

A BRIEF HISTORY OF KARST HYDROGEOLOGY: CONTRIBUTIONS OF THE NSS

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Abstract: The hydrology of karst aquifers has been of interest since early historic times with caves serving as water-carrying pathways. The modern period of karst hydrology can be said to have begun roughly in the 1960s with the work of the International Hydrologic Decade and with the recognition of the relationship of cave exploration to groundwater basins. A theme for the 40 year period between the 25th anniversary of the NSS and the present is the gradual melding of traditional hydrogeology, which does not work well in karst, and the contributions of cave explorers who have provided tremendous detail about the conduit systems in aquifers. Important progress has been made in techniques for water tracing in karst areas and in systematic mapping of karst groundwater basins. Qualitative studies have largely been replaced by quantitative measurements of spring flow and water chemistry. The current research front deals with the construction of flow models for karst aquifers.

INTRODUCTION

The most direct interface between cave exploration and the earth sciences is the hydrology of karst aquifers. No wonder. Here goes a survey team of cavers, splashing through a base level water cave up to their belly buttons (or chins) in the karst water table. How much more intimate a connection can there be? Cavers have a deep understanding of the movement of groundwater in carbonate rocks, but it took some time to convince the professional community that they were worth listening to.

The purpose of this article is to trace the gradual evolution of understanding of karst aquifers by the professional community and the role that cavers have played over the past 40 years. Cavers with their detailed maps and their deep understanding of the layout of conduit systems can take credit for a substantial portion of the modern view of karst hydrology. The article does not claim to be a comprehensive review of karst hydrogeology as a whole. For more traditional and extensive reviews see White (1993, 1998, 2002, 2006).

SOME HISTORICAL PERSPECTIVE

Although the primary focus of this article is karst hydrology as it has evolved during the past 40 years, it is of interest to look much farther back to see how caves have figured in the precursor history. Summaries of these pre-scientific roots of hydrology may be found in Adams (1954) and LaMoreaux and Tanner (2001).

ANCIENT HISTORY

Because some of the earliest writings on the natural world come from Greece, a country that is largely karst, it is not surprising that springs and caves were strongly linked. Early Greek writers such as Plato and Aristotle

incorporated caves as channel ways carrying water from the sea up into the mountains from which it emerged from springs to form rivers. Springs were of great importance as water sources in the ancient world and many were karst springs, fed by obvious cave passages. The ancient writers were also aware of a version of the hydrologic cycle, perhaps best said in Ecclesiastes (Chapter 1, verse 7). “All the rivers run into the sea; yet the sea is not full; unto the place from whence the rivers come, thither they return again.” It was not, however, our contemporary hydrologic cycle in which water evaporates from the sea, drifts over land, and falls as rain. The means by which “thither they return again” were thought to be caves.

After the long hiatus of the Dark Ages, one of the most elaborate models for cavernous flow of groundwater was proposed by Athanasius Kircher in his *Mundus Subterraneus* in 1664. Kircher proposed that water from the sea moved through an elaborate system of conduits to discharge into large cavernous chambers in the hearts of mountains from which it emerged as springs at the heads of rivers. Kircher also postulated subterranean fires and when the feeder conduits passed near the fires, the water emerged as hot springs. Springs and underground rivers acquired a large literature prior to the extensive work that appeared in the late 1800s and early 1900s. See Shaw (1992), especially Chapters 13 and 14.

THE EARLY EUROPEAN VIEWS OF KARST AQUIFERS

Two developments took place in Europe in the latter years of the 19th Century. One was the beginning of systematic cave exploration especially by Schmidl in Austria and Martel in France. The second was the emergence of geomorphology as a science. Geomorphology had two fathers – William Morris Davis in the United States and Albrecht Penck in Vienna, Austria. These two towering intellects laid the foundations of geomorphology

and both had at least a passing interest in karst. They even participated in a joint excursion through the Adriatic karst in 1899 (Davis, 1901). Penck's influence on karst research was amplified by his student Jovan Cvijić with his 1893 *Das Karstphänomen*, although a sequence of circumstances greatly delayed final publication of his ideas (Cvijić, 1960). Another Penck disciple, Alfred Grund, was the primary contributor to one of the main European views of karst hydrology. Davis' influence on karst research remained minor until his classic interpretation of cave origins published many years later (Davis, 1930).

European thought on the behavior of water in karst aquifers divided into two distinct schools (Roglić, 1972). The karst groundwater school, championed by Grund (1903), was that sinking streams drained down into a central body of groundwater. The groundwater body had a water table that rose continuously from the sea into the hinterlands and was essentially stagnant. Underground streams were peripheral to the main water body. The opposing view was that water drained through the karst as independent rivers, flowing at different levels, and eventually draining through springs with no common groundwater. In many ways these were an essentially phreatic concept and an essentially vadose concept. The independent underground river concept was supported by those with the greatest experience with cave exploration and the observed behavior of cave rivers (von Knebel, 1906; Katzer, 1909; Martel, 1910). As is frequently the case in geological debates, both sides were partially correct. Later stream tracing results showed that many alpine karst regions with rushing underground rivers also contained a deeper and more slowly moving groundwater body (Zötl, 1961).

EARLY VIEWS OF KARST AQUIFERS IN THE UNITED STATES

Discussion of caves in the United States often begins with the Davis (1930) cave-origin paper. But, in fact, studies of water resources were well underway in the United States early in the 20th Century and many of these studies were of karst areas. There was Greene (1908) on southern Indiana, Matson (1909) on the Kentucky Blue Grass, Weller (1927) on the Mammoth Cave area, and Piper (1932) on the Cumberland Plateau of Tennessee. All of these reports recognized the role of joints and bedding-plane partings as permeability in otherwise impermeable massive limestones. All recognized the interrelationships of sinking streams, cave streams, and springs. In general, these papers presented a reasonable qualitative picture of the movement of groundwater in karst aquifers.

The hydrology of limestone terranes was recognized as a distinct subdivision of the rapidly growing science of groundwater hydrology (or hydrogeology) in Oscar Meinzer's classic book (Meinzer, 1942; Swinnerton, 1942). However, the Davis monograph recast the framework from one of sinking streams, caves, and springs to one in which

caves were remnant features formed beneath old peneplains and only fortuitously re-excavated and used by contemporary drainage. Debate shifted to the vadose/phreatic mechanism for cave origin and there were fewer investigations from a hydrological perspective.

THE TRANSITIONAL PERIOD 1942–1966

J Harlan Bretz's (1942) monograph marked the end of the early period for both karst hydrology and cave-origin theory. The succeeding several decades, which, curiously, extend up to the appearance of the 25th anniversary volume of the National Speleological Society Bulletin, were a period of transition. Davies' (1966) own review of the earth sciences and speleology has little to say about karst hydrology. But, in fact, the dry period from 1942 to 1957 had ended and the modern period of karst research in general and karst hydrology in particular was well underway.

One of the transitional markers was Davies' (1960) demonstration that caves are graded to present or past local base levels. Other than its implications for the theory of cave origin, this paper returned caves to their proper role in the hydrology of contemporary karst-drainage basins. In Europe, karst hydrology was high on the list of priorities for the International Hydrologic Decade, 1964–1974. Research shifted from qualitative descriptions of cave systems and karst aquifers to quantitative measurements on aquifer properties and groundwater movement (IASH, 1965). The change in approach was nicely described in Burdon and Papakis' (1963) *Handbook of Karst Hydrology*. Unfortunately, this exceedingly important document appeared only as a manual for a UN training course and never appeared as a more formal publication. As a contribution to the IHD, Stringfield and LeGrand (1969) prepared a comprehensive review of karst hydrology mainly in the United States.

It was at the beginning of the transitional period that the NSS and systematic cave exploration and survey got underway. By the end of the period, systematic cave data had been published for several states including California (Halliday, 1962), Illinois (Bretz and Harris, 1961), Indiana (Powell, 1961), Maryland (Davies, 1950), Missouri (Bretz, 1956), Pennsylvania (Stone, 1953), Tennessee (Barr, 1961), Texas (P.J. White, 1948), Virginia (Douglas, 1964), and West Virginia (Davies, 1949). Conditions were in place for a melding of the groundwater hydrologist's approach to karst aquifers and the caver's approach to karst aquifers. What has happened in the succeeding 40 years is the topic for the remainder of this review.

CAVE EXPLORATION AND SURVEY: A NEW PERSPECTIVE

Cave exploration in the old days was a straightforward business. Cavers went to areas where there were known caves, talked to farmers, hunters, and the good-old-boys hanging out at the general store, and with some luck were

instructed as to where they could find new caves. Having hiked across the fields following “over yonder in that clump of trees,” they would sometimes be rewarded with a nice new entrance yawning at the head of a wooded ravine. Exploration was a matter of poking through all of the accessible passages. Some would end in breakdown. Some were choked with sediments and some by flowstone. Regardless, all caves were thought of as ending. Some caves descended to flowing streams and some did not. Some caves were entered at spring mouths or at stream sinks. Others were entered high on the hillsides. Regardless, all caves were tallied separately. Cave catalogs and cave data bases listed as separate caves those that were clearly fragments of a once continuous master cave. Likewise, every passage that could be accessed through the same entrance was considered to be part of the same cave. A large cave might contain high level passages dating far back into the Pleistocene and also base level stream passages that are part of the contemporary drainage system. No matter, it was considered to be a single cave.

Sometime in the 1960s came the gradual recognition that caves in general do not end. Cave passages are fragments of conduits that once carried water from some recharge area, possibly a sinking stream, to an outlet at a spring. These once continuous conduits are broken up by processes of collapse, truncation by surface valleys, and by sediment in-filling. This gradual realization was not a documented discovery although Brucker (1966) formalized it as a way of splicing together the passage fragments that make up what was then the Flint Ridge Cave System. With this understanding, it became possible to consider individual caves as simply puzzle pieces of a larger master drainage system.

With the insight of continuous conduits, cave explorers could search for the missing pieces, either by digging, moving breakdown, sump diving within the cave or by excavating new entrances from the surface. Sometimes a long and persistent effort paid off with a map of an entire drainage basin. Over the past 40 years, a considerable number of examples have been documented. One example is the Mystery Cave – Rimstone River Cave complex in Perry County, Missouri (Fig. 1). Extensive exploration and survey have produced a detailed map of 40 km of mainly two south-north master stream passages along with many more kilometers of disconnected cave fragments (Walsh, 1988, 1989). Those who think such data are easy to obtain are advised to read Walsh’s (2002) account of the actual history of the exploration and survey.

CAVE MAPS AND MAPPING

Perhaps the caver’s greatest contribution to karst hydrology is their current “map as you go” philosophy. From the earliest days, cavers have prepared cave maps. The reason is simple. On the land surface, a view from a high ridge or an over flight in a small plane gives an excellent perspective of the landscape. However, one

cannot see a cave. A caver can see only a small section of passage at any one time. Without mapping, cavers must depend on memory and have no way to accurately display the layout of the cave or to share their discoveries with others.

An accurate traverse line is important but so also is an accurate sketch. For geological or hydrological interpretation of cave maps, it is the accuracy of the sketching that is most useful. One of the early pioneers in precise renditions of cave passages was the late Bernard Smeltzer in Pennsylvania. One of the finest examples, drawn in 1951, is the Fleming Caves in Huntingdon County (Fig. 2). There is accurate floor detail, the walls are sketched with an artist’s eye, and the cross sections show the relation of the cave to the structure of the bedrock. Other pioneers were Paul Johnson, Tex Yocum, Lang Brod, and their colleagues in the Missouri Cave Survey, whose outstanding maps began appearing in the early issues of *Missouri Speleology* in the late 1950s and early 1960s.

There have been great strides in the processing and display of cave survey data. Computer programs are available for compiling, plotting, and adjusting closure errors. Maps can be displayed electronically so that they can be expanded, contracted and rotated. Maps stored electronically can have embedded photographs or additional passage detail. Behind the computational magic, however, the primary data source remains the compass and tape measurements and the notebook sketches of the cavers patiently slogging their way through the cave, station by station. From the point of view of the hydrogeological use of cave maps, current concerns with cave conservation have an unfortunate side effect. Most of the early cave data bases, such as those referenced above, were public documents, many even public domain documents. As population has increased over the past 40 years, access to caves has become more limited at the same time that sport caving has become more popular. Cave maps and cave data bases have become proprietary information, often highly restricted. Hydrogeologic investigations that require access to extensive quantities of cave survey data also require investigators to establish confidence and good working relations with the caving community.

CAVE DIVING

The active conduit-drainage systems can often be accessed either from cave entrances at stream sinks or from cave entrances at spring mouths. Unfortunately, these accessed caves often terminate at sumps. As equipment and techniques for SCUBA diving have improved, many of these sumps have been penetrated to the great improvement of our understanding of conduit systems.

Ford and Ewers (1978) laid to rest the vadose/phreatic debate of the 1930s by showing that caves could form in any relation to the water table depending on the local geologic setting. One of the most common geologic settings was a bedding and fracture guided conduit that would, at

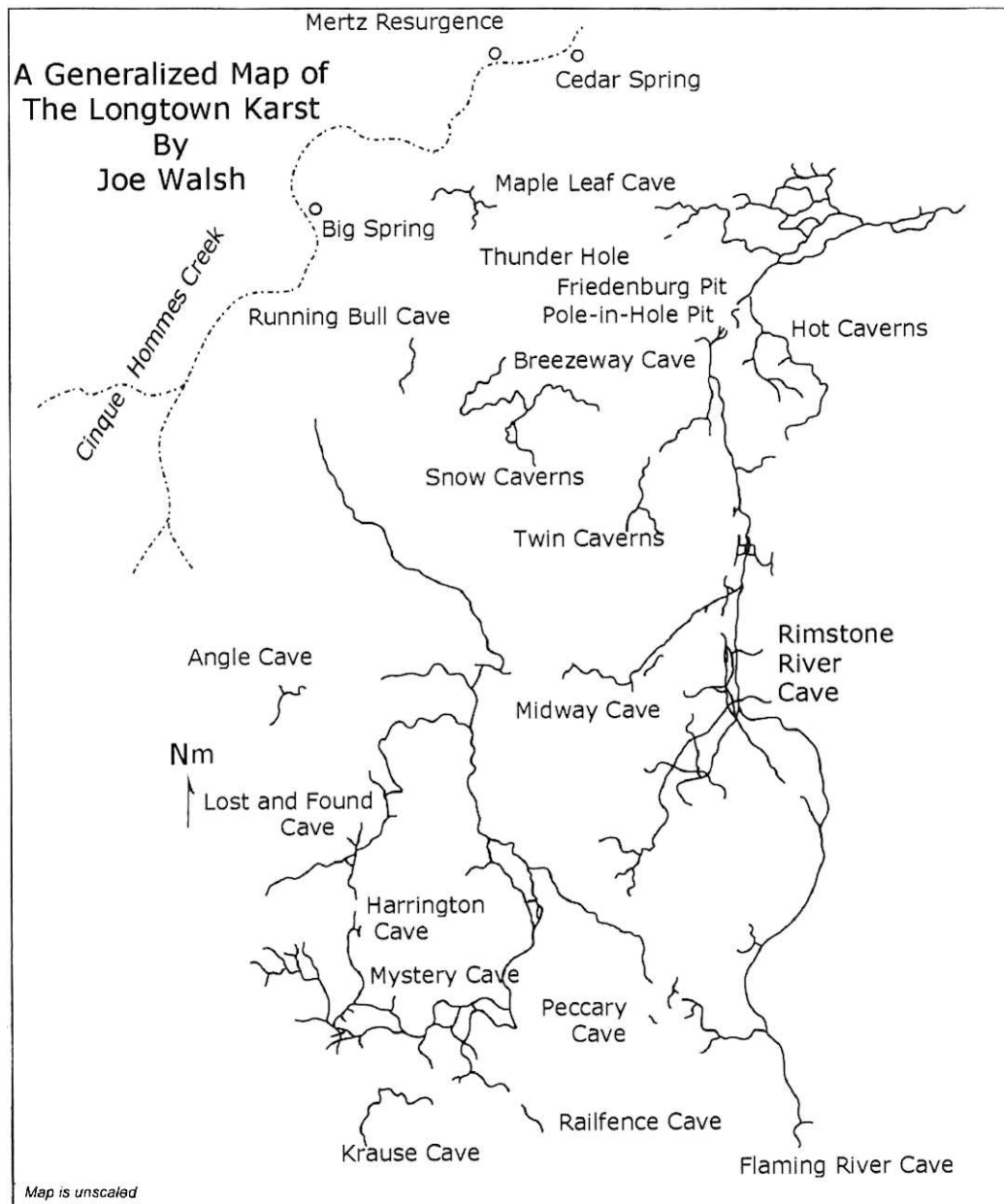


Figure 1. Stick map of Mystery Cave, Rimstone River Cave, and associated smaller caves in Perry County, Missouri. These collections of caves represent two master drainage lines carrying water north to Cinque Hommes Creek. From Walsh (2002).

base flow, consist of a sequence of air-filled, open-channel-flow cave segments interspersed with flooded, pipe-flow segments. Any segment that happened to have an entrance would appear as a stream cave sumped both upstream and downstream. A number of such conduits have been explored by divers and indeed, sumps are often relatively shallow, relatively short, and link segments of air-filled stream cave. Diving also shows the existence of deep conduits well below present day base levels.

An example of the value of diving as part of a hydrogeological investigation is Tytoona Cave, Blair County, Pennsylvania, now an NSS Cave Nature Preserve

(Fig. 3). The entrance to Tytoona Cave, in a karst window, gives access to about 300 meters of open streamway. At the end is a sump, followed by a chamber, a second sump, a small chamber, a third sump, and finally, a long streamway ending in a fourth sump. From the resurgence end, at Arch Spring, there is immediately a deep sump, then a streamway ending in a deep sump which is likely the downstream end of the 4th sump in Tytoona Cave. The diver's sketch map here reveals both the undulating pipe/open channel flow system and also the presence of a deep system into which the present day drainage has collapsed.

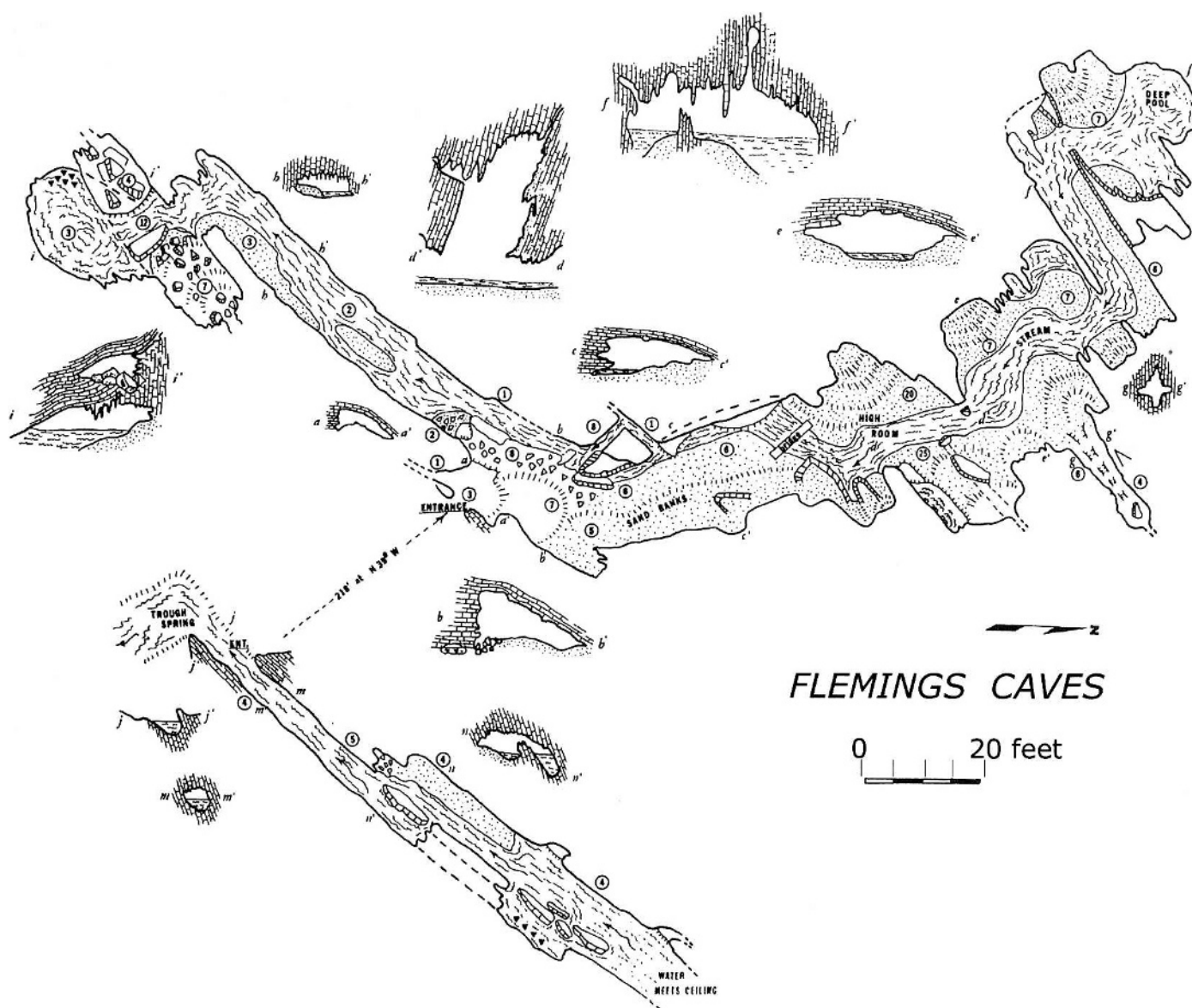


Figure 2. Map of Fleming Caves, Huntingdon County, Pennsylvania. A Bernard Smeltzer map illustrating the early presentation of geologic detail. Map from the files of the Pennsylvania Cave Survey.

TRACER TECHNOLOGY

The routes of underground streams from their surface sources to their emergence in springs have been traced by a variety of methods since the 19th Century. The original method was to add large quantities of dye, often tens or hundreds of kilograms, at the sink point and wait for colored water to appear at the spring. In addition to the necessity of having observers stationed at all possible rise points, springs and streams were often turned green or red to the great consternation of local citizens and the authorities. Although other tracers such as spores and salt brines are occasionally used, fluorescent dyes have remained the tracer of choice, although with many modern improvements.

The first major innovation was the invention of the charcoal dye receptor by J.R. Dunn (1957). Dunn discovered that activated coconut charcoal would effectively sorb dye from water and more importantly, would not release the dye as more water flushed over it. This meant that inexpensive charcoal packets could be placed in all suspected resurgence points and collected at the investigator's convenience. The dye could be elutriated with an alcoholic solution of strong alkali and its presence determined by the color or by the fluorescence of the elutriate. Charcoal packets eliminated the need for continuous observation. The charcoal also accumulated dye as the pulse passed by, thus allowing smaller charges of dye to be used so that visual coloring of the resurgence is unnecessary.

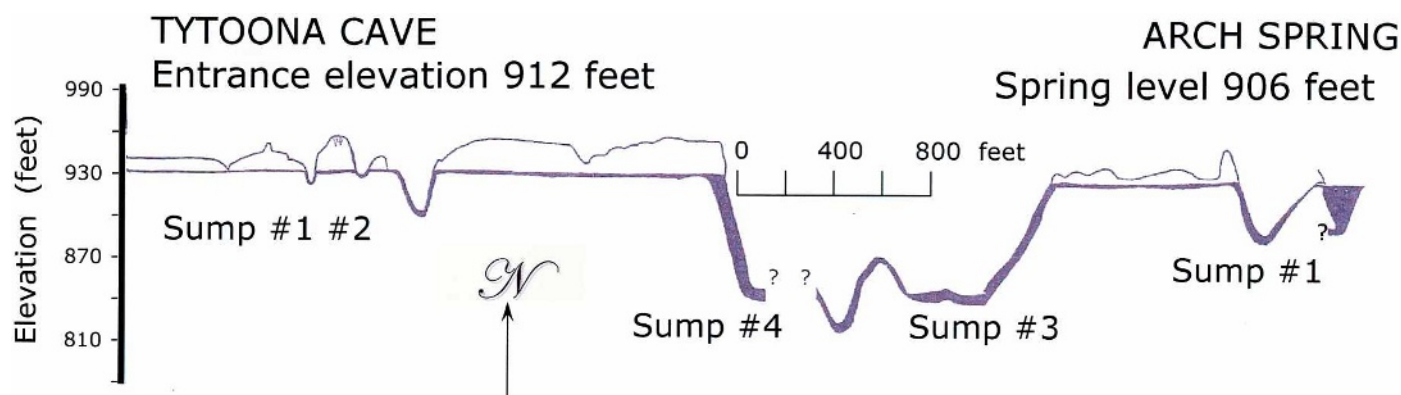


Figure 3. Profile of Tytoona Cave – Arch Spring, Blair County, Pennsylvania. Constructed from sketches by John Schweyen and other divers. Entrance and spring elevations by altimeter measurement.

The second major innovation was the use of quantitative fluorescence spectroscopy to identify dyes and determine dye concentrations. A great variety of dyes have been used for water tracing although only a few are routinely used (Table 1). Each has a characteristic fluorescence peak wavelength. By measuring the fluorescence spectrum instead of simply observing the color, multiple dyes can be distinguished at the same time. Fluorescence bands of organic dyes are broad and overlap, but because the line-shape is Gaussian, computer programs such as Peak-Fit can be used to separate the dye fluorescence bands and thus determine dye concentrations of each. Thus multiple injection points as well as multiple resurgence points can be tested.

A third major innovation was the introduction of quantitative tests using automatic water samplers. Because of the high sensitivity of modern spectrofluorometers, small concentrations of dye can be measured directly from water samples rather than from charcoal elutriates. By collecting water samples at regular time intervals and analyzing dye concentrations in each, a dye breakthrough curve can be constructed that displays the dye travel time and sometimes gives information on the geometry of the flow path (Jones, 1984).

Dye tracing is one of the most powerful tools in the karst hydrogeologist’s toolkit. Following the introduction

of charcoal dye receptors, the drainage patterns for many underground drainage systems were worked out. The Swago Creek basin in West Virginia (Zotter, 1963) was an early example. Contaminant transport over distances of tens of kilometers was demonstrated (Aley, 1972). With the increased sensitivity of modern spectrofluorometers, dye detection limits reached the part per trillion level. With high sensitivity came the necessity for careful protocols for dye injection and recovery to avoid cross-contamination and misleading results. Use of dye tracing in legal and regulatory issues forced more careful attention to quality control and chain-of-custody issues. Dye toxicity became an issue fairly early (Smart and Laidlaw, 1977; Smart, 1984) and some otherwise useful dyes were rejected.

Modern dye tracing requires a well-equipped laboratory and a great deal of practical experience. But in spite of the elaborate precautions needed and the equipment required for analysis, the details of the procedures are described mainly in reports and private publications (Alexander and Quinlan, 1992; Field, 1999; Aley, 2002). European practice, however, is laid out in detail by Käss (1998).

THE CONCEPTUAL DESCRIPTION OF KARST AQUIFERS

At the time of the 25th anniversary Bulletin, karst hydrology was pretty well divided into two camps. There

Table 1. Some commonly used tracer dyes for water tracing.

Common Name	Color Index	Fluorescence Wavelength (nm) ^a	
		Elutriate	Water
Sodium fluoresceine (uranine)	Acid Yellow 73	515.5	508
Eosin	Acid Red 87	542	535
Rhodamine WT	Acid Red 388	568.5	576
Sulpho Rhodamine B	Acid Red 52	576.5	585
Fluorescent Brightener 351	Tinopal CBS-X ^b	398	397

Data courtesy of Crawford Hydrology Laboratory, Western Kentucky University.

^a Fluorescence wavelengths (intensity) vary significantly with differing instruments and many of the listed values will be found to be in variance with reported fluorescence wavelengths in other publications (e.g., fluorescence wavelength for sodium fluorescein in water is typically reported to be 512 nm (the editor)).

^b Common Name for Tinopal CBS-X provided by the editor.

were the professional hydrogeologists, well educated in the intricate mathematical details of groundwater behavior in porous media and there were the cavers, not yet quite ready to call themselves hydrogeologists. The professionals drilled wells, ran pump tests, and made calculations. Sometimes, as when they drilled into a highly fractured dolomite, they got reasonable results. Sometimes, as when they drilled into a water-bearing conduit, their results were nonsense. There was a considerable effort (White and Schmidt, 1966) to convince the professional community that underground streams had something to do with hydrology. Cavers were accumulating maps and data on stream sinks, springs, and underground-drainage patterns, but generally didn't pay much attention to the mass of rock that surrounded the caves. One of the most important accomplishments of the past 40 years has been merging these divergent points of view.

THE GROUND-WATER BASIN CONCEPT

The framework for discussion of groundwater is the aquifer. Aquifers are characterized by the distribution and anisotropy of hydraulic conductivity among the various rock units that make up the aquifer. Aquifers often have well-defined thicknesses, but rarely is one concerned with the area of an aquifer. The framework for discussion of surface water is the drainage basin. Drainage basins have well-defined areas and a certain pattern of stream channels. For geologic settings other than karst, groundwater concepts and surface-water concepts rarely intersect. In karst they are completely entangled.

Just as the notion of reconstructing conduits from observable caves crept into karst thinking without much notice, so also did the concept of the groundwater basin. At some time it began to occur to karst researchers that it was more profitable to think of karst hydrology in terms of drainage basins with both surface and subsurface components rather than thinking of a karst aquifer. For the most part, it was a concept introduced by cavers because it provided guidance about where to search for new caves. Certainly the concept was established when Jones (1973) wrote his report on the karst-drainage basins in Greenbrier County, West Virginia. Jones was one of the first to use extensive dye tracing to map out the entire drainage system and subdivide spring catchments into distinct groundwater basins. An even more elaborate groundwater basin map was prepared by Quinlan and Ray (1981; Quinlan and Ewers, 1989) for the Mammoth Cave area in southcentral Kentucky. Underground drainage in southcentral Kentucky flows either northwest to the Green River or southwest to the Barren River. Quinlan and Ray used cave data, geologic data, more than 500 dye traces, and 1400 well observations to subdivide the Mammoth Cave area into 28 groundwater basins, show the main flow paths, and contour the water table. Many groundwater basins have now been mapped, especially in West Virginia (Jones, 1997) and in the series of drainage-

basin maps for Kentucky compiled by J.A. Ray and J.C. Currens.

If the groundwater basin divide can be accurately established, the basin area can be measured. Precipitation within the basin and discharge from the basin can both be measured. Essentially, the existence of a basin boundary puts a mass-balance constraint on water moving through the system. The various statistics developed for surface-water basins can be applied to groundwater basins. If the basin of interest discharges at a spring, the spring can be gauged and a record of discharge established over long periods of time. From these data can be calculated the mean flow either over one water year or over the entire period of record, the mean base flow, and the mean annual peak flow (known as the annual flood for surface basins). The normalized mean base flow is the base flow divided by the basin area. This quantity has been found to be unusually small for karstic basins compared with other surface water basins (E.L. White, 1977) because of the low hydraulic resistance of the conduit system which allows the aquifer to drain during period of low recharge. If a numerical value for the normalized mean base flow can be established for a given region, the basin areas of other springs can be calculated by simply multiplying the measured mean base flow of the spring of interest by the normalized mean base flow for the region. A comparison of various basins by Quinlan and Ray (1995) showed that this simple calculation works well if the local hydrogeology is taken into account. The calculation is a powerful check on spring ground basin areas estimated by other methods.

The boundaries of surface water basins are usually clearly defined by topographic highs and can be easily drawn from topographic maps. The boundaries of groundwater basins are more problematic. The boundaries of contributing sinking-stream basins can be delineated, but boundaries through the karst must be inferred from known stream caves, from tracer tests, from the local geology and from water-table maps constructed from depth-to-water measurements in wells. Unlike surface-basin boundaries, groundwater basin boundaries may shift with increasing or decreasing discharge. Generally, high gradient basins have the most sharply defined boundaries whereas low-gradient basins may have fuzzy boundaries. Tracer tests near the basin boundaries may indicate flow into several adjacent basins. Piracy routes and high-discharge spill-over routes are also common.

POROSITY AND PERMEABILITY

The treatment of a karst system as a groundwater basin leads to certain insights. Treatment of the karst system as an aquifer leads to other insights. These two conceptual frameworks have existed comfortably side-by-side for the 40 year period of this review. The most fundamental properties of an aquifer are its porosity and permeability. It was recognized early on that the permeability (or porosity) of karst aquifers has three components: the matrix

permeability of the bedrock itself, the permeability produced by fractures (joints, joint swarms, bedding-plane partings, and some faults), and the permeability due to conduits. This has now been somewhat formalized and researchers speak of the triple permeability model (Worthington, 1999).

The matrix hydraulic conductivities of most compacted limestones are in the range of 10^{-9} – 10^{-11} m s^{-1} and for most practical purposes can be ignored. The exceptions are the young limestones, especially those on carbonate platforms, that have never undergone deep burial or been subject to orogenic forces. For these, the matrix permeabilities are in the range of 10^{-6} to 10^{-7} m s^{-1} and matrix flow is an important component. For information on the hydrogeology of young limestones see Martin et al. (2002). Matrix flow in porous limestones is Darcian and not intrinsically different from flow in other porous media.

Limestones and dolomites are brittle rocks and subject to fracturing by tectonic forces and by stress relief caused by either erosion or glacier unloading. Fracture flow occurs in other brittle rocks such as sandstones and granites. Groundwater in fractures is a major component of the stored water and is the reason that wells drilled into limestone often produce useful quantities of water without the well having penetrated a conduit. Fracture flow is a major emphasis in contemporary hydrological research as attempts are made to model fractures with irregular apertures and also to model fracture networks.

The practical boundary between fracture permeability and conduit permeability occurs at an aperture of about one centimeter. In groundwater basins with typical gradients, a one-centimeter aperture corresponds to the onset of turbulence, to velocities sufficient to begin to transport clastic sediment, and to an increase in the rate of dissolution of the carbonate rock. Caves as conduit fragments, can be mapped by human explorers down to an aperture of about 0.5 m. Between 0.01 m and 0.5 m are solution openings that are too small for direct mapping but large enough to behave hydraulically as conduits. Very little is known about the conduit porosity in this size range. Some insight into the flow behavior can be obtained from the distribution of travel times obtained from tracer tests (Fig. 4). The distribution is log-normal with a considerable tail of the low velocity side. These measurements may indicate tracer dyes moving through small and hence low velocity pathways.

IMPORTANCE OF THE GEOLOGIC FRAMEWORK

The flow of water through karst aquifers is determined by relatively simple principles of fluid mechanics and the interaction of the water with the carbonate bedrock by relatively simple principles of physical chemistry. As in most of the Earth sciences, the devil is in the details. One of those details that was widely overlooked in the early development of karst hydrology was the geologic setting. What karstic rocks are available and how are they

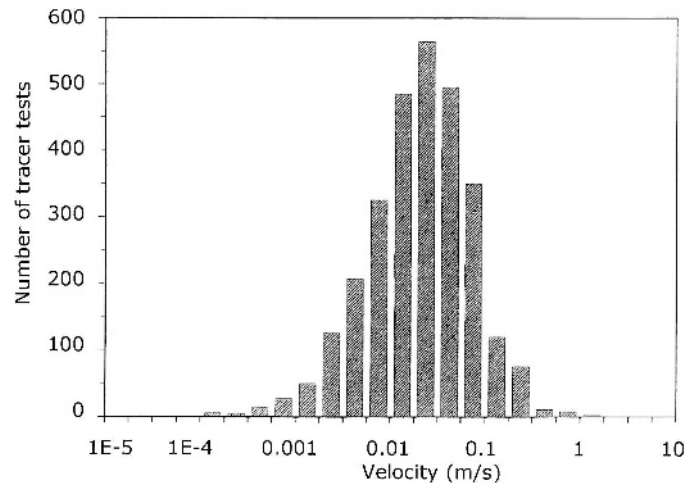


Figure 4. Distribution of travel velocities as determined from 2877 tracer tests between sinking streams and springs. From Worthington et al. (2000).

arranged with respect to other rocks? Any karst groundwater basin is a work in progress. It evolved from some precursor basin to its present configuration and the present configuration will evolve further into the future. The hydrology of the basin is controlled to a large extent by the underlying stratigraphy and structure.

The geological variables that distinguish one karst drainage basin from another include:

- Thickness of karstic rock units
- Placement of karstic rocks with respect to non-karstic rocks and location within drainage basin
- Bulk lithology: limestone, dolomite or gypsum
- Detailed lithology: micritic limestone, crystalline limestone, shaly limestone
- Stratigraphic homogeneity: bedding thickness, lithologic variations, shale or sandstone confining layers
- Large scale structure: folds, faults
- Small scale structures: density and connectivity of vertical joints, bedding plane partings, few master fractures vs. many smaller fractures

A great variety of karst drainage basins is possible depending on the listed parameters. A variety of placements of karstic rocks with respect to other strata were described early in the review period (White, 1969) and these possibilities have been embellished by others. Most of the karst of eastern United States is developed in at most a few hundred meters of limestone producing fluviokarst landscapes. In locations such as the Cumberland Plateau or the Ozark Plateau, the combination of low dip, limestones located under valley floors and on valley walls, and a protective sandstone and shale caprock on the plateau surface provides ideal conditions for the development of long caves and vertical shafts. Other locations such as the folded Appalachians, with carbonate rocks mainly in the

valley floors, produce strike-oriented caves and more limited drainage basins.

The most recent calculations on cave development (Dreybrodt et al., 2005) show that the patterns of conduit-drainage systems are determined during the initiation phase of cave development. At this time, the system is highly sensitive to details of the fracture pattern and to the presence of confining layers. A few centimeters of shale interbedded in the limestone is sufficient to deflect the initial pathway that will later become a cave passage.

A great deal of the literature on karst hydrology consists of studies showing how a particular drainage basin developed in response to its specific geologic setting.

QUANTITATIVE HYDROLOGY: SPRING HYDROGRAPHS

The flow of karst springs is often variable, rising and falling in response to storms. Some springs become muddy during storm flow. Springs can be gauged to produce a continuous recording of discharge as a function of time, a curve known as a hydrograph. The water flowing from a spring represents a composite of all inputs and flow systems upstream in the basin. Use of spring hydrographs to characterize karst aquifers developed early in Europe (Burdon and Papakis, 1963; Milvanović, 1981) and has been developed to a considerable mathematical elegance in France (Mangin, 1984; Labat et al., 2001). Only in the 1980s and later were spring hydrographs extensively used in the United States. In part, this was not due to ignorance but to the fact that most karst hydrology research was being conducted by academics and cavers on shoe-string budgets. Continuous stage recording was desirable but not financially achievable.

Examination of a large number of spring discharge records reveals a range of responses on a scale between two end-members. There are karst groundwater basins with very rapid response times so that the spring hydrograph has peaks corresponding to each individual storm. The other extreme are springs that exhibit essentially no response at all to individual storms and at best rise and fall a little in response to wet and dry seasons. In between are hydrographs with varying degrees of response (Fig. 5).

The aquifer characteristics that control hydrograph pattern are not completely understood. The very flashy response with individual storm peaks requires a small open aquifer with an overall transport time from recharge to spring less than the spacing between storms. Less well-resolved hydrographs can arise from aquifers sufficiently large such that individual storm inputs are damped before they reach the spring. Hydrographs with little storm detail can arise from aquifers in which most of the recharge is through the epikarst which tends to hold water in temporary storage. Springs fed by fracture flow will have less detail in their hydrographs, but a flat hydrograph is not evidence for the absence of conduits. The big Florida springs have almost no detail in their hydrographs but

most are known to be fed by very large water-filled conduits.

Sudden intense storms that follow several weeks without rain are the best probes of aquifer behavior. Figure 6 illustrates schematically the parameters that can be measured. The lag time between the storm and the time that storm water appears at the spring is a measure of travel time only if the conduit is an open streamway from sink to spring. If all or a portion of the conduit is flooded, rising head at the upstream end will cause water to discharge from the downstream end responding to a pressure pulse that travels through the system at the speed of sound. The time between the storm and increased flow at the spring can be very short. The ratio of the maximum flow to base flow is a measure of the flashiness of the aquifer, although this ratio also depends on storm intensity. The recession limb of the hydrograph can usually be fitted with an exponential curve (or several). The fitting parameter for the exponential has been called the exhaustion coefficient and has been used (Burdon and Papakis, 1963) to calculate the volume of water held in dynamic storage. The inverse of the exhaustion coefficient has units of time and can be taken as the response time of the aquifer.

CHEMICAL HYDROLOGY

One of the most important accomplishments of the 40 year period was to work out the chemistry of carbonate dissolution in considerable detail. The equilibrium chemistry of both dissolution and precipitation came first and is described in detail in several textbooks (White, 1988; Langmuir, 1997). The equally important kinetics of dissolution and precipitation rates, although more complicated and not so solidly established, has been largely worked out. The dissolution rates of carbonate minerals are important to many areas of science, resulting in a huge literature. Much of it has been reviewed by Morse and Arvidson (2002). Dissolution kinetics combined with flow hydraulics forms the basis for current theories of speleogenesis. A major contributor has been Wolfgang Dreybrodt and his students and collaborators at the University of Bremen in Germany (Dreybrodt et al., 2005). Studies of speleogenetic processes can be considered aquifer modeling along the time axis by calculating the evolution of the conduit permeability through a sequence of initiation, enlargement, stagnation, and decay phases. Although much has been accomplished (Klimchouk et al., 2000), this subject is outside of the scope of the present review.

Although many analyses of karst waters had been obtained, about the best that could be done with them was to plot the concentration of dissolved carbonates on the calculated calcite solubility curve, which then gave some indication of whether the water sample was saturated, supersaturated, or undersaturated (aggressive) with respect to calcite. In the early 1970s there were a number of efforts

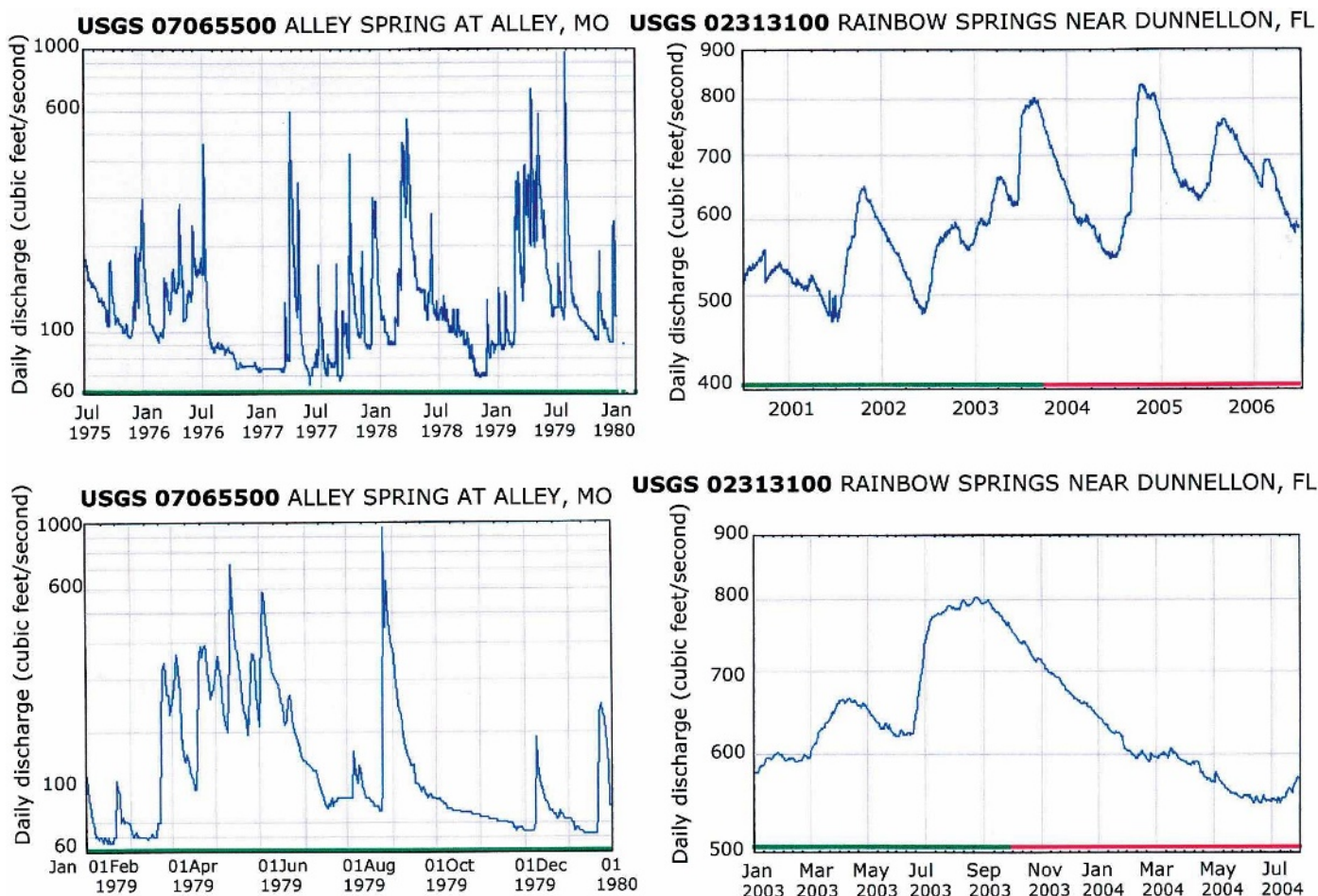


Figure 5. Some representative hydrographs for karst springs. These are selected from U.S. Geological Survey surface water records which are available online (<http://waterdata.usgs.gov>). Alley Spring is representative of the flashy, fast-response springs where individual storm events appear on the hydrograph. Rainbow Spring displays an annual rainy season/dry season response but does not respond to individual storms.

to more accurately measure the saturation state of cave waters. Most successful of these was the introduction of the saturation index and also the calculated CO_2 partial pressure (Langmuir, 1971). These calculations and other aspects of aqueous chemistry quickly evolved into a collection of computer programs that have continued to evolve down to the present time (Jenne, 1979; Melchior and Bassett, 1990).

In the late 1960s and early 1970s there began studies of spring-water chemistry in which the springs were sampled at regular intervals, typically one or two weeks (Pitty, 1968; Shuster and White, 1971). The dissolved carbonate content of some springs remains essentially constant through the year irrespective of the season or the influence of storm flow. Other springs exhibit a widely fluctuating chemistry and also a fluctuating temperature. There ensued a debate concerning the cause of the chemical fluctuations, with degree of conduit development, percentage of sinking-stream recharge, and flow-through time being offered. Then came the results of Dreiss (1989) who measured

a continuous record of the chemistry of Meramec Spring, Missouri. It turned out that the fluctuations observed in previous studies were due to a small number of sampling points extracted from a continuous curve (now known as a chemograph). Chemographs of carbonate species typically are the inverse of hydrographs and represent the dilution of the resident water in the aquifer by injected storm water (Fig. 6). Since their first introduction, chemographs has been constructed for many chemical parameters including groundwater contaminants.

The concentration of dissolved carbonate species in karst aquifers is proportional to the specific conductance of the water. Because specific conductance is easy to measure and easy to record on a data logger, such measurements allow easy determination of carbonate chemographs. Many such have been measured and, in combination with hydrographs, provide additional information on aquifer response. What is observed is that there is a sharp rise in the hydrograph in response to storms. However, there may or may not be an equivalent dip in the chemograph. If the

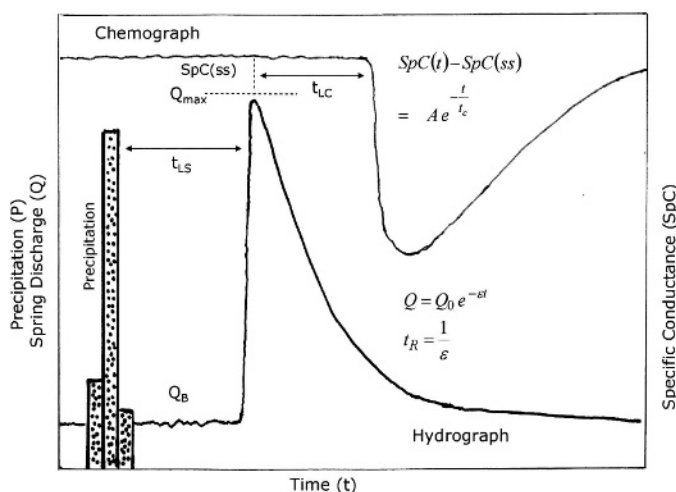


Figure 6. Schematic hydrograph and chemograph for a karst spring showing various measurable parameters. Q_B = base flow. Q_{max} = peak flow for the storm hydrograph. Two time lags are shown: t_{LS} for the lag between the storm and the rising limb of the hydrograph and t_{LC} for the lag between the rising limb of the storm hydrograph and the dip in the chemograph. Both the recession limb of the hydrograph and the recovery limb of the chemograph can be fitted with the functions shown.

rising hydrograph and falling chemograph are coincident, it indicates that the conduit is an open streamway and the rising hydrograph marks the arrival of storm water at the spring. In other cases, there is a delay between the rising limb of the hydrograph and the falling limb of the chemograph. This delay, along with the spring discharge, is a measure of the volume of water pushed out of flooded conduits by the storm pulse (Ryan and Meiman, 1996).

CAN KARST AQUIFERS BE MODELED?

At the end of the review period, much contemporary research on karst hydrogeology consists of attempts to construct a useful, perhaps even valid, general model for karst aquifers. The object of any groundwater model is to reduce the recharge, storage, and flow hydraulics of an aquifer to a computer program. With an accurate model, one should be able to calculate well yields and distribution of hydrostatic heads within the aquifer, as well as the response of the aquifer to varying recharge and to extraction of water for water supply. For a karst aquifer, an accurate model also should be able to reproduce the expected spring hydrographs in response to a specified precipitation event. Much karst hydrological research over the past several decades has been efforts to construct such a model. Results have been decidedly mixed. Summaries of some of the attempted approaches may be found in Jeannin and Sauter (1998) and Palmer et al. (1999).

The guiding parameter for any groundwater model is the hydraulic conductivity. The hydraulic conductivity can

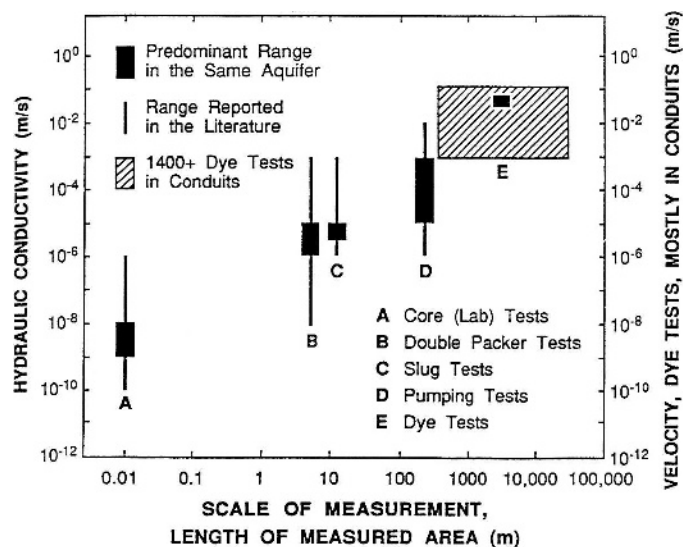


Figure 7. Dependence of hydraulic conductivity on the scale of measurement. From Quinlan et al. (1992).

be anisotropic and different values can be used for different rock formations, but it should be constant within these constraints. One of the most important difficulties in modeling karst aquifers is that the hydraulic conductivity is scale dependent. It was pointed out by Sauter (1991) and Quinlan et al. (1992) that hydraulic conductivities for highly karstic aquifers can vary over 8 orders of magnitude depending on the scale of measurement (Fig. 7). In an aquifer with this range in values over short distances, any attempt to reduce the aquifer to a single value of hydraulic conductivity can best be described as nonsense.

Without going into very much detail, the main approaches to karst-aquifer modeling are summarized below. Only a few key references are given. This subject is beginning to develop a very large literature.

EQUIVALENT POROUS MEDIA MODELS

Standard porous-media models such as the USGS MODFLOW program assume that at large enough scales, the heterogeneities of the karst aquifer are smoothed out and can be represented by an average hydraulic conductivity. Scanlon et al. (2003) had some success in applying this type of model to the Edwards Aquifer in Texas. Equivalent porous media models work best for aquifers in which the karstic-flow paths are dispersed and consist mainly of solutionally-widened fractures. They work least well for aquifers with well developed conduit systems, particularly those with large inputs of allogenic recharge.

PIPE FLOW MODELS

Equivalent porous-media models ignore the conduit permeability and its localized turbulent flows. Pipe-flow models focus entirely on the conduit system. Pipe-flow models treat the conduit system as a network of pipes

subject to the usual laws of fluid mechanics. The drawback of the pipe flow models is that conduits are not exactly pipes. They have varying cross sections, complicated interconnections, and are often further modified by breakdown and sediment infillings. Much detail about conduit pattern is needed. However, calculations of travel times, head losses, and discharges for known conduit systems have been generally successful (Halihan and Wicks, 1998; Jeannin, 2001).

COUPLED CONTINUUM/PIPE-FLOW MODELS

Eventually, karst-aquifer modeling must face the reality of the combined matrix, fracture, and conduit components of the permeability. The conduit system is strongly coupled to surface water through sinking streams and closed depressions and so has a very dynamic response to storms. The fracture and matrix systems receive most of their recharge through the epikarst and have a slower response. A dominant component of the total flow system is the exchange flow between the conduits and the surrounding fractured matrix. During storm flow, heads in the conduit system rise rapidly and water is forced into the surrounding fractures. After the storm flow recedes, the conduit system drains rapidly, heads reverse, and the water stored in the fractures drains into the conduits.

Models have been constructed in which the fracture and matrix system is described as a continuum with Darcy flow. The conduits are put in by hand and described by pipe-flow models. There is an exchange term that describes the influx and outflux of water between the fracture system and the conduits. This model was developed for the Gallus Spring in southern Germany (Sauter, 1992). This model worked well in the sense that it accurately reproduced the storm hydrographs measured at the spring. The drawback is that the conduits must be put in by hand. Tracer studies and cave exploration must supplement the strictly model calculation. Continued development of this approach to modeling has been very promising (Bauer et al., 2003; Liedl et al., 2003).

INPUT – OUTPUT MODELS

All of the modeling approaches described above require considerable knowledge of the aquifer – the geometry of the conduit system, the hydraulic conductivities of the fracture and matrix systems, and any geologic-boundary conditions. In general, the more pre-knowledge available, the more accurate the model. Of course, if all available knowledge is used to construct the model, there may be nothing left for the model to calculate. The diametrically opposite approach is to treat the aquifer as a black box and assume nothing about its internal properties. Instead, models are built from inputs and outputs, both of which can be measured directly. These models make use of linear-systems theory as pioneered by Dreiss (1982, 1989) with more recent applications described by Wicks and Hoke (1999). The idea is to use measured input and

output data to construct a kernel function (the black box) which will connect all other relations between input and output.

CONCLUSIONS

In the 40 years since the 25th anniversary Bulletin, knowledge of karst hydrology has made giant forward strides. By borrowing concepts from both groundwater hydrology and surface-water hydrology, an excellent conceptual model for karst aquifers has been developed. There is good understanding of the physical and chemical processes that take place in karst aquifers. The current cutting edge is the development of a reasonable and accurate model to describe the flow behavior within the aquifer. Although there has been some success, a complete model has yet to be obtained. However, the eventual construction of such a model does not seem as remote as it did only a few years ago.

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