utilisation of the water of Cerničko polje.

Analysis of the production, after construction of the tunnels Dabarsko polje-Fatničko polje (1986) and Fatničko polje-Bileća (2006) or, in the other words, conditions for transition of water from Dabarsko polje to Fatničko polje indicate the following facts and realization with water utilisation of Cerničko polje:

- Production of electricity in the HPP Trebinje I and the HPP Dubrovnik is less than before the construction of the tunnels! It is caused by water losses from the Trebišnjica river basin, in the tunnel Dabarsko polje-Fatničko polje. It means that expected effects of transferred water on electricity production (160 GWh from 220 M m^3) are not realized.
- Example: the volume of transferred water in the period October 2017 - May 2018 is only 27 m m^3 or 12.2% of the value given in the official decision on water transition
- Provision of additional water in Dabarsko polje from Nevesinje (by the tunnel Nevesinje-Dabar) extends level and time of flood and additionally increases "pressure" on Dabarsko polje and Fatničko polje
- Construction of the reservoir in Cerničko polje, of 90 M m^3 volume, decreases discharge of Obod spring and other springs in Fatničko polje and flood intensity as well. It provides conditions for the adequate transfer of water from Dabarsko polje and the HPP Dabar toward the downstream HPP system Trebišnjica.
- Transition of the water from Malo Gatačko polje to Cerničko polje, by a tunnel 800 m long and the construction of a dam and an embankment in the Cerničko field (around main ponors), there will be a reservoir of 90 M m^3 formed. In energetic sense it is huge potential, especially in the summer period.
- Also, the reservoir in Cerničko polje in rainy years, when huge amount of water is not utilised, would make energetic potential for production of 75 GWh in the existing power plants.
- Retain and accumulation of water in Cerničko polje in the first stage (later on also the construction of the HPP Cernica) is the only way to reduce impact of high water on downstream fields (in the first order Fatničko polje) and to provide utilization of huge amount of unutilised water from Dabarsko polje and the HPP Dabar in the downstream HPPs.

- Analysis of precipitation trends in the Trebišnjica river basin indicates more and more uneven regime of the precipitation in the basin, with very dry periods on one hand and extremely high precipitations in the short period of time on the other. Based on this fact, the construction of new reservoirs in the river basin is fully justified.

Dye tests indicate that water from Cerničko polje entirely belongs to the Trebišnjica river basin

7. Conclusion

- Cerničko polje is one of the highest fields in the Eastern Herzegovina, Bosnia and Herzegovina.
- In geological sense, the field floor consists of flysch sediments of the Paleocene-Eocene age. It is surrounded by the Cretaceous and the Jurassic limestones.
- In the southern edge of the field, close to the contact of impermeable flysch sediments with the Upper Cretaceous permeable limestones, there are numerous ponors, which drain waters from the field. The most important are Ključki ponor and Jasovica ponor.
- Based on the results of the previous dye tests it is possible to conclude there are two separated, more or less concentrated, underground channel systems in the field, the first one toward Fatničko polje (and further to Trebišnjica spring/Bileća reservoir) and the second one directly to the Trebišnjica springs or indirectly, via Plane.
- For the first time the utilization of water from Cerničko polje was considered during the early 60s of the last century. The concept was based on utilisation of the water from Gatačko polje in the power plant in Cerničko polje, located in the northern edge of the field. The next step is the utilisation of water accumulated in Cerničko polje on the power plant located in the northern edge of Fatničko polje. But after the 60s of the last century this concept is not further considered, and it is practically left. The latest activities on construction of the facilities within the project named „Upper Horizons“ and some recent analyses provided from the expert of the HPS Trebišnjica trigered the idea again.
- Key questions regarding the utilisation considered in the paper are:
  - geological and hydrogeological conditions of the Cerničko polje and regulation of swallow holes on the sothern edge of the polje related to water storage;
  - possible volume of stored water for different levels of the reservoir;
  - the retardation of maximum inflows into the Fatničko polje, allowing water transfer in efficient way;
  - management of the stored water related to water management in Nevesinjesko polje, Dabarsko polje and Fatničko polje.
- Adoption of 855 or 860 m a.s.l. as maximal level of the reservoir will request significant technical measures regarding water loss prevention.

It is necessary to provide technical solution and to close the ponors in the southern edge of the field.

- It is concluded that about 90 M m^3 should be stored in Cerničko polje after the construction of a dam and an embankment. It makes energetic potential for production of 75 GWh in the existing power plants.
- Water storage in Cerničko polje and its final utilisation in energetic purpose directly depend on water management in the Trebišnjica river basin and water transfer from the Neretva river basin to this river basin.
- Result of the observations of the Bregava river flow after constructed tunnel Dabarsko polje- Fatničko polje (1986), does not decrease flows of the Bregava river (what was expected), because of insufficient capacity of the accumulation in Fatničko polje which is not enough to accept and transfer of its own waters as well as the water of the Dabarsko polje and the HPP Dabar.
- Provision of the additional water in Dabarsko polje from Nevesinje (by the tunnel Nevesinje-Dabar) will affect on extension of level and time of flood in these fields and additionally increase "pressure" on Dabarsko polje and Fatničko polje.
- The inflows in the Fatničko polje are mostly underground and extreme, and the field has a smaller volume than the Dabarsko polje. The inflows in Dabarsko polje are mostly surface, extreme and coincide with the inflows into the Fatničko polje. Taking into consideration the water and the work/power production plan of the HPP Dabar, the situation will be more complicated. Therefore, it is necessary to retard the inflows into the Fatničko polje, which is possible only by an accumulation in the Ceričko polje.
- Construction of a reservoir in Cerničko polje must be considered only as an integral part or water management in the whole Trebišnjica river basin and supported by further intensive geological and hydrological explorations.

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GROUNDWATER MANAGEMENT VS ANTHROPIC STRESSES IN A PROTECTED AREA: CASE OF PEȚA LAKE, ORADEA - BĂILE FELIX – 1 MAI SPA, ROMANIA

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Abstract
The most known deep geothermal area in Romania is located in the nothwestern corner of the country i.e. Oradea – Satu Marea area, with Băile Felix – 1Mai Spa areas being mentioned in documents since centuries. During the last 10-15 years it was noticed that the overexploitation of the geothermal (karst) system concluded in persisting drying-up periods of the protected thermal lake (vauclusian type spring) hosting three endemic species. The main goal of this paper is to present the main findings leading to the improvement of the actual manner of exploitation of the geothermal karst system of Oradea - Băile Felix – 1 Mai along with the rehabilitation of the Natura 2000 site – Peța Lake.

Key words: karstic aquifer, geothermal groundwater, conceptual model, management

Introduction

When speaking about water management the simplest form to express it is to compare the volume of the dynamic reserves with the volume demanded by or allocated to beneficiaries. This appears as complicated in case of surface or groundwater fresh water but is usually assumed much simpler for deep geothermal water, considering the financial efforts and the more controlled exploitation manner of the ressource.

The most known deep geothermal area in Romania is located in the northwestern part of the country i.e. Oradea – Satu Marea area, with Băile Felix – 1Mai Spa areas (Figure 1, project area in green) being mentioned in documents since centuries.

Figure 1 Geothermal areas in Romania

However in case of Oradea – Băile Felix – 1Mai geothermal system, the situation is complicated by the geostructural setup concluding in two geothermal sub-systems considered connected albeit they may appear as highly different.

Geothermal aquifer systems

The main characteristics of the geothermal system and sub-systems (Figure 2) as resulting from several unpublished and published documents (Paal 1975, Paal 2013, Cohut 2013) can be summarized as follows:

- Recharge area – Northern slopes of Padurea Craiului Mts via Borod Basin,
- Aquifers (sub-systems):
    - Triassic (Middle): fracturated limestone and dolomites exploited in Oradea area (TD wells: 2300-3300m); T=70-110°C; calcium-sulphate-bicarbonate- type of water; mean licensed discharge rate – 100 l/s;
    - Cretaceous (Lower): fracturated limestone exploited in Băile Felix – 1 Mai area (TD wells: 100-400m); T=32-47°C; calcium-bicarbonate type of water; mean licensed discharge rate – 200 l/s);
- Sub-system's connection: Velenta Fault System.

The mean apparent age of geothermal water in Oradea sub-system has been identified as decreasing from 20,300 years in 1976 to 13,740 years in 1987 whilst in case of Băile Felix -1Mai sub-system the same parameter decreased from 15,190 years in 1976 to 12,150 years in 1987 (Țenu and Diaconu, 2010).

The components of the cumulated output from the geothermal system are:

- Deep explotation wells in Oradea area, used mainly in winter by public heating system of the Municipality of Oradea but also hospitals and green houses;
- Exploitation wells in Băile Felix – 1Mai Spa area (BF-1Mai);
- Peța (karst) Lake: protected area included in EU - Natura 2000 network.
- <u>An unknown component of the total discharge rate of the geothermal system that is allegedly represented by non-licensed discharge rates (either through licensed or non-licensed wells).</u>

During the last 10-15 years it was noticed that the overexploitation of the geothermal (karst) system (legal and illegal private wells) concluded in persisting drying-up periods of the protected thermal lake hosting three endemic species: *Nymphaea Lotus Thermalis*, *Scardinius Erytrophtalmus Racovitze* and the snail *Melanopsis Parreyssi*.

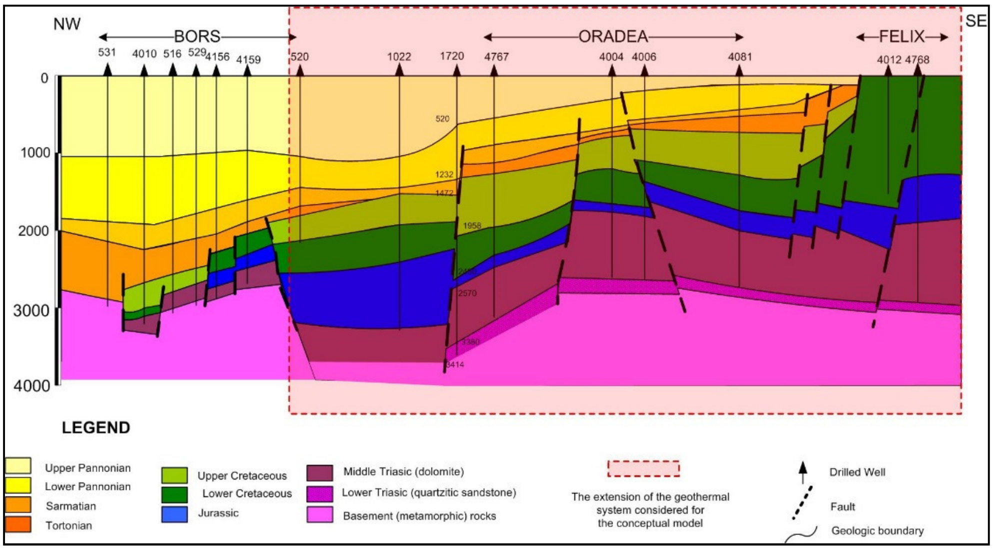

Fig. 2. Geological cross-section through Bors-Oradea-Baile Felix area (redrawn and modified from Plate 62 Atlas of Geothermal Ressources in Europe and unpublished reports)

Consequently, starting with the second half of 2014 a team of the RAH (Romanian Association of Hydrogeologists) has been entitled with a study targeting the rehabilitation of the Natura 2000 site – Peța Lake along with the re-assessment of the exploitable geothermal resources of the geothermal system Oradea – Băile Felix – 1 Mai.

Several papers based on the preliminary interpretation of the data resulting from this project were already published (Orășeanu et al 2015, Orășeanu and Malancu 2016, Țenu 2016).

The main goal of this paper is to present the main findings leading to the improvement of the actual manner of exploitation of the geothermal karst system of Oradea - Băile Felix – 1 Mai along with the rehabilitation of the Natura 2000 site – Peța Lake.

Methodology

Proposed and applied methodology included historic data acquisition, installation of a monitoring system for piezometric level (pressure sensors installed mainly in BF-1Mai exploitation wells and Peta Lake) as well as for exploited discharge rates (electromagnetic flowmeters in all wells), sampling the surface and groundwater sources for chemical and environmental isotopes analyses (24 locations, H^2, H^3, O^{18}), pumping tests in few exploitation wells.

Results and discussions

Historical data analysis (documented precipitation and discharge rates) revealed a significant influence of the climatic fluctuations (rainfall) particularly during the last 10-15 years, with the head in the geothermal sub-system of (BF-1Mai) continuously degrading from fully free-flowing (first wells drilled in 1885 and 1886) to a very sensitive artesian-free flowing level nowadays (including Peța Lake). In case of rainfall, data from CARPATCLIM database were also used (Szalay *et al*, 2013).

The time series of the piezometric level of Afrodita Well (not operational and marginal to the main exploitation group of wells in BF-1Mai area) was found similar in pattern to the water level fluctuation in Peta Lake. Base on this similarity a local black-box model was build on the basis of a simple equation allowing for the simulation of the cumulated discharge rate (Q_{Oradea} + $Q_{BF\text{-}1Mai}$, including also not-licensed discharge rates) as represented in Figure 3.

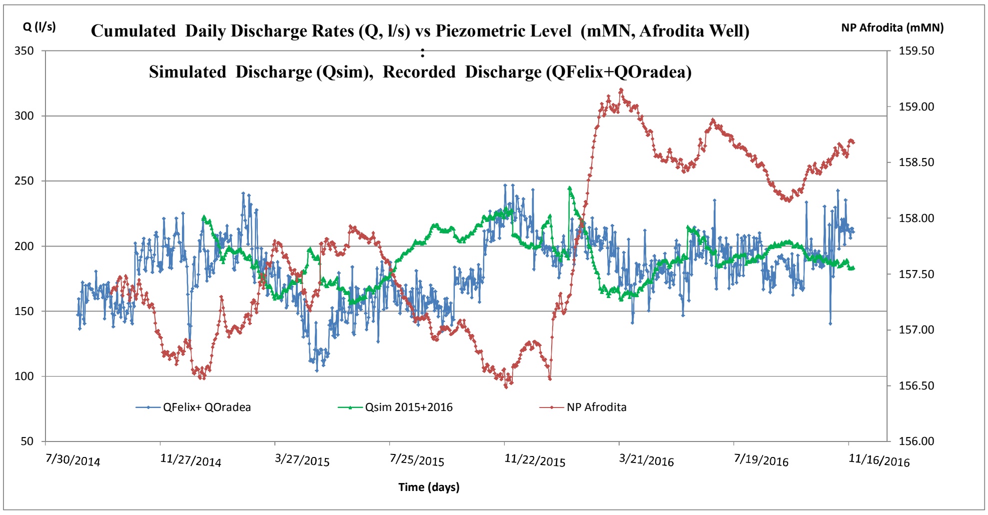

Fig. 3 The comparison of the simulated and recorded (cumulated) discharge rates

The simulated values of the discharge were compared with the monitored values this revealing peaks of the non-licensed discharge rates (pumped from either licensed and not licensed wells) during July-September periods, reaching 40-80 l/s in 2015 and 20-40 l/s in 2016 (Figure 4).

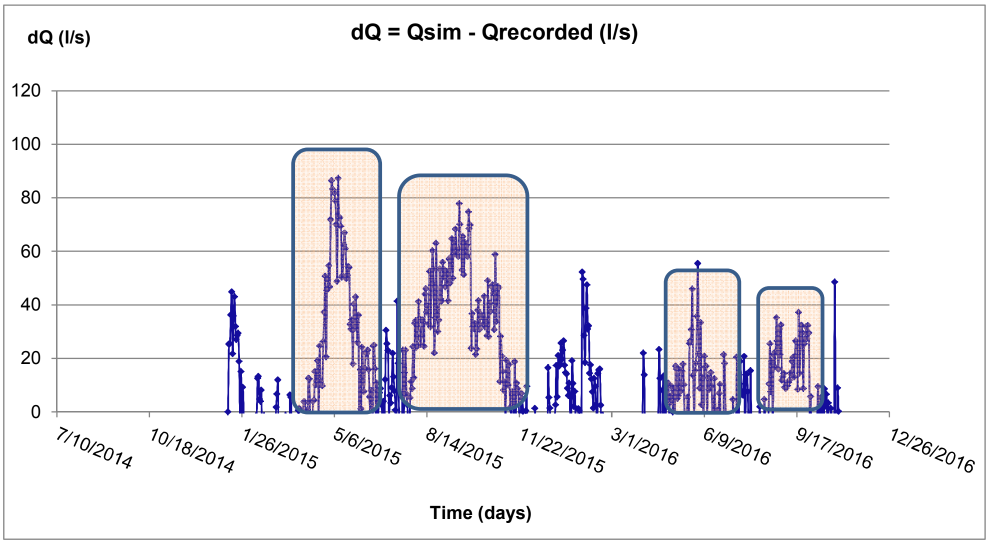

Fig. 4. Non-licensed discharge rates as resulting during 2015-2016 period

The re-interpretation of the main interference test between Oradea wells and BF-1Mai wells that has been considered as the benchmark for the licensed discharge rates during 30 years (Plavita, 1989, Plavita & Cohut 1990, Paal & Cohut 1985 – unpublished report), showed a more reduced influence of the former on the later and in fact a higher degree of independence of the two sub-systems.

Consequently a different recharge input (considered with a stronger and faster effect on the piezometric level fluctuation) has been sought for BF-1Mai sub-system this being hypothesized as represented by the western flank of Northern Apuseni Mountains via Galben Fault System (also supplying Beiuș Geothermal Area, Orășeanu, 2016).

The main results of the project can be summarized as follows:

- Reframing of the conceptual model of the Oradea – BF-1Mai geothermal system as indicated in Figure 5,
- Flexible but limitated exploitation rates for legal wells in relation to annual and multiannual rainfall values,
- No new exploitation licenses allowed.

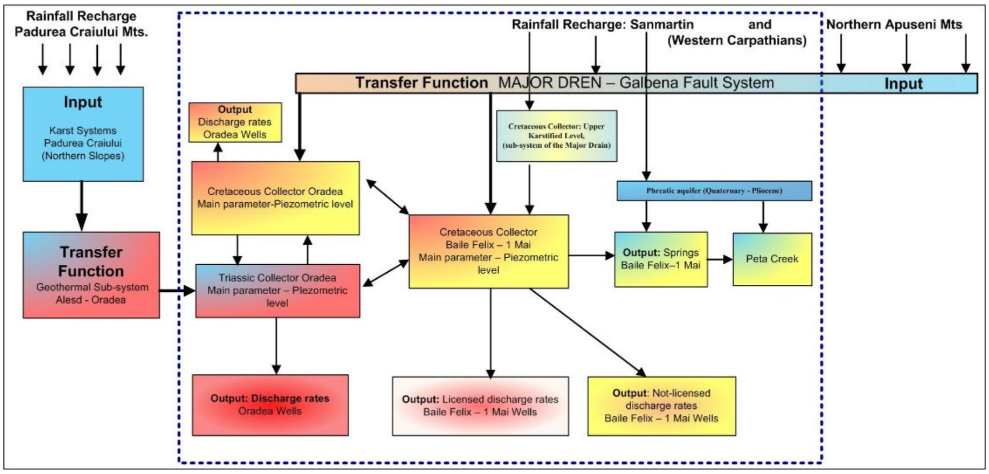

Fig. 5 The proposed conceptual model of Oradea - Băile Felix - 1Mai area

Conclusions

The long-term overexploitation of the geothermal system Oradea - Baile Felix - 1Mai concluded in persisting drying-up periods of the Natura-2000 protected thermal lake that is the only natural exit from the system.

The new structure of the geothermal system consists of two sub-systems with different recharge areas with a certain degree of interconnectivity. Aside with the exploitation rates, the fast component of the recharge determines the seasonal fluctuations of the piezometric level in Baile Felix-1Mai Spa area.

The existing licensed discharge rates for Baile Felix - 1Mai sub-system must be based on the annual and multiannual rainfall rates whilst no new licence shall be granted.

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IN MEMORIAM

Professor Borivoje F. Mijatović, 1931 – 2018

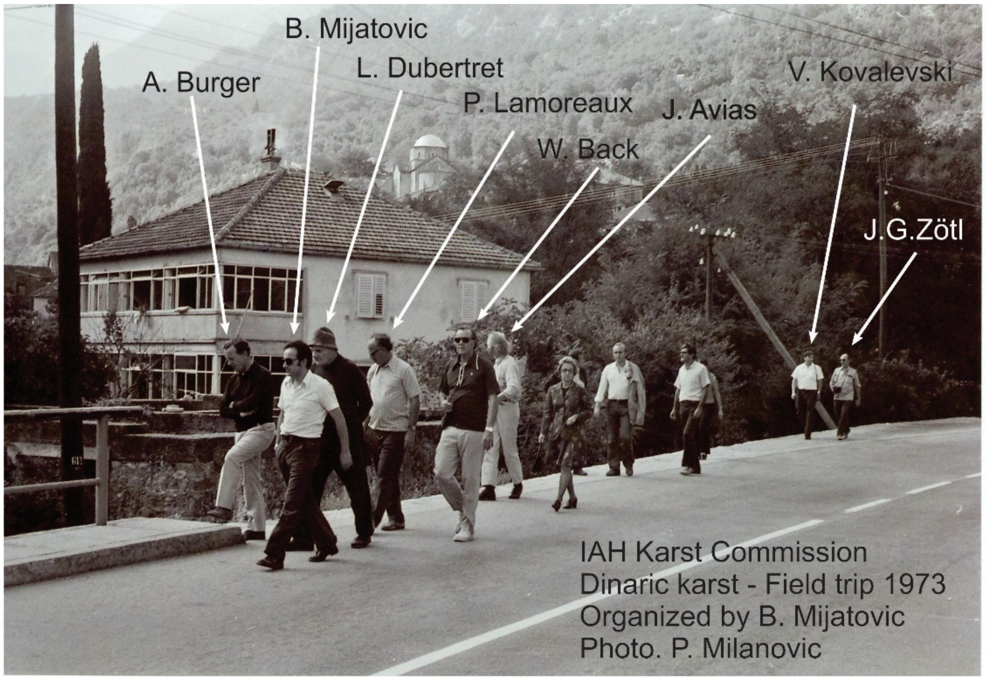
Anyone working in the area of karst water resources recognizes the name of Borivoje F. Mijatović, known between all foreign colleagues as Boris. His career started in the 1955 immediately after finished studies at the Geological Faculty in Belgrade. In a career spanning more than 60 years Boris's passion for karst and karst hydrogeology led him to many karst regions of the world. As UNESCO expert he participates number of projects in Lebanon, Turkey, Libya, Greece and some other countries. To solve hydrogeological problems in so complex environment as it is karst he perfectly combines science and practical solutions. Behind him is a long list of high productive wells and tapping galleries mainly in areas with shortage of potable water. One of the key areas in his early studies, where Boris made a significant scientific contribution, was complex problem of sea water intrusion into the coastal karst aquifers. However, his hydrogeological interest was much wider, and a detailed description is far beyond the scope of this profile. As professor he shared his knowledge with his students and younger scientist creating the new generation of high educated scientist in groundwater sphere.

Boris's interests included number of activities in national and international hydrogeological community. In former Yugoslavia he was one of founders of the National Committee for Hydrogeology and Engineering Geology and organiser of the First Symposium of Hydrogeology and Engineering Geology. Many years this symposium becomes traditional place for the growing scientific and professional capabilities of Yugoslav hydrogeologists.

In 1961 Boris becomes member of International Association of Hydrogeologists. Together with top world karstologists: Dubertret, Avias, Lamoreaux, Burger, Paloc, Zötl and others, in 1970 he was one of founders of the IAH Karst Commission. Next 40 years he was permanent and very active member of the Karst Commission. He organises a few conferences and field trips along the Dinaric karst (1973, 1983, 1986), and was one of key organisers of the International Conference "Water Resources & Environmental Problems in Karst" held in Belgrade/Kotor, 2005. He was, also, one of prominent members of IAH Commission for Hydrogeological World Map.

Beside more than 150 scientific articles Boris is author of monograph "Kras – Hydrogeology of Karst Aquifers"; editor of "Hydrogeology of the Dinaric Karst" published by IAH; and co-editor of "Cvijić and Karst" published by Serbian Academy of Sciences and Arts.

Now Boris is not with us, but he continues to be remembered for his contributions to hydrogeology, particularly to karst hydrogeology, and for his friendly and generous spirit.



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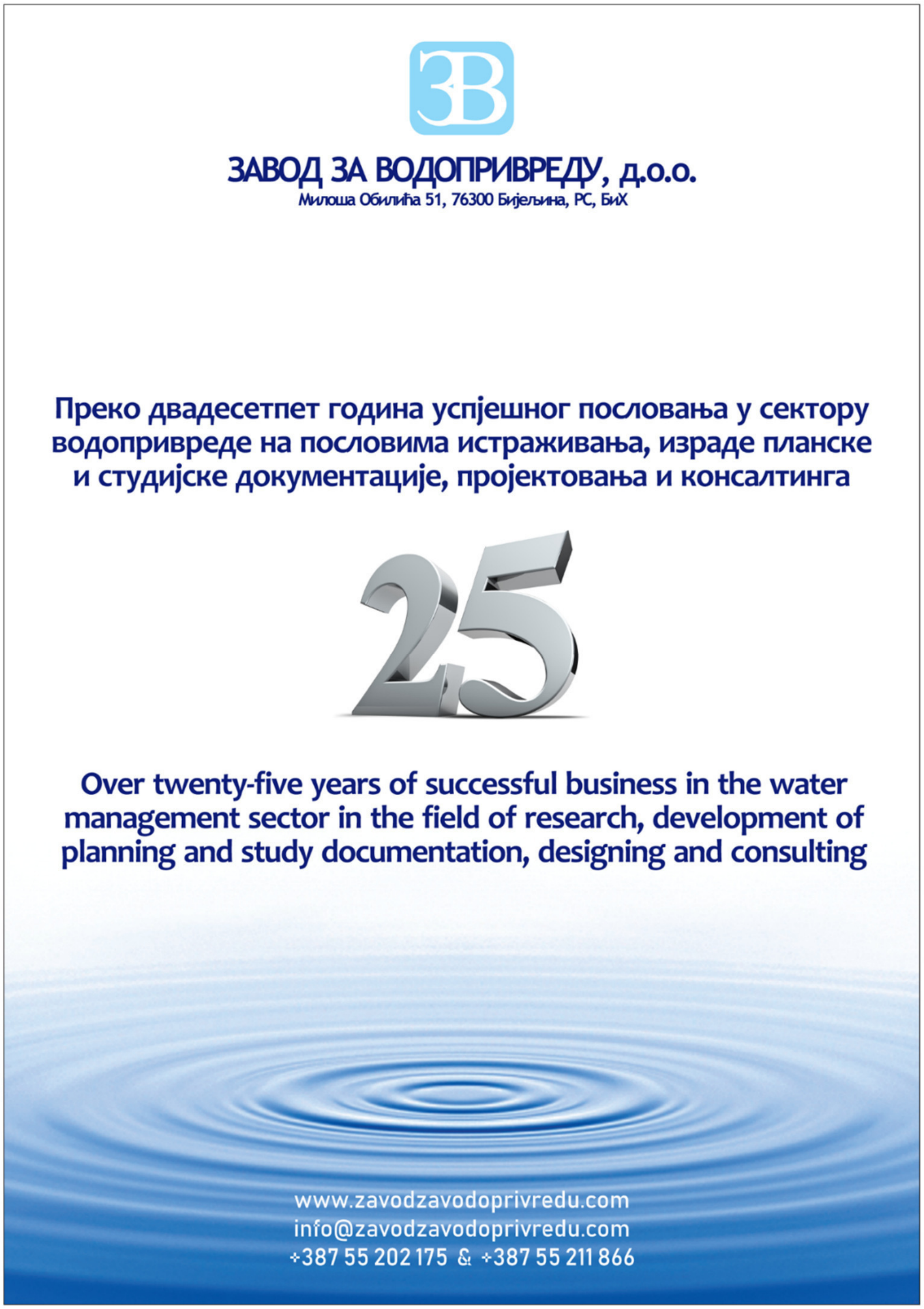
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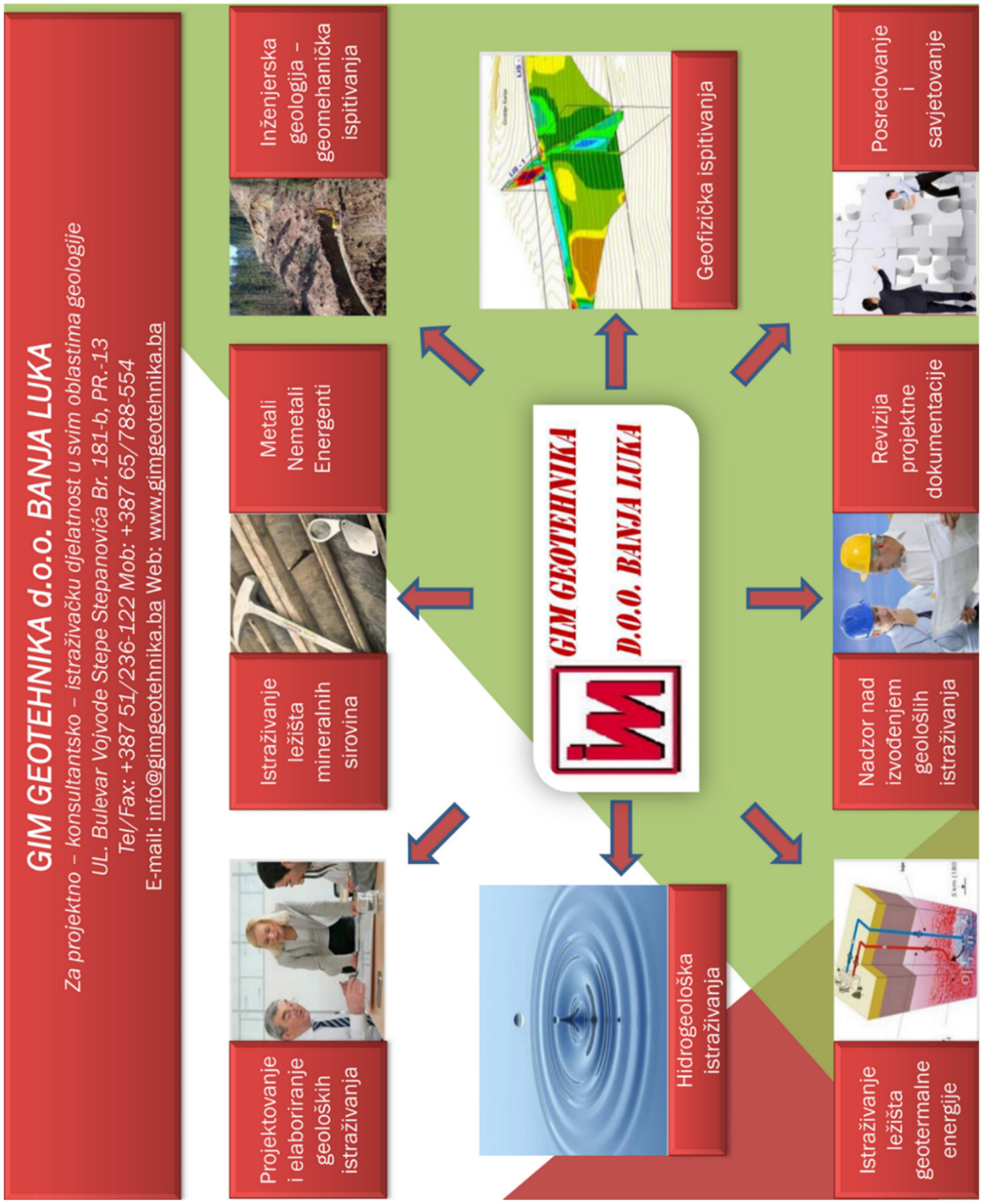
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