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Appendix A. Karst Terranes

Karst terranes are distinct landscapes that develop when fractured, soluble bedrock interacts with surface water or groundwater to develop macroscale secondary porosity in the form of subsurface voids, conduits, and caves. Often, the presence of subsurface voids is expressed as distinctive surface landforms that are collectively defined as a karst terrane. However, dissolution and void development in soluble bedrock can also occur in the deep subsurface so that there is no land surface expression of the karst groundwater hydraulics.

Approximately 25% of the United States has the potential for karst development (Weary 2014), and it is estimated that as much as 40% of the U.S. population gets drinking water from karst aquifers.

Karst aquifers are, fundamentally, fractured rock environments. Soluble rock alone is not sufficient to generate a karst terrane, because these rock types often have low primary porosity that inhibits water infiltration and movement. For karst to develop, the introduction of groundwater through secondary porosity features, specifically fractures or bedding, is necessary. Groundwater flow in fractures or bedding of soluble rock is the embryonic stage of karst development, often generating anastomosing dissolution features. As groundwater moving through the fractures continues to dissolve the host rock, the solution features enlarge and the fracture system becomes increasingly more karstic.

Most karst landform development occurs in highly soluble carbonate and evaporite bedrock, such as limestone, dolomite, marble, and gypsum. However, all bedrock is soluble to some degree, depending on the rock and groundwater chemistries. Solutionally enlarged fractures have been found in granular, nonsoluble rock (Halliday 2007), sinkholes have developed in sandstone (Alexander 2005), and karst-like groundwater flow has been reported in sandstone and quartzite (Wray 1997). Additionally, conduit flow and similar landforms can develop in vesicular basalts and in association with volcanic lava tubes. Often, these noncarbonate terranes are referred to as *pseudokarst*.

For site investigation and management of karst aquifers, these terranes are often viewed as mysterious areas where the standard principles of hydrogeology do not apply and where even data from the most basic tools (such as monitoring wells, potentiometric surface maps) are often unreliable or confusing. Like other fractured bedrock environments, groundwater investigations in karst often end up with numerous monitoring wells with a variety of different heads and chemistries depending on which fractures or conduits are intersected. However, with a working knowledge of karst aquifer characteristics and how its development and morphology can affect localized and regional groundwater flow, an effective investigation can be easier to design and implement that those in other fractured rocks—especially if approached at the macroscopic scale.

Because karst groundwater systems often develop a diverse landscape of macroscopic scale features like caves, sinkholes, sinking streams, and large springs, they are often more easily identifiable than other fractured rock environments. In the subsurface, the conduits and interconnected solutional features develop hydrologic systems that in many ways behave as surface drainage basins. Additionally, karst surface features can provide clues to the location of the hidden subsurface drainage patterns, streams, and resurgences (points of exposure). By understanding how these macroscopic features develop, it is often possible to begin to decipher the groundwater flow directions and patterns in the subsurface and develop a preliminary CSM without conducting any intrusive activities.

A.1. Identification of Karst Terranes

As with any environmental investigation, development of the typical CSM begins at the macroscopic scale. To understand the karst environment, the researcher should take a systematic approach to build the model through a process often referred to as a karst features inventory. A karst features inventory is simply an accounting of recognizable karst features, beginning at the macroscopic scale, and eventually using those features as indicators of both the surface morphology and the subsurface architecture (i.e. the fracture and conduit system) (Quinlan 1991).

Topographic and geologic maps along with aerial photography are often excellent resources for identifying the presence and degree of shallow (near land surface) karst development. Any closed depression identified by hachures on a topographic map should be identified as a potential solutional feature for further investigation. Areas that appear to lack surface drainage features also suggest a dominant subsurface drainage system. Blind valleys with streams that disappear or that appear from large springs are other easily identifiable indicators of karstic systems. Even place names on topographic maps

such as Bottomless Lake, Big Sink, Cave Springs, Dry Valley, Lost Creek, or Sinking Creek can be good indicators of karst.

Geologic maps can be used to identify the extent of any soluble rock formations exposed at the surface, but be careful to evaluate potential karst formations that may be present beneath the surface rock as well. Many of the most extensive cave systems in the world (for example, Mammoth Cave in Kentucky) are developed beneath a caprock of sandstone.

Aerial photographs are helpful in some areas, for instance circular lakes in Central Florida, circular areas of lush vegetation in arid regions of Texas and New Mexico, or groupings of trees in otherwise cultivated land in the Midwest are all worthy of closer scrutiny. Additionally, recent advances include high resolution light detection and ranging (LiDAR) data to develop improved sinkhole maps in Kentucky (Zhu 2014).

Soils maps can also be used to aid in karst identification. Karst areas often have a conspicuous “terra rosa” coloration and the soil type may be different in a depression that is internally drained compared to the surrounding soils. Soils in karst areas commonly exists as a thin layer over the bedrock or may not be present at all.

The following descriptions summarize some of the common surface features that can be indicators of karst development.

A.2. Sinkholes and Dolines

Sinkholes are defined as closed topographic depressions, typically circular to subcircular and with side slopes ranging from shallow to vertical that form from dissolution, collapse, or subsidence of the underlying rock. The term *doline* (Cvijic 1893) takes precedence in international literature and is preferred in Europe, but in the U.S., *sinkhole* is the term used most often. Sinkholes form as the result of several processes related to dissolution, and they are considered an index landform for karst. They can range in size from a few feet to over 20 miles in diameter. They are usually dry, but if they intersect the water table or become sediment clogged, they can be filled with water. Sinkholes are important recharge features to a karst aquifer system. Note that only large sinkholes are found on topographic maps. One study found that 85% of the sinkholes in Winona County, MN, were not shown as depressions on the 7.5 minute topographic maps compared to field investigations (Dalgleish 1984).

Some karst-prone areas have developed databases documenting the locations and types of karst features, particularly sinkholes, to help with land management and planning. These databases, if available, can be a useful aid for CSM development.

A.3. Springs

Proper delineation of springs is an essential element in understanding the transport and discharge of groundwater in a karst hydraulic system. While large springs are not unique to karst, they are a common karst feature and some of the largest springs in the world occur in karst aquifers. Springs are an essential part of a karst characterization. Like other fractured rock aquifers, springs represent discharge points of the solutional channel network and therefore may include inputs from sources from a large catchment area.

Like sinkholes, only the largest springs can be identified from topographic maps and smaller springs and seeps may only be found through field reconnaissance. Springs may also discharge underwater (in lakes, streams, or coastal environments), making their detection more difficult. Often, they can only be found through careful delineation within a water body or indirectly through calculating a water budget. Determination of source areas and catchment basins for springs often involves the use of tracer studies (fluorescent dyes or other techniques) to determine flow pathways and source areas for individual springs.

Sinking Streams and Dry Valleys

The lack of surface streams in a humid environment is a common indicator of subsurface drainage. This may also be seen in valleys with upland streams that abruptly disappear when they reach the valley floor or a stream valley that abruptly ends with no apparent outlet. Larger sinking streams are often visible on topographic maps and aerial photographs. In humid regions, the streams may be obvious, but in arid regions, such features may be blind arroyos or small canyons devoid of visible streams. These macroscopic features can most often be found through a review of maps and aerial photographs.

More difficult to observe are streams that are losing or gaining in less dramatic fashion, but also may be indicators of karst development. Any area underlain by soluble rock and generally lacking surface drainage features should be suspected of subsurface drainage.

A.4. Epikarst and Karren

Epikarst, related to *karren*, is a term used to describe the complex uppermost, near-surface portion of a karst system that includes the soil/bedrock interface. The epikarst is generally defined as the irregular, solutionally-derived bedrock surface

that is often hidden beneath a layer of soil. The epikarst often includes perched groundwater conditions that are more susceptible to surface contamination (Cooley 2005). The epikarst is also a primary recharge pathway that funnels infiltration from the soil and surface features into the underlying conduit system. Generally, epikarst is comparable with the vadose zone, but may also include permanent or seasonal phreatic conditions depending on water table depths and aquifer morphology. The epikarst is one of the few portions of the karstic system that may provide aquifer storage (Williams 1983).

Karren is a broad term that refers to solutional fissures, rills and grooves often seen on rocks at the surface as part of the epikarst. These features may be spread over large areas and even seen on a microscopic scale. Often, these features are the result of solutional enlargement of bedrock fractures and can be important indicators for bedrock structures and local or regional fracture orientation. Karren can form a pavement when devoid of soil and may form a rectilinear *clint and grike* landscape (Ford 2007). In the U.S., karren is often soil-covered and is manifested as *pinnacle and cutter* structures at the soil/bedrock interface.

A.5. Caves

In simple terms, a cave is defined as a natural underground opening that is large enough for human entry (Ford 2007). This definition could include large vugs or voids, but such features are uncommon.

Cave are considered fragile habitats, and many caves have resident endemic, threatened, or endangered species. Consequently, the presence of caves near a contaminated site requires a greater degree of investigation to include potential faunal impacts that is beyond the scope of most site investigations. If a cave is near a site, consult with the National Speleological Society or state and local cave organizations, which potentially have locations, maps, and other data for area caves.

Animals may frequent openings that do not meet the definition of a cave, but may lead to larger openings or a cave accessible from a different location. In addition, cave-sized openings may be encountered at depth while drilling and may be identified on drillers' logs as voids or rod drops. A cave can open underground and still be inhabited. For example, two species of threatened blind catfish from the Edwards Aquifer near San Antonio, TX, are known only from individuals that have been recovered from water pumped to the surface from wells that are 1,350 to 2,000 feet deep.

The presence of large (or long) cave systems also can have a significant effect on local and regional water quality. Large cave conduits can transport large quantities of water over long distances in short time periods with little or no degradation of introduced contaminants.

A.6. Karst Site Characterization Methods

Karst sites and more traditional fractured rock sites have much in common. Consequently, the investigative techniques are often similar. Careful logging of borings and bedrock core, coupled with packer testing, surface and downhole geophysics, and many of the other common fractured rock investigative tools are also useful in karst environments. Some specific characterization methods and tools, however, have been developed to address the specific challenges of characterizing karst aquifers including those briefly outlined below.

A.7. Karst Features Inventory

A karst features inventory is a combination of desktop and field observations. The first step in site characterization and development of a CSM is to review available maps, photographs, and literature to locate and document identifiable karst features such as sinkholes and springs that may provide information with respect to subsurface flow conditions and preferential pathways. Because karst drainage basins can be large, desktop reviews should include the subject property, as well as surrounding properties and the region. Often, a primary groundwater resurgent spring is located several miles from a source area.

Many karst features are not discernable based on desktop surveys alone because they are too small or may be obscured by vegetation or topography, so field reconnaissance by a qualified geoscientist becomes valuable. Depending on the size of the study site, field inventory surveys involve a walking survey of accessible areas to identify and document karst features and to verify those features tentative identified from maps and aerial photographs. Typically, a survey uses an inventory form to quickly determine the feature identified. This form may include general information such as the features type, location (GPS), size, and other relevant information. If the feature is a spring or other groundwater resurgence, the estimated discharge should be recorded along with the temperature, pH, and specific conductance of the water if the appropriate instrumentation is available.

A good reference for conducting karst inventories/site assessments is the Texas Commission on Environmental Quality

(TCEQ) *Instructions to Geologists for Geologic Assessments on the Edwards Aquifer Recharge/Transition Zones* (TCEQ 2004).

Some state agencies (such as Kentucky) allow the use of karst springs as groundwater monitoring locations in place of monitoring wells if they can be shown to be representative of the groundwater source area in question. Consequently, locating and characterizing these features becomes an important part of establishing a CSM for subsequent aquifer characterization, monitoring, or remediation.

A.1.1 Tracer Testing

Fluorescent dye tracer has long been used to determine groundwater flow paths in fractured rock environments, especially karst terranes. By injecting one or multiple nontoxic fluorescent dyes, it is possible to trace the dye's movement through individual fractures and groundwater flow paths either visually or analytically (with the use of spectrofluorimetry). Dye tracing can provide valuable information about groundwater flow direction, preferential pathways, travel times, storage, or residence times. Dye tracing also provides insight into potential solute advection, dispersion, and dilution depending on the test design and equipment used. Proper test planning and execution by experienced personnel is essential to prevent cross-contamination and false positives, because many of these dyes can be detected at the ppt level.

Tracer tests can be conducted using a wide range of injection and monitoring points varying from naturally occurring springs to monitoring wells. Trace lengths can vary from tens of feet to tens of miles depending on site conditions and project needs. Some understanding of the site geology, fracture orientation, and groundwater flow is valuable to allow proper dye receptor placement and sampling frequency. In poorly understood or complex systems, it may be necessary to deploy many receptors to account for all probable flow scenarios to maximize the likelihood of dye recovery.

Dye tracing can be conducted by two different methodologies: qualitative and quantitative (USEPA 1988). Qualitative tests involve sample collection using passive dye receptors, typically small mesh screen packets filled with activated charcoal. Qualitative tests are used primarily for determination or confirmation of groundwater flow direction/pathway and delineation of drainage basins.

Quantitative tests typically involve the collection of discrete water samples for analysis and use automatic samplers to collect frequent samples over extended time intervals. Quantitative tests can also be conducted using field spectrofluorimetry instruments for real time data collection. Quantitative tests are used primarily to determine groundwater travel times and higher-level flow dynamics such as advection, dispersion, dilution, and residence time. A tracer analytical computer program, QTRACER2, can analyze tracer breakthrough curves to derive aquifer characteristics (USEPA 2002b).

While fluorescent dyes are the most common tracers used, successful tracer tests have bee conducted using a variety of other materials depending on the site conditions, tracer objective, and available material. Some examples of alternative tracers include:

- salts such as sodium chloride potassium chloride, and lithium chloride
- bacteria or other distinctly identifiable (nonpathogenic) microorganisms
- stable and radioactive isotopes
- buoyant artificial materials such as plastic spheres and shredded paper

A.1.2 Drainage Basin Analysis

Delineation of drainage basins in karst aquifers is an important tool in understanding subsurface flow dynamics and pathways. Because of the dominant fracture and conduit controlled pathways, it is not unusual for separate recharge features that are near each other to have completely different flow directions and transport times. Additionally, evaluating the inputs (such as precipitation or surface streams) and outputs (springs, seeps, and water withdrawal wells) can help characterize the storage and movement of water through the basins.

A good case study is the basin delineation study performed at the Fort Knox Military Reservation in north-central Kentucky to develop appropriate groundwater management and monitoring strategies. The study resulted in the delineation of more than 28 individual drainage basins covering over 130 km^2 containing over 200 inventoried karst features. The basins were delineated using a combination of dye tracing, structural and topographic controls, spring characterization, and normalized base flow (Connair 2002).

When working within multiple drainage basins, normalized base flow (NBF) can be an effective tool to evaluate the size and hydraulic character of individual basins. Designed to evaluate surface drainages, NBF can also be applied to karst drainage basins (Quinlan 1996). The method assumes that basins in a similar physical setting and climate have a similar base flow discharge per unit drainage area (in cubic feet/second/square mile of basin area, or cfsm). Comparison of NBF values for individual basins against a regional (or average) NBF value can identify basins that have anomalous discharge values. Anomalous values are indicators of additional, unrecognized natural or artificial inputs, improperly delineated basin

boundaries, or unidentified flow paths and discharge points.

A.1.3 Spring Hydrographs

> *"The spring is the pulse of a karst aquifer."*
>
> *(Quinlan 1991)*

Plotting spring hydrographs of discharge through time, especially in conjunction with precipitation, can provide important insight into the characteristics of the aquifer. Typically, karst springs tend to have a rapid, "flashy" response to precipitation events because the low primary porosity of the host rock and resulting limited groundwater storage potential. Bonacci (Bonacci 1993) showed that by analyzing the regression curves of spring hydrographs, it was possible quantify some of the aquifer storage and transportation characteristics. When a spring hydrograph is at its peak following a precipitation event, the karst aquifer storage is at its maximum and the slope of the subsequent regression curve is an indicator of the rate of withdrawal (Ford 2007). Additionally, evaluation of the different subsegment slopes in the hydrograph regression curves can be used to calculate specific yields associated with three types of karst aquifer storage: conduit, fracture, and matrix (Shevenell 1996).

A.1.4 Analytical Models

The application of analytical or digital models for karst aquifers is much more challenging and complex than nonkarst or homogeneous and porous aquifers. An inclusive karst aquifer needs to account for the effective triple porosity of the system including the pore matrix, fractures, and conduits or solutional voids (Palmer 1999).

However, most analytical modeling efforts typically focus on one, or at most two, porosity pathways. Additionally, most numerical groundwater models are based on laminar flow (Darcy's Law); however, groundwater movement through the karst aquifer is often subject to turbulent flow through larger aperture fractures and conduits (Ford 2007).

Palmer (Palmer 1999) notes:

> *The heterogeneity of kart aquifers is so severe that it is virtually impossible to acquire sufficient field information to construct a predictive digital model trustworthy enough to allow extrapolation of heads and flow conditions from known to unknown locations, let alone into the future.*

With the understanding of these limitations, analytical models can provide predictive information about potential water flow, chemistry, and fracture/conduit development and orientations. Furthermore, with continued improvement in analytical model development and computing capabilities, model quality and complexity continues to improve.

A.8. Groundwater Flow in Karst Aquifers

General fracture flow mechanisms and the principles of groundwater movement through fractured bedrock aquifers also apply to karst. Karst aquifers, however, also have distinguishing hydrologic characteristics that are specific to soluble rock environments. Entire books are devoted to the topic of karst hydrogeology, and a full discussion of the technical aspects of karst hydrogeology is beyond the scope of this guidance. A basic understanding of the geologic and hydrologic regimes that are unique to karst aquifers, however, can provide useful insight into expected conditions.

The distinguishing characteristic of karst aquifers are large-scale conduits resulting in anisotropic flow pathways that are capable of transporting water over long distances in relatively short amounts of time. Carbonate aquifers can be classified (Table A-1), generalizing the hydrologic conditions and the types of conduits (caves) likely to be present (White. W.B. 1969). Table A-1 can be used to initialize a site-specific CSM by identifying features and flow regimes that may be present given the base conditions.

From the geochemical perspective, there is constant chemical interaction between the groundwater and rock. The slower groundwater moves through the rock, the more time minerals have to dissolve out of the rock and into the groundwater. However, with time, the water also becomes more saturated with the soluble ions and the reaction slows.

When groundwater flows preferentially in fractures, the interaction changes. Increased flow causes disequilibrium as the groundwater is more rapidly replaced and the water/rock residence time is decreased. In karst, the more soluble the rocks, the more the fractures become enlarged as the rock dissolves. As the fractures enlarge, the groundwater flow rates and volumes increase, allowing for more rapid dissolution and even physical erosion. This process is the basic mechanism for

development of a karst aquifer.

The resulting architecture of the karst aquifer makes this environment problematic for investigators. The primary porosity of the rock matrix is usually unimportant as a flow mechanism and storage potential, while the secondary porosity, composed of the solutionally enlarged fractures and conduits, becomes the primary water transport and storage medium. Predicting the orientation, size, and interconnectivity of the solutionally enlarged fractures is the biggest challenge in characterizing the flow of groundwater through a karst aquifer.

Table A-1. Hydrologic classification of carbonate aquifers (White. W.B. 1969)

Table X-1. Hydrological Classification of carbonate aquifers (From While, 1969)

Flow Type	Hydrological Control	Associated Cave Type
DIFFUSE FLOW	GROSS LITHOLOGY	Caves rare, small, have irregular patterns
	Shaley limestones; crystalline dolomites; high primary porosity	
FREE FLOW	THICK, MASSIVE SOLUBLE ROCKS	Integrated conduit cave systems
Perched	Karst system underlain go impervious rocks near or above base level	Cave streams perched, often have free air surface
Open	Soluble rocks extend upwards to land surface	Sinkhole inputs; heavy sediment load; short-channel morphology caves
Capped	Aquifer overlain by impervious rock	Vertical shaft inputs; lateral flow under capping beds; long integrated caves
Deep	Karst system extends to considerable depth below base level	Flow is through submerged conduits
Open	Soluble rocks extend to land surface	Short, tubular abandoned caves likely to be sediment-choked
Capped	Aquifer overlain by impervious rock	Long, integrated conduits under caprock, active level of system abandoned
CONFINED FLOW	STRUCTURAL AND STRATIGRAPHIC CONTROLS	
Artesian	Impervious beds that force flow below regional base level	Inclined three-dimensional network caves
Sandwich	Thin beds of soluble rock between impervious beds	Horizontal two-dimensional network caves

Fractured bedrock aquifers are anisotropic and heterogeneous—controlled by the size, orientation, and density of the fracture network. Karst aquifers are often characterized as combinations of three types of porosity present in the host rock: diffuse (matrix), fracture, and conduit. The karst aquifer can also be subdivided hydrostratigraphically into the epikarst, vadose zone, and phreatic zone. In more typical aquifers, the primary storage and transport of groundwater occurs primarily within the phreatic zone. However, the vadose zone, and often the epikarst, can play critical roles in the storage and transport of water, and more importantly, contaminants, through the karst landscape. A generalized schematic showing the relationship between porosity and hydrostratigraphy in karst aquifers is presented in Figure A-1.

Flow in conduits in the vadose zone mimicks a surface stream incised in a rock gorge, where the stream receives little input or output from diffusion. Inputs come from tributary conduits and flow is flashy and frequently turbulent. A mature karst aquifer is riverine, complete with meanders, cutoffs, sedimentation, and often subject to flash flooding and turbulent flow. In contrast, groundwater flow in conduits within the phreatic zone are most analogous to sewer systems and the resulting flow is often laminar.

Relatively young aquifers are dominated by small aperture fractures with limited interconnectivity. But with older, more developed systems, those fractures enlarge and become interconnected and complex, with the potential to transport large volumes of water over long distances. Mammoth Cave is a mature karst system with over 400 miles of mapped conduits (cave passages) that have been developing for an estimated 10 million years. As another example, groundwater has been traced through a complex conduit groundwater flow system originating in the central part of Slovenia, crossing under the Italian boarder and discharging from springs along the Mediterranean coast near the Italian city of Trieste. Some of the springs have the remnants of Roman bath houses still intact around them as a testament to the duration of groundwater discharge from the same location.

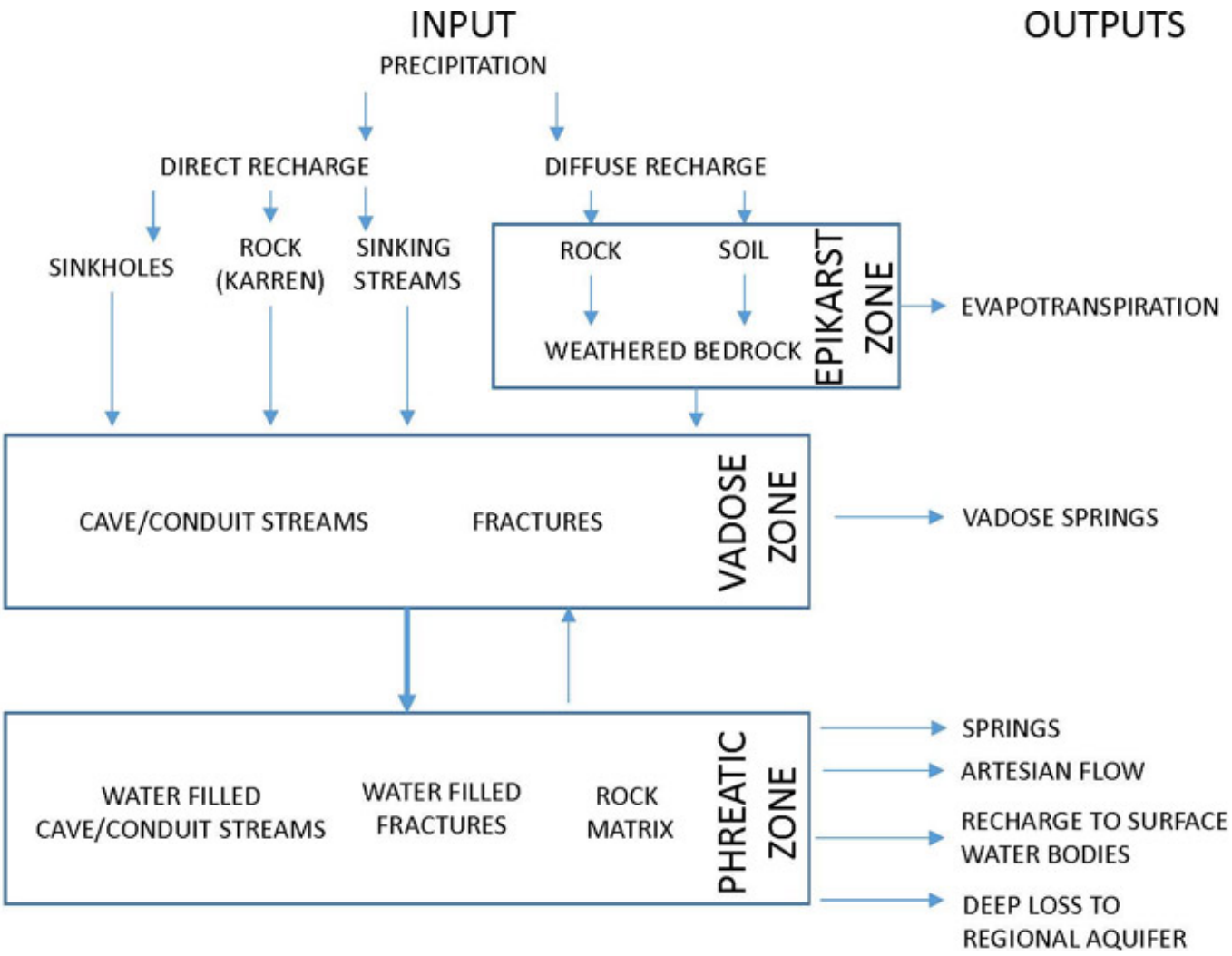

Figure A-1. A generalized flow diagram showing the primary pathways of groundwater movement through the different zones of a karst aquifer (Modified from (Ford 2007).

A.9. Karst Resources

Various agencies have attempted to compile records of karst features. GIS technology has allowed nongovernmental, regulatory, and other government agencies to compile spatial karst data for some specific regions that can be useful. These efforts, however, are piecemeal, often incomplete, and frequently difficult to locate.

One of the best sources for cave inventories is the local grottoes (clubs) of the National Speleological Society (NSS). NSS archives are primarily cave locations, but they often include cave maps, descriptions, and biological and archaeological inventories that can be useful. Multiple state level nongovernmental organizations, such as the Tennessee and Ohio Cave Surveys, inventory and maintain cave related databases.

Several karst research institutes include problem-solving as part of their mission. Resources in the United States include the National Center for Cave and Karst Studies, the Karst Waters Institute, the Hoffman Environmental Research Institute, and the Edwards Aquifer Authority. These institutions offer guidance, educational information, and support. A digital library for karst information from a variety of national and international sources is maintained at The Karst Portal. Researchers are encouraged to consult with these organizations when conducting karst investigations.

Response: connection of two normally divergent structures