Exchange of Matrix and Conduit Water with Examples from the Floridan Aquifer

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Abstract

Rapid infiltration of surface water and contaminants occurs in karst aquifers because of extensive conduit development, but contamination of ground water supplies requires loss of conduit water to the matrix. This process is also important for ground water management and for dissolution and diagenetic reactions. Many factors control exchange between conduits and matrix including the head gradient between matrix and conduits, the permeability of the matrix, the gradients of the regional water table and the conduits, and the relative elevation of the conduits and regional water table. The Floridan Aquifer, which is characterized by high matrix porosity and permeability, provides several examples.

INTRODUCTION

Dissolution of soluble minerals and development of conduits within karst aquifers results in high permeability and allows rapid and extensive mixing between surface and ground water (e.g. Kincaid, 1997; 1998). In places, particularly where the aquifers are unconfined, ground and surface water may constitute a single body of water (Katz et al., 1997). Consequently, contamined surface water can readily infiltrate ground water supplies (Field, 1988; 1993). Additionally, surface water is commonly limited in areas of unconfined karst, causing ground water to be the major source of water supplies. Protection of the ground water can be complicated, however, by the lack of correspondence to surface water drainage divides and limited information on subsurface flow paths and rates.

Karst aquifers are characterized by three types of porosity: intergranular matrix porosity, fracture porosity, and large cavernous conduits (e.g. White, 1969; 1977; Smart and Hobbs, 1986). These different types of porosity lead to heterogeneous distribution of permeability and consequently flow rates depend on whether the flow path is through matrix, fractures, conduits, or a combination. Early work on karst systems showed that variations in discharge, temperature, chemical composition, and the saturation state of calcite of spring water could be used to separate flow paths into diffuse versus conduit systems. Diffuse flow systems occur predominately within intergranular and fracture porosity, while conduit flow occurs within conduits (Pitty, 1968; Shuster and White, 1971; 1972; Paterson, 1979). Subsequent work showed that karst aquifers can not be separated simply into purely diffuse or conduit flow but were rather a combination of these two types of flow (Newson, 1971; Ternan, 1972; Atkinson, 1977a;b). This view of karst aquifers suggests that they constitute two component systems, in which a majority of the storage occurs within matrix porosity and fractures, while a majority of the transport occurs in the large dissolution conduits (Atkinson, 1977a). Matrix flow is likely to be laminar, whereas conduit flow will likely be turbulent. Except where noted in special cases, in this paper we will lump the intergranular and fracture porosity within matrix porosity as being distinct from large conduit porosity, essentially separating the two components into laminar and turbulent flow.

Contaminant distribution and flow rates within karst aquifers are clearly influenced by the relative proportions of laminar flow within matrix and turbulent flow within conduits. Surface contaminants will rapidly enter the subsurface conduits through openings such as sinkholes and swallets (Newson, 1971), but if they flow through the aquifers within conduits, they will rapidly be discharged at springs (e.g. Meiman et al., 1988; Ryan and Meiman, 1996; Mahler and Lynch, 1999). By this mechanism, contaminants will affect the surface water quality of the spring runs, but will be rapidly flushed from the ground-water reservoirs with little long term degradation to ground-water supplies. If matrix and conduit water mix, however, contaminants could infiltrate into the matrix, resulting in long residence times within primary karst ground-water reservoirs (e.g. Katz et al., 1999). Consequently, understanding the mechanisms and rates of exchange of conduit and matrix water is vital for karst hydrogeology and water resources of these areas.

EXCHANGE OF CONDUIT AND MATRIX WATER

The importance of conduits for flow through many karst aquifers has focused much research on

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characterizing the conduit plumbing system within the aquifer (e.g. Fig. 1). For example, variations in the chemical composition of spring water provides constraints for mathematical predictions of recharge rates and areas (Dreiss, 1989). This approach has been used successfully in Paleozoic carbonates of southeastern Missouri (e.g. Dreiss, 1989; Wicks and Hoke, 1999).

Variations in spring discharge, coupled with artificial dye tracing, have also been used to create detailed maps of the distribution of conduits and to estimate sizes of conduits and the relative contributions to flow of individual conduits within branched conduit networks (Smart and Ford, 1986; Meiman and Ryan, 1999). Such maps have been created in the Paleozoic limestones of Castleguard Meadows, Canada (Smart and Ford, 1986) and Mammoth Cave, Kentucky (Meiman and Ryan, 1999). In these dense and recrystallized rocks, intergranular matrix porosity is likely to be low, resulting in little matrix water exchanged with the conduits. Thus, the assumption of predominately conduit flow is reasonable for these well-studied Paleozoic systems.

In contrast, conceptual models that are based solely on conduit flow may be invalid in areas where carbonates have high porosity and permeability. Although there will be exceptions, high porosity and permeability are likely to be more common for young carbonates, such as Tertiary carbonate platforms of Florida, Yucatan and ocean islands. In these areas, extensive exchange may occur between matrix and conduit porosity, which would complicate a direct relationship between spring discharge and flow paths (e.g. Martin and Gordon, 2000). Areas that are characterized by significant exchange between matrix and conduits will require an understanding of the extent of the exchange, as well as the mechanisms that may control this exchange.

Possible Controls of Conduit-Matrix Exchange

Several factors are likely to control the loss and gain of water to conduits from the matrix. Most significant is the head gradient between the conduits and the surrounding matrix (White, 1999). At low flow conditions, the conduits will act as a drain from the surrounding matrix, providing a source for base flow from perennial springs (Fig. 2A). At flood conditions, the gradients may reverse, particularly where conduits are fed by allogenic recharge from sinking streams. In this case, the head within the conduit would be greater than the head of the surrounding matrix, causing water to flow from the conduits to the matrix (Fig. 2B). The

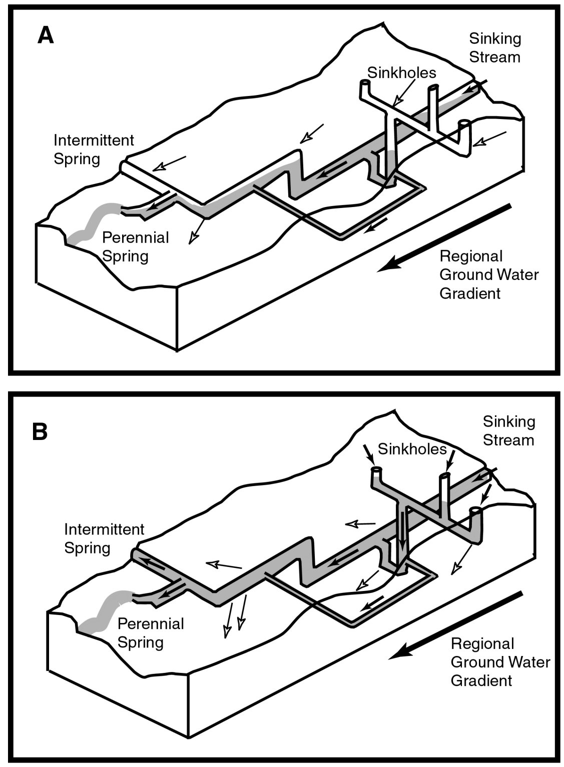

Figure 1 – Generalized diagram of the possible distribution of conduits in a karst region. The distribution of conduits is loosely based on results from Smart and Ford (1986). Solid arrows indicate direction of flow in conduits. **A**. Normal to low flow conditions when water enters conduits from matrix porosity and fractures. Some conduits may be only partially filled. Open arrows reflect flow from matrix to conduits except at constrictions where flow may be from conduit to matrix. **B**. Flood conditions when all conduits are filled from recharge into sinkholes and swallets. If head is sufficient, water would flow from conduits to the matrix, a flow path represented by open arrows. Depending on gradients, this water might become entrained in regional ground water flow.

water lost to the surrounding intergranular porosity and fractures may simply be stored until the head gradients are reversed. Depending on the orientation and magnitude of the regional ground water gradient and the matrix properties, flow of the water could become entrained in the slow laminar flow through the matrix (Fig. 2C).

In addition to temporal variations, the head gradient is likely to be variable along the route of flow within the conduit. These variations will depend in part on the orientation and structure of the conduits (e.g. Fig. 1).

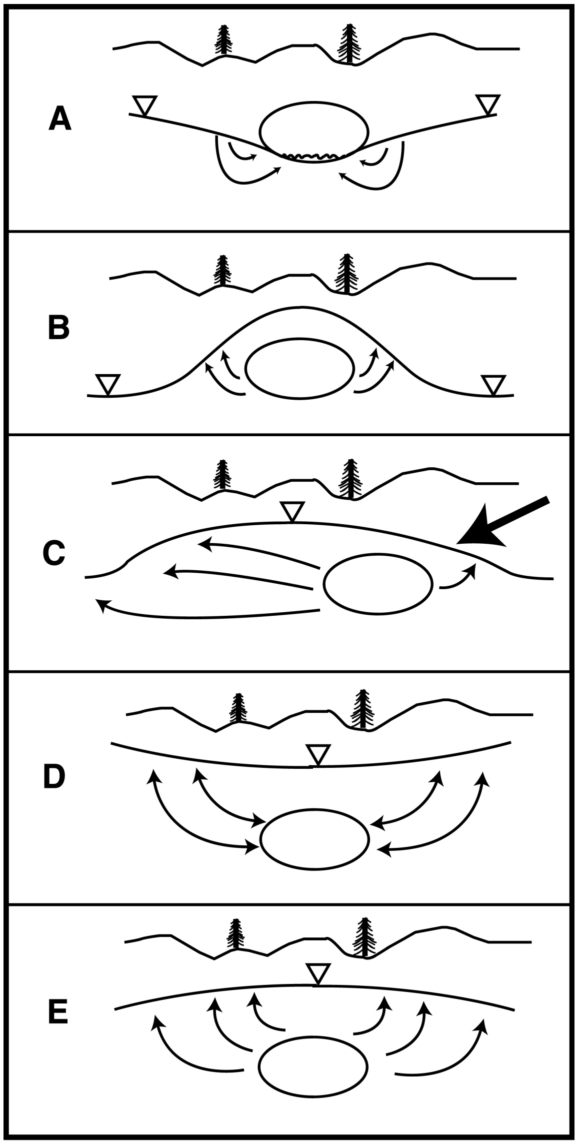

Figure 2 – Schematic and hypothetical examples of various potential controls on exchange of conduit and matrix water. Modified from White (1999). **A.** Base flow and **B.** flood with regional water table below conduit. **C.** Flood with external regional ground water gradient. **D.** Base flow and **E.** flood with water table above conduit level (i.e. permanently saturated).

For example, constrictions could increase the head within the conduits and cause water to flow into the matrix. Below the constriction, where the conduits widen, head in the conduits would be reduced, possibly allowing flow from matrix to conduits.

If conduits are located above the average elevation of the ground water table (i.e. vadose caves), then water is likely to be lost from the conduits during flooding under the force of gravity (Fig. 2A). Furthermore, this water will be permanently lost from the conduits as the flood recedes. Flood conditions within vadose caves are difficult to observe, however, because of complexities associated with fieldwork within flooded caves.

The coupling between the conduits and surrounding matrix is likely to be an important control of exchange between conduits and matrix (White, 1999). This coupling could be controlled by the hydraulic conductivity of the surrounding matrix, as well as the size of the conduits. There will be extensive exchange if the matrix is extensively fractured or dissolved, resulting in increased permeability (e.g. Wilson and Skiles, 1988). For example, as shown in Fig. 2D, water may alternately flow into or out of the conduits depending on changes in permeability of the matrix along the flow paths. Small anastomosing and branching conduits will increase the surface area of conduits relative to their volume, increasing the likelihood of exchange of water with the matrix. Large conduits are thus less likely to exchange water with the matrix than small conduits.

Other factors that could be important in the exchange include the relative elevation of the regional ground-water table and the conduits and slope of the ground-water table and the conduits (Fig. 2). The slope of the conduits and the ground-water table control the rate and direction of flow through the system. Direction of flow of the regional ground water would have to be non-parallel to the orientation of the conduits in order to entrain water lost to the matrix (Fig. 2C). Although regional ground water flow may follow relatively straight flow paths for many kilometers, the orientation of conduits is commonly curved over short distances (e.g. tens to hundreds of meters).

The physical coupling of the conduit-matrix system is clearly not static. Although the physical orientation of conduits and distribution of matrix permeability, which are invariant on short time scales, are important, the exchange of matrix and conduit water must vary with time and magnitude of recharge events. Consequently, observations of exchange between matrix and conduits must be made under widely varying conditions.

EXAMPLES OF EXCHANGE WITH EMPHASIS ON THE FLORIDAN AQUIFER

Flow from matrix to conduits

Some of the first studies to separate spring discharge into conduit and diffuse flow components focused on springs in the fractured limestones of Mendip Hills, England and other regions of Great Britain (Newson, 1971; Atkinson, 1977b). These studies showed that some springs cannot be classified into purely diffuse or conduit flow (e.g. Shuster and White, 1971). In a study of subsurface erosion, Newson (1971) found that water discharging from springs ranged from nearly all allogenic water recharged to swallets (e.g. "quick flow" which would represent conduit water) to nearly all water derived from the matrix porosity (referred to as "percolation water"). Although the fractions of these two water sources ranged widely through the group of springs being studied, they imply that the conduits gain water from the matrix feeding the springs. Similar results were obtained by Atkinson (1977b), who showed that water discharging from springs in the Mendip Hills is sourced approximately 50% from flow through conduits and 50% from slow percolation from the matrix.

Additional evidence for loss of water from the matrix to conduits comes from a study of environmental tracers in the Santa Fe River of north-central Florida (Martin and Dean, in press). Across north-central Florida, the Floridan Aquifer is separated into confined and unconfined portions with the semi-confined boundary referred to as the Cody Scarp (Fig. 3; Puri and Vernan, 1964). Discharge from the Santa Fe River averages ~10 m^3/sec once it emerges from an ~5 km passage underground where it flows across the Cody Scarp (at a first magnitude spring called the River Rise; Fig. 4). Discharge can be extremely variable through time, however, ranging from less than 1 m^3/sec to more than 100 m^3/sec. Furthermore, the discharge increases rapidly downstream from its resurgence point because of numerous springs that flow into the river. Because of the continuous flow of surface water into conduits at the River Sink (Fig. 4), as well as the large variations in recharge from base flow to flood conditions, the Santa Fe River provides an ideal field area to study the exchange of water between conduits and matrix through observations of changes in thermal and chemical compositions of the river water (Martin and Dean, 1999; in press).

At low flow conditions, changes in the natural chemical composition, temperature and discharge volume of the water as it flows through the subsurface towards the River Rise suggest that only 4% of the water is contributed from the river sink, while as much as 96% of the resurgent water comes from other sources (Martin and Dean, in press). The largest source is suspected to be a contributing conduit system, which has recently been mapped by cave divers (Fig. 4). This conduit system receives little direct recharge from the surface and consequently, most of the water in the conduit must derive from the matrix (Martin and Dean, in press). The fraction of river and other water depends strongly on the discharge of the river. At intermediate discharge, the fraction of other water drops to 27% with the remaining water originating from surface water flowing into the River Sink. The fractions of different water sources have not yet been measured at flood stage. These results support findings by Newson (1971) and Atkinson (1977b) that much spring water can originate from the matrix.

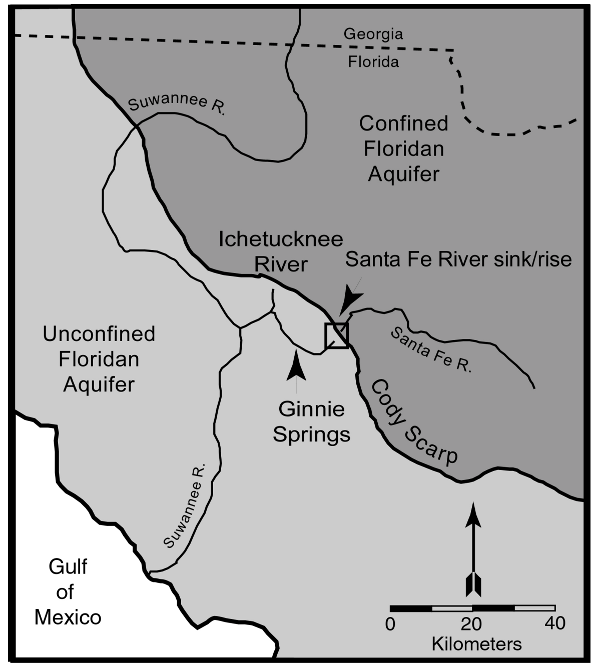

Figure 3 – Regional map of north-central Florida showing the location of three study areas – Santa Fe River sink/rise system, Ginnie Springs system, and Ichetucknee River. The darkly shaded region represents confined Floridan Aquifer and the lightly shaded region represents the unconfined Floridan Aquifer. The boundary is a semi-confined region referred to as the Cody Scarp.

These results also support findings of what appears to be substantial contributions by diffuse flow to springs discharging from the Floridan Aquifer (Martin and Gordon, 2000). The Ichetucknee Springs group discharges along the Cody Scarp to the Ichetucknee River (Fig. 3). Cave diving exploration and dye trace studies indicate that many of the springs in the group are connected to conduits. Annual and storm chemographs reflect little change in the composition of the spring water through time, however, as would be expected from purely conduit-fed springs (e.g. Pitty, 1968; Shuster and White, 1971; 1972). Consequently, the conduits that feed these springs are suspected to be predominantly sourced from the matrix (Martin and Gordon, 2000).

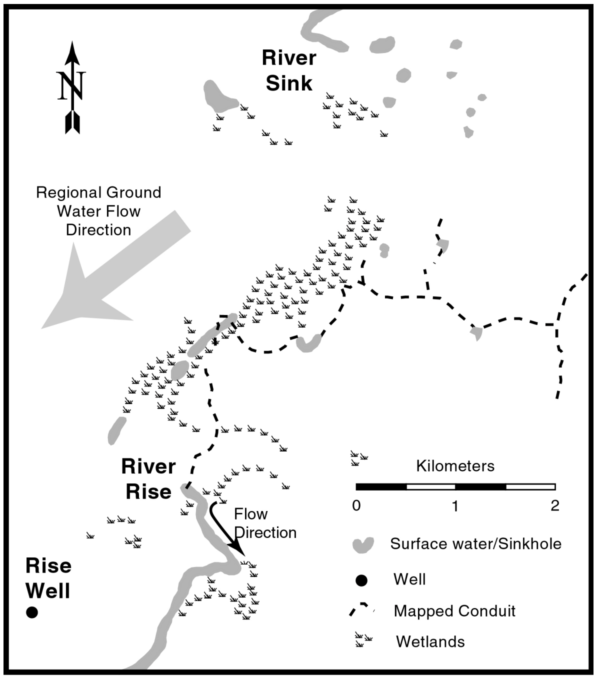

Figure 4 – Sketch map showing the location of Santa Fe River at the sink/rise system, surface water bodies that commonly represent sinkholes, distribution of wetlands and the extent of the mapped conduit system. The river sinks into the subsurface at the location labeled River Sink, and re-emerges at the location labeled River Rise. Modified from Martin and Dean (in press).

Flow from conduits to matrix

The converse situation, where water is lost from conduits to the matrix is more difficult to study and document, but has important ramifications for regional water quality. Contaminants flowing into the conduits would enter the matrix porosity along with the water and subsequently would require long periods of time to be flushed from the system. One possible example of matrix pollution by NO_3 contamination is illustrated by the Floridan Aquifer in north-central Florida where NO_3 concentration of spring water have been increasing through time (Katz et al., 1999). The cause of the elevated concentrations is not clear, and could reflect in part an increasing number of sources. The increase could also reflect slow flushing of contaminated water from the matrix.

The regional ground water chemistry of the Floridan Aquifer provides another example of how surface and ground water may mix by loss of water from conduits to the matrix. Along the Cody Scarp, numerous streams flow into the subsurface through sinkholes and either disappear completely or re-emerge, similar to the Santa Fe River. This allogenic water greatly influences the chemical composition of the regional ground water (Lawrence and Upchurch, 1976; 1982; Upchurch and Lawrence, 1984). A detailed statistical study of the distribution of major and minor element concentration in ground water found that water chemistry is controlled by several types of fluid-solid reactions and sources. In particular, infiltration by surface water along the Cody Scarp leads to water that is undersaturated with respect to carbonate minerals and leads to dissolution reactions and karstification. Much of the recharged water along the Cody Scarp flows into sinkholes and subsequently into conduits. Samples collected from water supply wells typically pump from the matrix porosity, reflecting significant variations in chemical composition of the ground water. These variations in chemical composition across the Cody Scarp qualitatively suggest that water is lost from conduits to the matrix.

Wilson and Skiles (1988) have experimentally studied the question of the loss of water from conduits to matrix. In their study of Ginnie Springs Group in north-central Florida (Fig. 4), rhodamine WT dye was injected into several wells drilled through conduits that range in size from 0.3 to 1.8 m high. Average dye velocities to the discharge point at three springs within the group ranged from 7.7 to 32 m/hr, reflecting primarily conduit flow. Mapped large cave passages are limited in the region, however, suggesting that flow along the entire flow path was not restricted to conduits. In addition, the dye return curves exhibited tails that were 5 times longer than the time between initial return and peak return, further suggesting that some flow occurred through matrix rather than conduits. Wilson and Skiles (1988) suggested that this matrix flow occurred in "sponge-like" dissolutional openings, and concluded that the flow was darcian in character.

Martin and Dean (in press) found that water in a water supply well located down the regional gradient from the conduits at the Santa Fe River became increasingly dilute in the concentrations of conservative solutes following a major flood (Fig. 3). This dilution was interpreted to suggest that water was lost from the conduits during the flood. On the basis of the observed time lag, Martin and Dean (in press) estimated that the rate of flow through the matrix was on the order of 0.4 to 2.7 m/hr. Although this range is an order of magnitude slower than that observed by Wilson and Skiles (1988), some of the flow they measured must have occurred as rapid flow through conduits. It is also likely that the matrix permeability of the Floridan Aquifer varies greatly over short distances. The temporally and spatially variable loss of water from conduits to the matrix may be an important control on the distribution of chemical compositions across the

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region, as was observed by Upchurch and Lawrence (1984).

SUMMARY

Although conduit-based models may be appropriate for low matrix permeability and porosity limestones, several studies of flow in karst aquifers suggest that significant volumes of water are exchanged between matrix and conduits. Quantifying this exchange is critical for developing conceptual and numerical models of contaminant transport and storage and the management practices in these aquifers. The number of studies is relatively limited, however, indicating the need for additional work. For example, the parameters that control the direction of water exchange, i.e. whether it is lost or gained from conduits, are currently poorly constrained. Controls include the permeability and distribution of fractures in the matrix, the gradient of conduits and regional water table, the variations in sizes of the conduits, the orientation of regional ground water flow relative to that of the conduits, and the extent of recharge into sinkholes.

Particularly important to assessing water quality in karst areas will be the ability to determine the volume of water lost from conduits to the matrix. This water has the greatest potential for dissolution of the matrix porosity, as well as contamination of the water in the matrix porosity, commonly the primary water supply. It is difficult to measure the volume of water lost to matrix because mixing within the matrix is slow, resulting in heterogeneous water composition, and environmental and the large volumes of water stored in the matrix porosity can dilute injected tracers. The Floridan Aquifer, with high matrix porosity and permeability provides an ideal location to determine the potential for the magnitude of this exchange.

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