Extended abstract of Plenary paper

CLASSICAL DINARIC KARST AQUIFER – AN OVERVIEW OF ITS PAST AND FUTURE

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INTRODUCTION

The Dinaric system (Dinarides) represents a geologically heterogeneous, south European orogenic belt of the Alpine mountain chain (Alpides). The Alpine and Dinaric belts are in contact either directly or through an Intermediate zone (Herak, 1972). This part of Europe is considered a classic karst region and not only was the term "*karst*" born in the area (the German derivation of the local name of the district between Italy and Slovenia "*Carso*" or "*Kras*") but also at the end of the 19th century a group of researchers including A. Penck, A. Grund, and F. Katzer led by Jovan Cvijić established a new scientific discipline - karstology. The Dinaric karst becomes the *locus typicus* area for dissolutional landforms (Ford, 2005) and some local terms were accepted, and are still used, in international karst terminology (e.g. ponor, doline, uvala, polje).

The main orientation of the system is NW-SE, parallel to the Adriatic Sea. The system extends from the Carso area around Trieste in Italy in the north over the countries of former Yugoslavia and ends in the south in the territory of Albania (Fig.1). The orogenic belt further extends in Albania and in Greece to the Pindes and Hellenides branches, respectively. The total surface area of the Dinaric system, including non-karstic rocks, is estimated at 140,000 km^2. Approximately 60% belongs to the Adriatic / Ionian basins, while the rest is a part of the Black Sea basin.

GEOLOGY AND HYDROGEOLOGY

The Dinaric karst is almost entirely carbonate (limestones and dolomites), its thickness is often over 1000m and it is mostly of Mesozoic age (Tethys sedimentary basin). The development of the Dinaric karst was gradual. Herak (1972) stated that at the end of the Triassic or during the Lower Jurassic, the Triassic carbonate rocks were first exposed to the impact of water circulation processes. The Laramian phase, between the Cretaceous and the Palaeogene, is characterized by the rising of large land masses, accompanied locally by intensive structural changes providing also potential for more intensified subsurface water circulation and widespread karstification (Herak, 1972). Since the Oligocene, the Dinaric region has been continuously exposed to weathering, providing favorable conditions for intensified subsurface water circulation and the development of karst features. The most distinctive effects can be found in the area of uplifting and subsidence. The areas of subsidence include the poljes where the water was active before and after the diastrophic movements. The Pleistocene started not only with climatic changes (glacial process, lowering sea level) but also brought a new structural and morphologic evolution. Climate change and the rate of diastrophic movements regulated the periods of accumulation and finally the removal of young deposits from the poljes, forming recent flat bottoms (Mijatović, 1983).

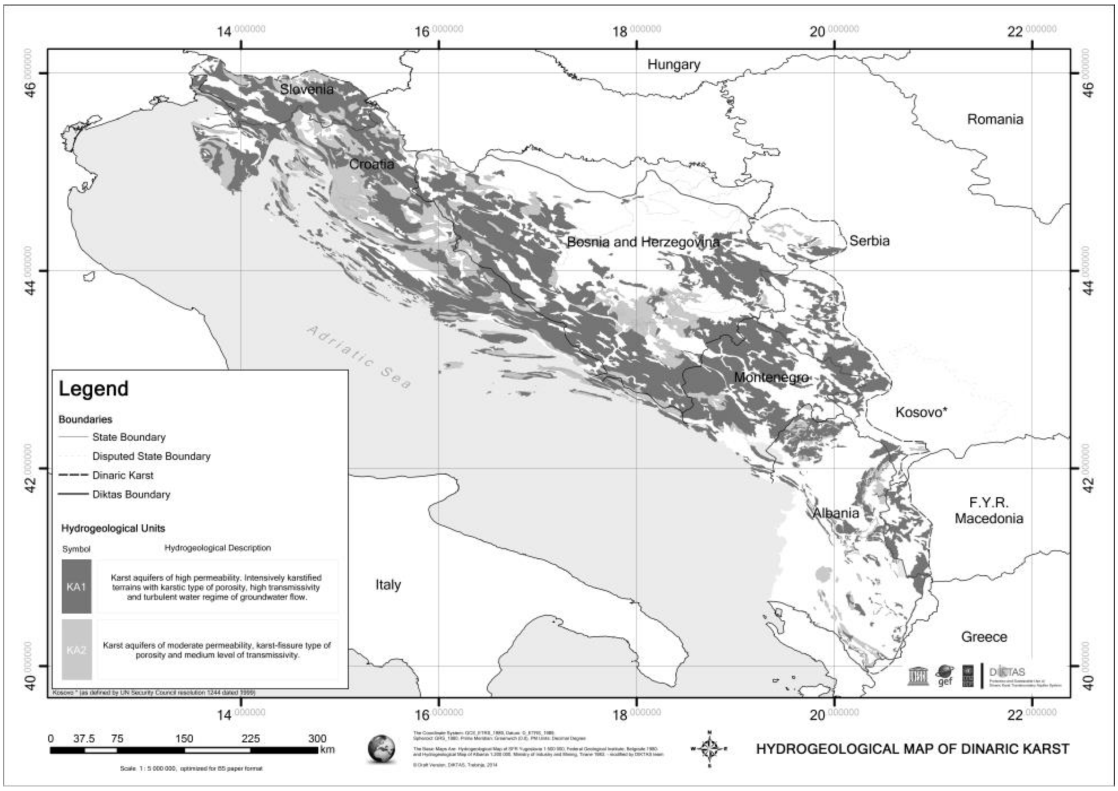

Fig. 1 Extension of Dinaric karst from Italy to Albania. The two types of karst aquifers are distinguished: KA1 – highly permeable and rich in groundwater reserves, and KA2 of moderate permeability and groundwater reserves.

The three major tectonic units are usually distinguished in the Dinarides: External, Central and Inner Dinarides. These can be additionally separated into several subunits (Herak, 1972). Accordingly, the hydrogeological classification of Dinaric karst indicates the following units: Adriatic karst belt, High karst belt, Fluviokarst and Isolated karst (Šarin, 1983; Mijatović, 1984). Although no precise equivalency between tectonic and hydrogeology units exists, the Adriatic belt could be considered an equivalent to External Dinarides, and the High karst to Central, while the last two are distributed over Inner Dinaric karst.

Dinaric karst is a mountainous region with a prevalence of highly karstified rocks and large karstic poljes and valleys created in tectonic depressions by perennial or sinking streams. Referring to the karstification base, deep boreholes have locally encountered karstified zones at depths of even 2,000 m but Milanović (2005) concluded that the average depth does not exceed 350-400 m. The karstification in the near-surface zone (0-10m) is about 30 times larger than at a depth of 300 m (Milanović, 2000). The Dinaric region contains all types of karst landforms and features including karren (lapies), dolines, jamas (pits), ponors (swallow holes, sinks), dry and blind valleys, caves and caverns as single forms, and uvalas, poljes and karst plains as larger complex forms (Cvijić, 1893; Božičević, 1966; Roglić, 1972; Krešić, 1988). As an example, the number of sinkholes (dolines) in certain areas can reach 150/km^2; Livanjsko Polje, considered the world's largest karst polje, covers an area of 380 km^2, and together with Buško Blato, which morphologically is its integral part, it totals 433 km^2. At the Kameno more („Stone sea") and the Orjen Mountain above Kotor Bay (Montenegro), within an area of only 8 km^2 more than 300 vertical shafts were registered (Milanović, 2005). Some of those shafts were speleologicaly investigated to depths of 200-350 m.

As a result of intensive karstification a network of highly permeable underground channels acts as preferential pathways of intensive groundwater circulation. Along with its richness in various karstic features, the Dinaric region is by far the richest in Europe in water resources but unequally distributed throughout the year, which results mostly from specific climate and a high karstification rate (Bonacci, 1987). Some areas, such as southern Montenegro, are characterized by a very intensive water balance where the average specific yield is over 40 l/s/km^2 (Stevanović et al. 2012). In the Dinaric region of ex-Yugoslavia there are 230 springs with a minimal discharge of over 100 l/s, while about 100 springs have a minimal discharge of over 500 l/s (Komatina, 1983). In the Albanian karst there are roughly 110 springs with an average discharge exceeding 100 l/s. It is assumed that 2/3 of all the groundwater resources in Albania are linked with karstic aquifers, providing roughly more than 60% of the water consumed in the country (Eftimi, 2010).

The karst aquifer recharges from precipitation and waters percolating from numerous sinking rivers. Depending on locality, morphology and karstification properties the average infiltration rate can be assessed to vary from between 50% to 80% of the precipitation. Considering that the rainfall rate is one of the highest in Europe (over 2000 mm annually in the southern part, and even up to 5,000 mm in Boka Kotorska Bay) the region is characterized by abundant but variable water reserves. Thus, many large springs with maximal discharges over 100 m^3/s (among the biggest recorded in the World) almost dried up during long and dry summer months. However, the three capital cities in the region and almost all towns and touristic centers along the Adriatic and Ionian coasts use karstic groundwater in their water supply systems (Stevanović and Eftimi, 2010; Fig. 3).

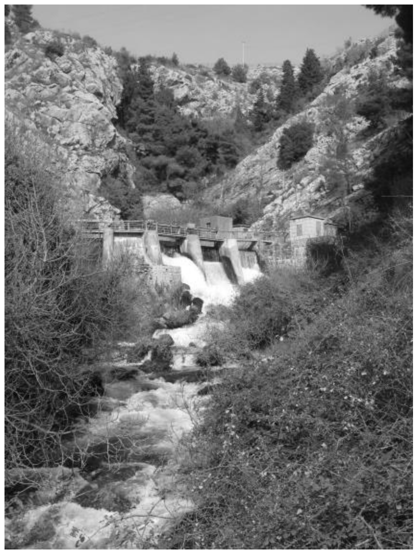

Fig.2 One of the largest springs on the Adriatic coast, Jadro Spring (3-50 m^3/s) supplies drinking water to Split (Croatia) which is the main reason why the city was founded close to it

A large fluctuation in the water table is common in the region (Pekaš et al. 2012). For instance, the water level can change by 312 m during a period of 183 days (for example, the observation borehole Z-3 in the Nevesinjsko Polje). In the Cetina River basin the maximum recorded water table increase was 3.17 m/h. This is also the main reason why large projects to regulate river flows were initiated in all the countries in the region after WW II and many of these were implemented during the 1960s and 1970s. Today many streams are dammed and their waters are utilized by hydroelectric power plants. Dinaric karst becomes therefore a referent area for the successful completion of dams in karst, very problematic media from the point of view of water losses (Milanović, 2000, 2006). The major dams and reservoirs have been built on the Cetina, Neretva, Trebišnjica, Zeta, and Drini Rivers.

KARST AQUIFER MANAGEMENT AND MONITORING

The project DIKTAS (Protection and Sustainable Use of the Dinaric Karst Transboundary Aquifer System) was implemented in the period of 2011-2014 with GEF funding and support of UNDP and UNESCO's IHP. The appearance of several new sovereign states from what was once Yugoslavia has established complex transboundary inter-linkages that impact on water use and water sharing for domestic supply, power generation, and agriculture. This is one of the reasons why the DIKTAS project was initiated and included three former Yugoslav countries (Croatia, Bosnia & Herzegovina, Montenegro) and Albania (Kukurić, 2011).

One of the main DIKTAS results in terms of the regional hydrogeological characterization is the GIS based digital Hydrogeological map of the Dinaric Karst region. Its creation involved harmonization of data, classifications, methodologies, reference systems, projections, semantics, etc. The map was used as a basis for the development of various thematic maps during the environmental and socio-economical assessment and will represent an important tool for various further analyses and karst aquifer management. Through the Transboundary Diagnostic Analysis (TDA) the DIKTAS project was focusing on selected and prioritized transboundary karstic aquifers (TBAs), examining current and potential issues of concern. Based on five criteria (importance, representativeness, data availability, issues of concern, relevance), eight TBAs were initially selected for detailed analysis: Una, Krka, Cetina, Neretva, Trebišnjica (all shared by Croatia and Bosnia & Herzegovina), Bilećko Lake, Piva (B&H and Montenegro) and Cijevna/Cemi (MNE and Albania). Six of these TBAs belong to the Adriatic Sea catchment area while two are part of the Black Sea basin (Una and Piva). The TBAs comprise a total surface area of 12,000 km^2, which is approximately 10% of the entire Dinaric karst. The later diagnostic analysis focussed on six more problematic TBAs, excluding Krka and Piva.

A delineation of the aquifer surface area was the first step in the hydrogeological analysis of each TBA. Further analysis included the characterization and development of conceptual models. GW budgeting of TBAs created a base for the assessment of groundwater reserves and availability, as well as for proposals and measures aiming to ensure sustainable development of TBAs. Some of the selected TBAs, such as Una, Neretva or Cijevna/Cemi, are of particular importance because they represent parts of designated protected zones, or wetlands, or the habitat for endangered species (Fig. 3).

Fig. 3 Karrens on the shore of Skadar (Shkoder) Lake which is included in the Ramsar convention for protected wetlands

The TDA indicated that water extraction was still far below the aquifer's replenishment potential, and there is no evidence of significant over-exploitation in the studied TBAs. For instance, in the case of Cetina and Neretva TBAs the average extraction of groundwater is ten times less than the total minimal discharge of the springs (dynamic reserves). However, shortage of water is locally in evidence during summer and early autumn months which coincides with increased demands during the tourist season. In such circumstances the fact that principles of EU Water Framework Directive (WFD) regarding ecological flow for downstream consumers have to be fully respected further complicates the water and environmental situation.

Concerning the karstic water quality, it is generally assumed to be relatively satisfactory even though Dinaric karst aquifers are very vulnerable to pollution which is mostly due to sparsely populated catchments in mountainous areas and the absence of intensive farming or industrial activities. However, when pollutants are present (mines, industrial and domestic waste waters, solid waste dumps, fertilizers), deterioration of water quality in unconfined karstic aquifers is almost assured.

Concerning the actual monitoring of GW, the situation in the region and in studied TBAs is far from satisfactory. Only in Croatia has the characterization of GW bodies been completed and monitored in accordance with EU WFD. One of the tasks of the DIKTAS project was to prepare a proposal for the creation of a new GW Monitoring network which will fully respect karst specific behaviour and include local water users (waterworks, dams, irrigation, industry). The Cijevna/Cemi TBA has been identified as the most problematic in terms of available data on water resources, and installation of a modern monitoring network for observation of climate elements, surface and groundwaters has been proposed.

Based on TDA a Strategic Action Plan (SAP) which includes different common activities, proposal for legal and institutional reforms and harmonization of legislatives has been prepared. In order to support sustainable utilization of groundwater in the Dinaric region, SAP is focusing on several priority actions: improvement of the quality of water, elimination of sources of pollution, improvement of minimal discharges, insurance of ecological flows, and establishment of proper water monitoring systems. Conceptual proposals for investment in all of these areas and at designated sites have also been prepared as a part of SAP.

CONCLUSIONS

Following Cvijić's research, a large number of specialists further improved the knowledge of the Dinarides in terms of hydrology, geomorphology, geology, hydrogeology. Today, more than a hundred years after the initial research, one can say that Dinaric karst is well investigated on a regional scale, but due to the complexity and intensity of the karst aquifer regime, detailed survey and systematic monitoring have to be further improved. The DIKTAS project contributed to better understanding of complex transboundary inter-linkages and the importance of sustainable and equitable use of water resources.

Due to its historical importance for the development of karst science (for its exemplary karst development with numerous geo-heritage sites, several national parks and protected areas such as those under Ramsar's Convention, endemic species which inhabit underground world of caves and abundant groundwater resources), an initiative has recently been taken to include the Dinaric region and its selected areas in the UNESCO list of World Heritage Sites. This will further strengthen activities on nature and water protection and raise awareness of the local population of the importance of sustainable use of natural resources.

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