Characterization of transboundary aquifers in Dinaric karst - a base study for sustainable water management at regional and local scale

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ABSTRACT
The Dinaric system (Dinarides) is a long, NW-SE oriented orogenic belt, parallel to the Adriatic Sea with numerous intermountain depressions, large karst poljes and valleys created by numerous perennial or sinking streams. Its NW fringe is the Crasso area around Trieste in Italy while the SW part extends deep into Albania. The Dinaric region is a karst holotype. The term karst was born in this region, as well as karstology - a new scientific discipline whose foundations were laid by Jovan Cvijić and his peers at the end of the 19 Century.

In the region, it is distinguished between three major tectonic units: External (closest to the Adriatic Sea), Central and Inner Dinarides. The main sedimentation cycle in the Mediterranean geosyncline (Tethys) started in the Permian and lasted through Upper Cretaceous. All the classic karstic features are developed; for example, there are more than 150 poljes and in certain areas a number of dolines reach up to 150/km^2. The average infiltration rate is 60% of precipitation. 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. Concerning karstic water resources, the Dinaric region is by far the richest in all of Europe: in southern Montenegro the average specific yield is 40 l/s/km^2. Nevertheless, there are numerous obstacles to sustainable groundwater utilization; first of all the huge annual variation of discharges and the vulnerability of aquifers to pollution.

The rise of several new sovereign states from what was once Yugoslavia created complex transboundary inter-linkages that impact on the use of shared water resources for domestic supply, power generation and agriculture. DIKTAS (Protection and Sustainable Use of the Dinaric Karst Transboundary Aquifer System) is an on-going GEF project implemented by UNDP and UNESCO's IHP, initiated to improve the understanding of shared water resources and to facilitate their equitable and sustainable utilization, including the protection of dependent ecosystems. Within the project, a regional hydrogeological characterization is carried out and seven transboundary aquifers are currently assessed in more detail in order to establish a common scientific understanding and an information system for the monitoring and management thereof. Five of them are set along the borders of Croatia and Bosnia and Herzegovina (B & H), one is between B & H and Montenegro and one is shared by Montenegro and Albania.

1 INTRODUCTION

The Dinaric system (Dinarides) represents a geologically heterogeneous, south European orogenic belt of the Alpine mountain chain (Alpides). It extends from Italy in the North over the countries of Former Yugoslavia (Slovenia, Croatia, Bosnia and Herzegovina, Montenegro, Serbia, FYR of Macedonia) and ends in the South at the territories of Albania and Greece. The main orientation of the system is NW-SE, parallel to the Adriatic Sea. It is a long, mostly mountainous structure with numerous intermountain depressions, large karst poljes or valleys created by numerous perennial or sinking streams.

Due to its historical importance for the development of karst science (for its exemplary karst development with numerous geo-heritage sites, and abundant groundwater resources) an initiative has recently been taken to include the entire Dinaric region in the UNESCO's list of a World's heritage sites.

1.1 DIKTAS project

'DIKTAS' is an acronym of the GEF (Global Environment Facility) regional project 'Protection and Sustainable Use of the Dinaric Karst Transboundary Aquifer System'. The Dinaric Karst Aquifer System, shared by several countries and one of the world's largest, has been identified as an ideal location for applying new and integrated management approaches to these unique freshwater resources and ecosystems.

At the global level the project aims at focusing the attention of the international community on the huge but vulnerable water resources contained in karst aquifers (carbonate rock formations), which are widespread globally, but poorly understood.

At the regional level the main project objectives are to (1) facilitate the equitable and sustainable utilization and management of the transboundary water resources, and (2) protect the unique groundwater dependent ecosystems that characterize the Dinaric karst region from natural and man-made hazards, including climate change,. These objectives aim to contribute to the sustainable development of the region.

The project will provide better knowledge of the resource and the causes of its degradation through a consultation mechanism (TDA - Transboundary Diagnostic Analysis) among the countries sharing the aquifer and a proposal (SAP - Strategic Action Plan) for common activities, including policy, legal and institutional reforms, and investments. Results will be measured in terms of the achievement of key benchmarks (i.e. establishment of national and international consultation mechanism, approval of TDA, endorsement of SAP, etc).

Following a completion of the preparation phase in December 2009, the full-size project execution started in November 2010 and will last 4 years. The project is being implemented by UNDP and executed by UNESCO's International Hydrological Programme (IHP), an intergovernmental scientific cooperative programme for water research, water resources management, education and capacity-building. UNESCO's regional office for science and culture in Europe, located in Venice, as well as the UNESCO office in Sarajevo are actively supporting the implementation of the project. In addition, a number of international organizations and institutions such as the IAH Commission for Karst and GWP-Med are also actively participating in the DIKTAS project.

This paper presents the major findings of hydrogeological analysis carried out at the regional level, and some preliminary results of a still on-going analysis of seven transboundary aquifers (TBA). More information on the DIKTAS project is available on the project site: http://dinaric.iwlearn.org.

1.2 Study area

Partner countries within the framework of the DIKTAS project are Albania, Croatia, Bosnia and Herzegovina, and Montenegro (Fig. 1) as GEF-fund recipient countries, as well as Greece, Italy and Slovenia as non-recipient countries.

Fig. 1 Study area of Dinaric karst (DIKTAS GIS DBase)

A literature review shows that most of the authors see the Crasso area around Trieste-Udine in Italy as the western boundary of the Dinarides. Its extent to the South is however less clear due to the sometimes hardly noticeable transition to Pindes and Hellenides geostructural units, in Albania and Greece respectively. The Hydrogeology Working Group (HGWG) of the

DIKTAS project decided to include the Vjosa River catchment in Albania in the project area, despite their opinion that the Dinaric karst border is ending already in the Albanian Alps (North of this catchment).

The Adriatic coastline and the islands make up the western border of the Dinaric system. A tectonic graben of the Sava River is usually considered as the northern edge of the Dinarides. The fringe of the Dinarides in Croatia and in Bosnia & Herzegovina is therefore placed some 20-30 km South of the Sava riverbed (Fig. 1). Montenegro is the only country whose entire territory belongs to the Dinarides; the karstified carbonate rocks cover more than 2/3 of the Montenegrin territory.

Besides the four project countries, the Dinaric system extends to the territory of several other countries (Fig 1). In Italy, the Crasso area around Trieste is a *locus typicus* of karst. In Slovenia the major structure is the Julian Alps which cover the southern part of the country. Over 30% of the surface area in western and southwestern parts of Serbia, which also belong to the Dinarides, are covered by carbonate rocks. The Dinaric system continues over the western part of FRY of Macedonia and ends at the country's southern border near Prespa Lake (some authors also include the western part of the Pelagonic basin).

The total surface area of the Dinaric system, including non-karstic rocks, is estimated at 136,700 km^2, out of which 110,410 km^2 belong to four project countries.

Table 1 Surface area of Dinaric system per country (km^2) and percentage of the territory included

CRO	B&H	MNE	ALB
27,445	45,375	13,345	24,245
48.5 %	88.6 %	100.0 %	84.3 %

2 PREVIOUS HYDROGEOLOGICAL RESEARCH

Classical karst terminology recognizes a karstic region as an area consisting mainly of compact and soluble carbonate rocks in which distinctive surface and subterranean features appear; caused by solutional erosion. The term can also be applied to any region made up of soluble rocks: anhydrite, gypsum, salt. In a broader sense, the term is utilized to describe every phase of the karstification process in karstifiable rocks.

The Dinaric region is a karst holotype. Not only was the term karst born in the area, but Jovan Cvijić also undertook most of his work in the Dinaric karst, laying the foundation for a new scientific discipline - karstology. In Das Karstphänomen (1893), Cvijić argued that rock dissolution was the key process in the creation of most types of dolines, 'the diagnostic karst landforms'. Hence, Dinaric Kras, Crasso or Karst (in a Germanized form) became a typical example of dissolution landforms and karst aquifers (Kranjc, 1994); this term is now applied to modern and paleo-dissolution phenomena worldwide. Cvijić is recognized as "the father of karst geomorphology" (Ford, 2005; Stevanovic and Mijatovic, 2005). Cvijić stated that "there is no deeper and more thorough karst development than Herzegovina-Montenegro's karst located between the lower Neretva River, Skadar Lake and the Adriatic Sea".

Following Cvijić's research, a large number of specialists from former Yugoslavia, Italy and Albania further improved the knowledge of the Dinarides in terms of hydrology, geomorphology, geology, hydrogeology and social/humanistic sciences. Preparation of the Basic Geological Map of Yugoslavia (some fifty years ago) on the scale 1:100.000 (with working sheets 1:25.000) substantially improved the geological knowledge on Dinaric karst. During several decades, large scale hydrogeological explorations were carried out for the purpose of challenging construction of dams in the Dinaric karst region. Technical applications of control and regulation of karst aquifer through the construction of galleries, batteries of wells, and groundwater reservoirs (storage) represent an important contribution to the international hydrogeological science. Petar Milanović's "Hydrogeology of karst and methods of investigation" (first edition in 1979, second in 1981) became one of the most important references when dealing with karst groundwater distribution and circulation. A monograph "Hydrogeology of the Dinaric Karst" (Mijatović, 1984) published by IAH, also confirms the wide interest of the hydrogeological community in the Dinaric karst.

3 GEOLOGY OF DINARIC SYSTEM IN BRIEF

Throughout its early geologic history, the Dinaric region was part of the Mediterranean geosyncline (Tethys). It was not until the Late Paleozoic that carbonate sediments were deposited in quantities favorable for karstification. The first sedimentation cycle represents the interval between Upper Devonian and Middle Jurassic. In the internal Dinarides, marine sedimentation started mainly in the Upper Permian and lasted until the end of the Lower Jurassic. In the External Dinarides this cycle extended until Upper Cretaceous.

There were a few distinctive phases during a long sedimentation cycle that started (for a major part of the study area) in the Triassic and ended in the Paleogene. At the end of the Upper Cretaceous and during the Paleocene, intensive uplifting and folding took place, during which most of the carbonate and flysch rocks were tectonized. After the Laramian tectonic phase, the next intensive movements occurred in the Helvetian phase (Eocene/Oligocene). All the main nappes along the Adriatic/Ionian Sea coastline can be related to this stage.

The Cretaceous sediments in the Dinaric region are almost entirely carbonate (limestones and dolomites) with the exception of the Durmitor Mountain in Montenegro, where Upper Cretaceous flysch also developed.

In the Dinarides it is usually distinguished between three major tectonic units: External, Central and Inner Dinarides. These can be additionally separated into several subunits. This classification, made by Croatian geologists (Herak, Polsak and others), is comprised of: A – Structural complex of the Adriatic carbonate platform (Adriatic) with the External Dinarides; D – Structural complex of the Dinaric carbonate platform (Dinaric) with the Central Dinarides; S – Structural complex of the

Internal Dinarides (Supradinaric). According to Herak (1972) two carbonate platforms existed in the area of the Karst Dinarides from the Late Triassic to the Eocene - the Adriatic Carbonate Platform (Adriaticum) and the Dinaric Carbonate Platform (Dinaricum), separated by a persistent deep-water inter-platform (Epi-Adriaticum).

The Albanian tectonic classification is relatively different in names and in structures. Nevertheless, the units such as the Adriatic depression (Fig.2) and the parts of the Ionian, Krasta-Cukali or Kruja zones, belong to the External Dinarides, while the Mirdita unit could be interpreted as an extension of the Central ophiolitic zone of the Central Dinarides.

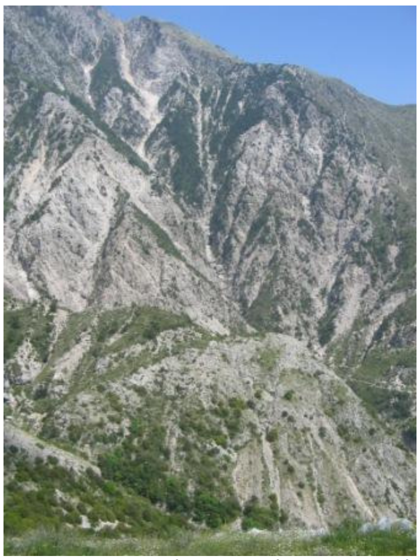

Fig. 2 The contact zone between large tectonic zones – Adriatic and Ionian (Dhermi, Albanian coast, photo Z.S.)

Herak (1972) divided the karst areas in Yugoslavia into three regions (Fig.3): (1) the Adriatic Insular and Coastal region, (2) the High Karst region (Central part), and (3) the Inner region. In his later works (1977) the name of the first region was shortened into Adriatic belt.

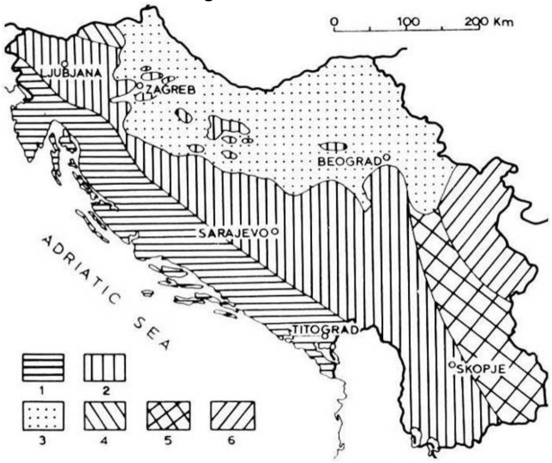

Fig.3 Major tectonic units of Yugoslavia (Herak, 1972).
1 = Outer Dinaric units (Adriatic and high karst); 2 = Inner Dinaric and south Alpine units; 3 = Pannonian Basin; 4 = eastern Alps; 5 = Serbian-Macedonian Belt; 6 = Carpathian-Balkanides Belt.

4 KARSTIFICATION AND KARST FEATURES

The development of the Dinaric karst was gradual, but with increasing volume and intensity. Herak (1972) stated that at the end of the Triassic or during the Lower Jurassic (old Cimmerian phase?), the Triassic carbonate rocks were 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 (Herak, 1972, Ćirić, 1984). Manifold disturbances caused relative block movements, connecting the carbonate sediments of distinctive stratigraphic horizons. Hence, for the first time in the geologic history of the region, there was a potential for more intensified subsurface water circulation and widespread karstification (Herak, 1972). The subsidence of large areas provoked new transgression and marine sedimentation of limestones, followed by the impervious flysch-like sediments.

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 bringing a new structural and morphologic evolution, especially in the Dinaric Mountains (Mijatovic, 1996). 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.

Referring to the karstification base as an approximate depth to which the soluble rocks were exposed to the karstification process, Milanović P. (2005) concluded that the depth of karstification in the Orjen Mountain (Montenegro) is about 350-400 m. Locally, in the wider area (Nikšićka Župa, Vilusi, Montenegro) deep boreholes have encountered karstified zones at depths of up to 500 m, and sometimes at depths exceeding 2,000 m. According to Milanović P (2000), karstification in the near-surface zone (0-10m) is about 30 times larger than at a depth of 300 m. For the depths larger than 300m, the index of karstification approaches its minimum value, almost zero.

The Dinaric region contains all kinds of karst features: karren (lapies), dolines, pits (jamas), ponors (swallow holes), dry valleys, caves and caverns as single forms, and uvalas, poljes and karst plains as larger complex forms (Roglić, 1965, 1972). Most of these features were carved in Jurassic and Cretaceous limestones.

Šarin and Kostović-Donadini (1981) stated that a number of sinkholes (dolines) in certain areas near Knin reach 150/km^2.

Dry and blind valleys are numerous in the Dinaric karst (Fig.4). Once these were filled with surface streams that were - in the course of time - diverted through ponors to the underground.

Fig. 4 A small depression - uvala used for crop cultivation (Orjen Mountain, Montenegro and B & H, photo Z.S.)

Though different in dimensions, they are similar in shape, and uvalas are commonly dry, while the poljes are characterized by very complicated hydrogeological relations. Some of them are lakes or swamps, the others periodically inundated or even dry. In general, the poljes are heterogeneous in respect to geological relations, but a great abundance of impervious rocks show that their depressions were formed with the impact of tectonic forces.

According to Milanović P. (2000), in the Dinaric karst region there are approximately 130 poljes. The total area of all these poljes is about 1,350 km^2. Drainage of surface water is achieved through many ponors. These are frequently located in the polje areas nearest to the prevailing erosion base. In the Nikšićko polje, about 880 ponors and estavelles were identified, 851 of which are located along its southern perimeter. In Popovo Polje there are more than 500 ponors and estavelles.

Poljes become flooded as soon as the sink or recharge capacity of the ponor becomes lower than the inflow quantity of water. Natural plugging of ponors may also lead to faster flooding and longer duration of floods. Flood durations can vary considerably."

The size of karst poljes is highly variable: some are very small, with an area of 1-3 km^3 (Fig. 5), while Livanjsko Polje, considered the world's largest karst polje, covers an area of 380 km^2, and together with Buško Blato, which morphologically may be considered its integral part, it totals 433 km^2.

Fig. 5 Plateau under the peaks of Velebit Mountain (Croatia, photo Z.S.)

There are some distinctive patterns in distribution of karstic features in the main geo-structures of the Dinaric system. In the Adriatic zone, vruljas (submarine springs, MIlanovic S.,2007), are the most specific hydrogeologic features. They are formed by the sinking of the sea bottom of the northern Adriatic Sea and rising of the sea level, so that karstified land submerged in the sea. The Central Dinaric zone is characterized by the presence of all the karst morphologic and hydrogeologic features, including a large number of poljes and estavelles, and by discordances between morphologic and hydrogeologic (i.e. surface and groundwater) divides. Anticlines with dolomites in their cores and clastic bedrock control the direction of the groundwater flow. The inner zone comprises areas where there are neither poljes, nor estavelles, nor large ponors, but sinkholes (dolines) are frequent (Šarin, 1983). In Albania best developed karst phenomena are in Albanian Alps, and in Mirdita and Ionian zones.

Krešić (1988) listed some 15 potholes (pits, shafts) in former Yugoslavia deeper than 400 m. In the meantime, some much deeper potholes have been discovered; Lukina jama-Trojama (-1392 m) and the Slovačka jama (-1301) at the mountain Velebit are among the deepest speleological phenomena in the World.

Some areas, such as Kameno more („Stone sea") and the Orjen Mountain above Risan (Kotor Bay, Montenegro), contain plenty of very deep vertical potholes. For example, within an area of only 8 km^2 more than 300 vertical shafts were registered (Milanović P. (2005). Some of those shafts were speleologicaly investigated to the depths of 200- 350 m.

According to the data obtained from S. Božičević (1966), potholes in former Yugoslavia have been recorded and measured with a total depth of about 45 km (in Croatia over 25 km). Herak (1972) confirmed that more than 12,000 caves have been explored in former Yugoslavia alone, more than 5,000 of which are in Croatia. More recent surveys confirmed the presence of over 7,000 underground openings (Fig.6).

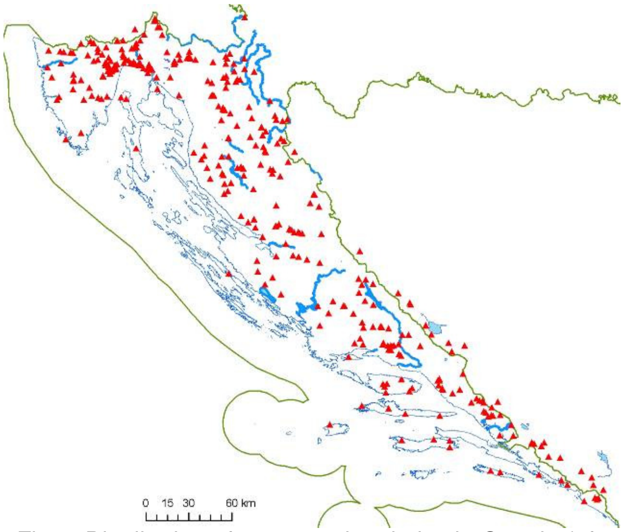

Fig. 6 Distribution of caves and potholes in Croatia (after Pekas, DIKTAS GIS DBase)

Although most of these explored speleological phenomena are dry objects, water is permanently or periodically present in some 25%. The ponors play an important role within the karst. Such a cave-ponor system is Đulin ponor-Medvednica near Ogulin with an explored length of 16,396 m which is the longest cave in Croatia.

5 CLASSIFICATION OF AQUIFER SYSTEMS AND CHARACTERIZATION OF DINARIC KARST AQUIFERS

In total, 22 different main litho-stratigraphical members are distinguished in the Dinaric region. They are accordingly classified into one of the six hydrogeological units. These are as follows: the two karstic aquifers (high KA1, and moderate KA2 permeability), the two intergranular aquifers (high IA1, and moderate IA2 permeability), fissure aquifers (FA) and aquitards (AT). The highly permeable aquifer KA1 is apparent in all lithostratigraphic members of the Mesozoic age, with the exception of the Lower Triassic and uppermost members of the Upper Cretaceous developed in non-carbonate facies. Some members of the same age were formed in diverse paleogeographic environments, consequently having a different lithology and different hydrogeological properties.

5.1 Groundwater flow and directions

The surface and groundwater of the Dinaric karst belongs to the two main catchments. The area of External (Outer) Dinarides belongs to the Adriatic catchment (a small part to the Ionian Sea), while the Internal (Inner) Dinarides are part of the Sava (i.e. Danube and the Black Sea catchment area (Fig. 7). The main river basins in the Adriatic/Ionian catchment area are the Vjosa, Seman, Drini, Buna (Bojana), Zeta, Neretva, Cetina, Krka, Zrmanja and Soča. Karstic groundwater from the river basins of the Tara, Piva, Vrbas, Pliva, Sana, Una, the upper course of the Kupa River and the Krka (in Slovenia) gravitates to the Black Sea catchment area.

About 60% (65,545 km^2) of the study area belongs to Adriatic basin, while the Black Sea basin is covering about 40% (44,865 km$^{2)}$.

Komatina (1983) noted that the tracer experiments were conducted at more than 650 sites in the Dinaric karst of former Yugoslavia. In eastern Herzegovina alone, tracers were applied at 281 sites, in the catchment area of the Cetina River at 99 sites and in the Skadarsko Lake catchment area at 77 sites.

According to Milanović P. (2000) "more than several hundred investigations have been performed in the Dinaric karst so far, for the purpose of finding the major routes of underground water circulation. Based on experiments, the average flow velocity is estimated varies between a wide range of 0.002 - 55.2 cm/s. Such extreme values are rare, whereas an average velocity is about 5 cm/s.

Fig. 7 Major catchments and river basins in study area

The results of recent investigations by various tracers have shown that the karst circulation velocity varies with the hydrologic conditions of the surface of the terrain; in other words, it depends on the instantaneous saturation of the aquifer. During the dry season and low aquifer water table, water circulation in the karst system is characterized by a slow movement of aquifer waters. The water waves labeled with dye take two- to five-fold less time to travel the same distance during a season of high hydrologic activity." (Milanovic, P. 2000).

Komatina (1983) referred to the work of Milanović P. (1976) and A. Magdalenić (1971) who concluded (based on 380 conducted experiments) that the frequency of fictive groundwater velocities in Dinaric karst is as follows: in 70% of cases from 0 to 5 cm/s; in 20% of cases 5 to 10 cm/s; and in 10% of cases more than 10 cm/s.

Groundwater velocity depends directly on the hydrological period and the water table position (Fig.8).

For instance, to cover the distance (34 km) from Gatačko Polje to the Trebišnjica Spring (Dinaric karst, Herzegovina), the underground flow takes 35 days when the water table is low and inflow is small. During high water levels and large inflow, the well-distinguished water wave takes only five days to cover the same distance. Similarly, between Čaprazlije ponor and Mali Rumin spring the velocity was as follows: in the dry period 5.1 cm/s; at high water levels 28.8 cm/s (Komatina, 1983). A much larger velocity value has been obtained by tracing tests conducted in Prespa Lake, connected with the Ohrid Lake. The maximum values in the test conducted in 2002 were between 19 and 80 cm/s (Amataj et al. 2005)

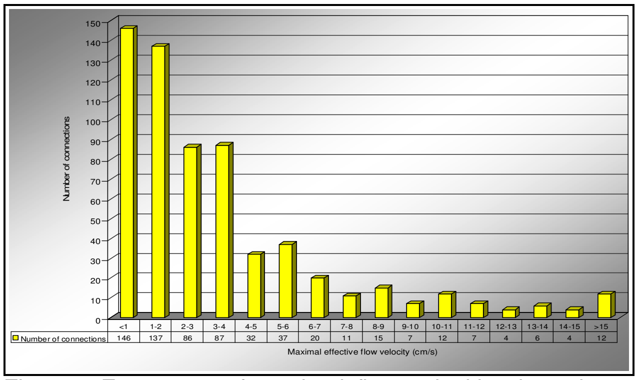

Fig. 8 Frequency of maximal flow velocities based on 623 confirmed ponor-spring connections in Croatia (after Pekas, DIKTAS DBase)

5.2 Recharge and discharge of karst aquifer

The Dinaric karstic aquifer system formed within a very thick (over 1000m) complex of limestones and dolomites. As a result of intensive karstification, carbonate rocks are characterized by well-developed morphological karstic forms, but also by a net of highly permeable underground caverns and caves as a privileged pathway for intensive groundwater circulation (Fig. 9).

Fig. 9 Highly karstified rocks in Karuč spring catchment (Skadar Lake, Montenegro, photo Z.S.)

The recharge of karst aquifers is from precipitation, percolated sinking rivers, and water infiltrating in some sections of perennial rivers.

The highest rate of precipitation is in the region between Skadar Lake to the East, the Neretva River as the western hydrological base level boundary and the Adriatic coast (Milanovic P. 2005). The average annual precipitation in the Kotor Bay area in Montenegro and Eastern Herzegovina varies from 2000mm to more than 5000mm (Milanovic P. 2005). More than 70% of the precipitation occurred during the wet season (October - March).

In the zones where highly karstified rocks are present at the surface, most of the rainfall infiltrates into karstic aquifer. On average (roughly estimated) about 60% of precipitation infiltrate the aquifer. According to Komatina (1983), in the Cetina River catchment area, more than 80% of the precipitation appears at the terminal water gauge controlled profile, while in the Trebišnjica River catchment area this percentage is even higher, reaching 90%. Effective infiltration in Albanian karst is on average made up of 40-55% from rainfalls (e.g. in Albanian Alps 1500-2000 mm/an; in Mali me Gropa 1100 mm/y).

Regarding karstic groundwater resources, the Dinaric region is by far the richest in all of Europe. 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.

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. Milanović P. (2005) noted that "only through three huge springs along the Neretva Valley and Adriatic coast (Buna, Bunica and Ombla) and a few spring zones in the Kotor Bay, more than 150 m^3/s is discharged annually into the Adriatic Sea directly or indirectly through the Neretva River".

Three capital cities of the core project countries receive drinking water from the karstic aquifers. Sarajevo obtains a part of its water supply from the Vrelo Bosne springs (Central Dinarides). The discharge of these springs (i.e discharge of the rich Triassic aquifer of Igman Mountain) is 1.4 – 24 m^3/s (Čičić & Skopljak 2004).

The Albanian capital Tirana is supplied in part from the spring that discharges the Triassic and Jurassic karstic aquifer of Mali me Gropa plateau. Since WW II the two main springs, Selita (0.24-0.86 m^3/s) and Shemria (0.45-1.50 m^3/s), have been tapped for the city (Eftimi 1971), while downstream from the third important spring, Buvilla, issuing from Dajti Mt. a large reservoir has been constructed.

Mareza spring (2.0–10.0 m^3/s) in the Skadar basin is the main source of water for the Montenegrin capital city of Podgorica (Radulović M. 2000).

Along the Adriatic, Ionian and Aegean coast, almost all cities and tourist centres use karstic groundwater (Stevanovic, 2010a, Stevanovic and Eftimi, 2010). Perhaps the most famous and the largest spring on the northern Italian coast is Timavo, with an average discharge rate of 30 m^3/s.

The Zvir group of springs were tapped at the end of the 19th century to supply water to Rijeka, the largest Croatian port. The discharge varies between 0.6 and 3.0 m^3/s. Jadro Spring is the main source for the water supply of Split. The average minimum discharge of Jadro during the recession period is 3–5 m^3/s, while maximum discharge is often over 50 m^3/s (Bonacci 1987).

Ombla Spring is the largest permanent karstic spring at the South Adriatic coast (Fig. 10). It supplies the city of

Dubrovnik; at maximum its discharge is about 154 m^3/s. Since the completion of the Trebisnjica Hydropower System and the regulation of this longest sinking river in Europe in the catchment of Ombla, the average discharge of Ombla was reduced from 34 m^3/s to 24 m^3/s. However, the minimum discharge (2.3 m^3/s) is not affected by the applied measures (Milanović P. 2006).

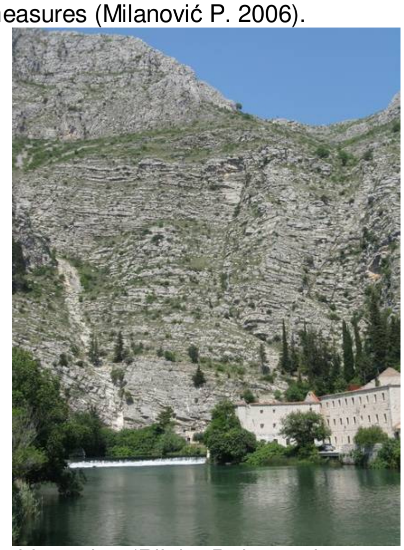

Fig. 10 Ombla spring (Rijeka Dubrovačka source, Croatia, photo Z.S.)

The main springs along the Boka Kotorska Bay in Montenegro are: Gurdić and Škurda spring near Kotor, Ljuta spring at Orahovac, Spila spring at Risan, Morinj springs, Opačica at Herceg Novi and Plavda at Tivat. The Sopot near Risan is a well known submarine spring (Fig.11). All these springs are characterized by a high variation in the discharges due to a highly karstified catchment and extremely fast propagation of the rainfall. Some of those springs even dry up completely during summer while after intensive rainfall some of them can discharge over 100 m^3/s.

Fig. 11 Sopot spring near Risan (Montenegro) during peak flow discharge (photo Z.S.)

In the Skadar Lake basin there is a large number of sublacustrine springs such as Oko Matice, Golač, Kaludjerovo Oko and many other along the edge of Malo Blato (Radulović and Radulović, 1997), Volač, Karuč, Bolje sestre (recently tapped for the regional water supply of the Montenegrin coastal area, Stevanović, 2010b); Grab and others in the flooded valley of the Crnojevića Rijeka.

In the Albanian karst there are roughly about 110 springs with an average discharge exceeding 100 l/s (Eftimi, 2010). The majority of these springs are in the Dinaric part of the country as proposed under this project (North from Vjosa). It is assumed that 2/3 of whole groundwater resources in Albania are linked with karstic aquifers, providing roughly more than 60% of water consumed in the country (Eftimi, 2010). The average potential yield of coastal karst aquifers in the catchment of the Ionian Sea in Albania is (roughly estimated) 15-20 m^3/s (Eftimi, personal communication).

According to Šarin and Kostovic-Donadini (1981), variations in the yield of karstic springs expressed by the ratio Qmax/Qmin may reach more than 100. For instance, this ration for the spring of the Una river is 197 and for the Cetina river spring — 100. In contrary, there are springs with a relatively more stabilized regime, such as the Gacka river spring (3.1), Varvara spring (3.3) and the springs of the Pliva river (4.4). In general, ascending and contact springs have more stable discharge throughout the hydrologic year than the gravity type of springs.

6 TDA-TRANSBOUNDARY DIAGNOSTIC ANALYSIS

The Transboundary Diagnostic Analysis one of the main DIKTAS project activities is to be completed towards the end of 2012. The TDA is a fact-finding activity, meant to improve the knowledge of the project area and provide a basis for the so-called Strategic Action Plan (SAP), to be produced next year. Unlike TDA, SAP is a result of negotiations and establishes clear priorities for action to resolve the priority transboundary waters problems.

The main TDA activities are 1. Regional hydrogeological characterization, 2. Regional environmental and socio-economical assessment, 3. Regional assessment of legal and institutional frameworks and policies, 4. Synthesis and finalization of the Transboundary Diagnostic Analysis, 5. Local Scale activities/Case Studies.

One of the main results of the regional hydrogeological characterization is the GIS based digital Hydrogeological map of the Dinaric Karst region. Its creation involved harmonization of data, classifications (as earlier presented), methodologies, reference systems, projections, semantics, etc. The map will be used as a basis for the development of various thematic maps during the environmental and socio-economical assessment. Thematic regional maps will contain information on, among others, (current and potential) pollution sources, population distribution, ecosystems, existing and planned infrastructures (reservoirs, dams, tunnels, channels), agricultural and recreation areas, etc.

The hydrogeological and thematic maps will eventually be integrated in the DIKTAS Management Map. A permanent international consultation commission (to be set up during the project) will ensure that this tool is used while discussing planning and developments in the Dinaric Karst region.

The DIKTAS project focuses on transboundary aquifers (TBAs), examining current and potential issues of concern. The analysis of TBAs also provides an opportunity to test the applicability of outcomes of the regional analysis at the local scale, dealing with concrete issues of transboundary concern. In total, seven TBA are selected for detailed analyses: Una, Krka, Cetina, Neretva, Trebisnjica (all shared by CRO and B&H), Bilecko Lake (B&H and MNE) and Cijevna/Cemi (MNE and ALB). Six of these TBAs belong to the Adriatic Sea catchment area and only one (Una) is a part of the Black Sea basin. The TBAs comprise of in total a surface area of 12,000 km^2, which is around 10% of the entire study area. The surface area of individual TBA varies from 668 km^2 (Krka) to 3,455 km^2 (Cetina).

Delineation of the aquifer surface area was a very first step in the hydrogeological analysis for each TBA. These areas usually comprise allogenic and autogenic zones of karst aquifer recharge. Further analytical steps included the characterization and creation of conceptual models for each TBA. For instance, out of five TBAs shared between B&H and CRO groundwater flow in four cases is defined to be from B&H to CRO, and only in one case it is *vice versa* (Fig.12). Groundwater budgeting of TBAs is a base for the assessment of groundwater reserves and availability. This analysis is commonly undertaken by WG Socio-Economy and will be a base for proposals and measures aiming to ensure sustainable development of TBAs.

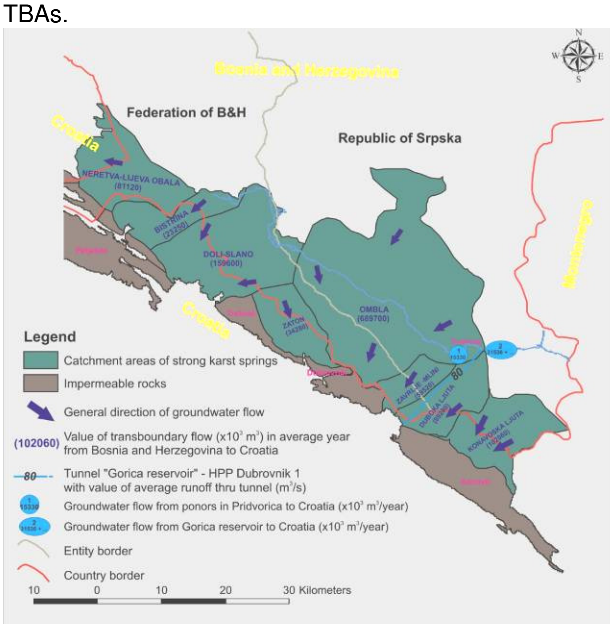

Fig. 12 Groundwater flow in southern part of Bosnia & Herzegovina along border with Croatia (after Jolovic, DIKTAS DBase)

Issues of concern for each of the TBAs is preliminary identified and are under evaluation. They include various examples of groundwater pollution, salt water intrusion, increased groundwater pumping, impact of hydro-energy systems on environment and similar.

7 CONCLUSIONS

The DIKTAS project is progressing well, yielding useful information on the state of the Dinaric karst aquifer system. The regional hydrogeological characterization whose main findings are presented in this paper is almost completed.

The analysis of groundwater utilization and demands as a joint task of the project Working Groups will also be finalized soon. The analysis of protection measures and their possible improvements will be addressed in more detail while preparing the SAP. The aquifer vulnerability will come in focus during the preparation of thematic components for the DIKTAS Management Map.

This paper is also a part of DIKTAS communication, dissemination and replication activities. The next two papers will be dedicated to issues of transboundary groundwater concern and the aquifer vulnerability analysis in the Dinaric region.

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