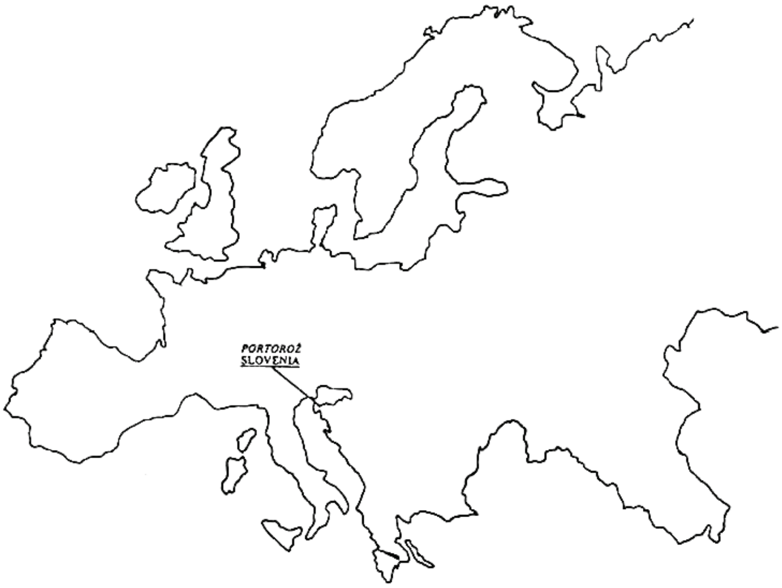
WORKSHOP

ENGINEERING IN KARST



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HYDROGEOLOGICAL ASPECTS OF KARST

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Abstract

The article describes development of karst hydrogeological system and distribution of water in karst. It is based on the data from Dinaric karst and the theories of its development. Described are hydrogeological definitions of karst, distribution of porosity in karst rock, development of hydrogeological profile in karst and hydrogeological conceptual model of karst.

1.0. Karst - hydrogeological definition

In commonsense karst is usually connected with carbonate rocks where large channels and caverns with beautiful flow stone draperies appear. For this viewpoint for the karst also some big springs with huge amount of water are significant. From the theoretical viewpoint it is more methodical to treat karst as (hydro)geological system with dissolvable rock in which it structure evolves in time and space.

Karst is a very complicated system that could be defined from many points. Intensive survey of literature shows us that there is no unique definition of it. There exist nearly as many definitions as researchers who treated karst as phenomenon. Speleological, hydrogeological, hydrological, sedimentological, geological definitions are only many of them.

From hydrogeological point of view it is useful to define hydrogeological definition. In this definition karst must be treated as hydrological system where subsystems of surface water and underground water interact. The latter prevails and from that very reason karst could be treated as hydrogeological system.

A system is a set of connected parts that form a whole. System consists of components that can be grouped into subsystems. (Chow et al, 1988) The system is characterized by structure, boundaries and boundary conditions. (Krešić, 1993)

The basic unit in the structure of hydrogeological model is groundwater aquifer. The fluctuation of water can be conceived of as the cumulative effect of the net groundwater recharge - discharge processes (Adamowski and Hamory, 1983). From this statement follows that karst hydrogeological system is a whole, having a karst aquifer for its basic unit. That unit may be considered under influence of more aquifers and surface streams. (Krešić, 1993) It could be treated as a specific subsystem of global hydrological cycle. (Brenčič, 1996)

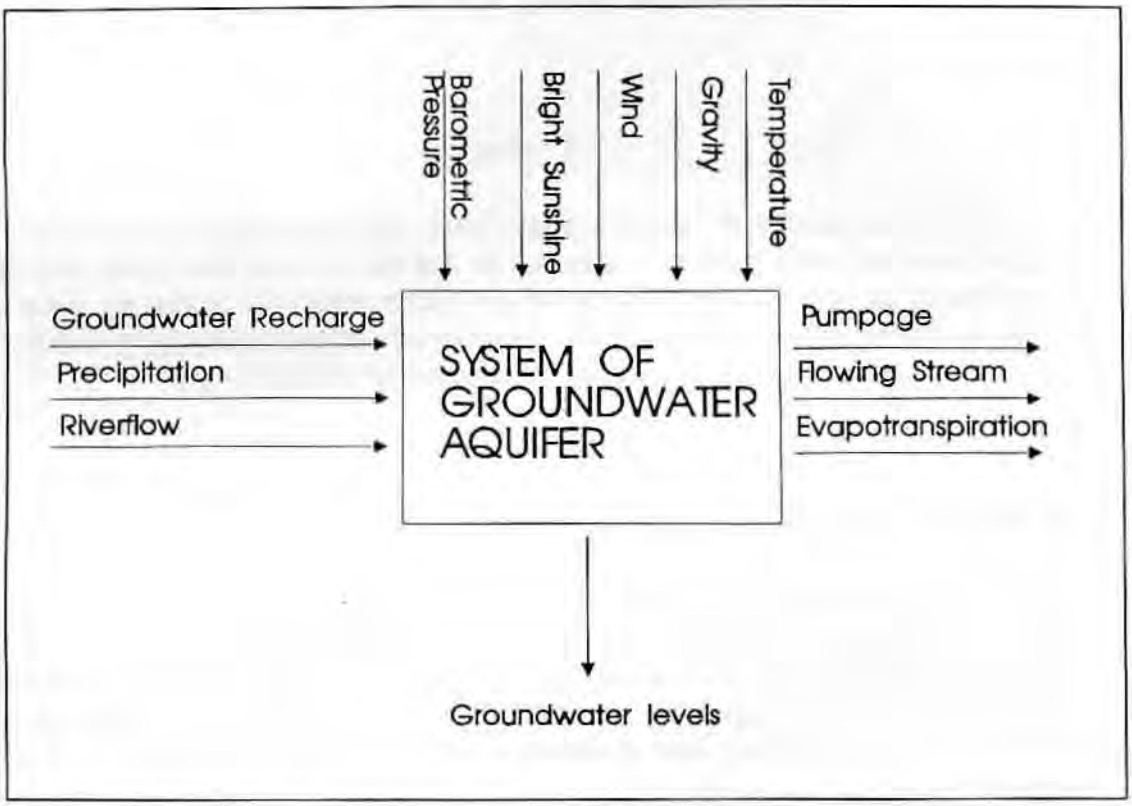

Figure 1 Structure of hydrogeological system (after Adamowski & Hamory, 1983)

2.0. Porosity in karst rocks

Water flows through karst rocks and dissolves it with aggressive water or seales flowing paths with sinter. For that reason in geological time scale porosity in karst evolves in time and space. Because of this process of porosity evolution is very important for the understanding of karst development and circulation of water in karst. Karst porosity could be defined as **evolving porosity** (Brahana et al, 1988). This is the property that separates karst from other hydrogeological systems. In the consequence it includes and explains why all characteristic features of karst system (e.g., channels, fast turbulent flow, chemistry of CO_2 - H_20 - $CaCO_3$ system) appear.

The saturation degree of rock with water depends on ratio of pores. With this ratio hydraulic conductivity is also connected. Porosity and hydraulic conductivity are not monotonicaly correlated. Total porosity of rock could be very high and effective porosity very low and so also hydraulic conductivity (clays, some dolomites, etc.) See Figure 2.

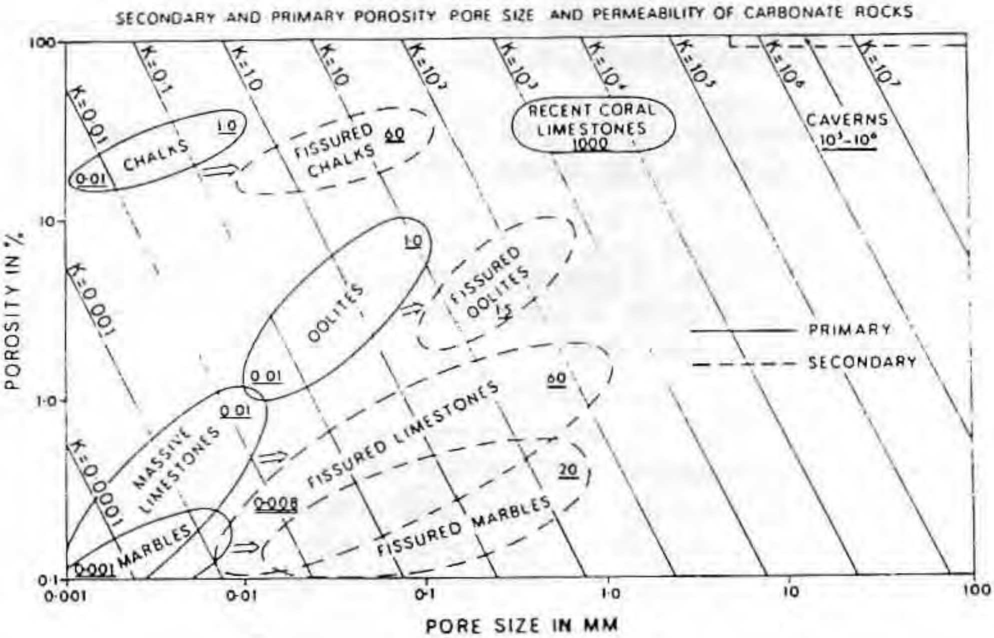

Figure 2. Relation between porosity, por sieze and hydraulic conductivities in karst rocks. After Smith et al, 1976.

Total porosity is defined as ratio between voids and total volume of rock.

$$n = \frac{Vp}{Vc}$$

V_p - volume of all pores
V_c - volume of rock

From hydrogeological point of view effective porosity is more important. It describes the ratio between interconnected voids and total volume of rock. This porosity allows circulation of water and influences hydraulic conductivity of rock.

$$n_e = \frac{V_{pe}}{V_c}$$

V_{pe} - volume of interconnected pores

Usually, total porosity and effective porosity of rock are not correlated.

The porosity consists of pores that are of various shapes. Concerning the shape of the pores there are three types of porosity (Figure 3.):

1. **Intergranular porosity** - it develops with connection between grains in sediment (e.g., alluvial aquifers) or grains in litified rocks. This pores are more or less circular in shapes in size up to few millimeters.

2. **Fissure porosity** - it consists of fissures. These are voids in which one dimension is stressed. The distance between walls in the fissures is up to few millimeters.

3. **Channel porosity** - it consists of channels. Channels are voids in the rock where length is extremely stressed. Cross sections of them are from some mm^2 to sometimes more than 10 m^2.

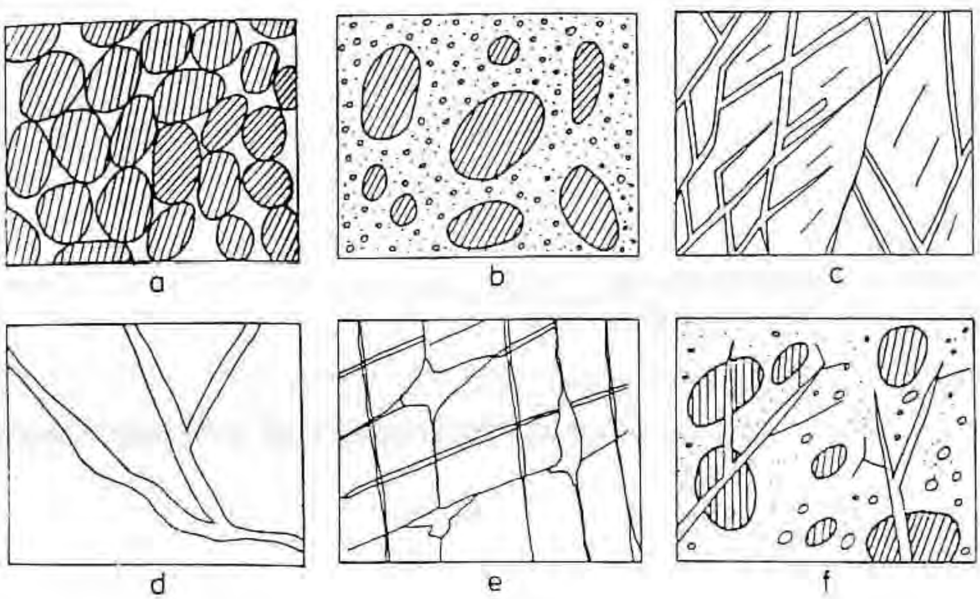

Figure 3. Porosity types
a) intergranular porosity
b) intergranular porosity with matrix
c) fracture porosity
d) channel porosity (in longitudinal section)
e) channel and fracture porosity
f) fracture porosity with matrix porosity (after Brenčič, 1994)

In the nature exist also combinations of those porosities that are usually defined as **double porosity**, specially in the case of combination between fissure and intergranular porosity (e.g., in oil geology).

In the developed "mature" karst we could find all those types. This porosity is define as a **mixing porosity**. In karst it usually consists of fissure and channel porosity. Hydrogeological system could be classified as karst only there where channel porosity with other porosity coexists.

From genetical point we could divide porosity in **primary** and **secondary** porosity. There is some disagreement about the definition of those porosities. In view of hydrogeology primary porosity very often developed during the litification of the sediment. From the same point secondary porosity develops after litification of the rock. In hydrogeology division between primary and secondary porosity mainly repose on the shape of the pores (e.g., fissures are treated as secondary porosities). From sedimentological point primary porosity develops during the deposition of the sediment and secondary porosity in postdepositional stage.

The range of porosity in karst rocks is very wide. Nonkarstified limestone and dolomites have similar range from 0 to 20%. For karstified carbonates the range is very huge from 5 to 50%. The reason for various values is not only the nature of karst but also different methodology for determination of porosity (e.g., pumping test, mapping, etc.) and in the measuring scale (representative elementary volume - REV) of the investigated area (Brenčič, 1996)

Older carbonate rocks have lower porosity than younger. Holocene limestones have porosity from 30 to 50%. Tertiary limestones from 20 to 35%, Mesozoic limestones have porosity up to 20% and Paleozoic limestones up to 10%. (Brenčič, 1996)

Effective porosity declines with the depth of the rock. Near surface of the Dinaric karst porosity is up to 10% and in the greater depths up to 3%. Average porosity in the Dinaric karst is 5%. (Brenčič, 1996)

3.0. Development of hydrogeological profile in karst

Only in some basaltic lavas channels in the genetically, primary stage of the rock (e.g., during the sedimentation) can be observed with cross section that are larger than few micrometers. From this it follows that some process triggered the development of the channels after the primary stage of the rock. On this thesis we can distinguish **prekarst** and **karst stage** of the rock (Brenčič, 1994). Both stages are separated by **inception** (Lowe, 1992).

In spite of the fact that distribution of water in karst is very complicated its general distribution is the same as in other aquifers. Hydrogeological profile could be divide into two separate zones. In the upper part is unsaturated (vadose) zone and in the lower part saturated (phreatic) zone. After the time in each of these zones mixing porosity develops but the geometrical shape of the channels is different. The border between vadose and phreatic zone represents ground water level.

Most of the older theories claims that karst in carbonate rocks develops with flow of water through the discontinuities in rocks that are the result of tectonics. This flowing water is aggressive and dissolves rock. The consequences of these process are channels. For karst aquifer channels in phreatic zone are most important. Most recent investigations show that some channels are not only the consequence of the tectonics but they are probably connect with discontinuities that are the consequence of sedimentological and petrologic properties of karst rocks. Some of these discontinuities were activated by the tectonics.

This dependency is mainly the characteristic of channels for which we assume that develops in phreatic zone. This zone contains channels with circular or elliptical cross sections. Sometimes on the Slovenian Dinaric karst phreatic channels develop along the bedding plane partings. (Brenčič, 1992; Šušteršič, 1994, Knez 1996) The question is what is the reason for that?

From the theoretical viewpoint we could assume two reasons of phreatic channel development along bedding plane partings. The first one is tectonic activation of bedding plane partings with interbedded wrench fault. This was prove in Škocjanske jame where three bedding plane partings along which primary channels developed were damaged by tectonics. (Knez, 1996)

The second reason is in the genesis of secondary porosity that is treated as postdepositional porosity. In this way we could treat development of porosity and the onset of the circulation of water more in detail and various processes that are in the background of various hydrogeological stages are more clear.

During the postdepositional stage we have three stages in carbonates (Choquette & Pray, 1970):

1.) **Eogenetic stage** - it forms after the termination of sediment deposition. Sediment is under the influence of meteoritic water and it is under the influence of evapotranspiration. Considerable mineralogical modifications are under the progress and from that reason porosity changes

2.) **Mesogenetic stage** - in this stage sediment is under the influence of near surface diagenetic processes and later diagenesis, compaction processes prevail.

3.) **Telogenetic stage** - in this stage porosity develop in litified rock and designate the erosion of rock.

In all of these stages water circulate through the sediment and the rock. The flow of water is not only the result of gravity driven flow but also the result of other processes as are compaction, consolidation and temperature gradients. All those processes suggest that in rock some predefined water paths could be establish already in the early stages of diagenesis.

In the classical theory karst develop in litified rock in telogenetic stage. However the theory of inception (Lowe, 1992) suggests that inception horizon could be established in the earlier stages of the diagenisis. Lowe interpreted inception with "non-carbonate" processes (e.g., dissolution by sulfuric acids, influence of non carbonate minerals and organic substances in rock, etc.) but from the stages of secondary porosity development we could see that processes that could trigger inception are the result of usual carbonate diagenesis. Non carbonate processes could be the inception agent but we think that are very rare.

If we accept these two causes of phreatic channel development we could establish the following stages of its development:

1.) **Early phreatic stage** - in this stage some predefined water paths develop in eogenetic and mesogenetic stage. These paths serve later as inception horizons. Maybe some small initial channels also develop. This stage could lead to the formation of the channels but is not necessary condition for the development in the later stage

2.) **Late phreatic stage** - in this stage channels develop in telogenetic stage in litified rock. It is usual stage of karst development where inception and gestation occur but also activation of inception horizons from early phreatic stage is possible.

3.) **Pseudo phreatic stage** - in this stage channels develop in vadose zone in perched groundwater. In the region of perched water hydrostatic pressure could be sufficient that the small channels with circular cross section could develop. Sometimes this water is call epikarst or subcutaneous water (Williams, 1983). Some authors denied the possibility that perched groundwater develops circular cross section and doubt in its existence in the karst (Šušteršič, 1995).

In the vadose zone more or less vertical channels developed. They are represented by potholes and chasms. The origin of the genesis of shuch shapes is in the telogenetic zone. They are the consequence of water transmission from the surface to the groundwater level.

4.0. Hydrogeolological conceptual model of karst

In the preceding chapters various aspects of porosity development were discussed, specially in the phreatic zone. In this chapter we will give organization of developed karst hydrogeological system with the help of conceptual model.

The components of karst hydrogeological system are numerous and interactions between them are complex. In the conceptual model this complexity is simplified in the proportion that we can treat its components separately (e.g., diffuse flow, the dissolution of rock).

The basis of the conceptual model depicted in Fig. 4 are general ideas of the global hydrological system (Chow et al., 1988). Detailed classification of the flow in karst rock is based on partially compilation from conceptual models after Smith et al. (1976) and White (1988).

In general karst hydrogeological system can be divided into subsystems of surface and underground water. In the karst, subsystem of surface water is rarely realised, only some components of them are present. These components are mainly connect the contact between karst and nonkarst systems.

The subsystem of underground water consists of vadose and phreatic zone. In the vadose zone Palmer (1984, 1991) distinguished between allogenic and avtigenic waters. Precipitation recharge avtigenic flow. They infiltrate into soils and there they percolate with diffuse flow into discontinuities which transfer water to ground water surface. Where soil is not developed infiltration is direct into discontinuities. Along the course diffuse flow can be transferred from slow diffuse flow to concentrated flow and can be a consequence of closed depressions on the surface.

Allogenic recharge is a consequence of swallowed streams. This recharge is very often in the contact area between karst and nonkarst systems. Usually the zone of sinking is also the beginning of the groundwater surface.

Vadose zone continuously passes through capillary zone to groundwater surface. The latter has continually changes with time. It can be free surface in open channels or water in interconnected discontinuities. Statistically speaking ground water surface in karst is very irregular continually changeable and connected surface. That is the consequence of highly anizotropic structure of the aquifer. From the that reason it can not be treated similarly as groundwater in alluvial aquifers.

If in the phreatic zone hydraulic gradient exists, circulation of water is established. Circulation of water can be deep or shallow. This depends on the size of hydraulic gradient. From this reason the karst aquifer is hydrogeochemicaly stratified. The waters which flows from the upper part of the aquifer have more simple carbonate composition (with various ratio between Ca^{2+} and Mg^{2+}) than the waters with deep origin where the concentration of sulphate is much higher. The differences from the concentration of trace elements also exist..

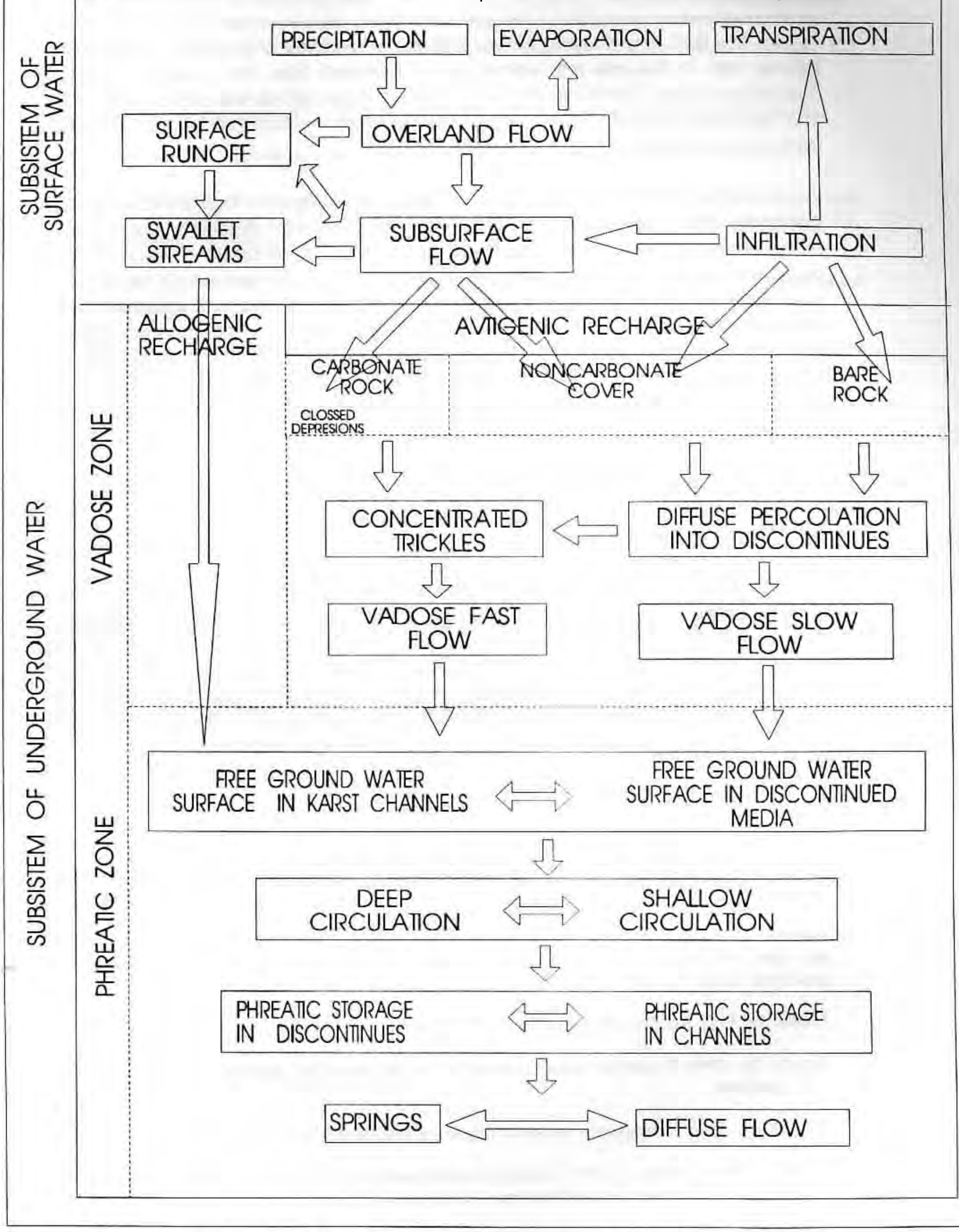

Figure 4. Conceptual model of karst hydrogeological system (after Brenčič, 1996)

The flow of water can be unconfined or confined. We could speak about laminar flow in fissures and sometimes of turbulent flow. For the mathematical description of the flow through it exist various approaches with different models that are: dual porosity model, equivalent porous medium model and discrete fracture flow model (HawLee & Farmer, 1993).

In the case of turbulent regime that usually appears in channels we can talk about open channel flow or about channel flow under pressure. The density of the channels depends on the shape of porosity of the prekarst stage. In the case when prekarst porosity is fissure porosity (e.g., in Dinaric karst) the density of discontinuities influences the density of primary developed channels. For instance if the density of discontinuities is low the density of the channels will be also low. In the case when the density is high the density of the channels will be higher till up to the extreme case where the density is so high that the diffuse flow of ground water appears. In this case diffuse flow made impossibly to form the channels (e.g., in some tectonized secondary dolomites)

5.0. Summary

In karst, flow of water mainly depends on the tectonic setting of the rock which control arrangement of porosity inside rock block. Sedimentological characteristics probably play important role in the inception of channels in the phreatic zone. Discontinuous porosity and channel porosities are prevailing in the karst system. Their ratio depends on the development of karst. Porosity has the influence on hydraulic regime and hydraulic conductivity in rocks and so also on the economic values of karst aquifer and on the interventions in it.

6.0. Literature

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Conceptual approach to modeling karst development

Summary

In spite of very intensive development of the karst theory in the last century many open problems are left, especially in the interpretation of karst development. Not much is known about transition from prekarst to karst features.

Modern science has developed many methods and approaches which can be used in karst studies. The most important among them is numerical modelling. From the application of this method substantial progress in the understanding of karst development can be expected. Some fundamentals that could help constructing models of karst development from prekarst to karst stage are discussed in this paper. In it the knowledge of karst hydrogeology, speleology and geomorphology is combined.

The approach is mainly conceptual and is based on the data from the Dinaric carbonate rock karst. This is the reason why the intergranular porosity is not treated as prekarst porosity.

Natural phenomenon are extremely complex and may never be fully understood. This is true also and maybe even more for the karst. However, in studying the natural processes they may be represented in a simplified way. This is enabled by the idea of the system. A system is a set of connected parts that form a whole. The components can be grouped into subsystems that can be treated separately. The results are combined according to the interactions between subsystems (Chow et al., 1988).

In the article karst is described as a specific subsystem of global hydrological cycle that in majority of its components interacts with the subsystem of underground water. For our purpose we define karst as hydrogeological system where interact the subsystems of underground water and surface water depended upon the karst rock.

We consider the karst as the rock mass in which water is transferred. Owing to that we use equivalently the term karst aquifer. The term aquifer is discussed more thoroughly than it is usual in hydrogeology. Our definition includes also aquitard. For the needs of our conceptual model we take the aquifer as a part of the rock massive which contains and transmits water.

Karst is a system in which structure changes with time. Its components are numerous and interactions between them are complex. This complexity is simplified in the proportion that we can model its components separately (e.g. diffuse flow, dissolution of rock).

The basis of the conceptual model depicted in Fig. 1 are the general ideas of the global hydrological system (Chow et al., 1988). Detailed classification of the flow in karst rock is based on partial compilation from conceptual models of Smith et al. (1976) and White (1988).

In general the karst hydrogeological system can be divided into subsystems of surface and underground water. In the karst the subsystem of surface water is rarely realized, only some components of them are present. These components are mainly connected at the contact between karst and nonkarst systems.

The subsystem of underground water consists of the vadose and phreatic zones. In the vadose zone Palmer (1984) distinguished between the allogenic and authigenic waters. Precipitations recharge authigenic flow. They infiltrate into soils and there they percolate in the form of diffuse flow into discontinuities which transfer water towards the ground water surface. Where soils are not developed infiltration occours directly into discontinuities. Along the course the diffuse flow can be trans-

ferred from slow diffuse flow to concentrated flow, and can be a consequence of closed depressions at the surface.

The allogenic recharge is a consequence of swallowed streams. This recharge is very often in the contact area between karst and nonkarst systems. Usually the zone of sinking is also the beginning of the groundwater surface.

The vadose zone continuously passes across the capillary zone to the groundwater surface. The latter continually changes with time. It can be a free surface water in the open channels or water in interconnected discontinuities. Statistically speaking, the ground water surface in karst is a very irregular, continually changing and connected surface. If in the phreatic zone hydraulic gradient exists, circulation of water is established. Circulation can be deep or shallow. This depends on the value of the hydraulic gradient.

In karst, the flow of water mainly depends on the tectonic setting of the rock which controls the arrangement of porosity inside the rock block. Discontinuous porosity and channel porosity are prevailing in the karst system. Their ratio depends on the degree of development of karst. The effect of mixed porosity and different proportion between discontinuous and channel porosity is clearly seen from Tab. 1 where data from various sources are presented. The reason for high variability of values is not only the nature of karst but also differing methodology for determination of porosity (e.g. pumping test, mapping, different representative elementary volume, etc.). Porosity has an influence on the hydraulic regime in rocks. The flow can be unconfined or confined. We could speak of laminar flow in joints and fissures. The flow could be described as flow between parallel plates. Sometimes we can approximate it with the Darcy flow. In the case of turbulent regime which usually appears in channels we can talk about open channel flow or about channel flow under pressure.The model of the karst development must strictly predict the flow conditions because water is the only transport medium in the proposed model.

Model of the pure karst was developed by Šušteršič (1986) with the aim to explain the morphology of the karst surface. He proposed eight hierarchical conditions that must be satisfied for the karst surface to develop. When all eight conditions are satisfied, the pure karst is developed. In the pure karst only karst phenomena and processes occur. With this approach all regional influences are neglected. Pure karst never exists in the nature. This is only an idealization that helps in determination of the typical karst processes and in understanding of their numerous combinations.

The model of pure karst described in the article should be understood in the context of the systems theory with clearly defined structure and control volume. With alteration of the input values and conditions we can observe the modification of the structure and variation of output values. This approach could help us in the realization of various scenarios that led to development of the pure karst. We are looking at the processes, conditions and their combinations under which pure karst can develop.

Many theories of the karst evolution primarily tend to explain the karst morphology. Alike we could realize the pure karst as a morphological category where the surface consists of centric depressions and hills (Šušteršič, 1986), and the underground is perforated by channels. From this it follows that all criteria that define when pure karst has begun to develop are mainly morphological, and for that very reason not exact.

The pure karst can develop where the mass transport through the system is in the solution and where aquifer with discontinuous porosity is transformed into the karst aquifer with mixed porosity. Mass transport in any other form (e.g. colloids) in our model approach represents a non-karst element. The discontinuous porosity is changed into the mixed porosity represented by the channel and discontinuous porosities.

The pure karst is fully developed when the penetration length (Dreybrodt, 1988) exceeds the distance between the sink into the system and the outflow from the system, and when the first of the channels exceeds the critical distance.

When this conditions inside the control volume are satisfied we could talk about the statistical presence of the turbulence regime which depends on the hydraulic gradient. From that point onwards only different realizations of pure karst are possible.

Further the model with the application of the system theory approach is described. This model is still conceptual but more rigorous than the model in Fig. 1.

The model consists of:

1. Control volume: the block of karst rock defined by its dimensions.
2. Initial structure of the system:
   2.1. Rock is defined by one mineral or as a system of minerals with congruent dissolution. For these minerals all necessary thermodynamic values, equilibrium constants and chemical kinetics are known.
   2.2. Porosity: discontinuous porosity with defined statistical parameters: length, width, dip and aperture.
3. Boundary conditions: sites at the system edges at which the system is opened or closed.
4. Input values:
   4.1. Chemical properties of water: the state of water saturation due to minerals in the control volume.
   4.2. Hydrodynamic conditions: initial hydraulic potential, with the assumption that after connection between inflow and outflow with one channel the potential remains constant. Accumulation in the system is negligible.

From these definitions it follows that the transition from the discontinuous aquifer to the karst aquifer depends on the size of the rock block. Under the same conditions of the penetration length and hydraulic potential the karst channel will be developed faster on the shorter distance as on the longer distance between the inflow and the outflow from the system. This effect that is independent of the system geometry is the consequence of mineral dissolution kinetics.

Till now in all simulations of the karst development the rock of the mass was represented by the mineral calcite (Dreybrodt, 1988, 1990, 1992). For calcite all thermodynamical data, and kinetics of dissolution are known. In the majority of cases the calcite is the prevailing mineral in the carbonate karst rocks, but it is not the only one. For other minerals that are also present in karst rocks (e.g. dolomite) their properties are less well known. Similarly the influences of impurities and rock structure upon the rock dissolution are unclear.

Because of all these problems we must, in the early stages of modelling, present the karst rock as a calcite mass. We assume homogeneous, isotropic and congruently dissolvable rock in which all processes of dissolution at any point within the control volume are the same.

Besides the solubility of rock we define the prekarst porosity and its distribution within the control volume. The prekarst porosity is presumed as discontinuous porosity. In the field studies of joints and fissures we usually use the statistical approach. Field data are fitted to some theoretical distribution or empirical distribution is found. This procedure could also be used in modelling studies. Each theoretical distribution is precisely defined by statistical parameters. In the modelling we suppose these values and the arrangement of discontinuities are simulated with the Monte Carlo techniques. The probability simulation must be done for every studied property of discontinuities, and later combined into a synthetical distribution that defines the spatial arrangement of the simulated prekarst discontinuous porosity within the control volume.

With boundary conditions we define the openness and closeness of the system. In this way we indirectly define the length between the sink and the outflow in the system.

Among the input values we must know the chemical characteristics of inflowing water, mainly its saturation state with respect to minerals in the control volume. Upon the saturation state depends the kinetics of dissolution. More undersaturated is the inflowing solution, faster will be the dissolution.

Hydrodynamic conditions are defined by the hydraulic potential at the borders of the system. Usually we could represent the hydraulic potential in the tensor form, as a property of space. Depending upon its principal direction and size only discontinuities with lower resistance will transfer water.

As an additional condition we could introduce in the model the mechanical properties of rock. From this condition depends initially the aperture of discontinuities and in the later stages the stability of the channels.

As a result of the model we could expect the morphologically remodeled rock block and the chemical composition of water in the spring that differs from the inflow waters. At the outflow we can define the ratio between diffuse and concentrate outflow.

With such a model we could observe the development of the global karst drainage network. For the observations of a particular feature (e.g. cross profile of karst channel) we must construct a somewhat different model.

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