

GROUNDWATER MANAGEMENT IN KARST TERRAIN

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ABSTRACT

Many decisions regarding the management of groundwater resources rely upon our ability to predict certain effects of site development, facility operation, or resource utilization projects. Soluble bedrock (karst) settings may present a challenging set of heterogeneous conditions in which conventional predictive techniques may be inadequate. An understanding of the physical nature of the karst subsurface can be useful a) to improve the reliability of predictions and b) to develop a realistic appreciation of inherent uncertainties in predictions of groundwater behavior in karst terrain. It is important to be aware of the underlying assumptions and theoretical or mathematical limitations of predictive groundwater models when utilized in karst settings.

Examples of environmental program areas in which karst phenomena may be significant include:

- Waste management (stability of liner systems; groundwater quality monitoring)
- Environmental cleanup (source identification, assessment of contaminant fate and transport, risk-based corrective action)
- Wastewater management (low-flow estimation; Act 537 assessments)
- Potable water supply (surface water influence; well yield; wellhead protection; groundwater withdrawal effects upon adjacent water resources)
- Mining (dewatering; water supply diminution/degradation)
- Stormwater management (pre- and post-development runoff calculations; stability of channels and impoundments)
- Contingency planning (industrial and hazardous materials; oil spill prevention)

A variety of techniques can reduce the degree of uncertainty regarding the behavior of groundwater flow systems in karst terrain. The results of such studies should include a sensitivity analysis (i.e., self-appraisal of potential areas of uncertainty), which can be either informal or formal in scope.

INTRODUCTION

Virtually every groundwater management activity that we undertake relies, to some extent, upon our ability to predict the behavior of groundwater flow systems. The focus of these predictions can range from natural system behavior to the prediction of the response of groundwater flow systems to transient or long-term stresses, such as pumping stresses, water allocation issues, contaminant transport, and the assessment of human and ecological receptor risk (e.g., risk-based corrective action or RBCA). Depending upon the nature of the individual groundwater management activity, such predictions may be qualitative in nature. However, it is common for a groundwater management decision-making process to involve detailed, quantitative, numerical, predictive statements concerning groundwater flow system performance.

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Areas that are underlain by soluble bedrock (karst areas) often contain groundwater flow systems for which conventional predictive techniques may be inadequate. In some cases, the accuracy and reliability of predictions can be improved through careful investigative and interpretive efforts. Knowledge of certain features of karst terrain can aid in the development of a meaningful, conceptual model of a groundwater flow system. This presentation addresses the following topics and their importance to groundwater management in karst terrain:

- Karst development processes, as they relate to present-day karst subsurface conditions.
- Karst hydrology.
- Distinctive hydrogeologic and hydrologic characteristics of karst watersheds.
- Considerations for numerical hydrogeology and the hydraulic properties of karst aquifers.
- Examples of environmental management program areas in which karst phenomena can be significant.
- Suggested methods that may be used to improve decision-making for groundwater management in karst terrain.

KARST DEVELOPMENT PROCESSES

Karst refers to a set of physical conditions, landforms, and bedrock attributes that may be present in areas that are underlain by bedrock that is appreciably soluble in water. In the eastern United States, the carbonates limestone, dolostone (dolomite) and marble are the most common karstic rocks.

As an illustration of the potential for the alteration of karstic rock, limestone is defined as a calcium carbonate rock that is at least 50 percent soluble in water. In addition to the potential for chemical alteration, all of the insoluble fraction of a karstic rock is subject to physical dislodgment and transport in flowing water.

Bedrock porosity may be:

- primary (1') porosity - porosity in intergranular spaces
- secondary (2') porosity - porosity in discontinuities or breaks in bedrock such as joints, fractures, bedding plane partings, faults, etc.
- "tertiary" (3') porosity - branching, interconnected solution conduits and/or dissolution-enlarged, quasi-planar porosity features generally greater than two millimeters to one centimeter in diameter or width

The generalized process through which karst features develop begins with bedrock that is penetrated by secondary (2') porosity features. Through time, nature and chance favor certain vertical pathways for infiltrating precipitation, which initiates a set of conditions that progressively sculpts bedrock and alters soil structure:

- Dissolution of bedrock begins to enlarge the favored, vertical, 2' porosity features into tertiary (3') porosity features.

- The soil/bedrock surface develops more deeply above the 3' porosity features than at surrounding areas.
- An interconnected, horizontal drainage system develops.
- Dominant 3' porosity features are further enlarged by the effects of hydraulic erosion and scouring.
- Groundwater flow develops a pattern of convergence towards dominant 3' porosity features (solution conduits, dissolution-prone beds, enlarged joints, etc.).

The angle of bedrock dip may significantly affect the development and expression of karst features. A gentle dip (up to approximately 15?) may favor bedrock dissolution and karst features along the strike of certain bedrock units. Steeper dip angles may somewhat inhibit karst development.

Significant void spaces in bedrock may be more likely to occur in certain settings:

- Dissolution-prone beds
- Zones of fracture concentration (sometimes discernible in aerial photographs)
- Faults and associated fault breccia
- Contacts between non-carbonate and carbonate bedrock units or between dissimilar carbonate bedrock units
- Near fold axes or other structural features
- Near regional groundwater discharge points

The factors that produce symmetrical or non-random associations of karst features may be a useful indicator of the general likelihood of the occurrence or tendency for similar karst features to occur in a nearby area with a similar setting.

Speleologists have proposed a number of physical models to explain cave development. A widely accepted theory is for the development of caves at or slightly below the water table surface (shallow phreatic model). In addition, deep (bathypheatic model) caves may develop under certain bedrock settings, such as thin-bedded versus massive bedrock.

Regional uplift and watershed base-level lowering may cause karst solution features to become detached and suspended above the water table surface while new karst features form near the water table surface.

In general, cave maps can be a useful tool to assess the overall structure and form of karst development in an area. Cave maps, in conjunction with geologic mapping, can indicate which bedrock units may be most subject to dissolution and void-forming, and may also indicate the morphology of karst conduits that are smaller in size than caves².

These observations on the development of caves provide an insight into the variety of subsurface solutional forms that may control groundwater circulation in a karst area.

² Most cavers define a cave as a hole or passage in the ground that is big enough for a human to fit into.

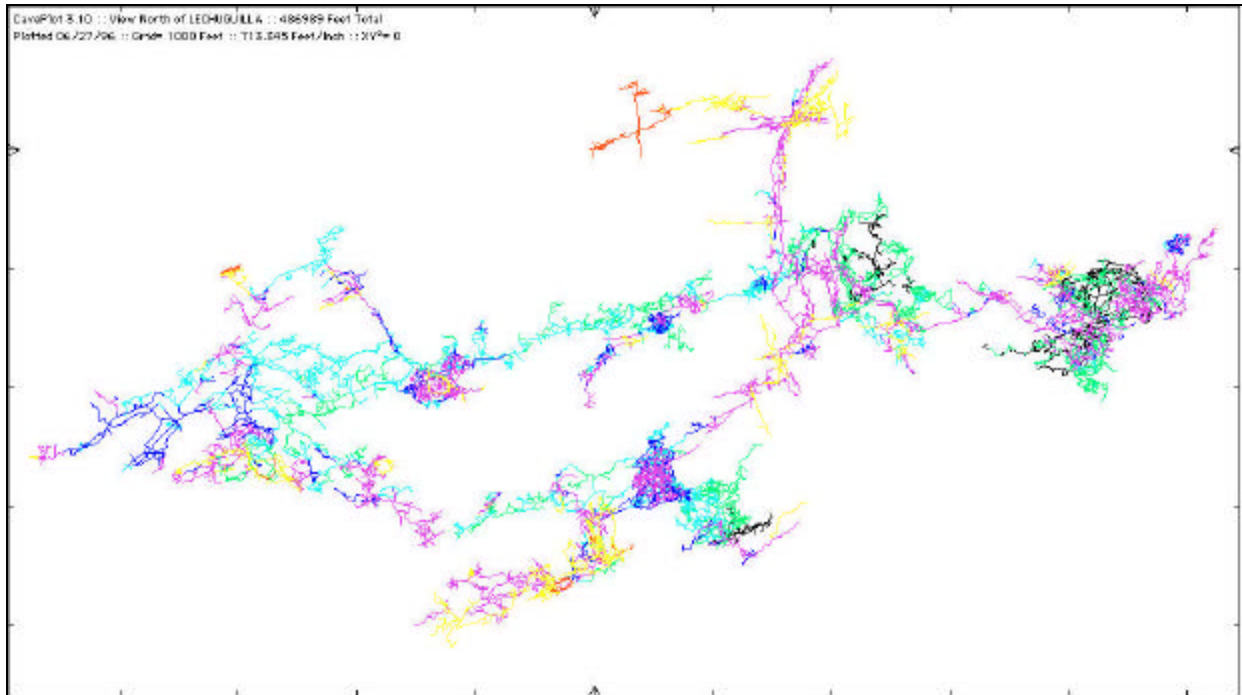


Figure 1. Cave Map of Lechuguilla Cave, New Mexico (from CavePlot® website)

HYDROLOGIC CONSIDERATIONS

Groundwater flow can be characterized into two flow regimes:

- Laminar flow - particles of groundwater tend to flow in parallel flow lines, with no transverse mixing between flow lines
- Turbulent flow – regions of no distinct flow lines, due to eddies (boundary effects) and mixing transverse to the direction of flow.

Groundwater flow in a mature karst region is best described using a “triple porosity” model:

- 1' porosity features contribute little to circulation of water; contribute mostly to storage; slow response to recharge or drainage.
- 2' porosity features contribute to local drainage of groundwater from or toward dominant 3' porosity features; moderate speed of response to recharge or drainage.
- 3' porosity features dominate the overall circulation of water; "first to fill, first to drain"; potentially very rapid, "flashy" response to recharge or drainage; may either drain or recharge 2' porosity features.

Anisotropy and Heterogeneity

Karst aquifers tend to be highly heterogeneous and anisotropic, although karst characteristics and structures are not totally random. Non-random features (e.g., lineaments, regional alignment of joints, aligned sinkholes, fault systems, the outcrop line of dissolution-prone beds, deformation of pumping cones of depression, etc.) may be an aid to building a conceptual model of subsurface hydraulic properties.

The orientation of conduits in the vadose³ zone tends to be controlled by dip, while conduits in the phreatic⁴ zone tend to be controlled by strike. The predominant direction of groundwater movement in the vadose zone is downwards along dip, while the predominant direction of groundwater movement in the phreatic zone is horizontal. These factors can influence contaminant transport, especially where the water table surface is deep.

Thinly bedded rock may exert more strike control on groundwater movement than massive rock for phreatic zone flow. Water-bearing zones may be very prominent in thin-bedded rock, while fractures and fracture-oriented conduits may be more prominent in massive rock.

Assessment of Groundwater Flow Directions

Figure 2 shows a simplified cross-sectional view of a portion of a karst aquifer. In this two-dimensional perspective, groundwater flow is generally toward the central, dominant fracture and conduit system.

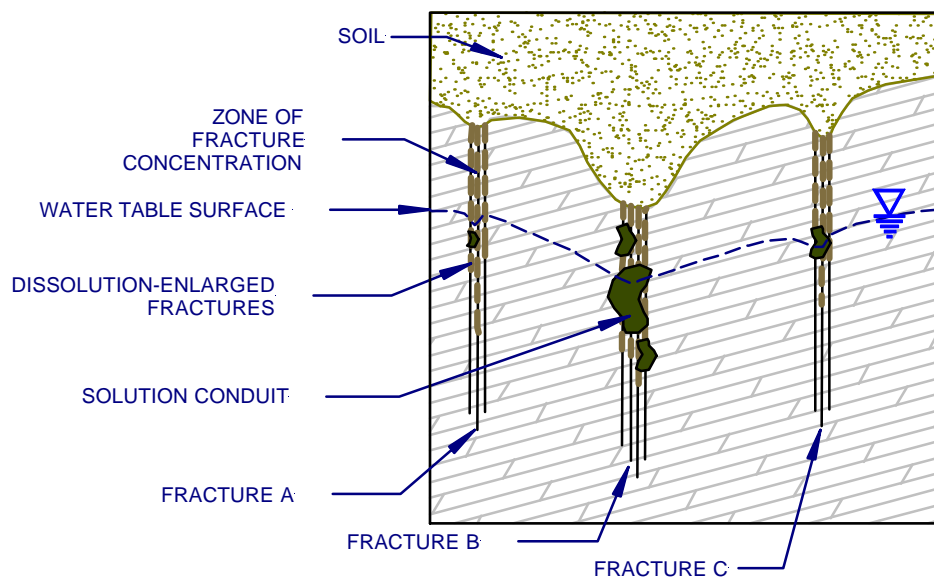


Figure 2. Simplified Cross-Sectional View of Karst Aquifer

³ unsaturated zone above the water table surface

⁴ saturated zone below the water table surface

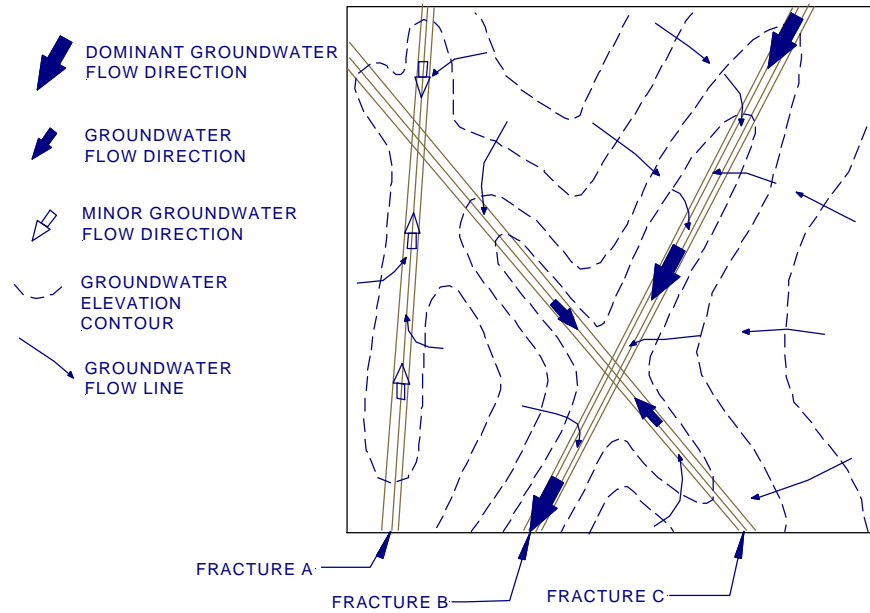


Figure 3. Plan View of Groundwater Flow for Figure 2.

Figure 3 shows a plan view of the three fractures that are shown in Figure 2. In plan view, areal groundwater flow is most strongly influenced by the large fracture-conduit system (Fracture B), but local groundwater flow directions are also influenced by the minor Fractures A and C.

Occam's razor, the principle that the simplest explanation is usually the correct one, seems not to have been written with karst groundwater flow systems in mind, since complex or elaborate explanations for groundwater flow system behavior are not uncommon in karst.

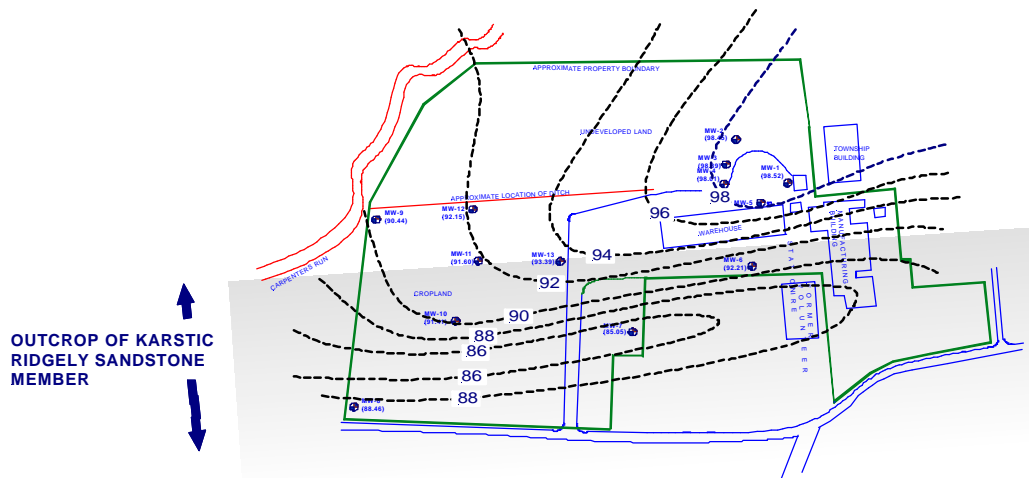


Figure 4. Groundwater Contours for Site Overlying Karstic Ridgely Sandstone

Figure 4. shows a groundwater contour map for a site that overlies the Ordovician Ridgely Sandstone member of the Old Port Formation. The cement for this bedrock member ranges from calcareous to silicious; where calcareous, the cement is often

removed by dissolution from the uppermost 50 to 250 feet of the formation (depending upon bedrock dip and other factors), and the Ridgely Sandstone can be a major avenue for groundwater flow. As of the present (mid-May, 2000), all of the empirical observations from this site (e.g., piezometric data and contours, ephemeral artesian head in confined portions of the Ridgely, groundwater quality isoconcentration contour interpretations, etc.) have been consistent with the conceptual model that was used to draw the Figure 5 water table contour map.

Variable porosity with depth

Because karst dissolution occurs at or near the water table surface, the highest porosity (and zone of most dynamic transport of groundwater) in a karst aquifer is likely to be near the water table surface. “Abandoned” karst features above the water table surface may be dry for most of the year, but may participate significantly in the subsurface transport of stormwater immediately following a precipitation event.

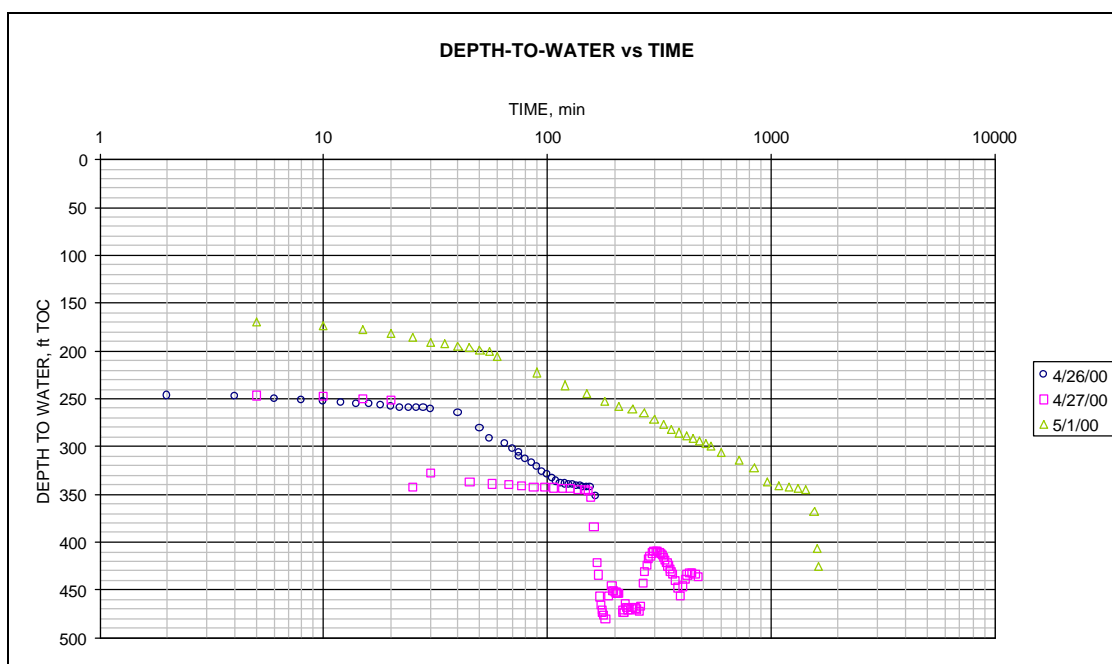


Figure 5. Plot of Depth-To-Water versus Time

The specific capacity⁵ of wells may vary significantly with depth and over time, depending upon the time of year and local groundwater level conditions. Figure 5 is a plot of time versus “depth below ground” that was utilized to identify the position of a high-yield, water-bearing zone for a well that is situated in the Ordovician Nittany Formation. Once the pumping water level dropped below this water-bearing zone (i.e., at 345 feet below grade), the yield of the well decreased by almost two orders of magnitude.

A large-scale example of the phenomenon of pronounced, declining porosity with depth is now under evaluation by a mining company that extracts limestone at a mining facility site in central Pennsylvania. Diminution of local water supply is a sensitive issue for this activity, which penetrated the water table surface many years ago. Anticipating

⁵ yield per unit drawdown; e.g., gallons per minute per foot – usually for a stated duration of observation.

declining porosity with depth, the permit application for deepening the mining area predicted that very little groundwater (in addition to the water already being pumped by the mine) was likely to be affected by the mine deepening activity. A mining permit was issued for a portion of the proposed expansion area, with the condition that groundwater impact issues be studied while the small area was deepened. Thus far, the deepened mine has produced a rate of mine pumpage that is virtually indistinguishable from the pre-deepening mine pumpage.

DISTINCTIVE HYDROLOGIC FEATURES OF KARST BASINS

Springs

Some of the highest flow rate springs in Pennsylvania are associated with karst groundwater flow systems. Springs with direct hydraulic connection with major karst conduits may exhibit "conduit" flow; flow rate may increase dramatically in response to precipitation and then exhibit a similar recession hydrograph to a surface water stream. Springs without such a direct hydraulic connection to karst features may behave as "diffuse" springs; flow is much less responsive to precipitation events.

Water Table Issues

Two interesting, related water table phenomena may occur in karst aquifers. First, the water table surface (as indicated by well inventories) may be highly variable, to the extent that it may be difficult to interpret groundwater contours and groundwater flow paths. A general explanation for this phenomenon is apparent in the hypothetical aquifer cross-section and plan views shown in Figures 2 and 3.

Second, the elevation of the water surface in 3' conduits may be poorly related to or else virtually independent of the apparent "water table" in adjoining areas. This phenomenon is due to the extremely high rate of drainage that is possible in karst conduits, in contrast with the slower drainage that may occur in adjacent 1' and 2' porosity features.

Groundwater Velocity Issues

As the result of patterns of urban growth and development since Colonial times, much of the investigative hydrogeology (contaminant transport, underground storage tanks, etc.) in central Pennsylvania is currently being practiced in river valley settings. Under the "typical" hydraulic conductivity and hydraulic gradient conditions that are encountered in the river valleys in Pennsylvania, the groundwater velocity is typically on the order of a few feet to a few tens of feet per year. In karst settings, groundwater velocity may range from a few centimeters per year in 1' tight rock to many centimeters per second in 3' conduits.

Stormwater

- Runoff generation for a karst area may be dramatically lower than for an otherwise comparable, non-karst area.
- Stream hydrographs may show "flashy" effects of groundwater runoff.

Streamflow

- Karst areas tend to have a lower-than-expected density of surface streams, due to underdrainage in rock.
- Low-flow characteristics are often not well suited to basin area-based estimating methods.

NUMERICAL HYDROGEOLOGY AND KARST

Groundwater models utilize input values (typically taken from published sources or from a limited number of empirical observations) and a set of equations to define the hydraulic characteristics of a 2- or 3-dimensional, physical earth system. Importantly, most models for the simulation of transient (e.g., pumping effects; contaminant transport) or steady-state (e.g., 3-D solutions of the groundwater continuity equation, such as MODFLOW) groundwater flow conditions incorporate underlying, simplifying assumptions and conditions that permit the method to simulate the physical aquifer setting.

Representative examples of these assumptions and conditions for many models include:

- The aquifer has a seemingly infinite areal extent.
- The aquifer is homogeneous and isotropic; transmissivity and storativity values are equal throughout the aquifer.
- Prior to pumping, the piezometric surface in the aquifer is horizontal and stable.
- The aquifer is pumped at a constant rate.
- Wells penetrate the entire thickness of the aquifer.

Together with the requirement that a well that is situated in such an aquifer setting must produce a straight line plot of time (log axis) versus drawdown (normal axis), these assumptions and conditions define an "ideal" aquifer, and very few natural aquifers are "ideal".

Karst aquifers, with their extreme degree of anisotropy and heterogeneity, may exhibit extreme departure from "ideal" aquifer conditions (see Figure 5). In addition, karst effects may be expressed differently when viewed at a local or site-specific scale as opposed to from a more regional perspective. Consequently, hydrogeologists and engineers must often interpret the effects of "non-ideal" aquifer conditions when interpreting the results of pumping tests or analytical/numerical modeling.

In order to utilize a groundwater model effectively, it is imperative that the user understand a few, critical elements that pertain to the model:

- Intended applications for the model
- Simplifying assumptions
- Rationale for assigning input values
- Consequences of departure from "ideal" aquifer conditions

Porous Media Flow

Darcy's law applies to groundwater circulation in 1' porosity features and may also apply to macro-scale groundwater circulation in 2' porosity features;

$Q = K I A$, where

Q = flow (length³/time)

K = hydraulic conductivity (length/time)

I = hydraulic gradient (unitless, or length/length)

A = area through which flow occurs (length²)

Where Darcy's Law applies, flow velocity is directly proportional to hydraulic gradient. Darcy's Law is applicable to laminar flow regimes .

Saturated Conduit (Pipe) Flow

In saturated conduits of various shapes, flow approaches laminar conditions under low velocity conditions, and becomes turbulent under higher velocity. Turbulent flow may be described using the Darcy – Weisbach equation, in which flow velocity is proportional to the square root of the hydraulic gradient.

Open Channel Flow

Hydraulic gradient doesn't exist in unconfined, open channels, and flow velocity is proportional to the square root of the channel slope through equations such as Manning's Equation.

KARST ISSUES FOR GROUNDWATER MANAGEMENT PROGRAM AREAS

Environmental Cleanup and Waste Management

A major concern for environmental cleanup activities in karst terrain is the issue of the validity of monitoring well (quality and piezometric) data. Data from monitoring wells with very low yields in a setting where some wells have high yields should be viewed from the perspective that the well may have poor hydraulic connection with local zones of active circulation of groundwater. In this case, extended well purging may be appropriate prior to groundwater sampling.

It may be useful to utilize a higher burden of proof for the assessment of contaminant transport in groundwater in karst settings, especially if the results of risk-based corrective action (RBCA) indicate that potential receptors are located near the transport pathway. RBCA activities should consider the possibility for error in assessing groundwater flow direction(s) and groundwater flow velocities.

Since 3' karst features may "fill first, drain first", transient groundwater flow direction reversals can occur. This phenomenon should be kept in mind when assessing source migration and contaminant transport issues.

Water Supply

Deformed cones of depression are common in karst areas, and pumping zones of influence can extend much farther than might be expected for non-karst area. For these

reasons, a reliable conceptual model of local and regional aquifer behavior is important for wellhead protection activities. As mentioned previously, it may be prudent to use extra caution in the evaluation of well safe yield in karst, especially if the time-drawdown data for a well are highly non-linear or "stepped".

Surface water influence, an increasingly important aspect of public water supply, may be especially important in a karst area. Although certain karst areas may produce high yields, it is the high yield wells that are most likely to be in direct communication with the dynamic, 3'-porosity features in the subsurface. Because karst areas often have a thin soil cover, infiltrating water may be poorly filtered. High yield wells are therefore more likely to exhibit surface water influence than low yield wells.

Spill Contingency Planning

Federal oil pollution prevention regulations (40CFR112) require certain entities to conduct Spill Prevention, Control and Countermeasures (SPCC) planning. Entities with more than a threshold quantity of oil or with the potential to discharge oil to surface water bodies must prepare and implement SPCC plans. Karst areas tend to have fewer than normal surface water streams, and an individual facility may be situated within a large, depressed area from which there is no apparent surface drainage. In such cases, the lack of apparent surface drainage may occur because there is an established, subsurface, karstic drainage system, with the potential for rapid transport of released oil through the subsurface to regional groundwater discharge points such as springs or seeps.

Stormwater Management

Induced, cover collapse sinkholes are a common result of man's alteration of natural stormwater flow regimes. To avoid the induction of cover collapse sinkholes, it is prudent to:

- keep recharge in uplands areas.
- reduce the convergence and collection of stormwater.
- minimize the depth of impoundments.

RECOMMENDATIONS FOR GROUNDWATER MANAGEMENT IN KARST

Build a Strong Conceptual Model

Since many of the effects of karst on groundwater flow system behavior are not directly observable, it makes sense to build a strong conceptual model of likely aquifer characteristics. Knowledge of potential karst issues will promote sensitivity to aspects of a groundwater management project that might not otherwise be considered.

In building a conceptual or numerical model, one should be alert to the following issues that stem from karst anisotropy and heterogeneity:

- likely morphology of the underlying 3' karst system.
- controlling features of the underlying karst (i.e., bedding control, fracture control, attributes of local and regional groundwater discharge points, etc.).
- regional versus local setting; scale effects.
- declining porosity with depth.

- seasonality of data that are used to build a conceptual model or to assess on-going groundwater flow system or contaminant transport behavior.
- "stranded" or perched karst features.
- transient reversals of groundwater flow directions.
- validity of single well data in a regional context.
- extrapolation (e.g., local versus regional groundwater flow regimes).
- interpolation (e.g., groundwater flow lines that cross apparent karst features).

Be Aware of Areas of Uncertainty

Predictive, groundwater modeling is somewhat comparable to statistical sampling, in that a limited, select group of data (e.g., numerical aquifer attributes) are used to characterize a population (i.e., the hydraulic performance of an aquifer). The reliability of predictions about groundwater flow system behavior are proportional to the precision, accuracy and representativeness of the input data.

Consider the Outcome of Uncertainties

Sensitivity analysis is a statistical tool that can be useful in the assessment of the reliability of a groundwater modeling effort. Using sensitivity analysis, the effect(s) of changing individual inputs or groups of inputs to a mathematical formula are examined.

For example, in Darcy's law, $Q = KIA$, Q (the outcome) is directly proportional to K , I and A ; a +50% error in K will result in a +50% error in Q , a -25% error in K will result in a -25% error in Q , etc. Obviously, errors in terms that appear in a mathematical formula raised to an exponent will have a non-linear effect on the outcome of the calculation. The effects of complex or dependent calculations or models can become quite difficult to evaluate. While the sensitivity of the outcome of groundwater modeling calculations to variations in input parameters can be the subject of theoretical evaluation (based upon the mathematical equations that are utilized), this type of rigorous mathematical analysis is beyond the scope of this presentation (and ordinarily beyond the capability of the author of this paper).

Sensitivity analysis can also be performed very simply using an empirical approach. First, a "base" set of input conditions to a groundwater calculation (or computer model, risk simulation, etc.) are chosen, based upon available data. Next, an upper and lower limit for each of the input conditions may be chosen, based upon professional judgement. Re-calculating (or re-running the computer model, spreadsheet, etc.) utilizing upper and then lower limit values for each parameter will ordinarily yield outcomes (e.g., piezometric head data, contaminant transport values, etc.) that will bracket the "base" set of conditions. This exercise will yield a range of upper and lower outcome values, and will also empirically reveal the input parameters that will produce the greatest variation in outcome (i.e., the input parameters to which the outcome is most "sensitive").