Complex Radial Flow of Ground Water in Flat-Lying, Residuum-Mantled Limestone in the Arkansas Ozarks.

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Abstract

Complex radial ground water flow characterizes an area surrounding a proposed landfill near Pindall, Searcy County, Arkansas. Six ground water traces using fluorescein and rhodamine WT dyes have been conducted in the study area. Dye injection sites have included sinkholes and losing stream segments. Tracer dyes have been recovered from several springs and wells.

This paper discusses mechanisms involved in the radial flow patterns observed in the study area. The mechanisms include appreciable water level fluctuations, localized ground water input points, conduit flow conditions, and localized areas of deep ground water circulation.

A graben, bounded by the St. Joe and Mill Creek Faults, bisects the study area. Ground water tracing has demonstrated that ground water flow occurs both along and across the faults. Deep vertical water movement along the fault zone and some fracture traces and lineaments in the area is inferred from the ground water tracing results.

Tracer dyes from three separate traces were recovered from the SPG Well. This public water supply well contains 500 feet of pressure grouted casing. The well, which is located in a losing stream valley, was intentionally located on a lineament in an effort to maximize water yields. Based upon ground water tracing results, 13.4 square miles of land lie within an area which should be viewed as the wellhead protection zone for this well. The entire area can contribute water rapidly to the well.

Mitch Hill Spring, located 2.3 miles south of the east-west trending fault zone, is the lowest elevation drainage point for the karst ground water system. Mitch Hill Spring is a major tributary to the Buffalo River in a river segment included within the Buffalo National River (a unit of the National Park System). The recharge area delineated for this spring encompasses 20.8 square miles.

Introduction

The study area encompasses 20.8 square miles of land which contributes recharge waters to Mitch Hill Spring. The area is near Pindall, Searcy County, Arkansas, and lies north of the Buffalo National River, a unit of the National Park System. Roughly, the south half of the study area is topographically tributary to the Buffalo River, and the north half is topographically tributary to the White River via Crooked Creek. The town of Pindall is located in the valley of Clear Creek, a surface tributary to Crooked Creek.

The area is sparsely populated, and most of the land is forested with oak-hickory stands predominating. There is a substantial amount of land in the northern part of the study area which has been converted from woodland into permanent pasture for livestock production. Row crop agriculture in the area is negligible.

Bedrock outcrops in the area are rare. Cherty to very cherty soils and residuum characterize the area, and can reach depths of 50 feet on some ridge tops and upper slopes.

Most of the area is underlain by the Boone Formation of Mississippian age. It consists of micritic limestone and chert; in some occurrences the chert may comprise as much as 60 to 70% of the rock. The total thickness of the formation in the area exceeds 250 feet.

The Everton-St. Peter Formations underlie the Boone Formation. Some of the valleys in the study area are entrenched into the Everton-St. Peter Formations. These formations contain interbedded dolomites and sandstones for most of the portions exposed in the study area.

Deep alluvial deposits fill many of the valleys. As an illustration, wells in Pindall have commonly encountered at least 30 feet of alluvium. Some of these wells, which are commonly 60 to 100 feet deep, may bottom in alluvium or residuum.

As much as 80 to 100 feet of the Batesville Formation remain in the Mill Creek Graben. The graben will be discussed shortly. The Batesville Formation, which is younger than the Boone Formation, consists of a medium-grained micaceous slabby sandstone in beds from 4 inches to two or three feet thick.

The Mill Creek Graben bisects the study area and ranges from 1,500 to 2,000 feet wide. The graben, which trends roughly east-west through the study area, is bounded on the north by the St. Joe Fault and on the south by the Mill Creek Fault. Both of the faults extend for about 15 miles (McKnight, 1935). In the study area the fault throw on the north side of the graben ranges from 150 to 350 feet; the fault throw on the south side of the graben ranges from 80 to 150 feet (McKnight, 1935).

Beds north of the graben dip gently to the north; those south of the graben dip gently to the south. Dips in the region are typically about 100 feet per mile. Geologic studies by Thomson (1985) concluded that "...the Mill Creek Graben in the area south of Pindall seems to be in an area of uplift in which fault movement occurred along the St. Joe Fault and the Mill Creek Fault allowing the center of the uplift to drop and the sediments both to the north and to the south to dip away from the graben. Because of the uplift and faulting, the rock is cut by many lineaments (probably fractures), most of which seem to be parallel to the fault trend and to the northeast".

Some sinkholes exist in the study area, but they are not common. Most are not large enough to appear on 7.5 minute topographic quadrangle maps with 20 foot contour intervals. The largest sinkholes found in the area are along the Mill Creek Fault; however, not all of the sinkholes in the area are associated with faults.

Essentially all of the streams in the study area are losing streams (they lose surface flow to the ground water system). Surface flow in many of the streams will last for less than 24 hours after a major rainstorm. One major losing stream in the area is Mill Creek; this stream flows eastward for about five miles along (and generally within) the Mill Creek Graben. Another major losing stream is Clear Creek; much of this stream follows lineaments and fracture traces identified from aerial photos.

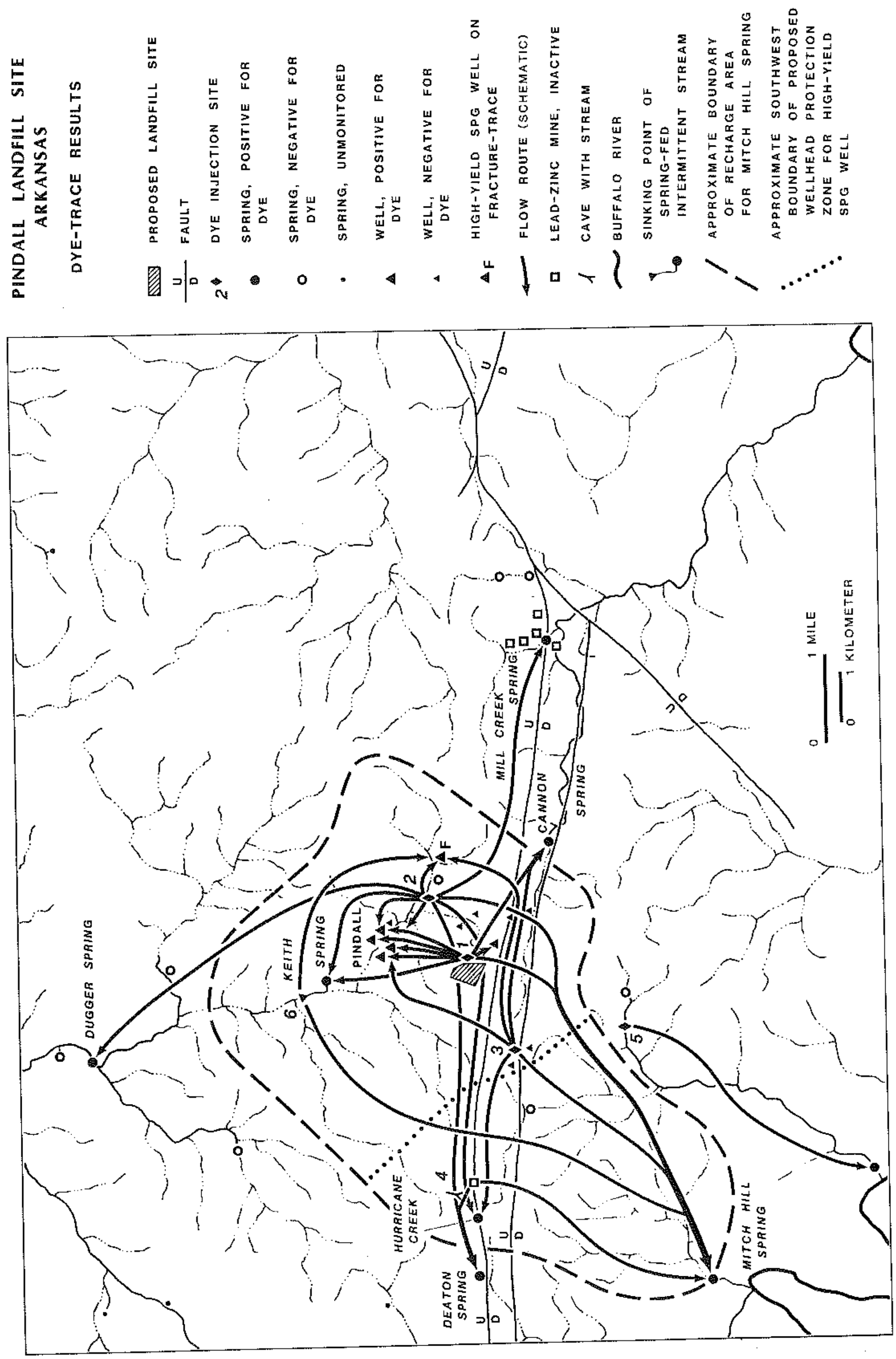
Various forms of evidence suggest that the fault zone is particularly cavernous. Substantial zinc and lead mining has occurred along and near the St. Joe Fault (McKnight, 1935). One of the mines encountered a sizeable cave passage with numerous stream-rounded pebbles; another mine encountered heavy flows of ground water which interfered with operations (McKnight, 1935). Eighty-five wells within 1.25 miles of the proposed landfill were inventoried (Aley, 1985). Of the 10 drilled wells in or near the fault zone, eight of them encountered caves. A log for one of these wells (the well nearest the proposed landfill) recorded six separate cavities with heights ranging from 2 feet to 17 feet; cavities represented 57 feet of the total 185 feet of well depth. In contrast, only five of the 75 wells away from the fault zone reportedly encountered caves.

Ground Water Tracing

Six ground water traces were conducted in the study area using fluorescein and rhodamine WT dyes. Dye tracing procedures generally followed those outlined in Aley and Fletcher (1976) and Aley et al. (1988). Packets of activated coconut charcoal were placed in springs, streams, and in waters pumped from wells for various periods of time ranging from a few days to a couple of weeks. The packets were periodically collected and eluted with an aqueous ammonia and isopropyl alcohol solution for one hour. A sample of the eluting solution was analyzed in a Shimadzu RF-540 spectrofluorophotometer using synchronous excitation and emission scans with a 17 nm separation to detect either of the tracer dyes. The first ground water trace used potassium hydroxide in isopropyl alcohol as an eluting solution and visual detection procedures; the results were verified with the RF-540.

Figure 1 depicts the results of the six ground water traces. Arrows are drawn schematically from the point of dye injection to the points of dye recovery. The six dye injections resulted in 26 separate dye recoveries from eight springs and seven wells in the area. Each dye injection is given a sequential reference number; the numbers are used below and are identified on Figure 1.

Figure 1. The Study Area and Successful Ground Water Traces.



Three of our dye injections provided good examples of radial ground water flow. These were injections 1, 2, and 3. Table 1 summarizes all successful ground water traces in the study area.

It should be noted that Mitch Hill Spring is located at the lowest elevation of any of the dye recovery sites. Based upon mapping by McKnight (1935), Cannon Spring is located on or very near the Mill Creek Fault and Deaton Spring #1 and Mill Creek Mine Spring are both located on or near the St. Joe Fault. The SPG Well is located on or near the intersection of a lineament and a fracture trace (Thomson, 1985). This well was intentionally located at this intersection in an effort to maximize water yields (Ogden, 1980).

Table 1.
Successful Ground Water Traces in the Study Area

Injection 1. Holder Sinkhole.
A shallow sinkhole in the floor of an unnamed tributary to Clear Creek. The sinkhole is adjacent to the proposed landfill.

Dye Recovery Site	Distance and Direction from Injection Site	Time of First Dye Arrival (Days After Injection)
Holder Well	1,500 ft. south	within 5 days
Cannon Spring	11,400 ft. southeast	3 to 5 days
Keith Spring	8,400 ft. north	26 to 33 days
Young Well	5,250 ft. north	38 to 41 days
Henson Well	5,200 ft. north	38 to 41 days
Herron Well	5,300 ft. north	38 to 41 days
Nichols Well	4,800 ft. north	38 to 41 days
Mitch Hill Spring	23,500 ft. southwest	about 61 days

Table 1 (Continued).
Successful Ground Water Traces in the Study Area

Injection 2. Clear Creek below Wylie Spring.
A losing stream segment.

Dye Recovery Site	Distance and Direction from Injection Site	Time of First Dye Arrival (Days After Injection)
Wallace Well	4,000 ft. northwest	within 7 days
Keith Spring	8,100 ft. northwest	within 7 days
Dugger Spring	21,800 ft. northwest	within 7 days
SPG Well	1,600 ft. southeast	within 7 days
Mill Creek Mine Spring	16,300 ft. southeast	7 to 14 days
Mitch Hill Spring	28,700 ft. southwest	14 to 21 days
Upper Hurricane Creek Springs	18,600 ft. west	14 to 28 days
Deaton Spring #1	22,700 ft. west	21 to 28 days

Injection 3. Kilburn Sinkhole.
A sinkhole on or near the Mill Creek Fault.

Dye Recovery Site	Distance and Direction from Injection Site	Time of First Dye Arrival (Days After Injection)
Wallace Well	9,900 ft. northeast	within 7 days
SPG Well	12,200 ft. northeast	within 7 days
Deaton Spring #1	12,700 ft. west	within 7 days
Cannon Spring	15,700 feet east	7 to 14 days
Mitch Hill Spring	17,800 ft. southwest	7 to 14 days

Injection 4. Hurricane Mine.
Partially filled open pit of the Hurricane Mine.
Located on the St. Joe Fault; waters rapidly sink into ground water.

Dye Recovery Site	Distance and Direction from Injection Site	Time of First Dye Arrival (Days After Injection)
Deaton Spring #1	4,800 ft. west	within 36 days
Mitch Hill Spring	15,100 ft. southwest	36 to 65 days

Table 1 (Continued).
Successful Ground Water Traces in the Study Area

Injection 5. Cave Spring Hollow.
Losing stream segment of Cave Spring Hollow downstream of Cave Spring.

Dye Recovery Site	Distance and Direction from Injection Site	Time of First Dye Arrival (Days After Injection)
Mouth of Cane Branch	17,000 ft. southwest	within 13 days

Injection 6. Clear Creek below Keith Spring.

Losing stream segment of Clear Creek. The entire flow from Keith Spring sinks in this area for a few days prior to the rather abrupt end of discharge from Keith Spring.

Dye Recovery Site	Distance and Direction from Injection Site	Time of First Dye Arrival (Days After Injection)
Mitch Hill Spring	29,000 ft. southwest	within 13 days
SPG Well	10,600 ft. southeast	13 to 24 days

Discussion of the Results

Directions of some ground water flow in the study area apparently change with changes in hydrologic conditions. This is indicated by two observations.

Dye injection 1 is located near the eastern boundary of a proposed landfill. Three monitoring wells were drilled near the perimeter of the proposed landfill and water levels in these wells were measured. Let us assume that these three monitoring wells provide a general depiction of the orientation of the water table; this is an admittedly questionable assumption in a karst area. However, what we find from water level data on the three wells is that, during wet-weather conditions, the apparent water table beneath the landfill area slopes northward (away from the Mill Creek Graben). During dry-weather conditions, the orientation of the water table is reversed almost 180 degrees; it slopes southward (toward the Mill Creek Graben) under these conditions.

Keith Spring is located north of Pindall. Two successful ground water traces to this spring (injections 1 and 2) demonstrate that most of the recharge area for this spring lies south of the spring, thus the dominant direction of ground water flow to this spring is northward. Injection 6 was made at a site about 1100 feet north of Keith Spring; the injection site was the point at which waters from Keith Spring were sinking into the channel of Clear Creek. None of the dye injected at this site was recovered from springs to the north of the injection site (including Dugger Spring which received dye from injection 2). Instead, the dye from injection 6 was recovered at Mitch Hill Spring (located to the southwest of the injection site), and at the SPG Well (located southeast of the injection site).

Large volumes of water enter the ground water system along the Mill Creek Graben during periods of wet weather. The stream channel of Mill Creek, which traverses a major segment of the graben, has high permeability and is supplied with large volumes of runoff water. One would thus expect appreciable increases in water level elevations along and near the Mill Creek Graben during storm periods.

Our ground water tracing has shown that about 4.7 miles of the Mill Creek Graben lies in the recharge area for Mitch Hill Spring. Surface stream elevations in the portion of the graben supplying water to Mitch Hill Spring range from 950 feet to about 1,250 feet. The elevation of Mitch Hill Spring is 720 feet; this is one of the largest springs in the Buffalo River Basin. The flow of this spring was 13.2 cubic feet per second (cfs) on May 31, 1986; it was 7.4 cfs on July 9, 1986; and it was 1.92 cfs on August 12, 1987. Ground water gradients along solutional conduits feeding karst springs are often very gentle (gradients of only one or two feet per thousand feet have been noted). In view of this, and the fact that the distance from the graben to Mitch Hill Spring ranges from 14,000 to 30,000 feet, water levels in the graben could be substantially lowered during dry weather conditions by water discharges through Mitch Hill Spring.

Three other springs also drain those portions of the Mill Creek Graben within the delineated recharge area for Mitch Hill Spring. Deaton Spring #1 is located west of the delineated Mitch Hill Spring recharge area. Cannon Spring and Mill Creek Mine Spring are both located east of the delineated Mitch Hill Spring recharge area. All three of these springs are located in close proximity to the St. Joe Fault. Dye from injections 2, 3, and 4 was recovered from Deaton Spring #1. Dye from injections 1 and 3 was recovered from Cannon Spring, and dye from injection 2 was recovered from Mill Creek Mine Spring. It is noteworthy that injection 3, which was located on or near the Mill Creek Fault and near the center of the delineated recharge area for Mitch Hill Spring, yielded dye to springs located both east (Cannon Spring) and west (Deaton Spring #1) of the Mitch Hill Spring recharge area boundary.

Combining wet-weather and dry-weather conditions, and other factors noted above, it is clear that there could be appreciable ground water level fluctuations in the graben. I believe this to be the actual case. Furthermore, it is likely that there are multiple solutional channel flow routes which can be utilized by waters moving from the Mill Creek Graben to Mitch Hill Spring. These conduits will occur at different points and different elevations and will have different flow capacities.

I anticipate that water level elevations in these recharge areas vary substantially with seasonal changes; this type of situation is commonly encountered in karst areas. As an illustration, water level fluctuations can exceed 40 meters in 24 hours in a well in the recharge area for Ombla Spring in Yugoslavia; seasonal fluctuations in this well can exceed 130 meters (Milanovic, 1981). Rapid and major changes in water level elevations are undoubtedly an important mechanism for explaining apparent reversals in ground water gradients in the study area in Arkansas.

Fracture traces and lineaments are readily discernable on aerial photos of the study area. There is extensive literature (such as Parizek, 1976; Wagner et al., 1976) indicating that fracture traces and lineaments in carbonate rocks are typically areas of greater well yields. In the Ozarks, these features are commonly associated with springs. In northwest Arkansas, ground water supplies along lineaments and fracture traces are commonly more susceptible to contamination than are ground waters in adjacent areas (Wagner et al., 1976).

Thomson (1985) mapped lineaments and fracture traces in a portion of the study area. Many of these features parallel the St. Joe and Mill Creek Faults or else have a northeasterly trend.

One of the major lineaments in the study area is oriented along a portion of the Clear Creek valley southeast of Pindall. The SPG Well, the public water supply for three communities, was intentionally located at the intersection of this lineament and an intersecting fracture trace in an effort to maximize water yields.

The SPG Well is located on a low terrace in a losing stream segment of Clear Creek. The well contains 500 feet of pressure grouted casing; the total depth of the well is 2,170 feet. At the time of well completion in January, 1982, the static water level in the well was 275 feet below the surface (the elevation of the static water level was thus 865 feet). The elevation of the bottom of the casing is 640 feet. While there can always be problems with the leakage integrity of any pressure grouted casing, we have no reason to suspect any significant problems with the casing or grouting in the SPG Well.

Water from the SPG well is chlorinated prior to distribution. During our ground water tracing work we sampled water from this well at the nearest private connection. An outside hydrant was allowed to flow about at a rate of about 1 gallon per minute; the flow was passed through a packet of activated charcoal.

Dye from injections 2, 3, and 6 was recovered from the SPG Well. The concentrations were always small, but chlorination does destroy some of the tracer dyes. The presence of tracer dyes in this well demonstrates that ground water circulation extends to more than 500 feet below the floors of major losing stream valleys in the study area.

Some workers in the Ozarks have assumed that each identified geologic mapping unit typically represented a separate aquifer. Sometimes units are grouped to produce two or more superimposed aquifers. While there may be hydrogeologic utility in this characterization, it frequently leads engineers and geologists into the routine presumption of negligible vertical interconnection of ground water systems in the region.

The recovery of dye at the SPG Well from three separate injections clearly demonstrates that deep and rapid ground water circulation occurs within the study area. Data on these three traces are shown in Table 2. The reader should keep in mind that the surface elevation of the SPG Well is 1140 feet, and the elevation of the bottom of the pressure grouted casing is 640 feet. For comparison, the elevation of Mitch Hill Spring is 720 feet.

Table 2
Summary of Dye Recoveries at the SPG Well.

Injection Site	Surface Elevation of Injection Site	Time of First Dye Arrival at SPG Well	Straight Line Distance to SPG Well
#2 Losing segment of Clear Cr.	1,095 ft.	Within 7 days	1,600 ft.
#3 Sinkhole nr. Mill Cr. Fault	1,240 ft.	Within 7 days	12,200 ft.
#6 Losing segment of Clear Cr.	1,005 ft.	13 to 24 days	10,600 ft.

In general, static water level elevations in wells in the study area tend to decrease with increases in the depth of the well. As an illustration, the reported static water level in the SPG Well at the time of well completion was at elevation 865 feet. Private wells in the vicinity with minimal amounts of casing have water levels which are at least 100 feet higher than this.

What is the nature of the flow system which conveys waters from the surface into the SPG Well with the rapidity discovered in our tracing work? We are dealing with straight line velocities as great as 1,750 feet per day or more. This obviously requires a solutionally widened system of karst conduits of major lateral extent. The ground water tracing data clearly indicate that such a system exists within the Mill Creek Graben and/or along the boundary faults. The SPG Well is located about 4,900 feet from nearest point on the Mill Creek Graben. Solutional openings along mapped fracture traces and lineaments in the area may provide much or all of the connections between the graben and the SPG Well.

It seems likely that deep circulation of ground water in the study area occurs primarily at localized sites along or near faults, lineaments, and fracture traces. If this is the case, there should be shallow ground water flow moving toward those faults, lineaments, and fracture traces which provide zones of deeper water circulation. With such a system, flow directions could readily change with changes in the flow rates of the various solutional conduits or with the total volume of flow. Based upon mapping of lineaments and fracture traces in a major portion of the study area (Thomson, 1985), there are essentially no areas located more than 1,200 feet from an identified fault, lineament, or fracture trace. If faults, lineaments, and fracture traces provide localized sites for deep ground water circulation, the area would be characterized by an extremely complex ground water flow system. Furthermore, these fracture zones would create a system in which radial ground water flow patterns from localized ground water input points would be a common situation.

Protection of Ground Water Quality

This paper has documented the complex ground water flow which occurs in an area of relatively flat-lying soluble rock units in the Arkansas Ozarks. Extensive ground water tracing in the study area has demonstrated complex radial flow, deep ground water circulation, and seasonal changes in ground water flow directions.

The delineated recharge area for Mitch Hill Spring comprises 20.8 square miles. Our dye tracing results demonstrate that 13.4 square miles of this area also contributes water to the SPG Well, a rural water district well which is the sole public water supply for three communities in the region. Tracer dyes injected into recharge waters entering the ground water system over 12,000 feet away have reached this well within 7 days.

The SPG Well contains 500 feet of pressure grouted casing; the well is located at or near the intersection of a lineament and a fracture trace. Our ground water tracing results indicate that protection of water quality in this well will require designation of the 13.4 square mile recharge area for this well as the wellhead protection zone. Wells on fracture traces and lineaments in karst areas may require particularly large wellhead protection zones.

It should be noted that the proposed landfill (which has now been denied a permit because of the impacts it would have had on Mitch Hill Spring and the Buffalo National River) is located within the area which should be designated as the wellhead protection zone for The SPG Well. During the design and review process, the landfill proponents and Arkansas regulatory agencies essentially ignored hydrologic assessment approaches appropriate to karst terranes; reliable monitoring is discussed by Quinlan and Ewers (1986). Had it not been for third party studies of the proposed landfill, and associated legal action, a landfill would have been located in the midst of an area which recharges water to a public water supply well and a major spring feeding the Buffalo National River.

A question for the future is whether the ground water system we have described is a unique occurrence, or whether it is a common occurrence in the Ozarks which is depicted uncommonly well in the study area. I suspect the latter, and urge other workers to consider similar situations elsewhere in the Ozarks and in other karst areas. It should be noted that, while mapped faults are not particularly common in the karst regions of the Ozarks, lineaments and fracture traces are almost always present.

Acknowledgements

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