GROUNDWATER IN KARST REGIONS

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Summary

Carbonate rocks are exposed at or underlie about one-fifth of the area of the earth's land surface. They contain large quantities of groundwater, an important part of the world's supply of petroleum and natural gas, and valuable reserves of metallic ores.

It is not only the extent of carbonate terrains and the productivity of their aquifers that engenders special attention. Their hydrology differs in several ways from that of other terrains. The main difference is due to the relatively high solubility of most carbonate materials. Hydrological characteristics, such as permeability, are often erratic, irregular, and not fixed with respect to time and space. To the extent that the movement of water aids solution it increases permeability, which may lead to an increase in the amount of water in circulation.

Water in carbonate rocks tends to move more freely along joints, fractures, and bedding planes than through the interstitial porosity of the rock material itself. The fracturing of carbonate rocks results from complex combinations of depositional conditions and deformational forces. As the water moves along the planes controlled by these two processes during the history of the rock, it dissolves the walls or precipitates carbonates. As a result, the permeability of carbonate rocks may vary widely within short distances.
The variable porosity and permeability of carbonate rocks, in combination with the features developed by hydrological forces, often provide extremes with respect to benefits and liabilities for humanity's needs. For example, the value of caves for historic reasons, as natural features, or for storage purposes, may be offset by the structural instability of the extensively channeled or cavernous limestone rock in which they most commonly exist.

1. Karst Geology and Hydrogeology

Karst hydrogeology research requires the use of special techniques because of the peculiar characteristics of karst phenomena. The movement of karst groundwater, especially through solution channels and cavities, causes difficulties in reaching a karst groundwater system by drilling. Moreover, leakages from reservoirs make it necessary to apply special monitoring methods. Karst hydrogeology research consists mainly of research in remote-sensing and geographical information systems (GIS) as well as special geophysical methods, groundwater tracing techniques, and environmental isotope studies.

Isotope methods for studying water flow in karstic systems use natural (environmental) tracers, artificial tracers, and groundwater tracing experiments.

Karstification depends on various conditions, including geological, chemical, and climatological factors. The main geological–chemical component is corrosion in

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limestones ($CaCO_3$) and dolomites ($MgCa(CO_3)_2$), which are soluble in water charged with carbon dioxide gas. In these carbonate rocks the dissolving capacity is related to rock properties, the permeability of the ground, and tectonic movements. Climate is also an important factor in the solubility of limestones and dolomites. Carbonate rocks in cold regions often form ridges, because vegetation (a major source of CO_2) is absent. The same will occur in arid zones, because the scarcity of water limits the solution of limestone. In humid areas, including the tropical zones, limestones will be readily dissolved.

The structure, topography, and presence or absence of other geologic formations play an important role in the development of hydrogeologic conditions, together with climatic factors, permeability, and soil formations. Pure limestone can be dissolved and leave essentially no residue. So, since no weathered clayey or sandy material is produced, soil is practically non-existent. In addition, however, the permeability developed from the dissolution of the limestone remains high in the form of open channels, because other sediments are not available to decrease the permeability by filling the corrosive gaps.

In forming a first, general idea of the groundwater flow in karstic aquifers, it is very important to take into account (a) the differences in altitude (massifs and plains) and (b) the base level of the surface and underground drainage.

The term “karst” defines a carbonate rock whose openings have been enlarged by the action of groundwater. The carbonate rocks are of sedimentary origin, and are composed essentially of carbonate minerals, containing mainly calcium, but also magnesium and minor, usually negligible, amounts of iron and other trace elements. The term “limestone” is considered to embrace true limestones, dolomitic limestones, and dolomite, unless it is clear that is restricted to its limited use as defining pure limestone in distinction to dolomitic limestone or dolomite.

Carbonate rocks may contain clays or silica grains in varying quantities. Their solubility in precipitation and groundwater decreases, and their insoluble residues increase, when there is a higher proportion of clay and/or silica; they thus evolve from the “holokarst” to the “mérokarst,” as defined by Cvijic in 1925.

“Primary porosity” refers to openings that have existed in the limestones since their initial lithification; “primary permeability” refers to the ability of water to circulate through ·the rock through, and by means of, the primary pores.

“Secondary porosity” refers to openings that were formed after lithification. These were mainly caused by tectonic stress, which produced joints, cracks, fissures, and faults, but in some cases stem from metamorphic–metasomatic action that produced openings by contracting the volume of the rock; “secondary permeability” refers to the ability of groundwater to circulate through the rock through, and by means of, these joints, fissures, and other secondary openings.

“Diffuse circulation” refers to the circulation of groundwater in karst aquifers under conditions in which all, or almost all, the openings in the karst intercommunicate and are full of water below the level of the water table.

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"Localized circulation" refers to circulation in karst aquifers in which the water moves in certain preferred zones and does not occupy all, or most, of the openings that lie below this level; the flow may take place as in open channels or in pipes.

The porosity and permeability of primary limestones have been well studied, and it is known that most primary limestones are impermeable. Studies have been made as to how openings are formed in limestones by cracks, joints, and faults. The enlargement of these openings by circulating groundwater is best examined after the hydrochemistry of the groundwater has been studied.

The porosity of a rock is its property of containing interstices, and is expressed quantitatively as the percentage of the total volume of the rock that these occupy. A rock is said to be saturated when all its interstices are filled with water. In a saturated rock the porosity is effectively the percentage of the total volume of the rock that is occupied by water. In general terms, porosity in excess of 40% is rare, except in some soils and poorly compacted sands and gravels. Porosity in excess of 20% is considered high; from 5% to 20% is normal, while a porosity of less than 5% is considered low. Typical porosity ranges for carbonate rocks are given in Table 1.

Rock	Total Porosity as a percentage
Carrara Marble	0.11 - 0.22
Marble	0.11 - 0.59
Compact Limestone	0.67 - 2.55
Chalk	14.4 – 43.9
Chalk from Northern France	22.2 – 37.2
Chalk from Vanne, France	30.5 – 44.0
Oolitic Limestone	13.6 – 20.2
Tufa – Travertine	Average %20
Dolomite	0.86 – 1.5

Table 1. Porosity of certain carbonate sediments, with interstices expressed as a percentage of the total volume of the rock

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The permeability of a rock is its ability to transmit water through its interstices; the forces causing movement are mainly gravitational, though capillary attraction, (molecular) may also assist movement over limited distances. The forces opposing motion are frictional (skin friction plus turbulent flow losses in some limestones), and molecular (surface tension holding water in place).

The capacity of a formation to transmit water is measured by its coefficient of permeability. Meinzer has defined a "Coefficient of Permeability," which in metric terms may be stated as "the rate of flow of water in cubic meters per day, through a cross-sectional area of one square meter under a hydraulic gradient of one-in-one, and at a temperature of 15.6 °C (60 °F)" (see Figure 1). On the other hand the "Coefficient of Transmissibility" has been, defined by Theis as "the rate of flow of water in cubic meters per day through a vertical strip of the aquifer 1 meter wide and extending the full saturated height of the aquifer under a hydraulic gradient of one-in-one and at a temperature of l5.6 °C." From Figure 1, it is clear that for limestone this figure must be an average, due to the irregular distribution of the fissures.

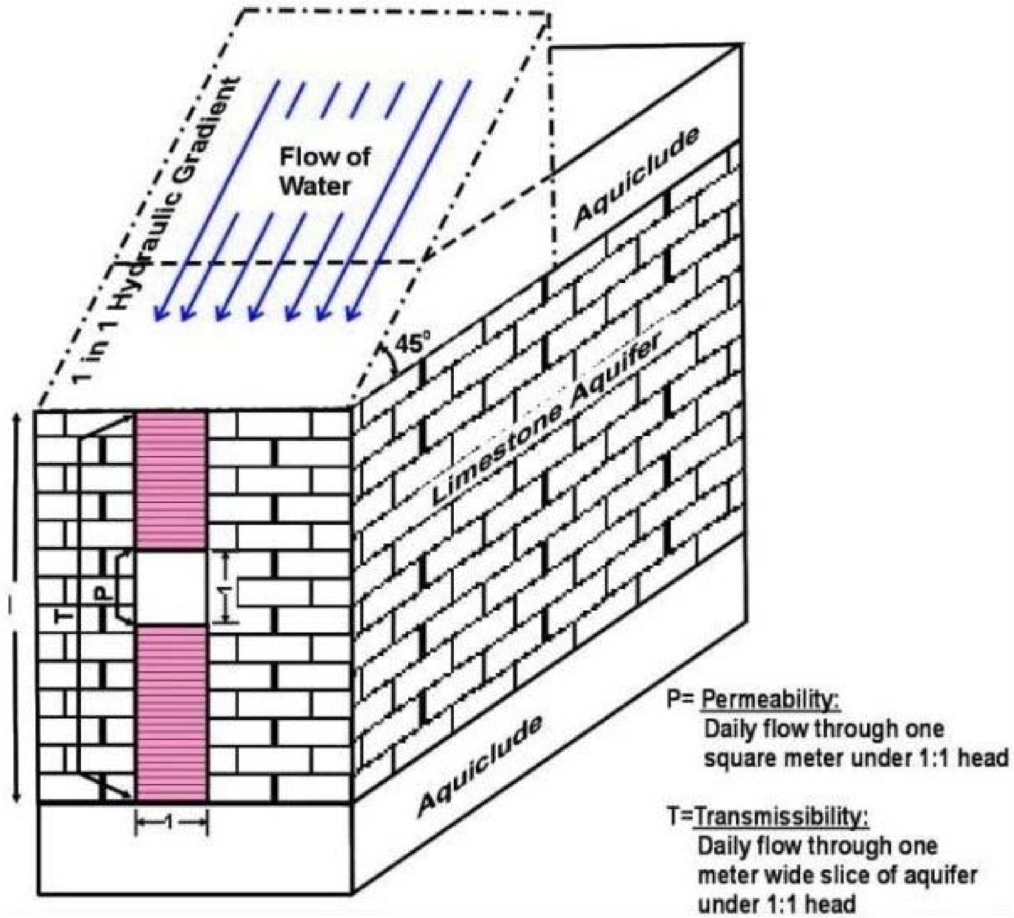

Figure 1. Coefficients of permeability and transmissibility

2. Karstification Process

The word karst is directly associated with carbonate rocks, more specifically the limestones and dolomites, though the karstification process also occurs within formations of gypsum and salt. "Karst" has become a synonym for carbonate rocks (limestone and dolomite), including all their varieties and conglomerates with carbonate matrix. Although limestone is the most important rock in which the karstification process takes place, the dolomites' susceptibility to karstification depends upon thickness and position within the geological structure.

Limestones are the most representative of all the carbonate rocks. They are largely composed of the mineral calcite ($CaCO_3$: Calcium Carbonate). They are very seldom composed only of pure calcite, and usually contain certain percentages of clay, bituminous matter, magnesium, silica, sands, and other minor components. Depending on the quantity of these inclusions, limestones may be classified as shaley, bituminous, dolomitic, siliceous, sandy, and so on. The solubility of limestones in karstification increases with their purity.

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Dolomites are carbonate rocks composed of the mineral dolomite. This is a dual carbonate salt of calcium and magnesium. Its chemical composition can be expressed as $CaMg(CO_3)_2$ and it is made up of 30% CaO, 22% MgO, and 48% CO_2. At the present time, there is no evidence of recent dolomite sedimentation in seawater.

Evaporite rocks (gypsum and salt) are the most soluble of the common rocks. Salt (halite) solubility in water is 35% by weight at 25 °C, and it increases at higher temperatures. The karstification process is identical to that found in carbonate rocks and forms the same types of karst features that typically are found in limestones and dolomites.

The formation of caverns and channels is the direct result of chemical dissolution, which at a certain stage of the process could be supported by an erosive action of water. As turbulence in the water increases, the quantity of solute also rises. The experimental work of Sweet and White led to the following conclusions: if the Reynolds number increases from 250 to 25 000, the rate of solution increases by a factor of approximately three. Fully developed turbulence on the face of a spinning disc appears at a Reynolds number of about 50 000. However, there is no evidence that a dramatic increase of the rate of solution occurs at the onset of turbulence. Although the increase in flow velocity and turbulence increases the dissolution process, it seems that a change from laminar to turbulent flow represents the initial factor in cavern growth.

Temperature is also an important factor controlling the dissolution process of limestone. It was established by Castany that 1 liter of water at a temperature of 0 °C can dissolve four to five times more limestone than at 30 °C, and six times more than at a temperature of 40 °C. Corbel also arrived at the same conclusions. After detailed investigations he concluded that the karstification process is more rapid in cold climates with higher snow precipitation than in regions with hot weather. According to Corbel the rate of erosion, both mechanical and chemical, in low mountains with 1000–1600 mm of precipitation and a cold climate is 160 mm per 1000 years. Over the same period in a hot climate, the erosion is 10 times lower (only 16 mm). In plains regions with 300–500 mm of precipitation with a cold climate, the rate of erosion is 40 mm per 1000 years, as compared to only 4 mm in a hot region.

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Biographical Sketches

Dr. Gültekin Günay was born in Karacailyas, Turkey, and studied geology at Istanbul University. He completed graduate studies at the same university and was awarded his doctorate in 1973. He worked as Geologist in the State Hydraulic Works (DSI) of Turkey between 1962–1966, Hydrogeologist 1967–1968 and was Chief Engineer, NPC of UNDP Project between 1970 and 1978.

Dr. Günay has continued his academic career at Hacettepe University since 1982. He was appointed Associate Professor in hydrogeology in 1979 and Professor in hydrogeology in 1988 at the same university. He founded the International Research and Application Center for Karst Water Resources in 1985 and has been the director of the center since then. His main specializations are karst hydrogeology and isotope hydrology, well hydraulics, salt-water intrusion, groundwater tracing techniques, and hydrogeochemistry. He has carried out many international and national investigation projects. He also organized several international symposiums on karst hydrology and hydrogeology.

Dr. Günay has presented more than 70 professional papers at many national and international conferences and in periodicals. He is a member of the International Association of Hydrogeologists (IAH), IAH-Karst Commission, International Association of Hydrological Sciences (IAHS) and International Association of Engineering Geology (IAEG). He is a member of the editorial board of *Environmental Geology* (Springer-Verlag) and *Journal of Hydrogeology* (Elsevier).

Dr. Petar Milanović was born in Belgrade, and studied geology at the University of Belgrade, where he completed graduate studies and was awarded his doctorate in 1980, after research studies at Colorado State University, Fort Collins, and EROS Data Center in Sioux Falls, USA, in 1977/1978.

Dr. Milanović has spent much of his career at the Karst Institute in Trebinje, Yugoslavia, and after 1987 at the Energoprojekt-Hydroengineering Co. in Belgrade. In addition to performing consulting services, in 1980 he was appointed Mostar University Professor of Hydrogeology at the Civil Engineering Faculty. On several occasions, acting as a UN expert, he took part in hydrogeological studies of karst in Turkey and Greece.

As a researcher and field geologist, project team member, consultant, technical control and board of experts' member, he has participated in various stages of investigation, design, and construction of a number of dams and reservoirs in Yugoslavia, Greece, Algeria, and Iran, as well as in a number of projects of underground excavation, grouting, water supply, irrigation, and groundwater pollution control.

As visiting professor, Dr. Milanović has delivered lectures on geological engineering in karst at several Universities in the United States, as well as at the USGS in Reston, Greek Geological Institute (IGME) in Athens, Gidroproject in Moscow, DSI in Ankara, and a number of water management organizations in Iran. He has also given a series of postgraduate courses in geological engineering in karst at different universities in Yugoslavia, the Application Center for Karst Water Resources of Hacettepe University in Ankara, and the Iranian Karst Institute in Shiraz.

Dr. Milanović has published more than 50 professional papers. As a participant in many international and national conferences he has also served as the key speaker and general reporter. He is a member of several international associations and has many years been a member of the IAH Karst Commission.

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