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STRATEGY FOR DEFINITION AND PROTECTION OF EAST TENNESSEE KARST GROUNDWATER BASINS

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Introduction

The bedrock geology of eastern Tennessee is typical of the southern Appalachian Valley and Ridge province. Carbonate beds (limestones and dolomites) of the Knox and Chickamauga Groups are bounded by non-carbonate beds, most of which strike northeast and dip steeply (10°-45°) to the southeast. The carbonate aquifers are maturely karstified and are extremely vulnerable to contaminant infiltration, thus necessitating appropriate land use planning focused on their environmental sensitivity. Urban expansion is resulting in greater land development in karst regions. Planned and existing activities produce wastes that may potentially leach into underlying karst systems. This waste may flow rapidly and untreated for many miles along strike. The potential degradation of aquifers and receiving streams due to the cumulative waste loading of numerous small enterprises may be more environmentally destructive than a few hazardous waste sites. Costs to remediate contaminated water supplies and streams can be in the millions of dollars versus the substantially lower costs of prudent land use planning.

Limestone and dolomite have approximately equal solubility in groundwater, with dolomite being volumetrically more soluble than calcite below 23°C (Palmer and Palmer, 1991). Although the ridge-forming Knox Group dolomites have a greater topographic relief than Chickamauga limestones owing to their greater resistance to weathering, exposure to millions of years of erosion has resulted in both operating as one carbonate hydrologic unit. This fact is amply demonstrated by the abundance of sinking streams, sinkholes, caves, springs, and wells encountering "cavities" in all carbonate units. Most cavities encountered during drilling probably represent dissolution along fractures, bedding planes, and conduits that integrate into connected solution conduit systems (or caves), because the removal of bedrock requires a conduit flow path with one or more spring discharge points.

East Tennessee Karst Aquifers

A strategy to protect karst groundwater basins begins with a conceptual model of the karst systems. Figure 1 is a cross

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section of a typical east Tennessee karst aquifer. The karst system as a whole is a mixed-flow system, containing slow-flow and quick-flow components (Davies, 1992). Infiltration may occur quickly in some portions of the epikarst (e.g., sinkholes, losing streams, and grike infiltration) and slowly in others. Karst aquifers are comprised of a continuum of increasingly more efficient flow paths, from slow-flow in poorly interconnected fractures and phreatic conduits to storm-induced quick-flow in dissolutionally enlarged fractures, bedding planes, and conduits. Most well-developed cave systems comprise vadose components that develop downward and downdip (e.g., northwestern portion of open cavity infeeder extending from conduit well in Fig. 1) until converging into phreatic segments that enlarge along strike, often well below the water table. Groundwater flow, and possibly contaminant transport, can occur along these coalescing flow paths. As aquifer discharge points, springs represent the mixed-flow of various portions of a karst system.

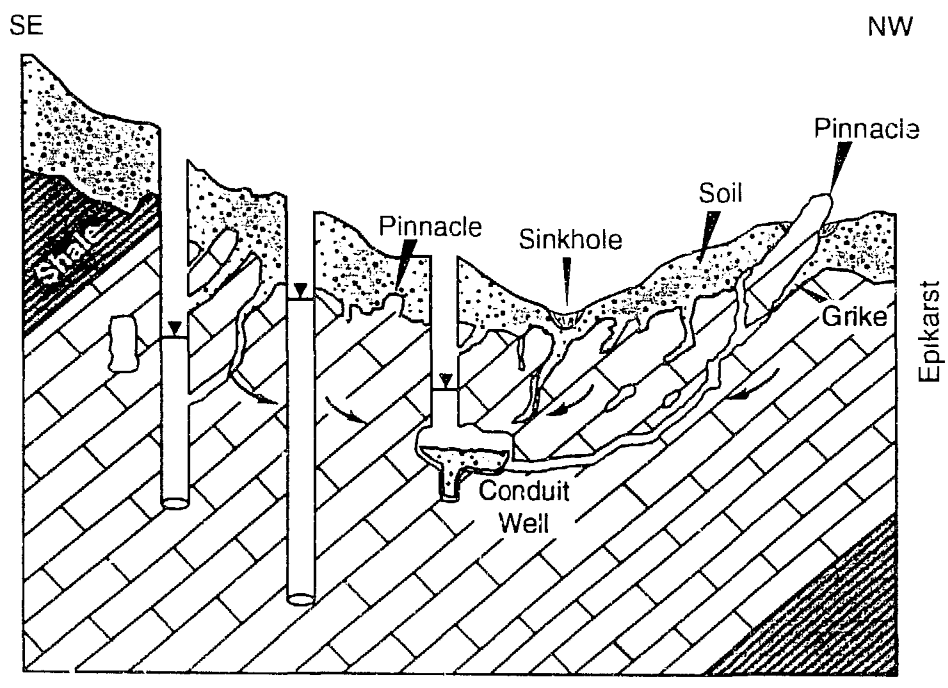

Fig. 1. Schematic showing a typical east Tennessee karst aquifer. The conduit contains mixed-flow integrated from slow-flow components (e.g., poorly interconnected fracture porosity and slow soil water percolation) and quick-flow components (e.g., sinkhole and losing stream recharge, grike infiltration). The flux in the karst system at any given time reflects a continuum of different water velocities. Whereas the discharge in the phreatic conduit normally reflects slow-flow, it may transmit quick-flow during storm events.

Water quality, hydraulic head, and hydraulic conductivity present in individual wells may not permit a true representation of karst aquifer conditions. The reason is that many fractures encountered in boreholes are poorly interconnected within the aquifer. They may comprise the slow-flow zone and may be poorly integrated with other slow-flow or quick-flow portions of the karst network. Figure 1 illustrates how marked water level differences can occur in a physical setting with wells placed only tens of meters apart, where one of the wells intersects a solution conduit. Wells within a few meters of a major flow path may provide no evidence of the existence of a solution conduit; other wells may intersect dissolutionally enlarged fractures. Differences in water levels can occur owing to the substantially different hydraulic conductivity and storativity between fractured bedrock and integrated dissolutionally enlarged fractures, bedding planes, and conduits. These differences in groundwater levels are important to consider when constructing groundwater contour maps.

Groundwater flow in mature karst settings converges toward large phreatic passages where zones of low head attract vadose and phreatic water from surrounding openings (Palmer, 1991). Short flow routes may also occur in the vadose zone, forming canyon-shaped passages in a downdip direction. Cave systems in the Valley and Ridge province can develop spatially, one above another. Often, a continuum of cave evolution may be seen in an area: from relict caves, to shallow caves draining to nearby stream baselevels, to deep master cave systems that may resurge many miles from their recharge areas.

Land Use Planning Above Karst Aquifers

Land use planning and watershed protection in karst groundwater basins must be within the natural constraints of a basin's geology and hydrology (Rubin, 1992). It is critical that the special concerns of karst watersheds be addressed by local planning boards, environmental conservation departments, and other state agencies. For example, towns continue to receive applications for single residences and planned developments atop maturely karstified limestone aquifers. The sale of property downgradient of hazardous waste sources fails to receive sufficient attention. An appropriate land use plan should evaluate the entire karst system, throughout the groundwater basin, before permitting additional development in any isolated segment of the aquifer. This evaluation should include characterizing items such as, the extent of the aquifers' watersheds, geology, flow paths, baselevel, and discharge area. Defining topographic and lithologic basins aids in defining the boundaries of groundwater basins; however, topographic divides rarely coincide with subsurface divides in karst terranes (Quinlan, 1989). Only after such characterization is complete, can the net effects of multiple contaminant inputs on the assimilative capacity of an aquifer be judiciously evaluated. Studies of this nature must not only define the dynamics of the karst system, but land use planners must then use the knowledge gained to protect subsurface and surface water resources.

A full inventory and characterization of karst features is needed to assess the karst system's recharge, discharge, water quality, and environmental sensitivity. Some of the important features and items that should be included in a karst inventory are the locations of 1) sinkholes; 2) caves; 3) springs; 4) sinking streams; 5) seasonally active overflow springs; 6) limited-to-nonexistent surface drainage; and 7) conduit wells. As karst features are added to the inventory, comprehensive evaluation of the importance of each and how they combine to define the hydrology of an area is necessary. Such an inventory is important in focusing future development proposals, in land use planning, and in aquifer characterization.

Because conduits represent significant drainage pathways for karst groundwater basins, determining either the location of solution conduits downgradient of waste sources or at least the springs where conduits discharge is necessary to adequately monitor and characterize carbonate groundwater flow systems. Unlike groundwater flow in porous or uniformly fractured media, preferential flow paths in carbonates cannot be predicted without detailed knowledge of solution conduit pathways (Palmer, 1992). In eastern Tennessee, information on geology (e.g., stratigraphic and structural controls), karst features, and baselevel make it possible to predict general areas of likely aquifer discharge. Spring discharge points for deep flow paths are likely to occur along carbonate strike-bands near a regional baselevel, such as the Clinch River (Rubin and Lemiszki, Fig. 1, this volume) or sometimes at more distant lower baselevels. Occluded conduits and/or shallower conduit flow paths, however, may resurge as springs and underflow in and along smaller surface streams. Conduit pathways may be identified through cave mapping, geophysical surveys, borings, and tracer tests. Tracer tests are particularly important for delineating aquifer flow routes to spring and underflow discharge points. Once discharge points are known, select water quality indicators, as well as suspected and known contaminants, should be monitored during periods of low flow and, most importantly, during short-term flood events. Without this knowledge, a defensible pathways' analysis for risk assessments is impossible.

Base maps should be maintained for plotting karst features. Placing known or suspected contaminant sources (e.g., sinkhole dumps, landfills, waste sites, junk yards) on this base map is also important. Continuous sources of contamination (e.g., feed lots, effluents from large and small industry, garage and dry cleaner effluents) must be placed on this map as well, for in combination, their waste streams may comprise much of an aquifer's contaminant assimilative capacity during periods of base flow. Assessing whether leakage from individual waste masses is likely to have transported contaminants away long ago, or whether waste continually leaches into the flow system, is also valuable. An aquifer's assimilative capacity and vulnerability to contamination requires information on recharge, subsurface flow paths, water quality, storage, and base flow.

An example of the steps involved in proper land use planning is presented using as a model the DOE Oak Ridge Reservation, where groundwater flow in steeply dipping carbonate beds is constrained by non-carbonate lithologic barriers.

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