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title: **Quality and quantity status and risk assessment of groundwater bodies in karst areas of Croatia**

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INTRODUCTION

Karst aquifers developed in south-western and southern part of Croatia occupy an area of approximately 26,750 km^2 of the total national territory (Figure 1). They are built mostly from karstified carbonate rocks that belong to the macro-structural unit "*Dinarides*" which extends along the northwest–southeast direction, from Slovenia through Croatia and Bosnia and Herzegovina to Montenegro. Karst aquifers in Croatia represent almost the half of total available amount of water in the country. For karst areas and economically developed coastal area these aquifers are the only sources of drinking water. One part of the Croatian karst areas belongs to the Adriatic Sea catchment, and other part to the Black Sea catchment.

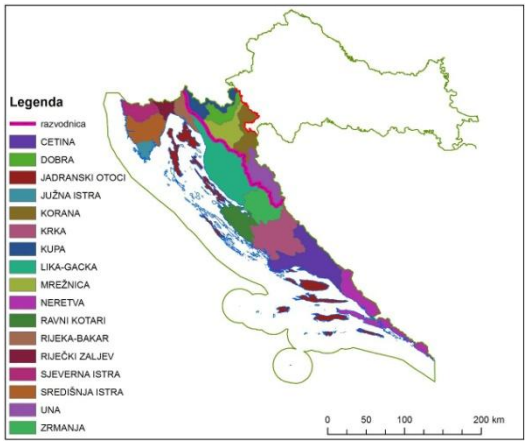

Figure 1. Groundwater bodies in Croatian karst area.

Basic characteristics of Dinaric karst aquifers are specific surface and subterranean relief, large catchments rich in precipitation (up to 4000 mm per year), low retentive capacity of karstified underground, rapid subsurface flows, periodic flooding of karst fields, appearances of large karst springs, multiple discharges and sinking of waters within the same catchment, long periods of drought, lack of covering layers and significant sea influence in coastal aquifers. All this facts makes karst aquifers naturally highly vulnerable that requires special protection measures if we want to preserve the quality and quantity of water in them. Only 2% of the total groundwater reserves are used for water supply of karst areas and almost 25% of the total reserves is accumulated in a numerous of surface accumulations and used for hydro power plants. Due to the complex needs of groundwater characterization according to European Water Framework Directive (hereinafter WFD), in Croatian karst area has been delineated 17 groundwater bodies (hereinafter GWB): 12 in Adriatic, and 5 in Black Sea catchment area. For purely practical reasons Adriatic islands are included and observed as one GWB, although each island functions as a separate unit. A large number of karst catchments in Croatia extend into neighbouring Slovenia and Bosnia and Herzegovina (hereinafter B&H), which open the need for joint research and management of transboundary water bodies. Towards the Croatian south, the number of transboundary GWB units is increasing, so in the most southern part of Croatia there are practically placed only discharges zones, while the most of catchments areas are in B&H.

An assessment of quantitative and qualitative status of GWBs is conducted during the characterization of GWBs according to WFD (WFD, 2000).

CHARACTERISATION OF GROUNDWATER BODIES

Impact and pressure and risk analysis were performed using a European approach described by COST project 620 (EU COST 620, 2004), which consists of three phases: analysis of natural vulnerability, hazard analysis and risk analysis.

Analysis of natural vulnerability of aquifers is based on geological structure, estimation of karstification degree, slope of terrains and quantity of rainfalls. This analysis separates areas with different levels of natural vulnerability. The final result is *Vulnerability map*, which is extremely useful in determining the sanitary protection zones of water supply sources.

Hazard analysis includes the development of databases for point and diffuses (agriculture) pollutants. The final result is *Classified maps of hazards*, which shows the location and weighted values of each pollutant. Special attention is paid to the impact of agricultural activities, because the chemical analyses of water in some regions have shown significant impact of agriculture on groundwater resources. *Risk map* is achieved by overlapping of Vulnerability and Classified hazard maps.

Qualitative status assessment (hereinafter QUAL) has performed individually for each GWB, according to chemical analysis of waters from 55 karst springs that are included in the *National monitoring network*, and according to detailed analysis of individual water supply springs in period 2000–2007.

For QUAL were used following basic parameters (WFD, 2000): dissolved oxygen, pH, electrical conductivity (hereinafter EC), nitrates and ammonia, and additional groundwater parameters such as free CO_2, water temperature (hereinafter T), orthophosphate, turbidity, Fe, Mn, mineral oils, As, Cd, Pb, Hg, chlorides, sulphates, trichloroethylene and tetrachloroethylene. Specific characteristics of karst aquifers in Croatia and elsewhere in the world are high groundwater velocities, relatively short residence time of groundwater and rapid hydrology and water quality changes in short time intervals. It is interesting to note that exceptional quality of water on karst springs is often during the long summer dry periods. This indicates the great and importance role of epikarst and unsaturated zone of karst aquifer, which prevent infiltration of contamination in the saturated parts of karst aquifer. Heavy rainfall after a long dry period causing strong and relatively short-term pollution of waters on karst springs. During these events several water quality parameters exceed the maximum allowed concentrations values (hereinafter MAC). Another major problem, especially of coastal karst aquifers, are occasional sea water intrusions deep into the coastal aquifers during the summer dry periods and water supply exploitations of these aquifers in terms of labile fresh water–salt water relationships. Illustrative parameters for QUAL of karst groundwater in Croatia are nitrates. In the central part of Croatian karst area (mountainous area) values of nitrate are of very low values and have constant uniform trend. Due to that, it is an indicator of humanly untouched GWB that is characteristic for sparsely populated Dinaric mountainous area. On the other hand, in Dinaric border areas, on Istrian Peninsula, the situation is much different. Although the nitrate values are in most cases still within MAC (on average 46.35 mg/L NO_3^-), they are yet very close to this limit. The reason for this is a much stronger agricultural activities on Istrian Peninsula. MAC of pH for drinking water is in range 6.5 to 9.5. Within this range are all analysis used during the characterization of GWBs, but in border parts of mountainous Dinaric area trends of pH show considerably decreasing values. Such trend is commonly associated with microbiological and chemical proc-

esses in natural systems as a result of pollution. But, in the case of Istria and Ravni Kotari regions it can also be partly an indicator of regional contaminant transport of acid rain from industrialized northern Italy.

The major problem of coastal and island karst aquifers in Croatia is also periodical or permanent sea influence on freshwater systems. During the first half of the 20th century for water supply needs numerous water springs were captured in coastal area and on islands, and in that time this water quantities were adequate for local population needs.

However, population growth and tourism development have caused increased demand for drinking water and existing water supply springs have become increasingly exploited. Increased fresh water exploitation has caused gradual increasing of salinity on these springs, and nowadays many of them are already out of service. This problem is especially significant on the islands where fresh water gradually disappears and today only three large islands (Cres, Krk, Vis) have their own fresh water resources. Water supply on other island is either associated with mainland water supply systems with undersea water pipelines, or islands have small devices for desalination of salted water or only water tanks. Increased fresh water exploitation is also the reason of increasing EC trend in coastal area and on islands.

QUAL analyses of karst groundwater in Croatia showed two GWB that have significant water quality problems in accordance with established criteria of EU WFD. Those are GWB "*South Istria*" and GWB "*Ravni Kotari*" (Figure 3 — left). GWB "*South Istria*" has problem with nitrates and chlorides that are increased during a summer dry periods, due to uncontrolled exploitation of water for agriculture purposes (Biondić et al., 2009). GWB "*Ravni Kotari*" has the biggest problem with sea water intrusions deep into the land that cause higher chloride concentrations on water supply wells. Fresh water resources on the Adriatic islands are also influenced by sea water, and because of that their QUAL status is "*potentially bad status*".

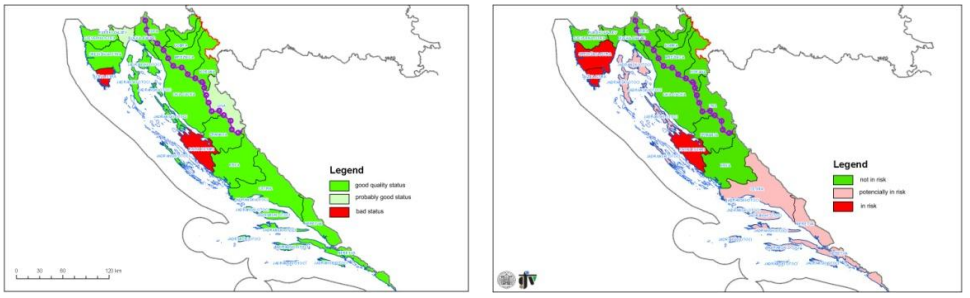

Figure 3. GWB qualitative status (left) and qualitative risk (right).

Under QUAL was also performed risk assessment based on analyses of trends for the specific parameters. The boundary condition of "at risk" is 75% of the allowable reference value at the end of the following reporting period, end of 2015. With this methodology GWB "Central Istria" also has the status "at risk", i.e. very big part of the Istrian Peninsula, entered the zone of high alert and needs for significant improvement of the qualitative status of groundwater. The risk assessment also includes the fact that most of transboundary GWBs have their recharge areas in the neighbouring countries (Slovenia and B&H). The problem is uneven water policies between these countries and Croatia, and because of that these GWBs are put in the category "potentially at risk" (Figure 3 — right).

In Quantitative states assessment (hereinafter QUAN) four comparative analysis (that included effects of anthropogenic changes in recharge, groundwater flow and discharge) have been applied: (1) analysis of GWBs water balance, with particular attention to the effects of exploitation of groundwater on viability of surface flows, (2) surface flow analysis, (3) impact analysis of quantitative relations in GWBs on terrestrial ecosystems and (4) analysis of sea water intrusion into coastal aquifers. For the purpose of QUAN analyses data period 1961–1990, with 567 stations, has been used. For the spatial coverage of boundary areas data from 85 stations in neighbouring countries also has been used.

Estimations of mean annual discharges have been made by frequently most used models of Turc and Langbein, and a comparison with the measured hydrologic data on several tested GWBs (Horvat, Rubinić, 2006). The relevant results were obtained by using Langbein method. According to approximated water balance calculation for Croatian karst areas, karst aquifers have a total volume of about 590 m^3/s of available water reserves per year, of which about 481 m^3/s per year inflows from neighbouring countries, mostly with Neretva River in the southern part of Croatia.

Effect of exploitation of groundwater for water supply on karst springs has a significant impact only during summer dry periods, when the maximum amount is taken, while the natural discharge is reduced to a minimum.

Most of the waters from karst catchments are used to generate electricity. Constructed accumulations in high zones of karst areas halt high water waves; thereby also reduce the risk of flooding of karst fields and valleys, from where the largest rivers in karst are drained to the Adriatic Sea or to the Black Sea catchment. Artificial accumulations have caused significant damage to environment when they were built, due to changes in natural conditions. But because of projected losses in their beds, nowadays they have a useful function and they increase flows of karst springs and streams during summer dry periods. For the period 1961–1990 estimated average amount of runoff from the Croatian karst areas toward Adriatic coast is about 420 m^3/s, adding inflow of 435 m^3/s from B&H. On natural way (springs, rivers) into the sea discharges about 210 m^3/s, and hydropower facilities discharges into the sea about 200 m^3/s. Even 445 m^3/s (52%) is hydrological uncontrolled groundwater runoff into the sea. Therefore, Dinaric karst area, which is drained toward Adriatic Sea, provides enormous amounts of fresh water, which nowadays freely drain into the sea, and can be used in the first place for Croatian needs (water supply of islands), but also for eventual commercialization of a part of those reserves in future market of water in the Mediterranean area.

Previous hydrological analysis shows that in the observed thirty year period is reduced water balance in Dinaric karst in Croatia for about 10%, and probably in the neighbouring countries whose water gravitate toward the Adriatic and Black Sea catchment, too. However, the water regime with today's used volume is not yet threatened so much to cause major problems in a whole area. Problems are only locally, during summer dry periods, when the exploitation is maximised and karst aquifer natural recharge minimised. This is particularly related to the maintenance of important ecosystems along karst rivers. However, water reserves are renewable and already first higher rainfalls after dry periods compensate all possible water deficits created by long term droughts.

QUAN analysis has shown that two GWBs have “bad status” (“South Istria” and “Ravni Kotari”), and two due to insufficient data for these areas and assessment of researchers “probably bad

status" ("North Istria" and "Neretva"). Except these GWBs with "bad status" or "possibly bad status" assessment of quantitative risk expends this list to GWB "Rijeka–Bakar" and GWB "Adriatic Islands" due to sea water intrusions and its effect on groundwater, which caused occasional stronger salinisation of water supply springs (Figure 4).

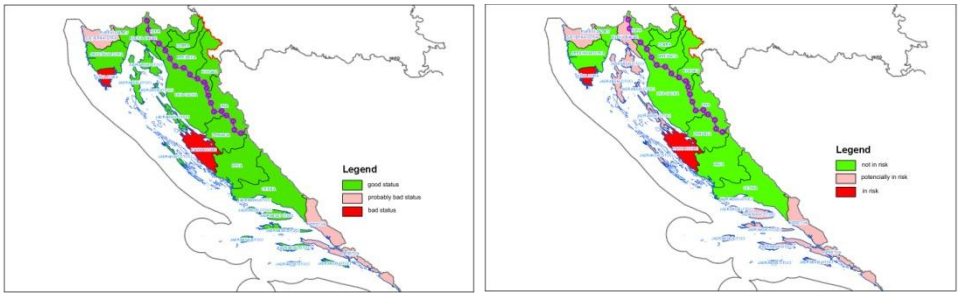

Figure 4. Quantitative status of GWBs (left) and quantitative risk of GWBs (right).

FINAL CONCLUSIONS

WFD as a strategic document for the organization of management and protection of water resources in the European Union to prevent degradation of water resources, effective protection, mimprovement of aquatic ecosystems and sustainable use of highly sensitive natural resources. Risk and states assessment of GWBs is a basic document for further monitoring of water resources value in the member countries and candidate countries for the EU membership. In the Croatian Dinaric karst region has been delineated 17 GWBs, of which 12 are in the Adriatic, and 7 in the Black Sea catchment. Analyses of pressures and impacts, qualitative and quantitative status of groundwaters, analysis of groundwater dependent ecosystems and risk assessment has been done for each GWB. Special attention is given to the monitoring network expand, because for further characterization of risk or potential risk there are not enough relevant data.

General assessment of the qualitative and quantitative status of GWBs in the Croatian Dinaric karst area is good status, which confirms that the Adriatic region has high-quality water resources in sufficient quantities for their own development, but also for the future commercialization of the Mediterranean region too. Problems with waters are registered in two GWBs, but with the possibility of alternative sources for water supply. Status "*at risk*" due to the high content of nitrate and occasional intrusions of sea water has two GWBs ("*South Istria*" and "*Ravni Kotari*"), and several GWBs have status "*the potential risk*": "*Rijeka – Bakar*", "*Adriatic islands*" and "*Neretva*" due to occasional sea water intrusions, and GWB "*Cetina*" and "*Neretva*" due to transboundary conditions and problems – the inability to control the recharge areas.

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