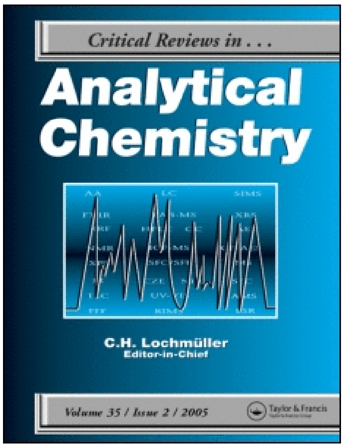

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Protection of Groundwater in Classical Karst Systems

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Water quality is of great interest in any development or management of water resources. With increased demand for water and with the intensification of its use, it is becoming the limiting factor in the development and use of water resources.

According to its objectives, groundwater pollution protection can be regarded as a part of the general environmental protection or, more specifically, only as water resources protection. In the first case, groundwater with little or no water resource value is protected as a potential transmitter of pollution to other groundwater and surface water bodies and to the rest of the environment. In the second case, protection refers to the aquifers representing actual or potential water resources and to water supply catchments.

In the first instance, we try to prevent any release of toxic substances from their source into the environment and to contain existing pollution within a given volume of rocks and of aquifers. In the second instance, groundwater protection consists of a complex combination of protection, prevention, and intervention measures and activities, initiated with the aim to keep the supplied water quality within the prescribed standards (Veseli, 1996).

When speaking of groundwater protection, we are generally thinking of protection from pollution only. But, this is only one aspect of the protection of natural resources. Apart from the quality protection, we also have to protect quantity. Economic activities have reduced groundwater quantity in many places without, at the same time, damaging the quality. The concept of groundwater degradation (Veseli, 1995) tries to involve both aspects of groundwater deterioration. Therefore, groundwater protection is to be understood as a prevention of their overall degradation and a reclamation of their local degradation. In matters of sustainable water resources management, it is advisable that policies follow exactly this approach. Science is there to assist politics with this respect.

WATER QUALITY AND POLLUTION

Water quality is a term relating to the physical, chemical, and biological characteristics of water (Pfannkuch, 1990). Most materials can be dissolved or suspended in water, which can also contain various amounts of energy (heat or radiation). Water quality can, therefore, be defined in terms of hundreds of parameters, making its determination very expensive, if not complicated.

The use of water determines the relative importance of water constituents and physical characteristics. Water quality can be defined with reference to its use, and that is what is being done in everyday life. Separate water quality standards were defined for drinking water, irrigation water, and various industrial and recreational water uses.

Pollution is the contamination of the environment and of groundwater with undesirable, harmful, or obnoxious substances (Pfannkuch, 1990). When speaking of 'water pollution,' rather than of 'water quality,' we generally have in mind the water quality deterioration to the point of being hazardous to the consumer. The following types of pollution are defined regarding its sources:

- *Environmental*: resulting from the environment through which the water flows.
- *Domestic*: resulting from accidental or planned, but poorly engineered releases from septic tanks, sewage systems and sanitary landfills and

accidental spills from house heating combustion oil tanks. Biological contaminants (bacteria, viruses) result from this source.
- *Industrial*: resulting from accidental or planned, but poorly engineered releases from industrial processes, from transport and from industry.
- *Agricultural*: resulting from farming and land cultivation and due to rain and irrigation water replenishing the underlying phreatic aquifers. Organic and inorganic contaminants (pesticides, herbicides, nitrates, etc.) and biologic contaminants result from this source.

With respect to the input area, it can be defined either as a *point source* or as *disperse source pollution*. With respect to its duration, it can be either a *single event* or a *repeated*, *periodic*, *seasonal*, or *permanent* pollution. With respect to the temporal stability of the involved pollutants, pollution can either a *short term*, a *long term*, even a *permanent* one. Finally, it can be, according to its source and nature, either *foreseeable* and anticipated or *unforeseeable* and unanticipated. This aspect is important when considering pollution control.

ROCKS

Earth's surface and its nearby solid underground are built of loose, layered material and of solid rocks, interwoven in a complex way, known as earth or geologic structure. It has become popular to designate all these as geologic media and integrate them with all surface land and life forms into the geo-environment.

Geologic media are constituted of solid mineral matter that builds mineral and rock grains or blocks and of voids. Filled with various types of fluids, these voids give geologic media a certain void to rock volume ratio, known as porosity. The mineral matter and the degree of its cohesion and solidification define the rock types and their petrophysical and petrochemical properties. The void size, geometry, and interconnections define porosity and nearly all the fluid flow impacting properties of geological media. Petrophysical and petrochemical properties of mineral matter influence both the fluid quality and its mass transport feasibility.

Porous geologic media are inherently heterogeneous. Fractured and karstified rocks are made of blocks of solid rock, intersected by discontinuities that may be locally developed into channels. Matrix, discontinuities, and channels all show certain porosity. In most fractured and karstified rocks the fracture and channel porosity are hydraulically preponderant. But, the matrix porosity can not be neglected, especially when considering void volume, water storage, or mass transport. As in a general case, several sets of discontinuities are present. Hydraulic conductivity of fractured and karstified rocks primarily depends on the fissure, fracture, and karst channel network characteristics. For most rocks, it varies over several orders of magnitude. In most intergranular rocks, for instance, variations will not exceed one to two orders of magnitude.

GROUNDWATER, AQUIFERS, AND KARST SYSTEMS

Generally, the voids in the geologic media are filled with water, whose mobility depends on the void size, geometry, and connectivity. Only large enough voids can convey free flowing water, while small ones retain or block its flow. Due to this, some geologic porous media act as pervious aquifers, others function as semi-pervious aquicluds (or aquitards), and a third as little pervious to non-pervious aquifobs. The joint effects of hydrologic cycle and topography make water close to the earth surface move through aquifers and even aquitards relatively quickly. Infiltrating precipitation water can not fill aquifers up to the earth surface, thus, leaving an unsaturated or vadose zone in their upper part. Underneath, the saturated or phreatic zone contains groundwater. The water in the unsaturated vadose zone is soil water (in soil) or vadose water (in rock). In the vadose zone, the water flow direction is generally downward and subvertical, but may occasionally be diverted, producing interflow. In the saturated phreatic zone, the lateral flow becomes prevailing and results in groundwater flow.

Karst aquifers are a subset of aquifers, prevailingly developed in carbonate rocks under the joint effects of weathering, water percolation, and groundwater flow in a tropical to moderately humid climate, and the resulting corrosion and subsurface erosion. It is important to note that, due to the nature of flow, subvertical karst structures will mostly develop in the vadose zone, while mostly subhorizontal ones will emerge in the phreatic zone. However, as the interface of these two zones may have been largely shifted during the geologic history, the real karst systems may not be so simple, and several superimposed karst conduit networks may have developed.

The most common rocks with a large channel porosity are the karstified carbonate rocks. As these rocks host important water resources in many parts of the world, they deserve to be given some more attention.

The nature of carbonate rocks depends very much on their past geologic burial and the resulting consolidation and diagenesis. By the nature of the rock, the carbonate rocks may be arranged into two large groups: the rocks that underwent a geosinclinal burial and a subsequent orogenesis, and the others that did not undergo them and have, at most, subsisted an epirogeneis. The first group has generally very little primary porosity, but usually, as a result of the past tectonic stresses, possess quite a dense microfracture network and beside the bedding planes, a considerable tectonic macrofracturation. The second group retains considerable primary porosity, but has a relatively loose and regionally unevenly distributed tectonically induced microfracture network, with tectonic macrofractures being relatively rare. With these rocks, the bedding planes represent the main group of macroscopic hydraulic discontinuities. Also the above two groups display a different nature when karstified.

In the first group of karstified rocks or the karst of ex-geosinclinal regions, the karst channels develop primarily along macrofractures and other features of tectonic origin (Knez, 1996) and along faults, with regional control provided by the regional structural setting. In the second group of karstified rocks, which may be called the karst of the continental platforms, the karst channels develop mostly along the bedding planes, with tectonic macrofractures providing additional control, and regional control is performed by large tectonic features (folds, faults). Due to the less complicated geologic structure, to the more regularly distributed karst channel network, and to the considerable role of the primary porosity, the karst developed within the second group displays less intrinsic irregularity and less uncertainty of the intrinsic pattern definition.

GROUNDWATER PROTECTION PARADIGM(S)

Protection zones around the water tapping structures represent, at the actual state of the art of groundwater protection, its main legal and preventive measure. The rational basis of protection, zone's definition is the expected pollutant travel times, namely those of dangerous microorganisms from their potential source to the protected spring or water tapping structure.

In the case of aquifers with intergranular porosity, it is generally easy to define their zones quantitatively. This is more difficult for fractured aquifers, and in the case of karstic aquifers, it becomes nearly impossible. This is due to the internal heterogeneity of these aquifers and the resulting complexity in pollutant spreading. According to this, most of the protection zones in karst aquifers are defined on qualitative and intuitive bases. In a series of countries, these aquifers are of great importance for public water supply. Due to the related actuality of their protection, a steady effort is being made to advance the methodology of protection zone's definition and to set it on a rational and quantitatively verifiable basis. The aim of these efforts is to reduce the qualitative and intuitive approaches to as few cases as possible.

In order to follow the spreading of pollution from its source to a spring, water tapping structure, or aquifer observation point, it is necessary to have the following information available at one's disposition: 1) type of pollutant, the locality of imission point or area, concentration of pollutant at the imission point or area, and distance from the point of imission to the point of observation; 2) hydrogeologic conditions of the aquifer; 3) flow conditions: flow rate, velocity and direction, water saturation, single-phase or multi-phase flow; 4) concentration of pollutant at the observation point (Veseli, 1996).

Before we are able to precisely define protection zones in all types of aquifers, the question will be raised whether the involved protection paradigm is still appropriate. Are water resources protection that are primarily based on the protection from dangerous microorganisms, still optimal at the present state of development in drinking water conditioning technology (micro-filtration and ultra-filtration)? Or should it become more closely related to the protection from some persisting toxic and from the point of drinking water conditioning unsuitable chemical pollutants? The views of engineers and hydrogeologists quite often differ in this respect.

Groundwater resources protection, however, does not require only the mastering of pollutant transport equations, but, above all, an overall capacity in territorial management. This means that hydrogeological information should be conveyed to physical planners in a consistent and easily understandable manner. The concept of aquifer vulnerability, as a general groundwater protection concept, was introduced for this purpose (Aller & all, 1987; Cichiocki & Zojer, 1999; GSI & EPA, 1999;

vonHoyer & Söffner, 1998; Vrba & Zaporožec, 1994). In combination with protection zones it should allow for a more transparent planning of the activities within a territory. The aim of research in this field is to achieve that aquifer vulnerability becomes a parameter, which will be scientifically rigorous enough and also practical enough for applications in physical planning (Dunne, 2000). But, this concept may contain some hidden traps as well. What is the relative weight of water resources in the general system of values of a given society?

KARST AQUIFER SPECIFICS

The above general considerations are the main open questions in the field of karst groundwater protection. Without pretending that the list might be complete within this framework, four questions certainly have to be put forward:

1. Protection Zones Sizing

Passive protection systems in Slovenia and in most European countries define the following groundwater protection areas (Veseli, 2000):

- Water protection area, aquifer area, and corresponding water catchment area
- Water protection zones

  1. inner water protection zone
  2. outer water protection zone
  3. impacting water protection zone

World trends go in the direction of defining a set of three water protection zones, which in Slovenia, were proposed under the above given terms. The outer limit of the inner water protection zone is based on the time needed for dangerous microorganisms to die in a water saturated medium, with the necessary safety margin amount $t_r = 50$ days. The outer limit of the outer water protection zone is set to one year, as a close approximation of a hydrologic cycle under middle-European conditions. The impacting water protection zone is identical to the corresponding water catchment area.

Great flow velocities encountered in karst aquifers cause difficulties in defining the limits of protection zones and make the above required residence times often unachievable. This is valid, especially in mountainous areas. Thus, the governing criteria in defining the outer limits of the individual water protection zones become the existence of an accident related intervention scheme within a given water supply system and the involved intervention time t_i. For karst aquifers, the following proposal was made in Slovenia: 1) the outer limit of the inner water protection zone (corresponding to the time t_i): $t_r = 4$–12 hours; 2) the outer limit of the outer water protection zone: $t_r > 12$ hours; 3) the outer limit of the impacting water protection zone: $t_r \gg 12$ hours.

It is obvious that by applying the criteria mentioned above, the protective function of the water protection zones qualitatively changes. As much as the involved protective measures are concerned, they ought not be assimilated with protection zones in aquifers with intergranular porosity.

2. Karst Aquifer Regionalisation

The definition of groundwater protection zones in karst aquifers has to follow the distribution of measured or supposed outflow times from areas in question. This means that it has to follow a spatial distribution of more pervious and less pervious zones. In karst aquifers, this distribution is very uneven, due to their heterogeneity (Doerflinger, 1996, Veseli, 1996). For this reason, the spatial distribution of protective zones, with respect to the protected spring or tapping structure, cannot be concentric, but zones of higher protection may be unevenly nested within zones of lower protection and vice versa.

A regionalization of karst aquifers, according to spatial distribution of their permeability, is, thus, one of the primary tasks in determining water protection zones. Professionally, this is not an easy task. One has to follow the guidelines of COST 65 (Bakalovicz & Biondi, 1995) and upgrade them with the newest results of related research (Goldscheider, 1999, Dunne, 2000).

3. Impact of the Unsaturated Zone of Karst Aquifers

The groundwater protection role of the unsaturated zone of the aquifers is an important issue. Clear standards for the evaluation of the protective function of this zone (cf. DVGW norms) have been defined for aquifers with intergranular porosity and even for those with fracture porosity. These standards translate the unsaturated rock thickness above a phreatic zone into the number of days for which the prescribed water flow residence time within this water horizon (i.e., the residence time of dangerous microorganisms within a saturated media) can be reduced.

For karst aquifers, a quantification of the protective function of the unsaturated zone this remains an open question (Veseli, 1999), and a definition of the spatial distribution of its impacts within the aquifers remains unclear as well. It is obvious that this zone impacts the vulnerability of karst aquifers and should influence both the position and the extent of groundwater protection zones. Experience shows that a detailed analysis of karst aquifers is needed to determine its impact. This can result in a definition of that are too small and homogenous from the groundwater protection aspect. Unfortunately, only karst aquifers, partitioning into big enough areas, satisfies practical needs of physical planners.

Maybe, the ultimate practical guideline to karst aquifer surface area partitioning, in general, would be to carry out this task by a joint multi-disciplinary team of hydrogeologists and physical planners. Within such a team, an optimum partitioning, according to the needs of physical planning, also could be achieved in areas where hydrogeologic limits cannot be unequivocally defined without really impacting the actual needs of groundwater protection.

It must be said, that there is no consensus within the world hydrogeologist community, as far as the impact of the unsaturated zone on the aquifer vulnerability (Dunne, 2000). This is especially true with respect to the karst aquifers. That is why this is one of the more important problems of karst groundwater protection, especially in karst aquifers with deep phreatic water horizons and great thicknesses of unsaturated zones.

4. Pollution Risk Conceptualisation and Risk Level Definition in Karst Aquifers

The concept of risk as a function of an existing hazard or set of hazards, extensively used for safety assessment in engineering practices, particularly in nuclear techniques, has been transposed to the environmental problems. Here, it became related to the vulnerability of the environment and of its constituents. Water, in general, and groundwater, as its subsystem, are part of the environment. The risk concept was, therefore, introduced for groundwater and karst aquifer protection (Civita & DeMaio, 1997, Doerflinger, 1996). From the aspect of these two, an introduction of the risk concept has to be understood in view of an effort to make their protection more rational by means of a quantification of the existing pollution risks.

Since we already dealt with questions about the karst aquifer vulnerability definition, we can now turn our attention to the fact that, in the engineering practices, the notion of a hazard implies a probabilistic approach. By now, solutions in the application of this concept to groundwater protection define a hazard as an existing or potential polluter or pollutant. Duration, spatial extent, and intensity of the related polluting activity define pollution incidence and intensity levels.

Particularly, with groundwater protection and karst aquifer protection, problems arise already with the risk conceptualization. This includes the definition of an economic value of the considered aquifer or part thereof, taking, therefore, some distance from the extreme concepts of groundwater protection. That is why, in the process of risk evaluation, some scientists try to attribute an absolute supra-economic value to each karst aquifer. It is obvious that by doing so the concept of risk substantially changes and loses its sense.

This is clearly a matter to be thoroughly discussed in hydrogeological scientific and professional circles. It is natural that we all, by the very nature of our profession, tend to maximize the protection of all groundwater, karst groundwater included. Yet, it is also in the very nature of science not to recognize anything as being absolute. Neither of these can be the interest of a profession trying to get involved and really impact processes and activities both in the environment and in the society.

CONCLUSION

To follow up on what has been before, many conceptual and practical questions addressing a perfect karst groundwater protection, still remain unanswered. Unfortunately, our science and profession encounters difficulties to reach a consensus on a world scale, since the extent of karst terrains and the nature of karst aquifers differ so much from country to country.

Where karst terrain and, karst groundwater are a natural scarcity and, because of that given by society a specific, supra-economic status, they will enjoy absolute protection. There, groundwater protection will become and remain a scientific and theoretical question.

Questions related to the rational protection of karst groundwater is economical and from a developmental aspect, very important for countries with large karst areas. For these countries, a rationalization of karst aquifer protection practically means a reduction in the extent of protected areas, by a better identification of low risk areas, and a simultaneous rise in the protection efficiency in areas where the pollution risks are really high. It is likely that this will not be achieved with passive measures only. Therefore, active intervention measures (cf. intervention monitoring) will get more and more involved in karst groundwater protection.

In a society taking rational karst groundwater protection as one of its important development targets, the hydrogeological science and profession are undoubtedly facing great tasks and challenges. I personally firmly believe, that if given fair chance for a continuous work effort, the hydrogeological science and profession will be able to face and master these challenges.

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