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HISTORY OF KARST HYDROGEOLOGICAL STUDIES

Philip E. LaMOREAUX
Senior Hydrogeologist
P.E. LaMoreaux and Associates, Inc.
P. O. Box 2310
Tuscaloosa, Alabama 35403

ABSTRACT

G.K.W.: Karst hydrology, history of natural sciences, karst hydrogeological research
Geogr. K.W.: World karst

The term "karst" has been used only since the 19th Century. It is a German term applied to an earlier Serbo Croatian term "krs". Descriptions of karst phenomena, caves, sinkholes, swallow holes, and underground rivers date back to antiquity. They were an integral part of Greek mythology.

Long before the word "karst" was used, the phenomena associated with dissolution of limestone were being described by humans fascinated with caves, large springs, and streams that disappear underground (ponors and katavothrons).

In the 20th Century karst research received great attention by a diversity of scientists. New methods employ sequential satellite imagery, air photography, remote sensing, computers, results from sophisticated chemical laboratories, new techniques of isotope hydrology and model analysis. During the same period there have been many textbooks published, thousands of technical papers written and over 150 symposia and congresses directed to the subject of karst.

INTRODUCTION

Man was intrigued with karst, particularly cave development, long before the word "karst" came into use. In pre-historic times caves provided humans with a living space, water supply, and protection. In the cave area of southern France, in the Pyrenees and in northern Spain that were outside the influence of the massive Continental Pleistocene Glaciers, the Paleolithic Period of man's evolution was a scene of remarkable cave drawings illustrating an amazing capability of early man to duplicate pictures of animals and hunting activities. He had chosen these caves as living areas, and his exploratory drive led him deep underground to sources of water. These were man's first attempts to explore and understand karst and use this natural phenomena to enhance his living conditions and safety. During Greek times, caves, underground rivers, and springs were a part of Greek mythology, and the subject of much discussion by Greek and Roman philosophers. The earliest hydrologic concepts of the hydrologic cycle, water source, occurrence, and quality were related to a karst

setting.

How important is karst to man's environment? In Yugoslavia, the home of the term "karst", 33 percent of the surface is karst terrain (Milanovic, 1981). In the USSR, 40 percent of the land area consists of carbonate and other soluble rocks, and in the United States about 25 percent is underlain by carbonate rocks. Approximately one-fifth of the earth's surface is underlain by carbonate rocks of a complex physical character that produced a diverse topographic expression by weathering under varied climatic conditions. Carbonate terranes in some areas are underlain by broad, rolling plains, whereas in others they are characterized by steep bluffs, canyons, sinks, and valleys. Owing to the variability of the solubility of limestone under different climatic and geologic conditions, man's inhabitation and development of limestone areas has often been difficult. In some areas the limestone is covered by fertile soils; in others soils are missing. In the midwest of the USA, a large area underlain by limestone covered by a very productive, rich soil that produces large quantities of food. This area is literally "the breadbasket of a nation."

Carbonate rocks are a source of abundant water supplies, minerals, and oil and gas. Even though there are many blessings associated with carbonate terranes, there are also many problems related to developing an adequate water supply, assuring proper drainage, providing stable foundation conditions, and preventing serious pollution problems. Because of this complexity, the evolution of concepts related to the movement and occurrence of ground water in karst, methods of exploration and development of water, safe engineering practices in construction of all kinds, and adequate environmental safety precautions cannot be based on one uniform set of rules.

The impact of karst terranes is great on man and of substantial interest financially. This is recognized by a few select references from recent publications: John Newton (1986), "Development of Sinkholes Resulting from Man's Activities in the Eastern United States", (19 States) reports that since 1950 there have been *more than 6,500 sinkholes* or related features that have occurred. Newton further states that the total cost of damage and associated protective measures resulting from these induced sinkholes is unknown, however, at 5 dam sites alone repair costs were in excess of $140 million. In a report presented by Dallas Peck, Director of the U.S. Geological Survey, in October 1988, in a paper, "Karst Hydrogeology in the United States of America", at an International Karst meeting in Guilin China, he makes the statement, "karst aquifers are a major source of drinking water in the USA that provided 25 million cubic meters of water per day in 1985". Finally, a Panel on Land Subsidence, U.S. National Research Council, in a report dated 1991, *Mitigating Losses from Land Subsidence in the United States*, states that 6 states have individually sustained $10 million or more from damages resulting from sinkholes, and an additional 4 states sustained from $1 to 10 million in damages from the same cause. As a result, in the USA there has been developed "awareness programs" for catastrophic subsidence areas and an insurance programs applicable to sinkhole problems.

Finally, *karst areas are dynamic* and environmentally sensitive. The geologic structure, solubility of the rocks involved, and the climatic conditions determine to a great degree how rapid these changes can take place. Therefore, karst investigations must consider the dynamic nature of karst. It is necessary to recognize the synergistic relation between circulation of water and solution of the rock, that the greater the solution - leads to changes in or progressive lowering of water tables - base levels, progressive cave enlargement, and changes in karst topography all can take place

within relatively a brief period of time. Rapid dynamic change can impact the hydrogeologic history of an area, and brings about major environmental problems. Four examples follow:

1. Yucatan - loss of a civilization.
2. Guilin - major climatological impact.
3. Shelby County, Alabama, USA - impact on water supplies, transportation, energy pipelines, mining, communication, health, and loss of life.
4. South Africa - condemnation of large areas of urban-agricultural land, and same as 3.

DEFINITION OF KARST

The term "karst" originates from the geographical name of the northwestern region of Yugoslavia near the Italian border which extends from Istria to Ljubljana. The people in this region use the Slavic word "kar" and Italian word "karso". Both words are of Indo-european origin. From the word "kar" meaning rock, Germanization of the word "kar" and the Italian word "karso" resulted in the term "karst".

The word "kras or kar" was first mentioned in written form on the island of Krk. The first written note that mentions the word "karso" dates back to 1292. The term "karst" was first cited in an Austrian document dated 1423 (Milanovic, 1981). The word "krs", meaning kras (karst), was used for the first time in 1894 (Roglic, 1960). All of these terms are used in Yugoslavia (kras, krs, and karst). They have identical meaning (Milanovic 1981). Analogous to the term "karst", the concept of karstification denotes the many geological processes that destroy soluble rocks, thus forming unique morphological features and specific types of porosity, or specific hydrogeological environment.

The evolution of the term karst and its meaning is as complex as the study of karst itself. In the book, *Morphogenetics of Karst Regions*, by L. Jakucs (1977), the author describes the karst concept. Originally, it was an orographic proper name. For example, karst is a geographic concept. Kadic (1939) described karst as a "limestone region rich in caverns", and stated the unusual features observed in karst regions are called karst phenomena. Kessler (1957) provided a definition that was speleologically oriented, relating the karst "phenomena connected with the subterranean activity of precipitations" in limestone mountains. Venkovits' (1960) definition was "the term karst, a portion of the earth's solid crust, made up of rocks effected more than the average by the dissolving power of surface or underground waters". Therefore, over time the term "karst" evolved and was applied to a geographic meaning and to the physical phenomena associated with dissolution, particularly of limestone beds. Eventually, recognition was made of the dynamic nature of karst areas.

The Yugoslavian scientist Jovan Cvijic became interested in karst and collected much valuable information for his doctoral dissertation "Das Karstphanomen" (1882). The dissertation was followed in 1900 by the book, *Karst Poljes of Western Bosnia and Herzogoviana*, and in 1926, *Geomorphology*. In his volume, *Geomorphology*, Cvijic studied water tables, karst springs, seepages, and estavellas and separated karst into three morphologic types of limestone terranes: Holokarst, Merokarst, and Transition karst. Subsequently, Monroe (1970), U.S. Geological Survey, Water Supply Paper 1899-K, provides us with a dictionary of karst terms.

HIGHLIGHTS IN KARST HISTORY

1. Cuneiform tablets provide the first records of karst hydrogeological research known and describes an expedition in 852 B.C. by the Assyrian King Salmanassar III to the headwaters of the Tigris. The source of the Tigris is a karst spring. Inscriptions on the cave states that the source of water to the Tigris immortalize Salmanassar III and is the first known representation of stalagmites.

2. In 650 B.C., there were two novel explanations of the hydrologic cycle. One group, including the philosophers Thales, Plato, and Pliny believed that water is forced from the sea into the rocks in which it is driven upwards, and its salts extracted, until it reaches the surface of the ground. The other group, including Aristotle, believed that springs originated from condensation in subterranean caves and caverns.

3. Large parts of Greece are underlain by karstified rocks. The term "katavothron" is an ancient Greek term applied to a surface stream that disappears underground into a swallow hole. Sophocles (496-406 B.C.) was the first to report on a katavothron on the river Inachos.

4. The Greek geographer Skilax of Karyanda (500 B.C.) reported on the karst springs of the Timavo.

5. The early Greek philosophers theorized on the movement of ground water in karst areas as related to the water cycle - some examples, Empedocles (490-430 B.C.) and Aristotle (384-322 B.C.).

6. Eratosthenes (276-194 B.C., as reported by Strabo in Book 8) described hydrologic the connection between Katavothra (Ponors) in Pheneos polje to Ladon Spring in the Peloponnesus of Greece - spring rains and discharge.

7. Poseidonios (135-50 B.C.) reported on the springs of Timavo and describes the River Timavius where it disappears in a cave underground.

8. Strabo (60 B.C.-28 A.D.) devoted his eighth book of 17 volumes, "Geographica" to the *Karst Phenomena of the Poljes* (underground streams), as well as other karst phenomena.

9. Jewish historian Josephus Flavius (37 A.D.) recorded in the History of the Jewish War the probable source of the Jordan and that Tetrarch of Trachonitis used a tracer (Chaff) to trace an underground stream.

10. Lucius Annaeus Seneca (4 B.C.-65 A.D.) was perhaps the most important Roman philosopher and writer regarding karst. In his book III, *Naturales Questiones*, he describes solution processes, the development of large underground caves, and explains the disappearance and reappearance of streams.

11. "An Encyclopedia of Knowledge" was compiled around 970 A.D. by members of the Arabian Order of the "Brothers of Purity". In these documents Arabian Monks wrote about caves inside of mountains and springs discharging the water stored in caves. There were many new ideas and concepts relating to hydrology and geology developing in the Arabian culture at this time; unfortunately however, this material is hard to acquire. One example is the writings of the famous Arabian Abdul Hasan Ali Masudi.

12. Accredited to 4th Centuries in Rome there is a map copied later during the 11th or 12th Century on a parchment that is known as the Tabula Peutingeriana, (4 cm wide and 6.8 m long). Even though the originals are missing, the copies indicate that a

Roman cartographer mapped the Fonte Timavi, or Timavo karst springs. This is probably the first known map locating a karst feature.

13. In the evolution of karst studies we should not overlook parallel work in China. A book on caves was written about 221 B.C. for North China that contains description of caves and hydrography. The Hongshan Karst Spring, discharging 3m3/s in Jiexiu County, Shanxi Province has been in use since the Song Dynasty (1000 A.D.), and in 1040 A.D. the springs discharge was separated into three channels and used to irrigate nearly 100,000 acres.

14. Chinese karst scientist Fan Chengda (1175 A.D. - Song Dynasty) gave an explanation of speleothems, saying that the milky water dripping continuously in the cave, through the process of condensation, created stalactites.

15. Xu Xiake (1586-1641 A.D. - Ming Dynasty) made extensive field trips into South China karst - Guilin area - for the study of the geomorphology of caves. He described tropical karst features, including fenglin, or peak forest karsts. He is known as "the father of karst studies in China".

During the 18th Century in Europe studies began with observation and description, for example, Melchior Goldast from Germany described the Blautopf, one of Germany's largest springs; A. Kirchner (1665) correctly interpreted fluctuations of water in a polje to the seasons, and theorized on the connection of underground streams; and Johannes Antonius Nagel (1748), a mathematician, was assigned by the Hapsburgs to study poljes and caves - the objective was the development of agriculture as the poljes remained flooded into the planting season.

Between 1778 and 1789, Hackuet, in a four - volume work, described many karst-hydrologic phenomena: the solution of limestone, dripstone, carbonate incrustation, joints filled with clay, the relationship between streams in a karst area, and poljes. Professor Josef Zötl (1980) states "Hackuet is 'the father of karst hydrology' in Europe", as he anticipated problems that would be the subject of controversy in the coming century.

By the 19th Century, there began natural scientific thought. Earlier work described the karst phenomena, theorized on the hydrologic cycle and, as in the case of Hackuet, identified some serious questions and problems that would need to be studied. It is not possible *to identify all* of the karst scientists that made contributions in the 1800s; however, in a paper, "Bibliography of the History of Karst Research", by Josef G. Zötl, published in the "Annotated Bibliography of Limestone Terrane" as Volume IV (1989), he provides us with the identity of many important scientists for this period. The following are selected for special recognition:

1. In 1834 in France, J. Virlet (1834) explained the development of dolines earlier than Cvijic, however, most of the karst work in France was related to speleology.

2. From the famous springs in southern France at Voucluse came the term "Vouclusian". It was generically used for karst springs with pronounced variations in discharge. The spring discharge at Voucluse has been systematically measured since 1853.

3. 1856 Frenchmen Abby Paramelle was the first to attempt to study the extent of underground karstification and identify the path of ground water movement in karst.

4. 1872, F. Pfaff explained limestone solution. He determined that a limestone slab exposed to weather erodes .177 m per year, or 1 m in 72,000 years. This value remains valid today.

5. 1873, E. Tietze, studying karst in the vicinity of Triest, was the first to reference

these areas to "karst formation"; and in 1876, K. Wessley was the first to mention the new meaning of the word "karst" for a rocky, barren area that was typical near the city of Triest.

NOTE: Zötl (1957) believes that karst research in the 19th Century was influenced greatly by the political situation. The Austrian Empire, acquired extensive land areas underlain by karstified rocks that required agricultural development in the poljes, the construction of roads and railroads. The problems of building roads in such an area required explanation and practical measures. Therefore, in addition to studies to meet agricultural needs, there were added the evaluation of problems associated with the building of highways and railroads, and the development of adequate water supplies.

6. E. Tietze, during the 1870s, was commissioned by the Austrian government to produce a geological description of the area, a discussion of the tectonics and stratigraphy, a description of "Terra Rossa", a treatment of limestone and dolomite solution, and the relationship of temperature, precipitation, and spring flow.

7. Toward the end of the 19th Century, J. Cvijic cooperated closely with Albrecht Penck at the University of Vienna. Penck published the journal, "Geographical Proceedings". In volume 3, 1893, Cvijic's monograph on karst was published. This work provided the first systematic treatment of karrens, dolines, karst rivers, karst valleys, poljes, and distribution of karst phenomena along the Adriatic Coast.

Karst Research in the Twentieth Century

At the beginning of the twentieth century, Cvijic's research provided systematic treatment of karrens, dolines, karst river, karst valleys, poljes, and other types of karst phenomena associated with the Adriatic coast area and the dalmatians. He also provided definitions and terminology. He was perhaps the greatest contributor "going into" the 20th Century, providing over 60 items to the literature on the subject.

1. In 1878, the first large, quantitative karst-water tracing experiments by injecting sodium fluorescein and potassium chloride were performed into sinkholes of the Danube. More recent studies were undertaken in November 1908 while investigating sinkholes in the Danube near Fridingen, at which time large amounts of sodium chloride were injected.

2. Grund (1903, 1914) recognized a zone of saturation in karst, noted that in the Adriatic region that seal level was the "base level" for a karst hydrologic system, and that recharge from precipitation caused the ground-water level to rise.

3. In 1907, Timeus and Bortmann, using lithium chloride and a radioactive substance, carried out tracing studies in the Istrian Karst even though little was known at the time of the dangers of radioactive materials. Timeus was using pitch blend.

4. In 1907, F. Lukas edited the works of E. Richter concerning water movement in karstified rocks; and in 1907, N. Krebs presented the concept that some veins dominated and assumed the appearance of streams, and that these waters were nonetheless connected underground, a major contribution because he was one of the first to recognize that in karst areas there can be a water table, a saturated zone, and streams or water in fractures and solution cavities that were connected and functioned as a hydrologic system.

5. In 1926, the first plant spores were used for tracing. The advantage of lycopodium was that the spores did not dissolve in water, but instead formed an emulsion of solid bodies. Also, due to their small size, they remain suspended in water (G. Vornatscher, 1962).

6. In 1930, Davis (1930, pp. 475-628) challenged the ideas that caverns are

developed above the water table and that solution below the water table is insignificant. According to his theory, which is known as the two-cycle theory, the major part of cavern development takes place by solution below the water table. The second cycle begins as the water table is lowered and the caverns are left in the zone of aeration, where they remain without water excepting when water from the overlying beds or surface streams drain into them.

7. Harned 1941, Corvell 1959, and a host of others advanced the concepts that limestone $CaCO_3$ and dolomite, MgCa $(C0_3)_2$ have solubility dependent upon the C02 content of the water, the purity of the carbonate rock involved, the joint pattern in fractures and faulting, the tectonics, and finally, temperature and climate.

8. In 1959, Dechant developed a method of permanent staining, in five different colors, of lycopodium spores. The use of lycopodium was far safer and provided a diversification of methods for tracing. Multiple colors permitted multiple injections under the same hydrologic conditions over a large area.

Experimentation, research, and emphasis on tracing methods resulted in the "Specialist Conference on the Tracing of Subterranean Waters" in Graz, Austria from March 28-April 1, 1966. One hundred and twenty-five participants presented results of their work. In 1975, Zötl and W. Back, through assistance of the Marshall Plan for Central Europe, injected commercial salt into the Lurbach System.

9. In 1967, Hanshaw and Back contributed a series of studies on differential dissolution of Pleistocene reefs in the ground-water mixing zone in coastal Yucatan and the evolution of a carbonate-aquifer system in the same area. The resulting papers provide contributions to a better understanding of solution processes in karst areas.

10. In 1971, first of the Atlas Series, "Environmental Hydrogeology of Karst", published by the Geological Survey of Alabama describing fragile nature of karst and providing guidelines for development in limestone areas-1972, 1974, 1975, LaMoreaux, Moser, Hyde.

11. In 1974, J. Zötl, in the text, "Karst Hydrogeology", clarified some of the concepts of O. Lehmann, particularly as it related to the question of base level of erosion and provided a solid source of basic information for the classroom.

12. A. Boegli, 1978, provided an exhaustive treatment of the solution processes in carbonate rocks. He supported some of the concepts of E. Tietze, 1873; and Boegli's recognition of corrosion caused by mixing of different karst waters, so called "mixing corrosion" made him world famous. Further, the concept that corrosion of carbonate rocks is a reversible chemical process, i.e., when the C02 content in water drops, dissolved carbonate rocks precipitate out in the form of center or calcareous tuffa should be noted. Other important reference books of the period included: Dreybrodt (1988), Milanovic (1981), Bonacci (1987), and LaMoreaux (1984).

Quantitative Methods in Karst

By the 20th Century, much qualitative work had been accomplished, and quantitative methods for determining ground-water velocity, permeability had been developed: Poiseville (1846), Dupuit (1848), Darcy (1856), Slichter (1899), Forchheimer (1901), Theim (1906), Theis (1935). However, most hydrologists during the first 50 years of the century applied these methods to water moving through granular materials, assuming homogeneity, infinite aquifer, isotropic conditions, conditions rarely encountered in a karst setting.

During the period beginning in the 1940s with the demand for specific numbers for hydrology during the war years, one of the most difficult problems facing the

development and management of ground water in karst areas was the application of quantitative methods to karst rocks.

In 1935, Theis published his equation to describe non-steady ground-water flow, a major breakthrough to modern quantitative investigations. In 1935, Stringfield interpreted regional ground-water flow with a potentiometric map of the Floridan aquifer. In 1959, Cooper reported on the dynamic balance between freshwater and salt water in the Biscayne aquifer in Florida, and applied pumping test methods using the Theis equation to a large scale pumping test on the Floridan aquifer at Fernandina, Florida. Following these successful quantitative approaches to younger cocina limestone beds (Miocene-Eocene), the same methods were applied successfully in the Huntsville, Alabama area in 1960 with major pumping tests on hard dense, karstified limestones of Mississippian Age. These older limestones were faulted, folded, and extensively karstified. Pumping discharge rates were about 10,000 gpm and impacted water levels and spring flows were monitored at over 100 points. Results were used to develop and expand the municipal water supply in the Huntsville area using a combination of wells and springs.

Many new techniques have evolved during the later part of the century that are used to describe more precisely the physical character of the geologic systems so that quantitative methods could be applied to fractured and soluble rocks that included: sequential satellite imagery, air photography, air and ground remote sensing (resistivity, sonic, radar), chemical laboratory sophistication (from ppm to ppt) and computer recording, storage, evaluation, and recovery of data, and computer graphic portrayal. With this more detailed knowledge of the geologic system, more meaningful results were obtained from pumping tests on karst aquifers. However, no quantitative study in karst can be accomplished without a thorough study and knowledge of the geology - stratigraphy, structure, depositional environment - because karst systems are so variable and complex it invites disaster to interpret quantitative hydrologic results without a detailed knowledge of the geologic factors that control the recharge storage and discharge from the system.

Culmination of a series of studies: well and spring inventories, test drilling, remote sensing investigation, pumping tests, and chemical analysis of karst waters resulted in the first compilation of "Environmental Atlas for Karst Areas." These atlases of the Geological Survey of Alabama described a karst region in the context of its fragility, and they have become the basis for water-supply development, urban planning, municipal rules and regulations, and to resolve damage litigation.

Environmental Impacts in Karst Areas

Environmental impacts in karst areas were studied, taking advantage of these methods. P.E. LaMoreaux, with the support of V.T. Stringfield; W.J. Powell; and H. Cooper began a multimillion-dollar program of investigation in the Huntsville, Alabama area consisting of specialized studies in a mature karst area - the Tennessee River Valley in north Alabama and specifically of Huntsville, Madison County, Alabama. Over the period from 1960 to 1975, work included extensive test drilling, down-hole geophysical logging, ground remote sensing, the use of satellite imagery and sequential air photography, large-scale pumping tests on wells and springs, using over 100 observation wells, tracer studies, and water-quality analysis; these investigations resulted in a series of traditional ground-water reports, Dodson (1965); Peace (1964); Harris (1965); and Causey (1965); specialized reports on the impact of geologic structure on ground-water occurrence and movement, LaMoreaux and Powell

(1960); results from pumping tests on a limestone aquifer of Mississippian Age, Malmberg (1957); air photography and satellite imagery, Powell (1970); a series of corollary reports by Newton (1971 and 1976); Harris (1963); Stringfield (1974 and 1977); LaMoreaux (1970 and 1975); Joiner (1969); Sonderegger (1970). The investigation also provided the first series of environmental atlases describing the fragile character of karst terranes. These were published 10 years before the environmental movement in the USA and have been repeatedly used for the rapid expansion of the space-age city of Huntsville. They provided guidance for the location and development of wells, pumpage from springs, protection of ground-water supplies, identification of possible areas of subsidence, construction of all types, a basis for city ordinances and planning, and for decisions involving litigation - LaMoreaux (1971); LeGrand and LaMoreaux (1975); Moser (1972 and 1975); and Moser and Hyde (1974).

Karst Commission - International Association of Hydrogeologists

Attention is again called to Zötl (1980) to illustrate the multidiscipline approaches used to solve the problems of karst areas. Over the past 15 years there has been an amazing diversity of multidisciplined scientific talent that became aware of the complex problems in karst settings over the world. By mid-twentieth century engineers, hydrologists, speleologists, chemists, geologists, biologists, botanists, and mathematicians began to tackle these problems. Karst panels - commissions and institutes, were organized, and there have been at least 150 special meetings and symposia held, more than 30 book-length publications written, and thousands of technical articles published. The "Annotated Bibliography of Carbonate Rocks" was one attempt to keep current on what was being done in karst areas. Note should be taken that outstanding research is being carried out in the following specialized areas of interest; and that anyone of these areas could provide critical information through a bibliographic search by special subjects as follow:

Tracing techniques
Isotope studies
Geomorphology
Geochemistry
Speleology
Sedimentation and depositional environments for carbonate rocks.

Special Karst Organizations and Activities

Constructive and thorough discussions on karst are carried out by a broad spectrum of interested multidisciplined scientists and researchers. Various regional symposia and colloquia have been organized worldwide over the past 20 years by IAH, IASH, FAO, and UNESCO within the International Hydrologic Decade (IHD) and International Hydrologic Programme (IHP), and by university groups. The IHD included a Commission for the study of carbonate rocks in Mediterranean countries, and since 1970 a permanent Commission for karst hydrogeology exists within IAH. The International Association of Hydrogeologists (IAH) is a scientific and educational non-profit international organization established to exchange hydrogeologic information and to advance the science. IAH, which promotes cooperation between scientists who are working on hydrogeologic problems, is affiliated with the International Union of Geological Sciences (IUGS). The Karst Commission is one of the most active, productive divisions of IAH.

Annotated Bibliography of Karst

During a meeting of the Karst Commission of the IAH in Cambridge, England, on September 8, 1985, the Association voted to issue a third volume of the Annotated Bibliography in the Spring of 1896, and additional volumes of the bibliography every other year. This bulletin represents the second of this new series of IAH bulletins on karst terranes. The first and second karst bibliographies, Bulletins 94-A and 94-E, were published by the Alabama Geological Survey under the direction of Philip E. LaMoreaux, who was at that time State Geologist of Alabama. Volumes 3, 4, and 5 were published through the Karst Commission of IAH as Volume 3 (1986), Volume 4 (1989), and Volume 5 (in preparation).

Karst Symposia/Congresses

The Karst Commission of IAH is comprised of scientists from many different research agencies around the world. During the past 20 years, under the auspices of the Work Group on the Hydrology of Carbonate Terranes of the International Decade, and the Working Group on the Hydrology of Limestone Rocks in the Mediterranean Basin of the FAO/IHD, much emphasis has been placed on the study of carbonate rocks. In addition to individual project activities, there have been over 50 field conferences, formal meetings, and congresses, at which results of research on the hydrology of carbonate rocks have been discussed indicating the interest in this subject since the last bibliography was published in 1975. A select list of these follows:

Future Activities

The following select list are recommendations for future work:

1. Refine quantitative methods to provide quantities and quality of water available, depth of cone of depression and area of influence.
2. Predict impact - subsidence and area and types of environmental impact.
3. Refine quantitative - modelling capability to identify areal extent and characterize movement of pollutants in a karst setting.
4. Provide a better understanding of the dynamic nature of karst under different geologic, hydrologic, and climatologic conditions.
5. Analyze karst evolution in response to man's activities, i.e., acid rain, deforestation, large-scale water development from springs and wells to determine long-term stocartic events and problems to provide a guide to future generations on how to develop resources in a karst area, for example, Guilin area of China.
6. More detailed studies of long-term climatic trends, tree-ring growth, coral evolution, chemical trends in atmosphere from ice-core analysis, etc. and relate to base level changes in oceans and effects on karstification of limestones and dolomites, particularly in coastal zones (Florida, Yucatan, Adriatic) and determine impact on permeability, movement, quantity, and quality of ground water.
7. Develop new techniques for modelling ground-water flow paths, flood and storm-water management.
8. Develop more adequate methods for evaluating waste landfills, hazardous, toxic, radioactive, and monitoring same.
9. Define water management needs for land-use planning, zoning regulations, identify risk assessment needs, and describe insurance programs applicable to karst areas.
10. Extend research and capability in use of geophysical methods in karst areas. Improve acceptance and reliability and define most effective use, seismic, resistivity,

radar equipment and methods.

11. Extend further the use and applicability of isotopic hydrology to karst areas.

12. Continue to improve the more definitive knowledge of the geologic stratigraphy and structure of carbonate rocks (geologic mapping, test drilling, geophysical logging, remote sensing, etc.) to identify in more detail the relationship of bedding, fracture systems, folding and dissolutioning processes, provide these parameters to support more precise interpretation of quantitative results.

13. Use a multidiscipline approach to solution and problems in karst areas. Encourage integration of results from other disciplines working on karst problems: ecologists, biologists, speleologists, environmentalists, problems such as: 1-2-3 in objective of this symposium in Italy, September 15-28, 1991.

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INTERNATIONAL CO-OPERATION IN RESEARCH ON KARST ENVIRONMENTS

Brian FINLAYSON* & Ugo SAURO°
* Department of Geography of the University of Melbourne (Australia)
° Department of Geography of the University of Padova (Italy)

ABSTRACT

G.K.W.: environmental changes, Karst research, conservation of Karst

This paper provides an overview of international organisations who have substantive interests in the field of Karst research. Details are provided of the current activities of the IGU Study Group "Environmental Changes in Karst Areas". The role of IGCP Project 299 "Geology, Climate, Hydrology and Karst Formation" is reviewed in relation to the present needs for international research and action in this field. Proposals are made for future international cooperation in Karst research, specifically with reference to the establishment of an integrated monitoring network along the lines of the IGBP "geosphere-biosphere observatories" and to the establishment of a UNESCO convention for the protection of significant Karst sites.

INTRODUCTION

International co-operation has long been a feature of both Karst research and caving in general. In this paper we briefly outline the international groups which presently exist in the field Karst research and deal with the problems of coordination between different commissions, working groups and projects. The future trends of Karst research will continue, as in the past, to be determined by individual workers or research groups aided, of course, by the existence of international forums for the communication of research ideas and results. The priorities now for international groups should be the fostering of lines of communication through workshops, conferences and study groups; facilitating the international exchange of data through the establishment of computer databases in agreed common formats; establishing an international inventory of Karst resources which could serve as the basis of a scheme for listing of threatened, rare or fragile Karst areas; and the establishment of an international scheme for such listing, probably through the auspices of UNESCO. This aspect will be discussed by the authors in more detail elsewhere.

An important opportunity for cooperation between the major international organisations with interests in Karst (see Table 1) is now given by projects such as the new International Geological Correlation Program (IGCP) Project 299 "Geology, Climate, Hydrology and Karst Formation" approved by the IGCP Board in 1990, and the International Geosphere-Biosphere Programme (IGBP) "A Study of Global Change". With reference to the Study of Global Change, Karst research now has the

opportunity to demonstrate that Karst sediments, speleothems and landforms may give fundamental data for the reconstruction of the evolution of terrestrial geoecosystems in recent geological time. It is also appropriate to consider the establishment of a permanent monitoring network of a large number of Karst environments and waters. This could be done co-operatively through the development of an "interdisciplinary integrated observatory network" as suggested in the IGCP project. These and other issues are elaborated below.

INTERNATIONAL ORGANISATIONS

The main international organisations either wholly devoted to Karst activities or which have an important component of Karst activities are listed in Table 1. This list is not meant to be exhaustive but to give an overview of the international scene. In addition there are many regional, national and local organizations such as the national speleological societies and many specialized institutes in different countries.

Table 1 Major international organisations with interests in Karst research.

Union Internationale de Spéléologie (UIS):
Five internal departments with commissions and groups:
A) Protection and Management
- Commission for protection, exploitation and tourism
- Commission for cave management

B) Research
- Commission for physics-chemistry and hydrology of Karst
- Commission for palaeokarst and speleochronology
- Commission for speleotherapy
- Working group on Karst and glaciers
- Working group on artificial caves
- Working group on hydrothermal Karst
- Working group on volcanic caves

C) Documentation
- Commission for bibliography
- Commission for large caves
- Commission for the atlas of Karst regions
- Commission for information
- Commission for the history of speleology

D) Exploration
- Commission for cave rescue
- Commission on materials and techniques
- Commission for cave diving

E) Education
- Commission for speleological education
- Working group on speleological education in schools

International Geographical Union (IGU):
Study group on environmental changes in Karst areas (S.88.6)
includes some national working groups (Japanese, Cuban, Polish, Czechoslovakian,...)

International Association of Hydrogeologists (IAH):
Karst Commission

International Geological Correlation Programme (IGCP): Co-sponsored by the International Union of Geological Sciences (IUGS) and UNESCO
Project 299: Geology, climate, hydrology and Karst formation.
Project 287: Correlation of Mesozoic/Tertiary bauxites and related paleokarst phenomena in the Tethyan realm

International Association of Geomorphologists (IAG)
At the second international conference held in Frankfurt in September 1989 a special symposium and excursion was held on Karst planation in tropical and middle latitude environments.

THE IGU STUDY GROUP: 'ENVIRONMENTAL CHANGES IN KARST AREAS'

This study group was established at the Sydney meeting of the IGU in 1988; It is based on an appreciation of the uniqueness of Karst ecosystems and of the fact that in many areas of the World this fact is not recognised and taken account of in their management. The objectives of the study group are: to enhance the study of environmental changes in Karst areas throughout the World; to analyse the human impact within the framework of natural Karst ecosystems; to elaborate the best techniques for monitoring the changes and collating the data; to classify Karst areas for their susceptibility to human impact at local, national and global scales. The group is currently preparing a publication on environmental changes in Karst terrains with the title: Environmental Changes and Human impacts in Karst Terrains", edited by the Paul Williams, which will be published as a Catena Supplement, hopefully in time for the Washington Congress of the IGU. A provisional list of chapters has been agreed and these are listed below together with the names of the authors:

Part A - A Background to Environmental Changes in Karst Terrains
1. Environmental Degradation and Rocky "Desertification" of Karstlands: an Introductory Review (Williams)
2. The Global Occurrence of Karst and its Relation to Population Distribution (Pfeffer)
3. Natural Environmental Change in Karst: the Quaternary Record (Lauritzen)
Part B - Human impacts on Karsts around the World
4. Environmental Change and Human Impact on Karsts in the Mediterranean Basin (Gams, Nicod, Sauro)
5. Environmental Change and Human Impact on Karst in Southern China (Yuan)
6. Environmental Change and Human Impact on Karst in Northern China (Song, Zhang)
7. Human Impact on Carribean and Central American Karst (Day)
8. Environmental Change and Human Impact on Raised Coral Reefs (Hori, Kawano, Miura)

9. Environmental Change and Human Impact on Karst in the United States (Beck, White)

10. Environmental Change and Human Impact on Karst in Western Ucraine, USSR (Andraithchuk, Klimchouk)

11. Environmental Change and Human Impact on Karst in Continental Europe (Pulina,Panos)

12. Human Impact on Karst in British Isles (Goldie)

13. Environmental Change and Human Impact on Karst in sub-Saharan Africa (Brook)

14. Environmental Change and Human Impact on Karst in Arid and Semi-arid Australia (Gillieson)

Part C - General issues of Human Impact on Karst Terrains: Principles and Case Studies

15. Impact of acid rain on Karst Environments (Inkpen, Trudgill)

16. The Nature of Karst Aquifers and their Susceptibility to Pollution (Smith)

17. Impact of Quarrying on Karst Resources (Gunn)

18. Impact of Tourism on Karst Resources (Huppert, Burri)

19. Human Impacts on Karst Soils Japanese and Other Examples (Urushibara-Yoshino)

20. Impact of Agricolture on Limestone Caves (Hardwick, Gunn)

21. Environmental Change and Human Impact on Karst in Areas with Sporadic or Continuous Permafrost (Ford)

22. Environmental Change and Human Impact in High Mountain Karsts (Kunaver)

23. Environmental Impacts of Karst Hydro-electric Developments (Lauritzen)

In addition, Prof. Gams (Jugoslavia) has proposed a project entitled "The Global Karst Environment and Its Fragility" which would aim to classify Karst areas on the basis of their fragility and susceptibility to human impact and which would include thematic mapping. This project has been discussed by the group and while it is very important it would be difficult to develop in the lifetime of the Study Group. The Study Group could consider the methodology for such a program and perhaps prepare special manuals as discussed below.

A proposal from Kevin Kiernan (Australia) to promote a volume on «Karst Heritage Conservation» has been accepted by the group and it is hoped that this will contain proposals and examples for an international register of heritage areas in Karst. The Editors of this volume could be George Huppert and Brian Finlayson (This topic is raised again later in this paper.). All interested persons are encouraged to make contact with them.

Jean Nicod and K.H. Pfeffer are planning to coordinate a project on medium and small scale mapping in Karst areas, which could fit with the project of Ivan Gams (see above); Kazuko Urushibara-Yoshino (Japan) is initiating an annotated bibliography on geomorphological and environmental mapping of Karst areas in the World.

A further proposal has come from Michel Bakalowicz (France) for the preparation of special manuals on Karst research methodology. The first manual about chemical analyses of karst waters is now nearing completion by Wieslawa Ewa Krawczyc.

Other basic research manuals could be prepared in the future on topics such as: Karst soils; Karst morphometry; large scale mapping of Karst areas; small scale mapping of Karst areas; cave environments; Karst nomenclature. These manuals should provide the necessary methodology for collecting the most significant environmental data and for the production of maps, files of data for statistical analysis, etc. These ideas are still being developed within the group. All Karstologists available to prepare a manual are requested to write to the Chairman of the Study Group.

In addition to these projects the Study Group has produced some scientific publications as:

- the Proceedings of the International Conference on Anthropogenic Impact and Environmental Changes in Karst, held in Czechoslovakia in 1990 (volume 2 and 3 of Studia Carsologica); also the volume 5 of Studia Carsologica is published with the participation of the Study Group and is dedicated to environmental changes in Karst areas; the 3 volumes contain more than 30 papers about Karst;
- the Proceedings and guidebooks of the International Conference on Environmental Changes in Karst, held in Italy in 1991; which will contain, in their definitive edition, more than 60 papers about Karst.

At the suggestion of Prof. Philip E. LaMoreaux, Chief Editor of the scientific magazine "Environmental Geology", some members of the Study Group are preparing papers for a number devoted to environmental geology of Karst areas.

IGCP PROJECT 299: 'GEOLOGY, CLIMATE, HYDROLOGY AND KARST FORMATION'

The initiative for this project came from the 18th meeting of the Karst Commission of the IAH in Guilin in 1988. Following further discussion at the 19th meeting in Florida in 1989, the project was accepted by the IGCP Board in February 1990. The general objectives of the IGCP is to establish correlations between different natural features needed to understand the patterns, characters and sequence in time of geological environments through to the present time. The first meeting of the international working group of the project was in Antalya, Turkey, in October 1990. The second meeting, with a long field Seminar, took place during July 1991 in China. During the meeting the objectives of the project were discussed.

Concerning the proposal of Professor Yuan Daoxian for a 'Registration Form for a Typical Karst Area' as a basis for the collection of information internationally within this project, the authors have presented some criticism at the Antalya Conference. The main criticism is that the information which this form requires seems inappropriate at the scale of the project. Also, the underlying philosophy of this form, the 'Karst feature complex' is poorly defined but appears to be based on the assumption that there are unique complexes of Karst features associated with particular climates; an unwarranted assumption in this context since the existence of such climate specific complexes is an hypotheses which could be tested by such a data set.

Three suggestions are given below which could form the basis of a revised registration project.

(I) It could lead to the production of a finalized database of all the characteristics useful for geological correlations, such as interrelations between geology and the Karst environment; stratigraphy, sedimentology and geochronology of paleokarst and other types of Karst sediments; landform "stratigraphy"; present denudational rates in relation to climate and geodynamic evolution; and present rate of landform development.

(II) It could be seen as a database which provides the opportunity for large scale (global) comparative work. Comparable work is currently going on in hydrology. The Centre for Environmental Applied Hydrology at the University of Melbourne now has a global database of monthly and annual river discharges which is used for studies in comparative hydrology. There is also the Flow Regimes from Experimental Network Data (FREND) project in western Europe and its broader extension as the Flow Regimes from International Experimental Network Data (FRIEND) project, now UNESCO Project IH 5.5. These hydrological databases have the advantage that the data consist of quantitative information on streamflows that can be analysed by statistical and numerical procedures. It is difficult to see how the essentially descriptive information in the proposed Karst registration could be used in this way. If it were limited to, say, spring discharges and water chemistry it would be more amenable to comparative analyses.

(III) A third possibility is that it could be seen as a Karst cataloguing system. As such it would uniquely identify each Karst area and its general characteristics (location, climate(s), controlling government(s), etc); contain a bibliography of publications on each area; and be associated with local Karst registration systems already in operation such as the Australian Karst Index.

Probably the project which fits better with IGCP is (I), but also (II) and (III) may be promoted, preferably in cooperation with other interested organisations

In the Newsletter IGCP 299 - 1991 Yuan Daoxian has answered defending the idea of a "Karst feature complex" as a good way to establish a base for the collection of data for a correlation between different Karst areas world-wide. In any case he suggests that the form is flexible and that this form may be used tentatively, "at this stage of work, not to establish an overall database of global karst, but rather to call for common attention of the major points of geological, climatic, hydrological, geochemical, biogenic background and results (combination of karst features and environmental impacts) of the karst process, so as to make international correlation on Karst more feasible", for Typical Karst Sites. In the volume is reported also a proposal for "a modified registration form for typical Karst Areas" suggested by David Gillieson, which considers most of the more important quantifiable aspects and parameters of karst relief and environment.

Many National Working Groups and and Thematic Subgroups are now cooperating inside IGCP 299 (see Newsletter 1991). Among the special topics of Subgroups are remarkable the following:

- comparison on Karst hydrogeological basins (Hess, Kovalevsky, Drew, Smart);
- coastal Karst (Back);
- Karst engineering (Milanovic);

- morphometry and controls of Polygonal Karst, Cockpit Karst and Tower Karst (Williams);
- reconstruction of paleoenvironment on the bases of Karst information (Bosak);
- impact of human activities on Karst water (Hoetzl);
- environmental archeology of Karst water with special reference to water management techniques;
- soil formation in karst (Urushibara-Yosino).

PERSPECTIVES ON THE FUTURE OF INTERNATIONAL CO-OPERATION IN KARST RESEARCH:

Future international cooperation in Karst research should be viewed at three levels: scientific collaboration in the establishment of databases and monitoring networks and the exchange of scientific information, including international conferences and meetings; fostering and developing educational activities in Karst areas and on Karst environments; and the more politically oriented activities designed to conserve and protect Karst resources and establish a system of international compliance with agreed standards. A better understanding of interactions within Karst systems both in natural conditions and in different human impact situations should be one of the main aims of Karst research.

SCIENTIFIC COLLABORATION

An important aspect of scientific collaboration is the provision of international forums for the exchange of ideas and information; a role partly filled by the international journals but also importantly by meetings and conferences. Face to face contact provides for communication of a type and quality which cannot be achieved by the written word. In Table 2 we list planned international meetings in the near future. This list is not exhaustive but even so it illustrates a growing problem for international collaboration; that of too many international meetings. Too many meetings could be as detrimental to international communication and co-operation as too few. Few people in full time employment as scientists, academics, environmental managers etc. can afford either the time or expense of attending so many meetings. It would be preferable if the various groups responsible for organising international meetings on Karst research were to coordinate their activities and perhaps run joint meetings to improve the level of cross-disciplinary interaction. During the last meeting of the Study Group in Italy on this problem the following resolution has been approved:

"Karst research requires an understanding of many disciplines including geomorphology, hydrogeology, speleology and chemistry. At present the efforts of physical Scientists with interests in these areas are dispersed over four international groups: IAH, IGCP, IGU, UIS

Many karst researchers are members of more than one group and some are members of all four. Each group holds regular international meetings but few people can attend more than one each year. As a result there is never a time when all karst scientists can meet together and share ideas. We propose that the leaders of the four groups should meet together and work towards closer cooperation. Such a coordinating meeting may be possible at the 3rd International Geomorphology Conference in Hamilton, Canada, which will be attended by members of all groups.

Table 2 Some planned and/or probable international Karst research meetings in the near future.

Title/Subject of Meeting	Location/Year	Organising Group
European Conference	Hélécine, Belgique; 1992	ISU
Karst Environmental Problems of the Appalachians	Washington DC, USA; 1992	IGU
Int. Conf. «Alpine caves: alpine karst systems and their environmental context»	Italy; 1992	SSI
Int. Symp. «Engineering Geology of Karst»	Perm, USSR; 1992	GSP
North American Correlation Seminar and Field Excursions	Washington DC, USA; 1992	IGCP Project 299
Int. Symp. «Karst and Climatic Evolution»	Bordeaux, France; 1992	A.F.K.
11th International Congress	China; 1993	ISU
International Meeting	China or Canada; 1993	IGU Karst Com. (?)
Third Int. Conf. on Geomorphology	Hamilton, Canada; 1993	IAG
General and Applied Karst Hydrogeology	Belgrade (Yu); 1993	IHA
International Meeting	Poland or Austria; 1994	IGU Karst Com.(?)
Int. Joint Meeting «Environmental Changes in Permafrost Karst»	Yakutsk, USSR (??); 1995	IGU Karst Com. and Frost Action Com. ?
International Congress	To be decided; 1996	IGU

We also propose a joint meeting of all groups in 1995 or 1996. This should be the only meeting of each group that year and should have lectures from invited speakers representing each group. A possible location which should be of interest to all groups would be the Moulis-Montpellier area in the South of France" (written by J.Gunn).

International communication between research groups working in different countries and in different languages will be facilitated by the preparation and dissemination of manuals of practice for the study of various aspects of Karst systems so as to achieve standardisation in terminology and in the reporting of results. It is now possible to exchange data directly by computer and to this end a uniform set of formats for the storage and retrieval of information would allow more efficient use of the available technology. International programmes, such as Karst spring water analysis using agreed standard methods and units for reporting and the establishment of a database of spring water quality parameters should be developed based on these standard methods.

The IGU Study Group is currently considering the establishment of an international list of scientists working on Karst. If such a list were to be compiled on one of the widely used desk-top computer database systems (such as Hypercard on the Macintosh) it could be widely disseminated and used for the mailing of conference information etc. A first partial inventory of scientists working on karst has been produced and some results of the analyses of the data collected are presented in the next paper in the Proceedings of this Conference.

INTERNATIONAL MONITORING AND MANAGEMENT

International programmes are already in existence for the listing and protection of sensitive areas. UNESCO have for some time been operating a system of World heritage listing. This programme covers all types of environments, both natural and artificial, and may not be providing the protection necessary for specific types of sites. This has already been recognised as it applies to wetlands with the establishment, also under the auspices of UNESCO, of the RAMSAR convention. The main purposes of this convention are the conservation of selected wetlands and to promote education in the understanding of the relation between man and his environment. One other more recent project is the WILD Campaign promoted by the Western Canada Wilderness Committee, which is a global project to inventory the World's remaining natural areas, to protect biodiversity and to promote ecologically sustainable land use.

Sensitive Karst areas will be better protected if a similar system is established for Karst areas of global importance. Karst environments offer ideal conditions to promote interdisciplinary research and to introduce young people to the environmental problems of the conservation of natural resources and interrelations between atmosphere, vegetation, landsurface, soil, subterranean waters and cavities. While Karst areas can now be nominated in the present world heritage listing they have to compete for attention with a wide variety of different types of sites.

The establishment of a UNESCO convention for the protection of Karst areas (International Register of Karst Geoecosystems - IRKG) would require that the necessary data be collected to demonstrate to bureaucrats with no specific understanding of Karst areas that such a protection scheme is necessary. One of the more important aims for the future is the collection and preparation of such data. Scientists in the field of Karst studies would also need to be active in setting up monitoring networks for sensitive Karst areas and in the international co-ordination of such monitoring. In this context it is useful to consider the proposals being made through the IGBP for "geosphere-biosphere observatories" and "data management and information systems". Large Karst springs reflect environmental changes through quantity and regime of flow and water quality and could be important elements in a geosphere-biosphere monitoring programme. Other significant sites in this programme could be large caves and surface Karst depressions. Strategies for the better conservation and planning of Karst resources will need to be developed if this international monitoring is to be successful.

These aims, especially as they apply to setting up international monitoring programmes, will be more easily achieved if the various international Karst groups mentioned in Table 1 act in concert. A registration project could be developed so as to be an inventory of Karst resources which could be used as the basis for protecting endangered Karst areas and features. This could be developed as a co-operative project between the major international organisations working in this field, UIS, IGU, IAH, IGCP and IAG. In this way it will be easierto lobby UNESCO to set up an IRKG Convention for Karst areas. The philosophy and framework of such a registration system will be discussed elsewhere by the Authors.