KARST GROUNDWATER PROTECTION:
THE CASE OF THE RIJEKA REGION, CROATIA

VARSTVO KRAŠKE PODZEMNE VODE:
PRIMER OBMOČJA REKE NA HRVAŠKEM

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Božidar Biondić: Varstvo kraške podzemne vode: primer območja Reke na Hrvaškem

Problem varovanja vodnih virov na Hrvaškem krasu je bil še posebej izpostavljen v zadnjih 30 letih. Posebni naravni pogoji, pod katerimi se oblikuje in razvija dinamika podzemne vode, so bili vzrok za težave pri pripravi enotnih meril varovanja. Sedanje izkušnje pa omogočajo bolj organiziran pristop k reševanju tega problema. Še posebej to velja za okolico mesta Reke, kjer so bila znatna sredstva vložena tako v iskanje novih zajetij podzemne vode kot tudi v njihovo varovanje. V članku je predstavljen splošen pristop k varovanju kraških voda na Hrvaškem. Ta vključuje razlago naravnih pogojev, potrebne raziskovalne dejavnosti, splošne kriterije in merila varovanja, izboljšanje sanitarnih pogojev v conah stroge zaščite, načrtovanje novih gradenj v varstvenih območjih, urbanistično planiranje in varovanje, itd. Del članka pa obravnava urejanje predpisov in organizacijske probleme pri tako aktivnem pristopu k varovanju kraških voda.

Ključne besede: varstvo kraške podzemne vode, kartiranje ranljivosti, gospodarjenje z vodami, varstveni pasovi, zaščitni ukrepi, raziskovalne metode.

Abstract

The problem of protection of water resources in the karst area of Croatia has been particularly acute for the last 30 years. Specific natural conditions under which the dynamics of groundwater is formed and developed were reasons for difficulties in preparation of uniform criteria of protection. Present experience makes it possible to establish a more organized approach to the problem. This applies, in particular, to the surroundings of the town Rijeka, where considerable funds were invested into research on new groundwater abstractions, but also toward their protection. In this paper the general approach to karst water protection in Croatia will be presented. This consists of an explanation of natural conditions, necessary research activities, general criteria and measures for protection, improvement of sanitary conditions in zones of high protection, design of new constructions in protection zones, urban planning and protection, etc. A part of the paper will be directed to the regulation procedure and organizational problems in such an active approach to karst water protection.

Key words: karst groundwater protection, vulnerability mapping, water management, protection zones, protection measures, research methods.
INTRODUCTION

In the past twenty years karst aquifers have gradually gained world wide importance, especially in last decade when European hydrogeologists joined efforts to promote karst aquifers within the EU through the COST project 65 (Biondić, B. et al. 1995; Almeida, C. et al. 1995; Bakalowicz, M. et al. 1995; Zwahlen, F. et al. 1995; Hoetzl, H. et al. 1995) and later the COST projects 620 and 621. A view of the European continent and the distribution of karst aquifers (Fig. 1) show the importance of these aquifers in the future development of Europe. The karst aquifers are of prime importance in Mediterranean regions, where in some areas they are the only potable water resource. Moreover, large central and northern European cities whose water supply depends on alluvial aquifers along major rivers are having problems and are recently moving towards supply from mountain karst regions with high quality water. An example of such practice is Vienna, which obtains a part of its potable water from the several hundred kilometre distant region of the Alps. Carbonate rocks cover almost 35% of Europe, or almost 3 million-km², which is in most part karstified.

The term karst is restricted to terrain of specific landscape and morphology, mainly developed on carbonate rocks. This term is also applied to the specific development of underground morphology and the aquifers that are developed in these underground landforms. The rock-water interaction is the basic process that leads to the development of conduits along faults, fissures and cracks.

**Fig. 1:** The distribution of karst aquifers in Europe.

**Sl. 1:** Razporeditev kraških vodonosnikov v Evropi.
in carbonate rocks, whose size can reach cave dimensions, and through which water dynamics in the karts are manifested. It sounds like a simple process, but karst hydrogeology is one of the most complex geological disciplines. It combines geological and geomorphological knowledge with information on underground and surface hydrodynamic and hydrogeochemical conditions. Therefore successful management of karst aquifers requires a high degree of knowledge about these very fragile natural systems.

Croatia is a Mediterranean country with extensive karst terrains in the Adriatic coastal region (Fig. 2), which are a part of the Dinaric mega-structural unit, which extends from Slovenia, through Croatia, Bosnia and Herzegovina, Montenegro and on into the Hellenids (Herak, M., 1986, 1991). The Dinarides, a typical karst region, covers approximately 50% of Croatian territory. The Adriatic Islands, which number over 1000, also are a part of the Dinaric karst belt. Karstified carbonate rocks (limestone and dolomite) characterize the geology of the Dinarides.

The importance of karst aquifers for Croatia is invaluable, in regard to the function of the present water supply system in the whole Dinaric karst region, as well as for the insurance of potable water for the future development of the whole country. Namely, the karst aquifers of the Dinaric Mountain region are strategic water resources for some regions (Biondić, B. and Pavićić,
A., 1998), which due to the deterioration of water quality are in danger of losing healthy potable water. To maintain high water quality standards, it is necessary to apply protection measures to the karst aquifers.

Croatia began with the policy of protecting its potable water sources very early, including karst aquifers. Such a case is the city of Rijeka whose management encountered the problem of insufficient quantities of potable water. The first karst aquifer protection studies were performed in 1979 (Biondić and Goatti, 1979), which are by far the earliest ever performed in any region of Croatia. During these projects the hydrogeological data were used to obtain larger quantities of potable water for the expanding city of Rijeka, which needs ever more potable water. On the other hand, there was no experience in karst water protection either in Croatia or in the former Yugoslavia, as well as in other more developed European countries. The usual practice was to apply experience from porous media but this failed to give satisfactory results due to the characteristic dynamics of these aquifers. It should be stressed that during that time the residence time effect was not recognized, and the function of the unsaturated zone was only speculated at. Also hydrochemistry was only directed towards water quality and not to identifying the dynamics of the aquifers, so most of the studies were principally directed towards the definition of the aquifer geometry. During these studies groundwater-tracing data was applied according to criteria which enabled production of regional effects.

However, what were the results of such investigations? It was possible to determine the arrangement of catchment basins of karst springs or groups of springs, which had a mutual origin, as well as the position of the major drainage directions towards the springs. Also numerous other data which promoted an understanding of the natural system were obtained. The protection zones are a special problem since the criteria for porous media were not applicable. Namely, whole karst drainage basins would be the first protection zone, making them ghettos closed to any development, as well as for normal human living conditions. For Croatia this was not acceptable since almost 50% of its territory is karst terrain, and in a hydrogeological sense this would mean the protection of most of this terrain. The “sustainable development” approach forced the investigators to determine new criteria, which would allow the normal development of the country and, at the same time, protect the karst aquifers.

The first criteria were mainly geological (Biondić, B. and Goatti, V., 1986.; Biondić, B., 1988). At the beginning four hydrogeological areas were determined, which according to their importance and possible influence on potable spring water, have a different degree of protection. These were as follows:

**Protection zone 1:** the immediate spring area, where possible polluted water flow towards the extraction sites, pumping facilities might occur.

**Protection zone 2:** the discharge zone- with high groundwater flow velocities.

**Protection zone 3:** the retention zone- the region where groundwater retention occurs.

**Protection zone 4:** the maximum catchment area of a karst basin.

With the aid of these criteria it was possible to produce a “general vulnerability map”, which was used together with well defined protection measures, as the basis for the water protection legislation passed by the Rijeka city council. During that time Water Protection Regulations did not exist, especially for karst aquifers. From the present viewpoint it is possible to understand the hydrogeological assumptions of that period. All protection measures were focused on bacteriologi-
cal protection of groundwater. It should be stressed that according to similar criteria all karst springs in Croatia were protected, and copies of this approach are also found in neighbouring countries, which were a part of the former Yugoslavia.

The result of such early beginnings of karst water protection is the relatively high quality of karst groundwater in Croatia today. The zones and the accompanying protection measures are a part of the spatial and urban planning of regions and cities, which allowed the local government authorities to follow a protection policy and rational spatial utilization for almost thirty years. For almost thirty years now all major facilities must have authorization from governmental protection agencies before construction. However, the situation is not ideal, because some basins were already impacted by potential pollution sources. This was the case with the potable springs that supply Rijeka. The permanent springs are located in the coastal region in the city centre, and parts of the city developed through the years towards the inner parts of the catchment basin. It is obvious that in these parts the prevention measures were less effective than in catchment areas lacking urbanization. In such regions the protective measures enforced mitigation, such as the construction of city sewers or the relocation of potentially hazardous facilities. Therefore the protective measures were focused on both preventive actions through spatial and urban planning and through mitigation actions in the catchment basins to improve the hydrological conditions. A third, but not least important part is the study and the construction of new intake galleries in mountain regions, not influenced by urbanization. These are the strategic reserves, which will be used when the existing springs will no longer supply water of satisfactory quality.

THE AQUIFER PROTECTION SYSTEM

The whole potable karst spring water protection system in Croatia can be divided into four phases (Biondić, B. et all, 1998):

1. **General vulnerability mapping** - the definition of protective zones and protection measures.
2. **Vulnerability mapping of highly-protected zones.**
3. **Final proposal of protective measures and their verification.**
4. **The implementation of protective measures.**

GENERAL VULNERABILITY MAPPING

From the hydrogeological aspect this is the most important step in the process of karst aquifer protection, because it is necessary to determine the natural drainage system, its geometry, dynamic functions and most important, which parameters should be given priority for the definition of basic criteria used for zone separation. In the past, criteria were focused towards the protection of water against bacteriological pollution, and the 50-day transport limit was accepted as the duration time of bacteria in karst groundwater. However, the situation has changed and bacteriological pollution is not the major problem of spring water quality.

Hydrocarbons, nitrates and other chemicals are becoming major pollution problems (Almeida, C. et al. 1995). The question is how to incorporate this element into the existing system of protective zone definition. It cannot be performed through transport time, because chemical pollution is
resistant, and some pollutants react to form even greater problems than the insured source materials. It would be ideal if it was possible to protect whole karst catchment basins, but this would lead to the total absence of urban infrastructures and industrial development in almost one half of Croatian territory. Therefore, this type of protective policy cannot be accepted. The only alternative is to classify the catchment areas according to their difference in hydrogeological functions and then to protect these areas in various degrees. The basic parameters should be hydrogeological, such as the groundwater flow velocity, type of infiltration, the function of the unsaturated zone and other natural factors which can reduce the pollution hazard. From experience the solution would be zoning.

Why create zones, when we are aware that the karst aquifers are vulnerable in the whole catchment area? Yes, vulnerable, but not in the same degree. The major drainage directions towards the springs and ponor zones which are directly connected with the water supply springs are a greater threat. This is why the principal criteria for the protective zone definition are linked with a combination of relative groundwater flow velocities and the transport time which still protect the karst springs from bacteriological pollution (Fig. 3).

The first protective zone or the zone of the strict regime consists of water occurrences and the immediate flooding area from which surface inflow of water to the spring is possible. The second protective zone or the zone of strict limitations is comprised of the major drainage directions with possible inflows through the karst underground during the high water conditions within a 24 hours period i.e. the areas within which groundwater flow velocities of over 3 cm/s were recorded. Within these terrains numerous restrictions are implemented, and the recharge of wastewater or treated wastewater to the underground, as well as the deposition of any type of waste is forbidden. The third protective zone or the zone of limitations and control, comprises the parts of the karst drain-

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*Fig. 3: The general karst water protection criteria.*

*Sl. 3: Splošna merila varstva kraških voda.*
age basins from which groundwater can flow under high water conditions within 1 to 10 days i.e. the areas where apparent flow velocities lie within the range of 1 and 3 cm/s. In these areas the recharge of untreated waste waters is forbidden, as well as the location of sanitary waste sites and the construction of chemical plants and facilities. Also certain restrictions are advised in relation to farming. The fourth protective zone or the zone of limited protection, consists of the remaining parts of the drainage basin of karst springs with possible ground water inflow in the range of 10 to 50 days and apparent flow velocities of less than 1 cm/s. It is suggested that in these areas the location of municipal waste sites and untreated waste water recharge has to be avoided. The water-supply reservation is a completely new idea in the process of karst water protection. It is related to hill and mountain regions, the main recharge and retention zones in the catchment basins. The most sensitive part within the first phase of a protective study is the classification of karst springs. This is important in urban areas where protective measures can change the spatial development plans of cities. Once again the case of Rijeka is a good example, where during the initial protective studies all springs and not only those used for water supply were protected. The whole city was hindered in its development because it was not possible to construct any serious facility, especially not petrol stations. Through the categorization of springs that was performed within the Water Supply Protocol large parts of the city were opened up to development.

It must be stressed that besides the elaboration of the protective zone criteria, the recommendations for the definition of the minimal investigation procedures necessary in the different phases of the protection process also remain. This is of prime importance for the first phase when the size of the protective area is defined. It is obvious that it is not possible to recommend every aspect of investigation since karst terrains are heterogeneous and unpredictable and therefore investigators should have the freedom of research, but only above the minimal contents:

- Lithological and structural - tectonic analysis
- Hydrogeological analysis (the evaluation of the degree of development of both surface and subsurface karst landscapes, water occurrences, spring categorization, exploration and piezometer wells, meteorological stations, hydrological measurements, the organization of the drainage system, the evaluation of the position of hydraulic discontinuities, etc.) - Geophysical investigations (regional)
- Determination of hydro-dynamical parameters in combination with hydrogeochemical studies
  - Water quality analysis
- Tracing of groundwater flow directions (both natural and artificial tracers)
- Karst drainage basin balances - The registration of potential pollutants
- Organization of the GIS system.

A general vulnerability map for the city of Rijeka was produced according to the described methodology; i.e. the recommended methodology was tested on the case of Rijeka. The map shows irregular distribution and separation of zones of the same degree of protection, as in the case of Grobnicko polje which is placed within a high protective zone because it is a distribution point for groundwater flows from the mountain region of Gorski Kotar towards the water supply springs in the coastal region. The protective measures have considerably altered this area. The spatial plan for the area was altered and potentially hazardous industry was relocated to a less vulnerable area and the existing quarry and asphalt production plant was closed down. The result of this action is the high quality of spring water along the coast.
The second phase of investigation within the karst aquifer protection process is layered and complex, because it requires a deeper understanding of hydrogeological problems and it offers solutions to groundwater protection problems. Why elaborate detailed vulnerability maps for highly protected zones (the first and second zone)? The answer is because these are areas of strict regime and strict limitation, where all activities besides extraction facilities, water purification and water-distribution are forbidden, or the restrictions are such that the urban activities are minimized and potential mitigation activities are expensive. Detailed mapping of these areas, especially of the second protective zone can reduce the surface area and the economic investments for reconstruction measures.

The hydrogeological mapping of the second protective zone is of principal importance and consists of complex investigations of the highly protected zones. In general, these consist of two parts:
- Investigation of the saturation zone or the zone of active groundwater flow.
- Investigation of the unsaturated zone of karst aquifers.

The results of both investigations can have a major influence on the final definition of the dimensions of zones of high protection and the allowed behaviour within them.

Detailed vulnerability mapping in zones of active groundwater flow is performed on topographic maps on the scale of 1:5000. During mapping the research methods applied during the elaboration of the general vulnerability map can be used, but focused towards the definition of drainage directions that supply the springs which are to be protected. During the mapping process, which includes geological and hydrogeological methods, the application of geophysical investigations is also of prime importance. Also the construction of observation boreholes and groundwater flow tracing from the boreholes should be utilized extensively. This results in the definition of a groundwater flow network and the highly protected zones with optimal dimensions.

The investigation of the hydrogeological function of the unsaturated zone within the framework of karst aquifer protection, especially the epikarst zone, is an vital necessity since the retention capacity of the cover deposits and the whole unsaturated zone play a important role in the development of the protection policy. The importance of these deposits is their capacity to retain pollutants, to slow their penetration and/or to transform the individual pollutants through various geochemical processes (acid-base reactions, redox processes, ion exchange, biochemical transformations, etc.). In Croatia there are no organized test sites as in Slovenia (Sinji vrh) to investigate these processes, but the hydrogeological function of the cover deposits was used to define the protective zones of the karst aquifer which is used to supply water for the city of Pula. This project is a pilot site within the EU COST project 620 which mainly dedicated to these problems (Kuhta, M., 1997). On the other hand, experience with the function of the epikarst in the region of Rijeka indicates that the retention capacity of the epikarst zone, within the framework of aquifer protection, should be viewed with caution, because retention can only slow down the pollutants and only delay the pollution. When pollution enters the aquifer cleansing is more complex, because when it enters the developed morphology of the epikarst zone its negative influence can last for a long period. Also the clay cover above the karst aquifers considerably lowers the in situ infiltration, but also directs surface water flow and pollution towards the insurgence zones. Technical interven-
tions in the landscape also present a potential hazard since they are usually accompanied by dislocation of the cover material. The negative examples do not imply that the hydrogeological studies of the epikarst should be abandoned, but the results should be handled with care and they should be carefully incorporated into the process of karst aquifer protection.

The detailed vulnerability mapping covers the most threatened parts of the drainage basin which supply the potable water springs of Rijeka, i.e. the Grobničko polje, where distribution of groundwater towards the coastal springs occurs. The water discharges and sinks in a relatively small area of the polje, and this area needed supplementary protection. The whole floor of the polje is a flattened landscape within the karst relief, which attracts various activities. However according to the general vulnerability map, the whole area should be protected to the level of the second zone (zone of strict limitations). The detailed vulnerability map showed that a part of the terrain is drained outside the insurgence zone which supplies the water for the springs important to Rijeka, and therefore this part of the polje was placed under a lower regime of protection, also offering a higher degree of development.

The strict regime zone, i.e., the first protective zone should be mapped on the scale of 1:1000. The principal function of this zone is to protect the extraction sites and the pumping station from the inflow of surface-borne pollutants; therefore the investigations are focused on possible surface inflows. This mainly consists of defining ravines and morphological features which would allow direct inflow of pollutants into the water extraction sites. Sometimes it is necessary to perform geophysical investigations and exploration drilling to aid mapping. With these studies it is possible to define the area which is determined by detailed mapping of the discharge area (spring), the facilities used for water extraction and the facilities used for the control of dynamic and hydrochemical parameters, as well as the immediate catchment area. In the report that describes the first zone it is necessary to present the pumping regime, the quantity of natural outflow and the changes in water quality in accordance with the quantities of water pumped. Also all possible pollution sources are defined and some of them have to be included in an emergency remediation programme.

THE FINAL PROPOSAL OF PROTECTIVE MEASURES AND THEIR VERIFICATION

The final karst aquifer protection proposal is prepared by a multidisciplinary committee, which consists of various professionals. The aim of the committee is to propose and to harmonize regulations within the defined protective zones. These protective measures are included in regulations defined in the Water Protection Protocol. The protective measures are adapted to the conditions that prevail in the area of the municipalities in question (cities, counties, districts and neighbouring districts). The protective measures should not only consist of restrictions, which can greatly diminish the quality of life in the protected area. They should be adapted to development plans, but in such a way that the efficiency of protection is not endangered. The protection of potable water viewed in this light is compatible with the concept of sustainable development.

The potable water protection regulations and the size and boundaries of the protected areas in compliance with the legislation, i.e. the Water Law of the Republic of Croatia, are accepted by district assemblies and in cases of dispute by the Director of the State Directory for Waters. This is
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Fig. 4: The general vulnerability map for the potable karst springs in the Rijeka region.
1. permanent spring; 2. temporary spring; 3. brackish coastal spring; 4. water-supply pumping station; 5. intake gallery; 6. springs in water-supply reserve area; 7. 1st class spring; 8. 2nd class spring; 9. zonal divide (watershed) between the Adriatic and Black Sea catchments; 10. zonal divide between catchments inside the Adriatic Sea; 11. groundwater tracing; 12. protective zone; 13. water-supply reserve - mountainous area; 14. 2nd protective zone; 15. 3rd protective zone; 16. 4th protective zone; 17. zone of partial limitations; 18. unprotected area.

Sl. 4: Splošna karta ranljivosti za kraške izvire pitne vode na območju Reke.
1. stalni izvir; 2. občasni izvir; 3. zaslanjeni obalni izvir; 4. črpališče za vodovod; 5. dovodni rov; 6. izviri v območju varovanja za vodooskrbo; 7. izvir 1. razreda; 8. izvir 2. razreda; 9. razvodna cona med jadranskim in črnomorskim zaledjem; 10. razvodna cona znotraj jadranskega zaledja; 11. sledenje podzemnih voda; 12. varstveni pas; 13. gorsko območje varovano za vodooskrbo; 14. 2. varstveni pas; 15. 3. varstveni pas; 16. 4. varstveni pas; 17. cona delnih omejitev; 18. nevarovano območje.
Fig. 5: Detailed vulnerability map of Grobničko polje.
1. temporary spring; 2. ponor; 3. temporary flood area; 4. temporary stream; 5. temporary recharge zone; 6. protective zone boundary; 7. boundary between carbonate rocks and polje sediments.

Sl. 5: Podrobna karta ranljivosti Grobniškega polja.
1. občasni izvir; 2. ponor; 3. občasno poplavljeno območje; 4. občasni tok; 5. občasno napajanje; 6. meja varstvenega pasu; 7. meja med karbonatnimi kamninami in sedimenti na polju.
not an easy task, because the decisions concerning protection and protective areas are accepted by people who live in these areas and who are affected by the protective measures in the sense that their personal freedom can be threatened to a degree. Therefore the proposals must be argumented and performed at a high professional and scientific level. The efficiency of the protective measures is dependent on the degree of environmental education of the population and the will of the local politicians to understand the protection of aquifers, and to implement the decisions that were made. The population must become aware of the importance of water protection and in to rationalize their demands in accordance with this important environmental action. This can be achieved through lectures, television commercials, radio broadcasts and through education in schools.

THE IMPLEMENTATION OF PROTECTIVE MEASURES

The protective measures for karst aquifers are part of the management of complex water resources, compliant with the Water Law of the Republic of Croatia and the State Plan for Water Protection. The definition of zones and protective measures has a preventive function and full efficiency is attained by their implementation into spatial plans and their utilization over longer periods, during which water exploitation permits are granted. All this must be combined with an active approach to spatial problem solving. What is the active approach to protection problem solving? Very often the potable water spring protective measures restrict the development of large cities, and due to the high degree of pollution it is not possible to find adequate urban, transport and similar solutions. In these cases it is recommended that the multidisciplinary committee continues its work in order to propose more adequate solutions. The basic principal in the work of the committee is to propose changes that will improve the existing conditions in the area. The committee also proposes mitigation priorities in the protection zones and prepares protection plans in accordance with the State Water Protection Plan. It should be stressed that the karst terrain is very sensitive to all types of negative influence caused by human practice, and therefore the management of this natural resource is a high risk, which can be reduced with appropriate application of protective measures and the competence of the professionals who implement these measures.

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