Ground-Water Quality and Geochemistry in the Strawberry River Watershed in Northeast Arkansas

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Acknowledgments

The present report on ground-water quality and geochemistry in the Strawberry River watershed was part of a larger 319 non-point source study of both surface and ground water, and was funded by federal Environmental Protection Agency 319 nonpoint source program funds. The Strawberry River watershed nonpoint source assessment took place over a two-year period, and included an aquatic macroinvertebrate survey, a land-use survey, a stream-bank stability analysis, and a fish community survey, in addition to surface- and ground-water quality analysis. A report documenting results of the entire investigation is slated for completion in the spring of 2004, and will be placed on the Arkansas Department of Environmental Quality website.

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BACKGROUND

Ground water has been an integral part of the growth of communities in the Strawberry River watershed since the early 1800's. Residents within the study area recall childhood memories of Sunday (and special event) gatherings around major springs in Calamine (Harry Howard, resident, personal communication) and Wiseman (Bobby Bookout, resident, personal communication) in the early 1900's. The perennial springs furnished ample amounts of water for drinking, cooking and cleaning at these events, and water was hauled throughout the year from the springs for domestic use by many of the early settlers in the area. The Wiseman town spring was used by residents to refrigerate their milk and other perishables prior to modern refrigeration techniques. The spring also supported a small cannery, a grist mill, and served as a water source for many residents when dug cisterns went dry. The town of Evening Shade clearly illustrates the importance of many of the larger springs in the area since the early and later part of the 1800's. In 1817, a cabin, grist mill and sawmill were erected by a Captain James Thompson in a tributary fed by a large spring. The immense popularity of the mill fueled early growth in the region, and Captain Thompson petitioned for a post office, listing as the name of the town, Evening Shade. Further growth resulted in the establishment of a store on a spot near Plum Spring, which became the focal point of all activity in the area. Plum Spring eventually grew into what is now the town of Evening Shade, and a rock structure that houses Plum Spring sits in the present-day town square (Sandra Taylor McCall, Evening Shade City Hall, written communication).

The importance of ground water to residents in the study area through present time is underscored by a review of water use from 1960 through 2000 (Table 1). Ground water has accounted for 99% of all drinking-water use from both domestic and municipal supplies from 1960 until 2000 for Fulton, Izard, Lawrence and Sharp counties. Minor use of surface water is evident only in Lawrence County, where water is extracted from the Strawberry River for municipal supply. Domestic wells accounted for most of the ground water produced during 1960, with 0.87 million gallons per day (mgd) from rural domestic wells versus 0.72 mgd from municipal-supply wells for the four-county area. Production from domestic wells continued to increase through 1985, although overshadowed by municipal-well production after 1965, and began to decline in every county except for Fulton County beginning in 1990. A review of the data from the four-county area reveals that domestic-supply wells accounted for approximately 30%-55% of the total ground water used from 1960 to 1985. Domestic-well use fell to 25% in 1990, 16% in 1995, and 12% in 2000, with the growth of municipal-supply systems. The decrease in the use of domestic wells is evident especially in Sharp and Lawrence counties, where the production from domestic wells was 0.47 mgd and 0.67 mgd, respectively, in 1985; 0.14 mgd and 0.36 mgd in 1990; and finally dropping to 0.08 mgd and 0.04 mgd in 1995, and 0.0 mgd and 0.01 mgd in 2000. Fulton County is the only county in the four-county study area, where production from domestic wells outweighed municipal-supply production in most years. The total production from domestic wells in 1995 was 0.63 mgd versus 0.41 mgd from municipal-supply systems, although production from municipal-supply systems was slightly greater than that from domestic wells in 2000.

Table 1. Public-supply and domestic-well water use in million gallons per day for the four-county study area.

Year	Fulton			Izard			Lawrence			Sharp		
	Public Supply (10)		Dom.	Public Supply		Dom.	Public Supply		Dom.	Public Supply		Dom.
	Surface	Ground		Surface	Ground		Surface	Ground		Surface	Ground	
1960 (1)	0	0.09	0.17	0	0.14	0.18	0.02	0.39	0.38	0	0.10	0.16
1965 (2)	0	0.12	0.20	0	0.11	0.20	0.02	0.71	0.41	0	0.14	0.16
1970 (3)	0	0.16	0.36	0	0.17	0.33	0.04	0.86	0.53	0	1.03	0.17
1975 (4)	0	0.29	0.45	0	0.64	0.37	0.09	1.20	0.56	0	1.10	0.11
1980 (5)	0	0.38	0.47	0	1.22	0.41	0.05	1.28	0.62	0	1.56	0.39
1985 (6)	0	0.34	0.52	0	0.86	0.43	0.05	1.43	0.67	0	1.42	0.47
1990 (7)	0	0.67	0.58	0	0.99	0.40	0.06	1.43	0.36	0	1.40	0.14
1995 (8)	0	0.41	0.63	0	2.05	0.32	0.08	1.52	0.04	0	1.48	0.08
2000 (9)	0	0.84	0.61	0	1.84	0.21	0.00	0.94	0.01	0	1.54	0

(1) Stephens and Halberg (1961); (2) Halberg and Stephens (1966); (3) Halberg (1972); (4) Halberg (1977); (5) Holland and Ludwig (1981); (6) Holland (1987); (7) Holland (1993); (8) Holland (1999); (9) Holland (USGS, written communication, 2003); (10) All values in million gallons per day – public supply includes surface and ground water, and domestic (Dom.) represents rural, domestic-well use.

The purpose of the ground-water assessment for this report was three-fold: to evaluate the potential impact of nonpoint sources on ground-water quality, to document general ground-water chemistry and water quality throughout the study area, and to review and compare trends in ground-water quality over time to other sources of data from the study area. In order to accomplish this goal, ground-water samples were collected from 53 wells and 9 springs, for a total of 62 ground-water sampling sites. Appendix I contains the complete ground-water quality analyses.

GEOLOGY

The Strawberry River watershed lies almost entirely within the Salem Plateau section of the Ozark Plateaus physiographic province. Lower and Middle Ordovician rocks are exposed at the surface within the watershed boundaries and extend out of the study area to the west and north of the watershed. Sparse erosional remnants of Mississippian rocks cap the hills along the southern watershed divide and form the boundary between the Salem and Springfield Plateaus to the south. Thin exposures of Cretaceous rocks are present in the southeastern and extreme northeastern portions of the watershed. Pleistocene deposits extend into the lower reaches of the Strawberry River and Caney Creek valleys and are truncated at their confluence by unconsolidated Holocene sediments of the Mississippi alluvial plain. Small remnants of Tertiary gravels are scattered on hilltops throughout the watershed (Figure 1) (Haley et al., 1993).

The geology of the Ozark Plateaus Province consists of flat-lying to gently-dipping sedimentary rocks of Cambrian through Pennsylvanian age. The foundation on which these rocks were deposited are crystalline rocks of Precambrian age which crop out in southeastern Missouri and form the St. Francois Mountains (Adamski et al., 1995). The relationship between the strata and the Precambrian rocks records a dynamic configuration between land and shallow interior seas

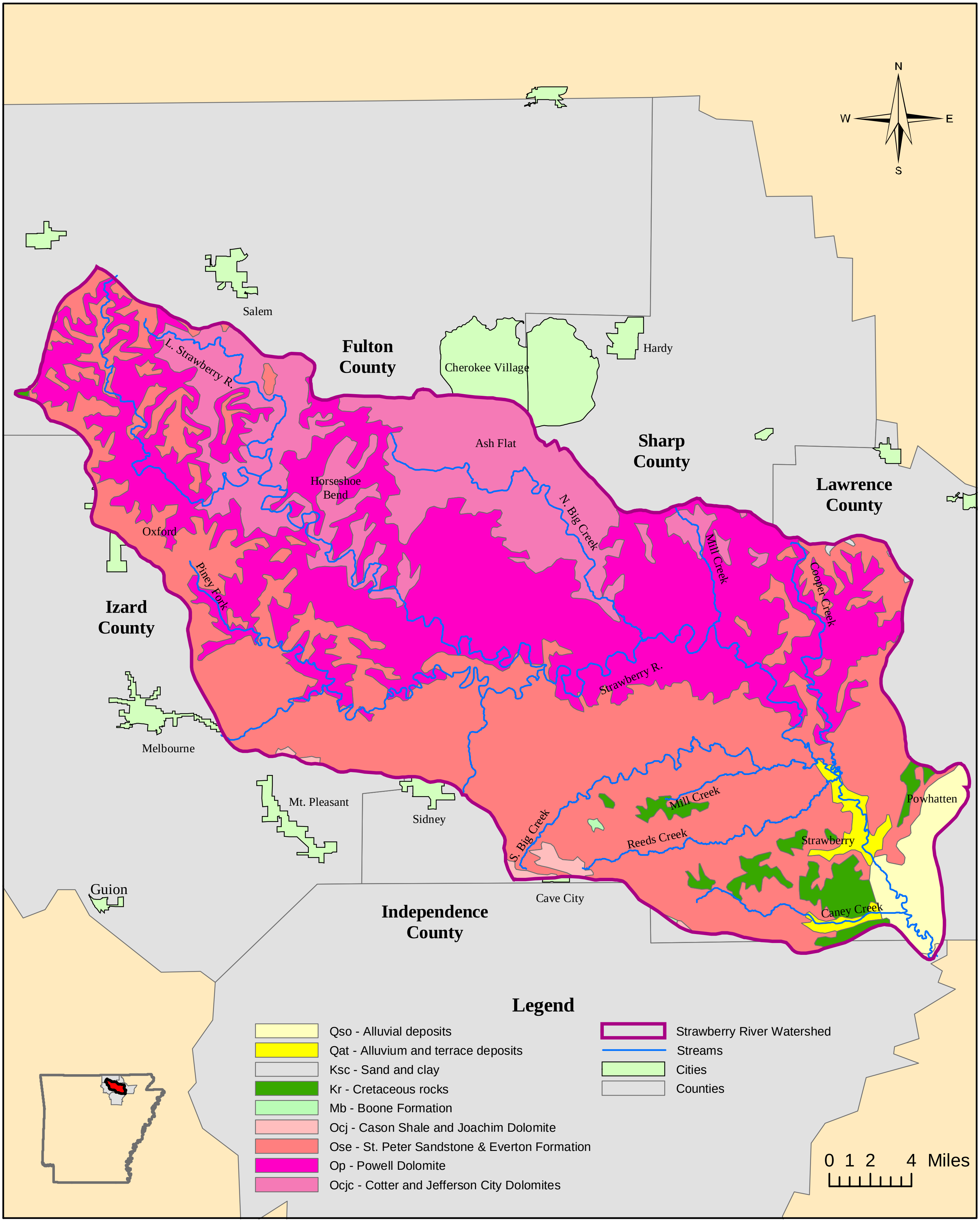

Figure 1. Geologic map of the Strawberry River watershed

throughout much of this time interval. Numerous unconformities in the stratigraphic section account for most of the discontinuities in the distribution of the formations. These unconformities increase in number from south to north. The regional distribution and thicknesses of the formations, combined with regional structure, indicate that the Ozark region had been differentially uplifted along the general location of its present axis prior to deposition of Mississippian sediments (McKnight, 1935).

Thick deposits of mainly calcareous sediments were deposited during the Cambrian and Lower Ordovician. Uplifts near the end of Late Cambrian time and throughout Early Ordovician time resulted in extensive fracturing, jointing, and faulting of the competent carbonate rocks. Diagenetic processes involving the mixing of freshwater and seawater resulted in the conversion of limestone to dolostone. Uplift at the end of the Early Ordovician caused deep and pervasive erosion of the exposed landmass and development of an extensive karst surface now observable as paleokarst. Advancing seas during the Middle Ordovician resulted in widespread deposition of sand and calcareous sediments, which constitute the sedimentary rocks attributed to this period of inundation (Imes & Emmett, 1994). Collectively, the Lower and Middle Ordovician rocks represent the vast majority of strata represented at the surface in the Strawberry River watershed.

Geologic quadrangle maps, areal geology superimposed on 7.5 and 15 minute topographic maps, were used to examine the spatial distribution and position of stratigraphic units and structural features within the Strawberry River watershed. In addition, they were used to determine the thicknesses of rock units penetrated by wells sampled for this study. These unpublished maps were constructed by E.E. Glick, USGS, from 1971 through 1974.

Regional dip of the rock units is to the south into Arkansas, generally resulting in progressively younger rock formations exposed at the surface as one traverses south. Greater degree of uplift and erosion to the north contributed to overall thickening of the units to the south (Imes & Emmett, 1994). Within the eastern portion and along the southeastern boundary of the Strawberry River watershed, the rocks are normally faulted, resulting in increased dips in the vicinity of the faults (Glick, 1972b,d,g; Glick, 1973a,b).

The majority of domestic wells sampled for the study penetrate Lower and Middle Ordovician formations in ascending order from oldest to youngest; the Jefferson City Dolomite, Cotter Dolomite, Powell Dolomite, Everton Formation, and St. Peter Formation (Table 2), all of which crop out at the surface in the watershed. In the southeast portion of the watershed, three wells penetrate thin intervals of exposed Cretaceous rocks that unconformably overlie rocks of the Everton Formation, and likely are completed in the Everton. Two public supply wells penetrate the Roubidoux and Gasconade Formations (Prior et al., 1999), which are present only in the subsurface in Arkansas. Four irrigation wells are completed in Quaternary deposits of the Mississippi alluvial plain.

Table 2. Stratigraphic column with descriptions of lithologic and geohydrologic properties of the Ozark aquifer and adjacent confining units within Arkansas (after Schrader, 2001).

ERA	PERIOD	GEOLOGIC UNIT	GEOHYDROLOGIC UNIT	LITHOLOGY	THICKNESS (feet)	GEOHYDROLOGY
Paleozoic	Devonian	Chattanooga Shale	Ozark confining unit	Shale unit that crops out in a narrow band that outlines the Ozark Aquifer and is missing where the Ozark aquifer is exposed at the surface.	0 – 200	Unit is relatively impermeable because of large shale content.
		Clifty Limestone	Ozark aquifer	Chert with lenses of limestone, dolomite, and cherty sandstone.	0 – 250	The residual cherty rubble, weathered from cherty limestone and sandstone of the unit, may yield 2 to 5 gallons per minute (gpm).
		Penters Chert				
	Silurian	Lafferty Limestone		Limestone, dolomite, sandstone, and minor amounts of shale.	0 – 2000	The limestones and dolomites commonly yield 5 to 10 gpm from solution channels, bedding planes, and fractures. Similar yields may be obtained from the sandstone where it is porous or fractured. These units contain many springs. Yields from the springs and some wells may exceed 50 gpm.
		St. Clair Limestone				
		Brassfield Limestone				
	Ordovician	Cason Shale				
		Fernvale Limestone				
		Kimmswick Limestone				
		Plattin Limestone				
		Joachim Dolomite				
		St. Peter Sandstone				
		Everton Formation				
		Smithville Formation		Dolomite, dolomitic limestone, and minor amounts of sandstone and shale.	100 - 1000	The solution channels and fractures in the dolomite and dolomitic limestone commonly yield 5 to 10 gpm. Wells that tap large solution channels may yield more than 50 gpm, but large yields are uncommon. These units yield water to several large springs.
		Powell Dolomite				
		Cotter Dolomite				
		Jefferson City Dolomite				
		Roubidoux Formation		Sandstone and sandy dolomite. Not exposed in Arkansas.	100 – 250	Yields up to 450 gpm may be obtained from some wells, but yields are highly variable and generally average less than 150 gpm.
		Gasconade Formation		Dolomite, sandy dolomite, and sandstone. Not exposed in Arkansas.	350 - 650	The most productive water-bearing part of this unit is the Van Buren Formation. Wells that tap this formation commonly yield 150 to 300 gpm and may yield as much as 500 gpm.
		Van Buren Formation				
	Cambrian	Eminence Dolomite				
		Potosi Dolomite				
		Doe Run Dolomite	St. Francois confining unit	Shale and shaley dolomite, siltstone, and limestone conglomerate. Shales present both as distinct beds and disseminated throughout dolomite matrix. Not exposed in Arkansas.	0 – 750	Permeability is minimal to moderate. Unit is more permeable where transected by fault and fracture zones.
		Derby Dolomite				
		Davis Formation				

The Gasconade Formation unconformably overlies the Upper Cambrian Eminence Formation in northern Arkansas. The Gasconade consists of a well-defined basal sandstone member, the Gunter Sandstone, and overlying upper and lower medium-crystalline, light brownish-gray dolostone units. Chert is present in the dolostone units and may constitute more than 50 percent of the lower unit. The Gunter Sandstone member is a fine- to coarse-grained sandstone, which may be dolomitic. The thickness of the Gasconade Formation ranges from 300 to 600 feet in northern Arkansas (Prior et al., 1999; Adamski et al., 1995).

The Roubidoux Formation unconformably overlies the Gasconade (Prior et al., 1999) and consists of sandstones, dolostones, and sandy to cherty dolostones. The sandstones are loosely- to well-cemented rocks. The dolostones are light gray to brown and are finely to coarsely crystalline, and may contain several distinct sandstone bodies. Thickness ranges from 100 to 450 feet (Adamski et al., 1995; Imes & Emmett, 1994).

The Jefferson City Dolomite rests unconformably upon the Roubidoux Formation in northern Arkansas and consists of light- to dark-tan, fine-grained, crystalline dolostone and considerable chert with some rare thin beds of sandstone, shale, and oolitic dolostone. The lower contact is not exposed in Arkansas. Few fossils are present in the formation. The Jefferson City Dolomite has not been successfully differentiated from the Cotter Formation in Arkansas (McFarland, 1998). Formation thickness averages about 200 feet (Adamski et al., 1995).

The Cotter Dolomite is composed of dolostone of predominantly two types: a fine-grained argillaceous, earthly-textured, relatively soft, white to buff or gray dolostone referred to as “cotton rock”, and a more massive, medium-grained, gray dolostone that weathers to a hackly surface texture and becomes dark upon weathering. The formation contains concentrically-banded chert nodules, some minor beds of green shale, and occasional thin, interbedded sandstones. Fossils are rare, but include cephalopods, gastropods, and *Cryptozoan*, a reef-building algae. Although not differentiated from the Jefferson City Formation in Arkansas, the contact is considered disconformable. Thickness ranges from 340 to 500 feet (McFarland, 1998).

The Powell Dolomite is generally a fine-grained, light-gray to greenish-gray, limy, argillaceous dolostone with thin beds of shale, sandstone, sandy dolostone, and occasional chert. In the lower half of the formation, a dark, massive ledge with abundant drusy quartz has been located in many places. Although not known to contain many fossils, the Powell contains cephalopods, gastropods and trilobites. The lower contact with the Cotter Dolomite is considered disconformable. According to McFarland (1998), the maximum thickness is approximately 215 feet. However, a local, apparent thickness of at least 260 feet (dip ≈ 50 ft/mi) was measured from the Poughkeepsie geologic quadrangle map (Glick, 1972d), and a local, apparent thickness of 320 feet (dip ≈ 100 ft/mi) was measured from the Sitka geologic quadrangle map (Glick, 1971e). In the northwestern portion of the study area, the Powell thins dramatically to a 20- to 30-foot thick belt. In most of the area covered by the Salem geologic quadrangle map, the Everton Formation lies directly upon the Cotter Dolomite (Glick, 1972f).

The Everton Formation displays considerable variability in lithologic character from one place to another. This unit is composed of mixtures of dolostone, sandstone and limestone and, in limited areas, has traces of conglomerate, shale and chert. The limestones are light-gray to brownish-gray and are generally dolomitic and sandy. The dolostones are light to dark gray and are generally limy and sandy. The Everton Formation includes thick members of friable sandstone dominating local sections in some areas. These sands commonly consist of white, well-rounded, frosted, medium-sized grains and are almost indistinguishable from the overlying St. Peter Sandstone, where sandstones of both formations are in contact. Bedding is thin to massive throughout the Everton Formation. Lithologies commonly grade laterally into one another along the bedding. Fossils are uncommon; however, ostracods, cephalopods, gastropods, bivalves, trilobites and bryozoans have been noted within the formation. The lower contact with the Powell is unconformable, and numerous disconformities occur within the formation. Thickness ranges from about 300 to 650 feet in Arkansas (McFarland, 1998). The Everton and St. Peter Formations are not differentiated on the geologic quadrangle maps covering the watershed extent, except where residual thicknesses of Everton cap hilltops, and the overlying St. Peter is not present.

The St. Peter Sandstone is generally a massive-bedded, friable, white sandstone with minor beds of shale, limestone, and dolostone. The sands are frosted, well-rounded, fine- to medium-sized grains. The cement is commonly calcite, often with single crystals incorporating hundreds to thousands of sand grains. The unit is a frequent bluff-former. Cross-bedding and ripple marks are rare. No body fossils are known from the formation in Arkansas, but a few trace fossils have been reported. The base of the St. Peter Sandstone is unconformable, often with several feet of relief. The formation ranges from a feather edge to as much as 175 feet thick (McFarland, 1998).

The Joachim Dolomite Formation upward through the Kimmswick Limestone Formation comprise the remainder of the Paleozoic strata represented in the watershed. These formations are of limited areal extent and are not penetrated by any of the wells sampled for this study. They are composed of limestones, dolomites, and minor amounts of sandstone and shale (McFarland, 1998). Cumulative thickness in the watershed is 100 feet or less (Glick, 1971d; Glick 1972b,c).

Three wells penetrate thin intervals of Upper Cretaceous rocks in the southeastern portion of the watershed. These rocks consist of black, shaley clay and gravel, and unconformably overlie the Everton Formation in this area (Glick, 1973b). Fossils present in this sequence suggest a possible correlation with the Ozan Formation. This sequence has not been assigned to a specific stratigraphic unit (McFarland, 1998).

Four shallow wells penetrate unconsolidated Holocene alluvium near the extreme southeastern boundary of the watershed. The lower portion of the sediments consists of coarse sands and gravels, and the upper portion is made up of fine to medium sands. Almost everywhere the sequence fines upward, but not in a uniform manner. The sequence is confined where the fine-grained top stratum is thin and continuous, but is an otherwise open hydrologic system. The alluvial deposits have a nominal thickness of approximately 125 feet (Kresse & Fazio, 2002).

Appendix II lists estimated penetrated thicknesses of formations for most of the wells sampled for the present study. Considerable variability in formation thicknesses exists within the watershed according to 7.5 and 15 minute geologic quadrangle maps (Glick, 1971a-e; Glick, 1972a-g; Glick, 1973a,b; Glick, 1974) coincident with the watershed extent. USGS- and author-constructed structural contours enabled the determination of elevations of formation contacts where upper- or lower-formation contacts of interest were not mapped at the surface in the well vicinity. Areally-mapped contact elevations were traced to the well along a line parallel to the strike of the rock units to reduce overestimating or underestimating penetrated thicknesses. Penetrated thicknesses equal total formation thickness only where a given well intersects upper and lower contacts along its length. Formation thicknesses are apparent, as local variability in dips was not calculated for determination of true formation thicknesses. Well-location coordinates were recorded in the field using a hand-held Trimble Geo*Explorer II* global positioning system. Locations were differentially corrected in Pathfinder and exported to and plotted in ArcMap on 7.5 minute topographic quadrangle map coverages. Mapped contacts were transposed from the geologic worksheets to larger-scale, ArcMap topographic coverages to better evaluate contact elevations. Well depths were subtracted from well elevations to determine well-bottom elevations. Local variability in strata dips, interpolation of contact elevations, the scale at which the contacts were originally plotted, and topographic contour intervals are all factors contributing to a margin-of-error of ± 20 feet or greater for local formation penetrated thicknesses and/or formation thicknesses.

HYDROGEOLOGY

Except for a small outcrop of alluvial sediments in the southeastern portion of the watershed, which serves as irrigation supply for row-crop agriculture in the study area, ground water is extracted entirely from the Ozark aquifer, which serves as the dominant source of ground water in the Ozarks of northern Arkansas and southern Missouri. The Ozark aquifer is a thick sequence of water-bearing rock, ranging in age from the Late Cambrian to Middle Devonian. The formations comprising the Ozark aquifer are mainly dolostone, limestone and sandstone, ranging upward to 4000 feet in thickness (Imes and Emmett, 1994). Average thicknesses of the aquifer throughout most of the Salem Plateau range from approximately 1,500 – 2,000 feet (Imes and Emmett, 1994; Adamski et al., 1995). In the study area, only Ordovician-aged rocks of the Ozark aquifer are exposed at the surface and are represented by the sequence of rocks from the Jefferson City Dolomite to the St. Peter Sandstone (See Table 2). These formations serve as the source of ground water for almost all of the domestic wells in the study area. Most municipal-supply wells extract water from deeper and more productive subsurface units, including the Roubidoux Formation and the Gasconade Dolomite. Depths to the top of the Roubidoux Formation and total depths of municipal wells in the study area range from approximately 400 feet and 1,500 feet, respectively, in the northwestern part of the watershed, to approximately 1,500 feet and 2,700 feet, respectively, in the southeastern portion of the watershed (Prior, et al., 1999). The greater depth for the municipal wells is rewarded by yields that range upward to greater than 600 gallons per minute (gpm) (Schrader, 2001; Prior et al., 1999). These yields stand in stark contrast to well yields calculated from driller's logs for 100 shallow wells (< 300 feet) in the watershed, which ranged from 1 – 60 gpm, with a mean of 16 gpm. Lamonds (1972) similarly cites common yields of 5 – 10 gpm with some yields that may exceed 50 gpm for those formations above the Roubidoux Formation in the Ozark aquifer.

Ground-water recharge to the Ozark aquifer occurs through direct infiltration of precipitation through thin soils, near-surface fractures, and sinkholes, and through losing stream segments (Harvey, 1980; Imes and Emmett, 1994). Primary porosity and permeability are low for most of the rock units forming the Ozark aquifer. Secondary porosity and permeability results from fracturing and dissolution, resulting in extremely heterogeneous values that vary widely, even on a local scale (Adamski et al., 1995). In some formations, sandstone is present in massive, clean, well-sorted bodies and is relatively permeable, where it is not cemented (Imes and Emmett, 1994). Ground-water flow directions are well established in the Ozark aquifer in northeastern Arkansas, including flow across the study area, and trend in a southeastward direction toward the Mississippi River Basin (Lamonds, 1972; Harvey, 1980; Imes and Emmett, 1994; Schrader, 2001). Potentiometric surface maps have not been constructed for individual units within the Ozark aquifer; however, Imes and Emmett (1994) state that because most wells are open to at least several hundred feet of the aquifer and that the variation of head with depth is not large in comparison to the variation of head laterally in the aquifer, potentiometric maps for the Ozark aquifer are probably a good representation of the lateral head distribution in the aquifer.

In the watershed, water levels range from slightly greater than 700 feet above mean sea level (amsl) in the northwestern portion of the watershed to less than 300 feet (amsl) in Lawrence County in the southeastern portion of the watershed. In general, the flow mimics and is controlled by topography, especially where the unconfined portion of the aquifer intersects the land surface, resulting in springs and perennial streams (Lamonds, 1972; Imes and Emmett, 1994; Schrader, 2001). Because the topography of the Ozark Plateaus in eastern Arkansas was influenced strongly by the Ozark Dome in Missouri, difficulties arise in assessing the amount of influence by stratigraphic versus topographic controls on flow in such a large aquifer system. Although the contours of the upper potentiometric surface of the Ozark aquifer have been shown to mimic topography, Imes and Emmett (1994) state that water in the deeper portion of the aquifer discharges into the alluvial sediments within a few miles of the Ozark Escarpment, and some of this water ultimately may discharge into the Mississippi River. Both Imes and Emmett (1994) and Lamonds (1972) discuss confining conditions in the Roubidoux Formation and Gasconade Dolomite, and Lamonds (1972) states that some wells completed in the Roubidoux and lower formations flowed under artesian conditions. Prior et al. (1999) mapped water levels in the Roubidoux Formation and Gunter Sandstone member of the Gasconade Formation and noted that the potentiometric surface follows the regional dip of rock units toward the south and southeast in the vicinity of the study area. As such, there would appear to be major differences between the deeper units versus rock formations above the Roubidoux. However, Harvey (1980) cited turbidity in deeply-cased (1000 feet) municipal wells during storm events as evidence of the deep circulation, rapid infiltration, and well-defined connections to upper formations. In any case, potentiometric surface maps for the Roubidoux and lower rock units (Prior et al., 1999; Lamonds, 1972) show similar flow directions to the Ozark aquifer as a whole.

Galloway (USGS, Little Rock, written communication) constructed a water-level map for an approximate 120 square-mile area in the vicinity of Evening Shade (Sharp County) and demonstrated that water-level contours generally follow land-surface topography and indicate discharge into local streams including the Strawberry River and the Piney Fork. From this information, and the regional reports cited above for the Ozark aquifer system, water levels throughout the watershed study area can be assumed to be strongly influenced by local topography, and act as base flow for the Strawberry River and its major tributaries.

METHODOLOGY

Ground-water quality in the Strawberry River watershed was assessed by the sampling of domestic, irrigation and municipal wells, in addition to nine perennial springs in the study area. Because the overall project objective was to assess potential water-quality impacts from nonpoint pollution sources, shallow wells of less than 600 feet were the primary focus of the sampling program. However, two municipal wells approximately 2,000 feet in depth were sampled in order to describe water chemistry and quality in the Lower Ordovician Roubidoux Formation in the watershed. The shallow wells sampled for this report include 47 wells completed in the Ozark aquifer, which is comprised of rocks dominantly of Ordovician age, and four irrigation wells completed within a small portion of Quaternary-age alluvial sediments, which overlie the bedrock in the southeastern portion of the watershed.

Figure 2 shows the locations of the wells and springs sampled for this study. Although a uniform random distribution of sampling locations was one of the objectives of the study, the absence of operational wells as a result of residents converting to municipal-supply systems, combined with the distribution of residents over some sparsely populated areas, resulted in a patchy network of wells and springs. However, the distribution of sampling locations is sufficiently random to adequately represent water-quality variation as influenced by both geology and land use within the watershed.

The wells and springs were sampled during August and September, 2002. All wells were sampled as near to the wellhead as possible through available faucets and other outlets. Most wells had been in use during the day of sampling; however, all wells were allowed to run for a minimum of ten minutes until field-measured parameters had stabilized prior to sampling. All samples were collected in approved containers for the selected parameters. Samples were filtered through disposable 0.45 μm pore-sized membranes in the field for analysis of dissolved metals and preserved with nitric acid to a pH of 2.0. All other samples were unfiltered, stored on ice, and delivered to the Arkansas Department of Environmental Quality (ADEQ) laboratory under chain-of-custody requirements. All samples were analyzed for major and minor cations and anions, nutrients, trace metals, and total dissolved solids. Analysis for pH, conductance and temperature were performed in the field at the time of sampling with an Orion^{tm} multifunction portable meter. Because 18 of the resulting samples contained NO_3-N concentrations equal to or greater than 1.0 mg/L, these wells were resampled and analyzed for fecal coliform and *E. coli* bacteria. Because each of the well locations had onsite septic systems, 18 samples additionally were forwarded to the USGS laboratory in Denver, Colorado, for analysis by method Schedule 1433 wastewater scan. This method includes analysis for approximately 62 compounds, which include, among others, various estrogen metabolites, fecal indicators, detergent metabolites, other detergent-related compounds, caffeine, cholesterol, and compounds used in the perfume and fragrance industry. Because the occurrence of elevated nitrogen species and bacterial contamination can occur from several sources, including animal waste and septic systems, the analysis provided an additional tool in determining the source of contamination.

Figure 2. Map showing ground-water sampling locations in the Strawberry River watershed

INORGANIC AND GENERAL WATER QUALITY

In general, ground-water quality within the Strawberry River watershed is good, as compared to national drinking-water criteria. Complaints by local residents are normally in reference to hardness and scaling associated with elevated Ca and Mg concentrations in the ground water. Iron concentrations were below 100 µg/L for most samples, except for three samples from wells completed in the alluvial aquifer in the southeastern portion of the watershed that ranged from 2,610 to 6,830 µg/L, and exceeded the secondary maximum concentration limit (MCL) for Fe of 300 µg/L. Samples from these wells similarly contained Mn concentrations ranging from 650 to 1,053 µg/L, which exceed the secondary MCL (50 µg/L) for Mn. Secondary MCLs are established for aesthetic reasons associated with problems ranging from staining and scale formation to objectionable taste and are not related to hazards to human health. A sample from one of the alluvial wells, LAW103, also exceeded the secondary MCL for total dissolved solids (TDS) of 500 mg/L. IZA104 was the only sample from a well completed in the Ozark aquifer that exceeded MCLs for both Fe (300 µg/L) and Zn (5,000 µg/L), which appears to be associated with leaching from metal plumbing. Samples from two wells, LAW109 and LAW110, exceeded the primary MCL of 10 mg/L for NO_3-N (see "Nutrients and Bacteria" in section below).

Hardness

Although there are many scales for determining hardness in the literature, most are similar in their descriptions and within 10 mg/L of one another. The present study uses Doll et al. (1963), which states that soft water has hardness values less than 60 mg/L; moderately hard between 61 and 120 mg/L; hard between 121 and 180 mg/L; and very hard water greater than 180 mg/L. Accordingly, 57 of the 62 ground-water samples collected for the present study are classified as very hard. Three of the remaining five wells are classified as hard; one as moderately hard; and only one well that is classified as soft. The property of hardness primarily has been associated with the effects of soap, and with the encrustations left by water when heated. Because most of the effects observed with soap results from the presence of calcium and magnesium, hardness is now generally defined in terms of these constituents (Hem, 1989). In this report, hardness is computed by multiplying the sum of milliequivalents per liter of Ca and Mg by 50 and is reported as mg/L $CaCO_3$.

Water Type

Ground water is frequently defined by water type, which generally classifies a water sample by the major cation(s) and anion(s); i.e., Na-Cl, Ca-HCO_3, etc. Although these classifications are fairly straightforward and simple in their conception, classification can become confusing in cases where the molar percentages of cations and anions are distributed somewhat evenly between one or more cations and/or anions, none of which comprise greater than 50% of the total cation and anion concentrations, respectively. For example, a ground water with Ca comprising 62% of the total cations in meq/L and bicarbonate comprising 94% of the total anions in meq/L would be typed as a Ca-HCO_3 water. A sample with a cation distribution of Ca (35%), Mg (25%), and Na (30%), and bicarbonate as the dominant (> 50%) anion, the water would be defined by the dominant constituents as possibly a Ca,Na-HCO_3 or even a Ca,Na,Mg-HCO_3 water type.

Imes and Emmett (1994) show a range of water types for the Ozark aquifer throughout the Salem Plateau, including Ca-HCO_3, Mg-HCO_3, and Na-Cl. For the area encompassing the watershed, Imes and Emmett (1994) show an approximate even split between a Ca-HCO_3 and a Na-Cl water type. However, analyses from 62 sampling sites for the present study and 28 sites sampled for the Hardy monitoring area (ADEQ, unpublished data) in Fulton and Sharp counties (dominantly north of the Strawberry River watershed area) reveal no Na-Cl water types. Prior et al. (1999) describes the water chemistry in the Roubidoux Formation and Gunter Sandstone as a "magnesium-bicarbonate type with generally low chloride." However, a review of the 46 wells that contain chemical analyses in Prior (1999) revealed that Mg was the dominant cation in only 6 of the 46 wells, and usually by only a few hundredths of a meq/L, whereas Ca was the dominant cation in 40 of the 46 samples. Galloway (USGS, Little Rock, written comm.) discusses the chemistry of the Evening Shade area and states that "wells and springs in the study area demonstrate a calcium-bicarbonate type water typical of the Ozark aquifer." Harvey (1980) states that Ca/Mg ratios in water from the Ozark Plateau region are close to one for dolomite aquifers and range from 1-10 for limestone aquifers, and additionally cites ratios for Ordovician dolomite aquifers that increase to 2-3 in the Springfield Plateau area as a result of leakage from the overlying limestone formations.

Water analyses for 58 samples from the Ozark aquifer for the present report reveal that Ca exceeds 50% of the total cations (meq/L) in 46 of the 58 samples, with Mg as the dominant cation in the remaining 12 samples. The mean percentage for Ca is 51.6% and highest value is 56.8%, whereas Mg percentages rarely drop below 44% and average 45.4%. These figures reveal only slight increases of Ca relative to Mg in the Ozark aquifer. Hem (1989) states that water in which no one cation or anion constitutes as much as 50 percent of the totals should be recognized as a mixed type and identified by the important cations and anions. Because the "50%" boundary has been adopted by most ground-water scientists, then the dominant water type in the watershed in most cases can be defined accurately as a Ca-HCO_3 type water. However, 7 of 11 samples from the Boone Formation (limestone) in the Omaha monitoring area in northwest Arkansas (Springfield Plateau) reveal Ca percentages greater than 90%, with a mean of 88%, and Mg percentages all under 10%, with a mean value of 4.9% (Huetter et al., 1997). These percentages stand in stark contrast to the close distribution between Ca and Mg concentrations for the Ozark aquifer in the study area, which results from the dominance of dolomite in the strata. Ca/Mg ratios calculated for this report range from 1.0 to 1.4 with a mean of 1.1; whereas, ratios from the 11 Boone Formation samples range from 10 to 41 with a mean of 24. Referring to ground water from each of these geologic regimes as a Ca-HCO_3 water type negates the large difference between the Ca/Mg ratios and resulting water chemistry as influenced by the rock type. The authors believe that ground water from the Ozark aquifer is more appropriately termed a Ca,Mg-HCO_3 water type, and recommend that the nomenclature be changed to reflect the differences in water from the limestone of the Springfield Plateau and the dolomite of the Salem Plateau in cases where Mg exceeds 40% or more of the total cations.

Figure 3 presents a Piper diagram of the data from the study, which depicts the distribution of the major cations and anions for each sample. The "cations" triangle reveals that most samples plot near the midpoint between the %Ca and %Mg endpoints, and provides a visual representation of the water type. Samples that deviate from the general cluster toward the %Na+K endpoint are represented by alluvial wells (squares) which are higher in both Na and Cl (see section below), and Ozark aquifer samples which contain higher salts and nutrients dominantly as a result of impacts from septic system effluent (see section "Nutrients and Bacteria").

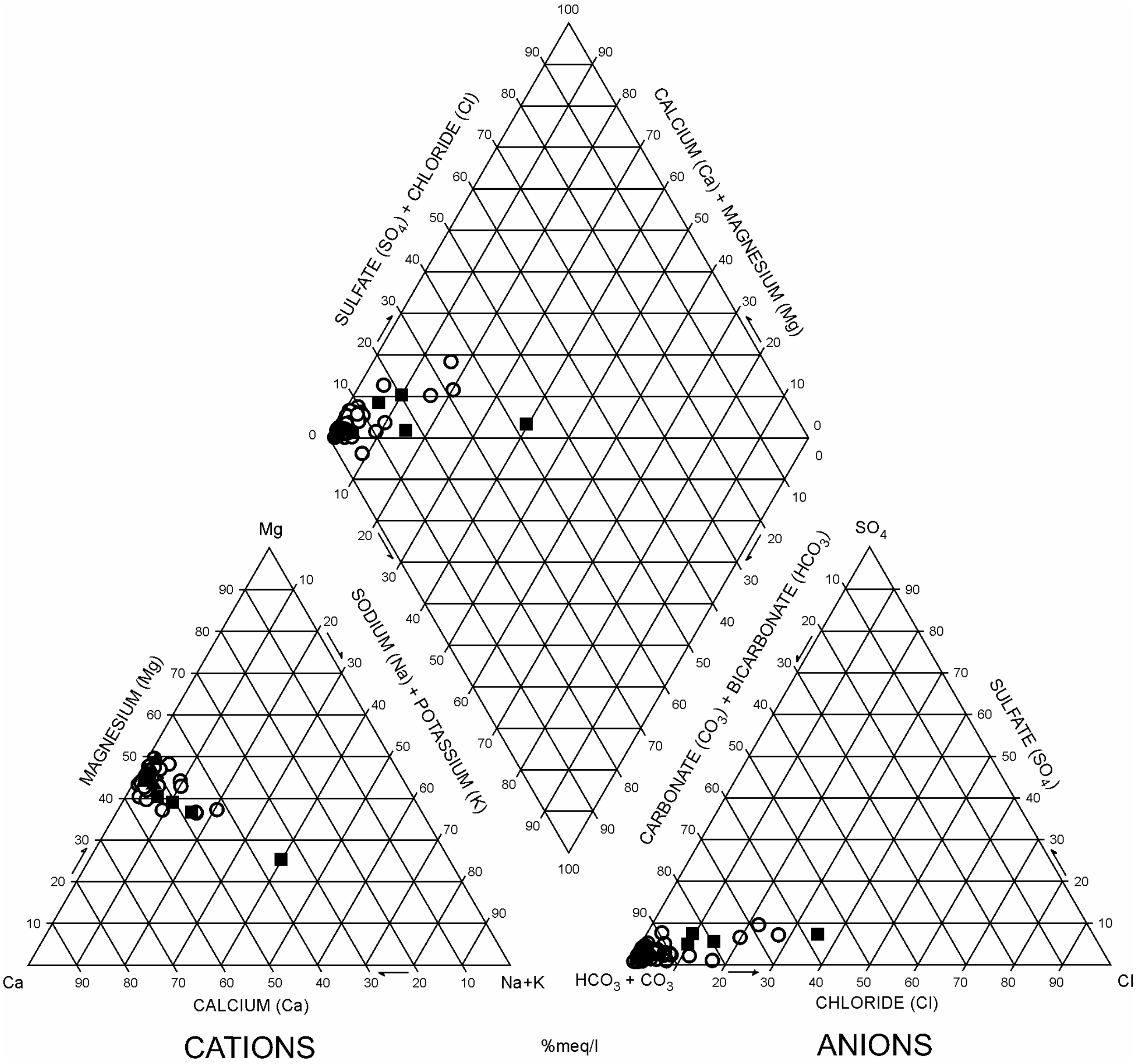

Figure 3. Piper diagram showing distribution of cations and anions in ground-water samples taken from Strawberry River watershed study area. Alluvial-aquifer samples are represented by squares; Ozark-aquifer samples are represented by circles for wells and triangles (hidden) for springs.

INFLUENCE OF ROCK TYPE ON WATER CHEMISTRY

Comparison of Water Chemistry in Exposed Ordovician Formations

The relationship of rock type to water chemistry was evaluated for the three major groups of Ordovician formations outcropping in the watershed. Problems often arise when attempting to define the water-producing formation for a well that penetrates more than one formation. Some investigators tend to use the lowest formation in these situations; however, drillers frequently advance borings to greater depths to obtain better yields, and merely obtain additional storage in cases where water is not encountered below the original producing zone. Because only the regolith is cased in most domestic wells, water can be produced from many zones, resulting in the physical mixing of water from one or more formations. Appendix II lists the formations penetrated by the wells sampled for the present study, and demonstrates the difficulty in assigning the water-producing zone to a particular formation.

As a cursory review of the differences in water chemistry and quality across the watershed, each well was assigned to a specific formation based on its position on the Geologic Map of Arkansas (Haley et al., 1993). In cases where a well was near to or located on a formation boundary, and/or intercepted less than 20 feet of the upper formation, the well was assigned to the lower formation. Table 3 lists the minimum, maximum, mean and median concentrations for selected water-quality parameters for each of the three geologic designations as assigned by the Geologic Map of Arkansas: the St. Peter and Everton Formations (Ose), the Powell Dolomite (Op), and the Cotter and Jefferson City Dolomites (Ocjc).

Because some differences in concentrations can occur simply through the distribution of data with a wide range of concentrations, a *z*-test was performed to investigate the statistical significance of the perceived differences. A *z*-test is a statistical test that evaluates the differences between the means of two sample populations using calculated variances for each set, and was chosen because of the distribution of the sample concentrations. Results of the *z*-test are provided in Appendix III. Because a difference in the mean concentrations can be the result of one or more wells with unusually high or low concentrations (outliers) relative to the rest of the data set, median concentrations were reviewed to verify trends in the mean concentrations.

One apparent trend noted in a review of Table 3 is the increase in Ca, Mg, HCO_3, and TDS concentrations from the Ose to the Ocjc. Because Ca, Mg, and HCO_3 concentrations are controlled by dissolution of the carbonate rock and serve as the dominant ions contributing to the TDS concentration in each well, a review of TDS concentrations is adequate for describing all four parameters. The three formations identified Table 3 are listed in order of their outcropping position from the southernmost formations (Ose) to the northernmost formations (Ocjc), and, as such, TDS concentrations increase from the south to the north in the watershed. Increases in TDS are the combined result of the solubility of the rock type (including cementing material), the pH of the infiltrating water, the presence of organic carbon, and the residence time of the ground water along the flow path from recharge to discharge areas. As such, the rock mineralogy combined with the hydraulic conductivity, as controlled by the size and abundance of fractures and bedding-plane openings, contribute to the overall TDS concentration along the flow path. However, there is scant literature available for reviewing either the mineralogy or hydrology of the Ozark aquifer in the study area, and only future research can validate the importance of and the controls on the increasing TDS concentrations from south to north.

Table 3. Comparison of water chemistry in the three groupings of Ordovician formations outcropping in the Strawberry River watershed study area.

	Ose (1)				**Op** (2)				**Ocjc** (3)			
	Min.	Max	Mean	Med.	Min.	Max	Mean	Med.	Min.	Max	Mean	Med.
Ca (4)	29.1	62.3	46.4	46.4	4.6	101	57.0	57.8	44.5	89.4	63.6	61.2
Mg	12.4	33.8	23.0	22.5	2.2	57.9	31.4	31.9	25.2	47.6	34.6	36.0
Na	0.9	3.6	1.8	1.4	1.2	21.9	3.6	2.1	0.7	6.0	2.0	1.6
Cl	1.6	8.4	3.3	2.3	1.8	35.3	6.9	3.5	1.6	33	6.1	3.8
HCO_3	144	338	257	252	13	559	303	302	242	451	345	355
SO_4	1.7	9.9	4.8	4.3	1.2	21.2	7.7	6.7	1.7	19.6	7.3	6.9
NO_3-N	0.11	2.73	0.81	0.48	0.02	14.0	1.88	0.51	0.02	3.81	0.83	0.53
TDS	142	144	216	212	57	465	278	291	222	414	301	309
Ca/Mg	1.12	1.42	1.24	1.2	0.96	1.27	1.10	1.08	0.98	1.28	1.11	1.11

[1] Ose = St. Peter and Everton Formations

[2] Op = Powell Dolomite

[3] Ocjc = Cotter and Jefferson City Dolomites

[4] Concentrations in mg/L; Ca/Mg ratios are calculated using equivalent concentrations of calcium and magnesium.

A review of the data from the Hardy monitoring area to the north of the watershed (ADEQ, unpublished data) reveals a mean TDS of 323 mg/L, which appears to validate the increasing TDS concentration to the north. A review of the *z*-test results reveals statistically-significant differences in TDS concentrations for both Op and Ocjc versus Ose, but not for Op versus Ocjc.

Statistically-significant differences additionally are noted for Ca/Mg ratios between both Op and Ocjc versus Ose. The differences in Ca/Mg ratios are evident from a review of Table 3. The minimum ratio of 1.12 for the Ose is slightly higher than the mean and median ratios for both the Op and Ocjc. A review of the data from the Hardy monitoring area (ADEQ, unpublished data), which is situated entirely within the Ocjc on the Geologic Map of Arkansas, reveals a Ca/Mg ratio of 1.08, which is similar to the mean values for the Op and Ocjc listed in Table 3. The higher Ca/Mg ratios for the Ose probably results from the higher content of calcite in the St. Peter Sandstone. McKnight (1935) states that the sand grains of the lowest member of the St. Peter Sandstone are cemented by calcite, and that the middle sandstone member is very limy with interstitial lime that tends to segregate into definite crystalline growths. Although sections of the St. Peter contain massive dolomite, sandy dolomite and dolomitic sandstone, the higher percentage of limestone in the Ose versus the Op and Ocjc contributes to the higher Ca/Mg ratios in the Ose. Figure 4 reveals the general trend for ranges of Ca/Mg ratios as plotted on a geologic map of the watershed.

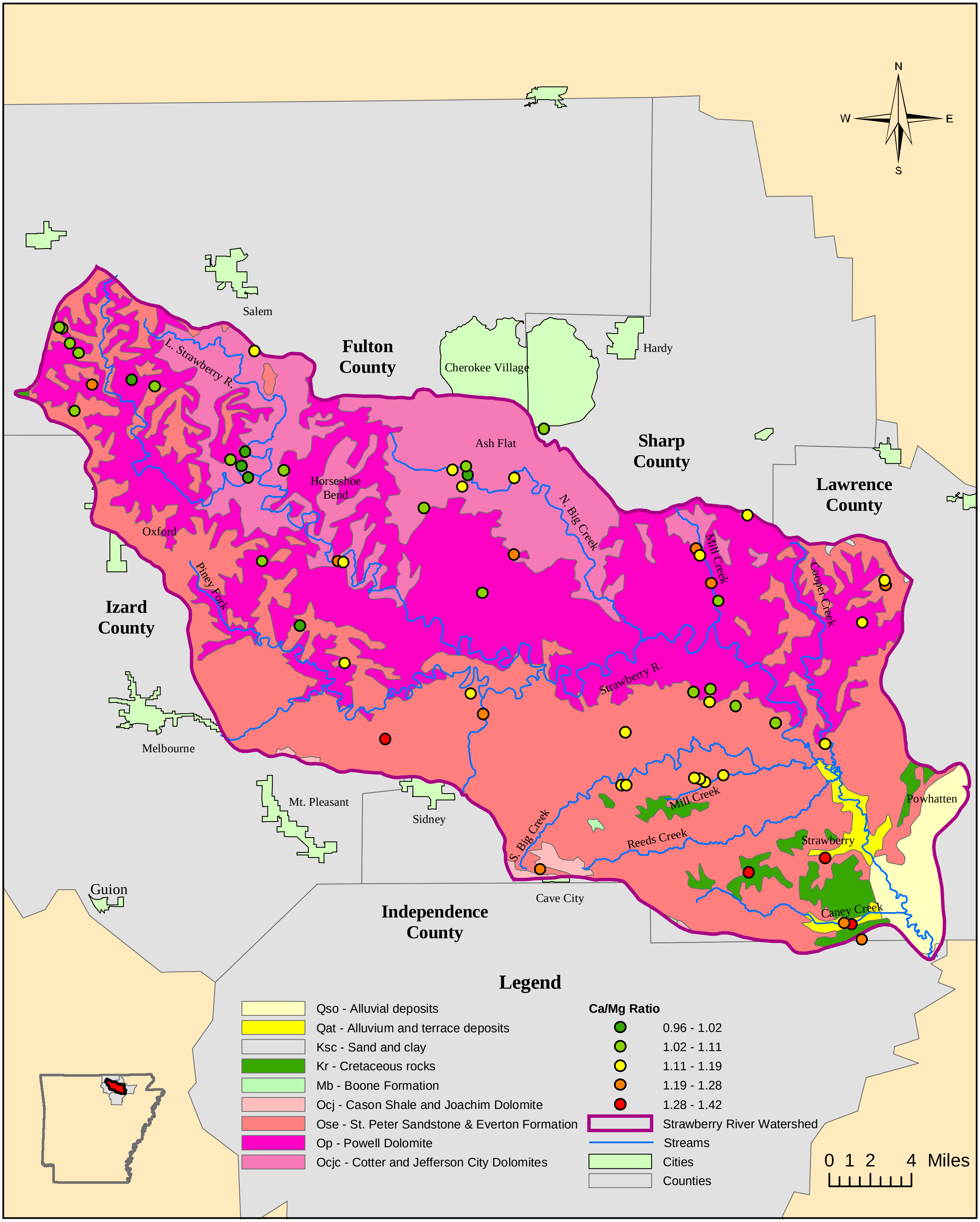

Figure 4. Map showing distribution of ranges for Ca/Mg ratios from the Strawberry River watershed ground-water database

Although the minimum Ca/Mg ratios are near 1.0 for the Op and Ocjc wells (0.96 and 0.98, respectively), mean and median Ca/Mg ratios clearly reveal higher equivalent concentrations of Ca relative to Mg. In the absence of retardation processes (cation exchange, precipitation, sorption, etc.) that can affect ion concentrations in solution, dissolution of a pure dolomite produces a ground water with Ca/Mg ratios equal to one. The higher Ca/Mg ratios calculated for the present data indicate a source dolomitic rock whose mineralogy is part calcite. This is a reasonable assertion given that the geologic record contains ancient limestones that range from partial to complete dolomitization (Tucker, 1982). There is also evidence based on ion-pair relationships that cation exchange may have affected the Ca/Mg ratios in some areas. Figure 5 depicts Na/Cl ratios versus Ca+Mg/HCO_3 ratios and provides evidence for cation exchange between Na and Ca ions as ground water is transported through both the unsaturated and saturated zones. Figure 5 additionally demonstrates an association between excess salts and nitrate sources, as most samples with NO_3-N concentrations greater than 1.0 mg/L have Na/Cl ratios less than one. Figures 6 and 7 reveal correlations between increases in Na and Cl concentrations, respectively, to increases in Ca/Mg ratios. Although there is abundant scatter of points in Figures 6 and 7, the general trends in Figures 5 - 7 suggest that as sources of Na and Cl are introduced into the aquifer system (including the unsaturated zone), some of the Na may be replacing Ca at exchange sites (i.e., clays) and increasing the Ca concentrations in the ground water at the expense of Na, while simultaneously increasing the Ca/Mg ratio in the ground water.

Roubidoux/Gasconade Formation Water Chemistry

Two deep wells completed in the Roubidoux and Gasconade Formations were sampled for the present study. These wells are 1850 feet and 1900 feet in depth and are used as municipal-water supply for the town of Calamine. Prior (1999) provides chemical analyses for five wells completed in the Roubidoux/Gasconade Formation within the four counties encompassing the study area. Concentrations of TDS for the five wells range from 240 to 298 mg/L, which compare closely to TDS concentrations (249 and 259 mg/L) measured in the two Calamine wells sampled for the present study. The narrow range of TDS concentrations demonstrates a very consistent chemistry for ground water within the Roubidoux/Gasconade Formation of the Ozark aquifer system. The maximum, mean, and median TDS concentrations for samples from the shallower units (Ose, Op, and Ocjc) are 465 mg/L, 278 mg/L and 290 mg/L, respectively. As such, this information suggests that water quality in the Lower Ordovician rocks is as good as or better than that from the more shallow units from the standpoint of total dissolved load, in addition to the higher yield obtained from the deeper units.

Alluvial Aquifer Water Chemistry

Four ground-water samples were collected from irrigation wells completed in alluvial sediments, which occupy a small area in the southeastern portion of the watershed. The four wells actually plot slightly south of the watershed, but are used to irrigate fields within the watershed. There are currently no operational wells in the portion of the watershed with exposures of alluvial sediments; however, the proximity of four alluvial wells sampled for the present study should be highly representative of alluvial ground-water quality in this area. Table 4 compares sample analyses from the alluvial wells to samples from the Ozark aquifer. Mean and median concentrations of TDS are higher for the alluvial aquifer samples than for the Ozark aquifer samples. The maximum TDS concentration of 709 mg/L for the alluvial aquifer samples is similar to the maximum of 746 mg/L cited in Kresse and Fazio (2002) for 118 alluvial aquifer

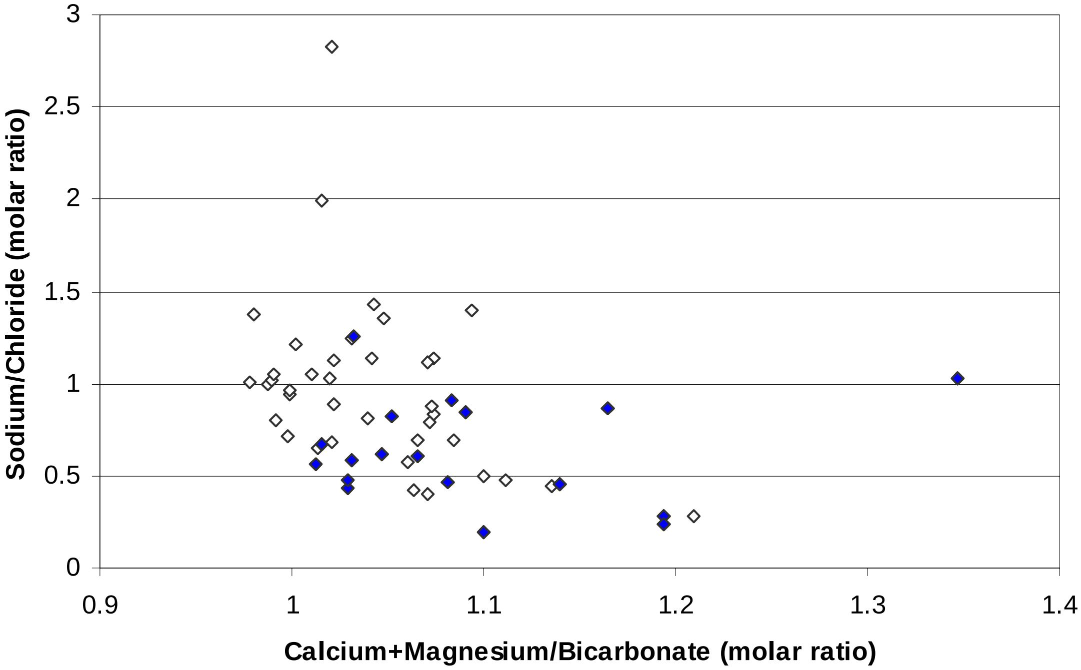

Figure 5. A graph of sodium/chloride ratios versus calcium+magnesium/bicarbonate ratios. Darkened data points represent samples with nitrate-N concentrations greater than or equal to 1.0 mg/L.

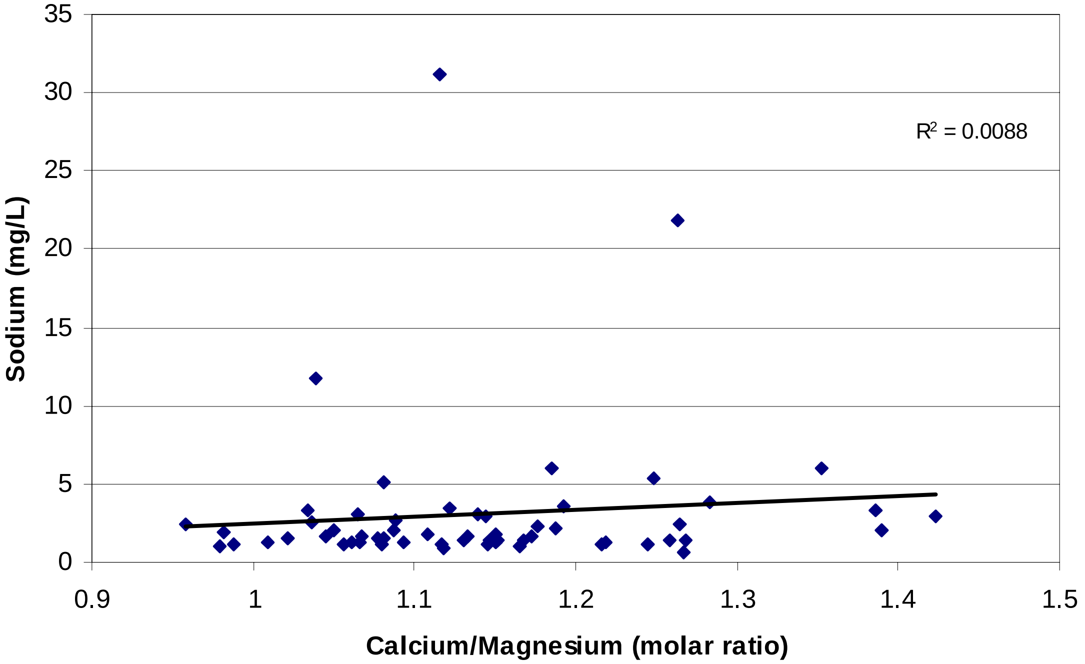

Figure 6. A graph of sodium concentrations versus calcium/magnesium ratios. Goodness of fit represented by R^2 value.

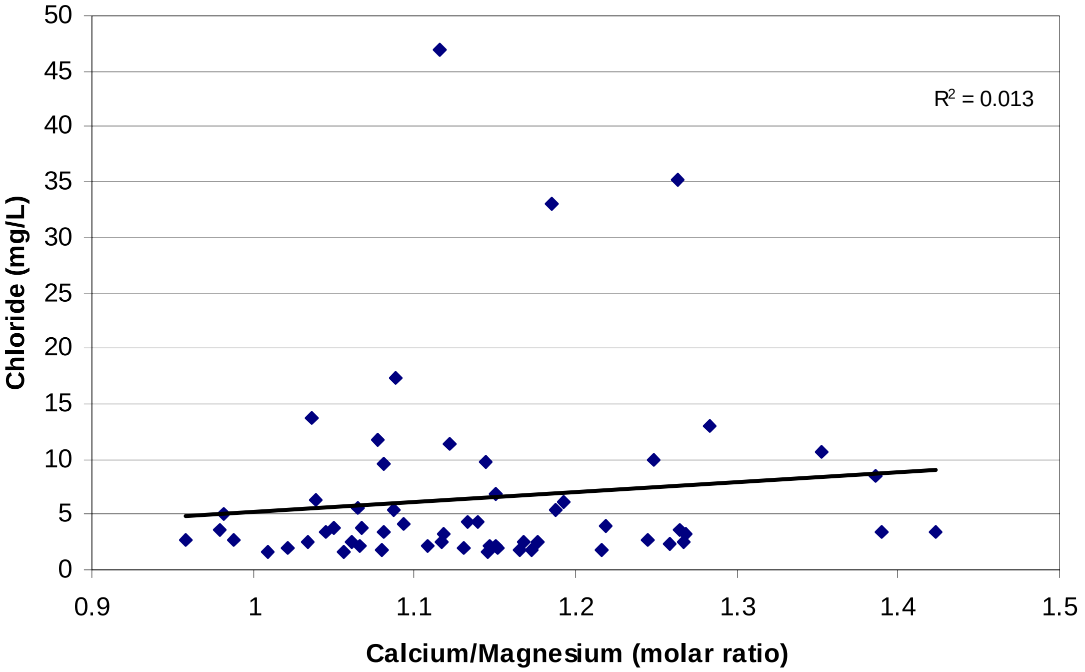

Figure 7. A graph of chloride concentrations versus calcium/magnesium ratios. Goodness of fit represented by R^2 value.

Table 4. Comparison of water chemistry in samples from the alluvial and Ozark aquifers in the Strawberry River watershed study area.

	Alluvial Aquifer				**Ozark Aquifer**			
	Min.	Max	Mean	Med.	Min.	Max	Mean	Med.
Ca (1)	64.0	90.7	75.2	73.1	4.6	101	57.6	57.3
Mg	30.4	40.8	35.0	34.4	2.2	57.9	30.9	31.5
Na	9.2	116	41.5	20.5	0.7	31.2	3.1	1.6
Cl	22.6	159	60.4	30.0	1.6	46.9	6.5	7.5
HCO_3	310	439	368	362	13.4	559	310	302
SO_4	15.4	44.7	26.3	22.6	1.2	27.4	7.4	6.7
NO_3-N	0.02	0.41	0.13	0.05	0.02	14.0	1.39	0.52
TDS	335	709	368	362	57	465	278	283
SiO_2	23.4	29.1	25.3	24.4	8.5	20.8	11.7	11.2
pH	7.02	7.56	7.29	7.30	5.9	8.3	7.57	7.57

(1) All parameter concentrations in mg/L, except for pH values, which are in standard pH units.

samples collected in the Bayou Bartholomew watershed in southeastern Arkansas. Mean and median concentrations of Na, Cl, and SO_4 are similarly elevated in the alluvial samples relative to the Ozark aquifer samples. Imes and Emmett (1994) state that discharge of poor-quality water from the lower portion of the Ozark aquifer within a few miles of the Ozark Escarpment can account for elevated salt content and TDS in the alluvial aquifer. Kresse and Fazio (2002) cited mixing of poor-quality water as the reason for increased Na, Cl and SO_4 concentrations in the alluvial aquifer in southeastern Arkansas. Their report additionally noted that increases in Na, Cl and SO_4 concentrations correlated to decreases in pH, %Ca (of total cations) and % HCO_3 (of total anions) at an approximate TDS concentration of 350 mg/L along a flow path defined by increasing TDS concentrations.

Mean and median NO_3-N concentrations for the alluvial aquifer samples (0.13 mg/L and 0.05 mg/L, respectively) were ten-fold lower than mean and median concentrations for the Ozark aquifer (1.39 mg/L and 0.52 mg/L, respectively) (Table 4). Kresse and Fazio (2003) identified reducing conditions in the alluvial aquifer of the Bayou Bartholomew watershed in southeastern Arkansas and attributed low NO_3-N concentrations (mean and median NO_3-N concentrations of 0.06 mg/L and 0.02 mg/L, respectively) in the alluvial aquifer to denitrification within the reducing zone.

NUTRIENTS AND BACTERIA

One of the primary objectives of the study was to evaluate impacts to ground-water quality from nonpoint sources of contamination, which consist dominantly of confined-animal operations. Most NH_3-N and ortho-P concentrations were nondetect at 0.005 mg/L. As such, only NO_3-N concentrations were considered as a first indication of anthropogenic impacts to ground-water quality. Because of the six-hour holding time, fecal coliform and *E. coli* bacteria were not analyzed during the August, 2002 sampling events, and a sampling event for bacteria analysis was planned for all wells exceeding 1.0 mg/L NO_3-N. Sixteen of the 58 total samples (26%) collected during August, 2002, contained NO_3-N concentrations greater than 1.0 mg/L. Because NO_3-N concentrations in two other wells were near the arbitrary limit of 1.0 mg/L (0.91 mg/L and 0.96 mg/L), these wells were also included in a sampling event on September 16, 2002. All samples were transported to the ADEQ Little Rock office and plated for fecal coliform and *E. coli* analysis within six hours of the collection time. Only one sample revealed any bacterial colonies, which was from a small, open pool of water in Evening Shade fed by an underground spring. Because the water was vulnerable to surface sources of contamination, the presence of bacteria is probably the result of the pool becoming contaminated at the surface. This theory is further supported by the fact that three wells, two of which were greater than 6.0 mg/L NO_3-N and one which exceeded 12.0 mg/L, revealed no bacterial colonies. During this re-sampling event, four samples were collected from new sites for complete chemical analysis. One of the new samples was from the well of a resident next door of the household whose well water contained 12.9 mg/L NO_3-N. This new sample contained 14.0 mg/L NO_3-N, and analysis of the sample for fecal coliform and *E. coli* bacteria revealed no colonies, similar to the other samples.

Adamski (1997) conducted a review of nutrients and pesticides in ground water of the Ozark Plateaus in Arkansas, Kansas, Missouri and Oklahoma as part of the USGS National Water-Quality Assessment Program. In establishing background concentrations for NO_3-N, he used 25 samples from relatively pristine sites (forest cover greater than or equal to 90 percent) and calculated the 90th percentile concentration for NO_3-N as 0.98 mg/L. However, because domestic wells, in addition to springs, were sampled for the study, impacts from septic systems cannot be discounted as a potential source of nitrogen to the wells, regardless of land use in the vicinity of the wells. As such, the nitrogen content of ground water in pristine areas may be significantly lower in areas void of input from septic systems. Adamski (1997) listed 45 of 98 samples (45.9%) collected for the random-unit survey in the Ozark Plateaus as containing NO_3-N concentrations that exceeded the background of 0.98 mg/L. For the present study, 17 of 58 samples (29.3%) collected from the Ozark aquifer were greater than 0.98 mg/L NO_3-N. The higher percentage for the data from Adamski (1997) appears to result from the inclusion of samples from both the Springfield Plateau and Salem Plateau aquifer systems. Agricultural land use is much greater in the Springfield Plateau area, and median NO_3-N concentrations in springs (2.6 mg/L) and wells (1.0 mg/L) in the Springfield Plateau aquifer were much greater than those from springs ($\approx$ 0.4 mg/L) and wells ($\approx$ 0.6 mg/L) in the Ozark aquifer (Adamski, 1997), which compared closely to median values for springs (0.47 mg/L) and wells (0.63 mg/L) in the Ozark aquifer for the present study. Adamski (1997) additionally noted that although springs in the Springfield Plateau aquifer contained significantly higher NO_3-N concentrations than wells, no significant difference was noted between springs and wells in the Ozark aquifer. Similarly, no significant difference in NO_3-N concentrations was noted between springs and wells for the present study.

The identification of the source(s) of nitrate contamination is complicated by the poor knowledge of the contribution from multiple sources including animal-waste lagoons, land application of solid and liquid animal waste, fertilizers, bat guano and septic-tank effluent. Several sources have linked elevated NO_3-N concentrations in ground waters of northern Arkansas to the explosive growth of the poultry industry in the area, although most of these studies acknowledge the complications in identifying either the specific source and/or the contribution from the various sources (Steele and McCalister, 1990; Smith and Steele, 1990; Austin and Steele, 1990; Steele and Adamski, 1987; Peterson et al., 2002, Davis et al., 2000). Steele and Adamski (1987) and Steele and McCalister (1990) compared wells and springs in a watershed with extensive pastureland to a watershed with forest cover as the dominant land use, and found statistically higher concentrations of NO_3-N in the watershed with extensive pasture use. Although septic systems were acknowledged as a potential source of contamination, Steele and McCalister (1990) cited figures that revealed a greater amount of nitrogen from poultry production than other sources, and listed waste from poultry production as the major source.

Adamski (1997) noted that NO_3-N concentrations in samples from wells and springs were positively correlated to percent agricultural land use around each sample site (within a mile), and negatively correlated to percent forest cover around each site (Figure 8). Because of the large area encompassed by the study and the quality of land coverage in the mid 1990's, all land that was not labeled as forest was considered agricultural land. Although septic systems are possible contamination sources for the domestic wells, regardless of the land use, the trends in Figure 8 can be interpreted as representing the additional nutrient input contributed by the application of animal waste. However, the upper boundary in Figures 8a and 8b reveals elevated (>5 mg/L) NO_3-N concentrations regardless of the percent land use, and the lower boundary appears to drive the trend. This phenomenon strongly suggests that septic-tank effluent is a major contribution to the total nutrient input, especially for ground water supplying domestic wells.

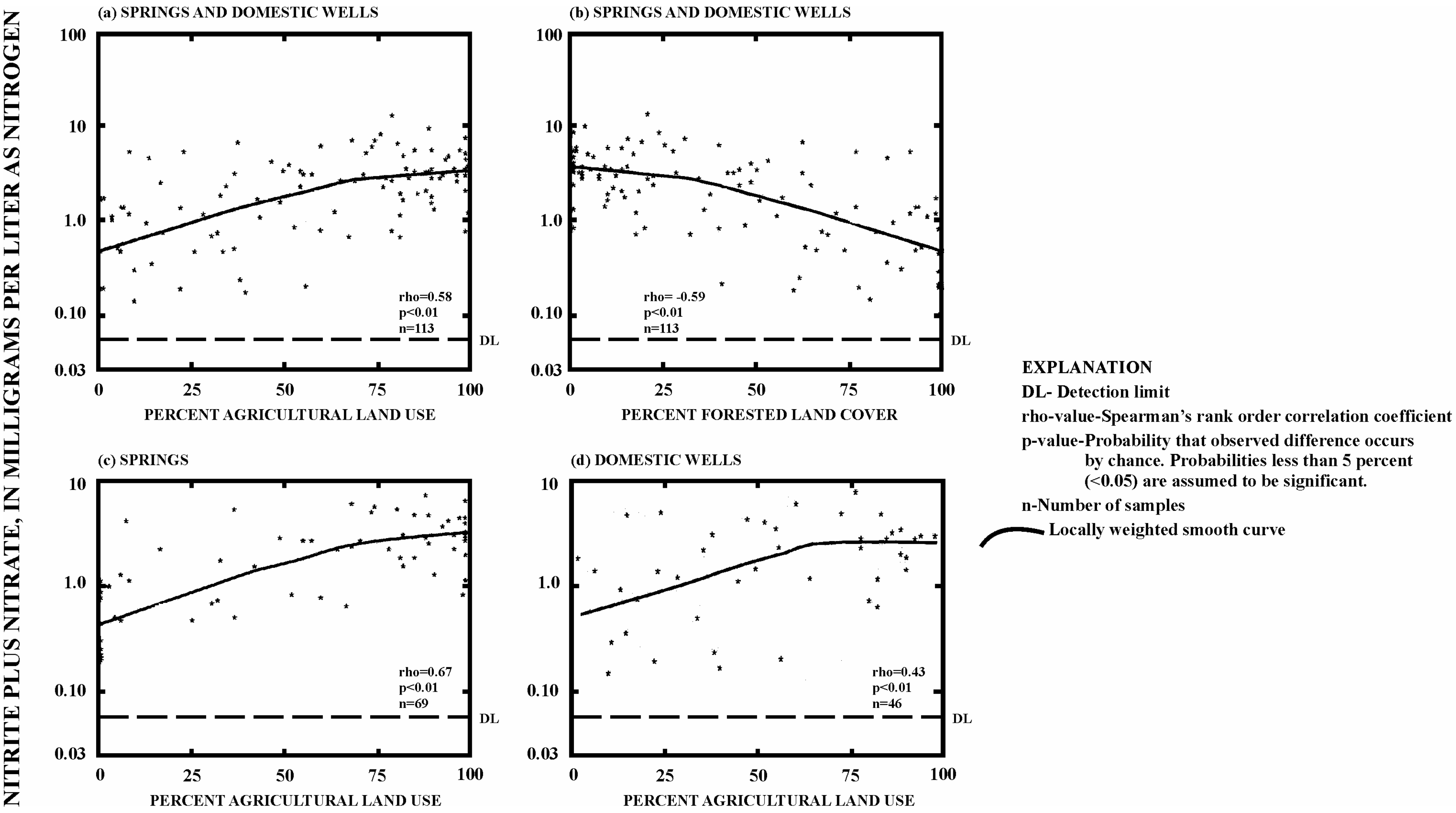

Figure 8. Relation of nitrite plus nitrate concentrations to agricultural land use and forested land cover for ground-water samples from (a) springs and domestic wells, (b) springs and domestic wells, (c) springs, and (d) domestic wells (from Adamski, 1997).

Nitrate-N concentrations for wells and springs sampled for the present study also were compared to land use for comparison to the findings in Adamski (1997). The percentage of various land uses surrounding each site was determined by performing a GIS analysis of CAST GAP 100 Ha land use data using ArcGIS software. A one-mile buffer was created around individual site locations, which were plotted using a Trimble III GPS data collection platform. An analysis of the various land-use types present within the one-mile buffer of each well was conducted to determine the composition of land uses surrounding the sites. Figures 9 and 10 depict NO_3-N concentrations versus percent forest cover and agricultural land use, respectively, and reveal poor correlations based on the R^2 value and from a general inspection of the trendline. However, NO_3-N concentrations greater than or equal to 6.0 mg/L are strongly suspected of contamination from septic wastes, and removal of these outliers results in general trends (Figures 11 and 12) that compare more closely with the trends revealed in Figure 8. Figure 13 depicts ranges of NO_3-N concentrations for the present data as plotted on a land-use map. Although several land uses are listed for Figure 13, only pasture and forest land use were used for the statistical analysis associated with Figures 9 through 12.

Over the years, different methods have been used in Arkansas to separate sources of nutrient and bacteria contamination including the use of fecal coliform/fecal streptococci bacteria ratios (Leidy and Morris, 1990). However, although these ratios exhibit wide differences in various waste sources, their different rates of transport and mortality in ground water complicate interpretation and ultimate determination of source. The use of nitrogen isotopes has been employed to differentiate nitrogen input from synthetic fertilizer versus animal manure. Unfortunately, processes in the subsurface, including denitrification and mixing of nitrogen sources, can affect the $\delta^{15}N$ concentration. Recently-developed methods for simultaneous determination of ^{18}O as well as ^{15}N in nitrate have eliminated some of the complicating factors in determination of nitrogen sources using isotopic analyses, because O and N behave differently when subjected to various subsurface processes: however, such analyses still do not proffer a definitive identification for all sites (Phil Hays, Univ. of Arkansas, personal communication).

A new laboratory method was recently created by the USGS for identification of wastewater contaminants, and was tested using samples from 139 streams across the United States. Organic wastewater contaminants (OWCs) were found in 80% of the streams from a wide range of residential, industrial, and agricultural origins with 82 of the 95 OWCs being found during the course of the study (Kolpin, et al., 2002). The Department selected 18 wells and springs which exceeded 1.0 mg/L NO_3-N, and submitted samples to the USGS laboratory in Denver, Colorado for a Schedule 1433 Wastewater Scan. This method tests for approximately 67 compounds, which include, among others, various estrogen metabolites, fecal indicators, detergent metabolites, other detergent-related compounds, caffeine, cholesterol, and compounds used in the perfume and fragrance industry. This abbreviated scan did not include the antibiotics measured for the Kolpin et al. (2002) study. No OWCs were detected in any of the samples, except for a detection of phthalate, which is frequently associated with laboratory contamination. Table 5 lists the OWCs analyzed for this report.

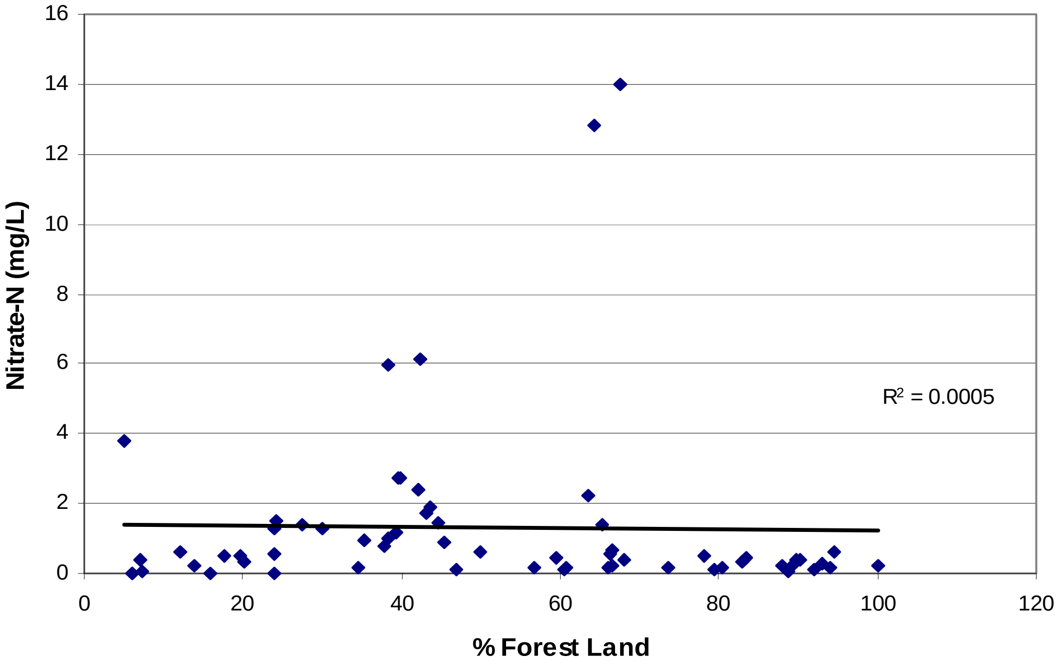

Figure 9. A graph of NO_3-N concentrations versus percent forest land cover for study area. Goodness of fit represented by R^2 value.

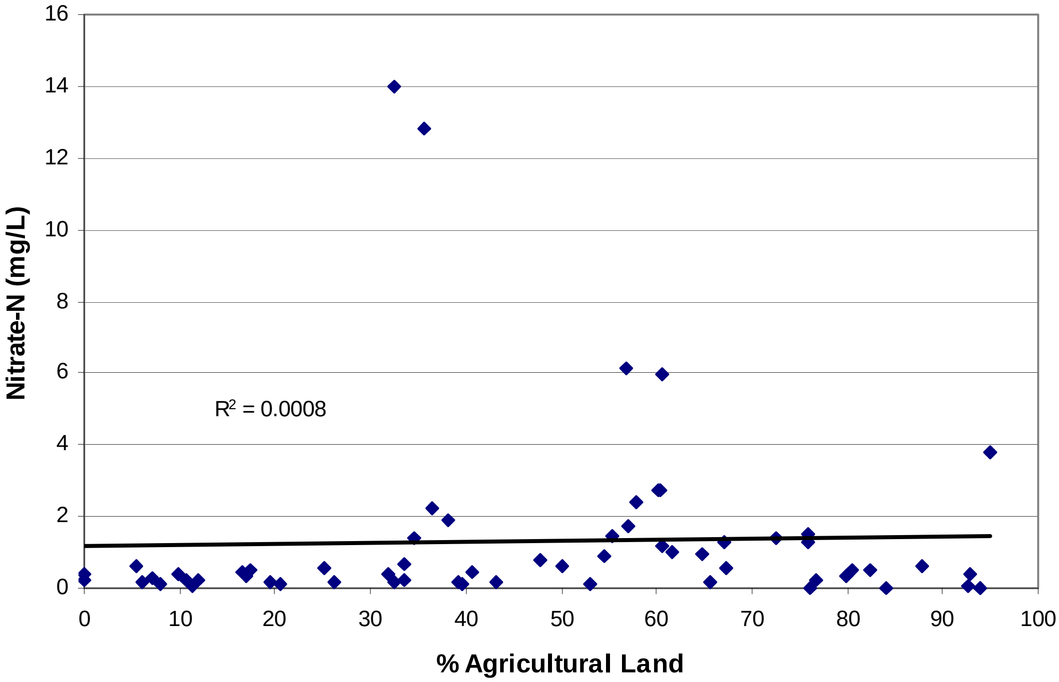

Figure 10. A graph of NO_3-N concentrations versus percent agricultural land use for study area. Goodness of fit represented by R^2 value.

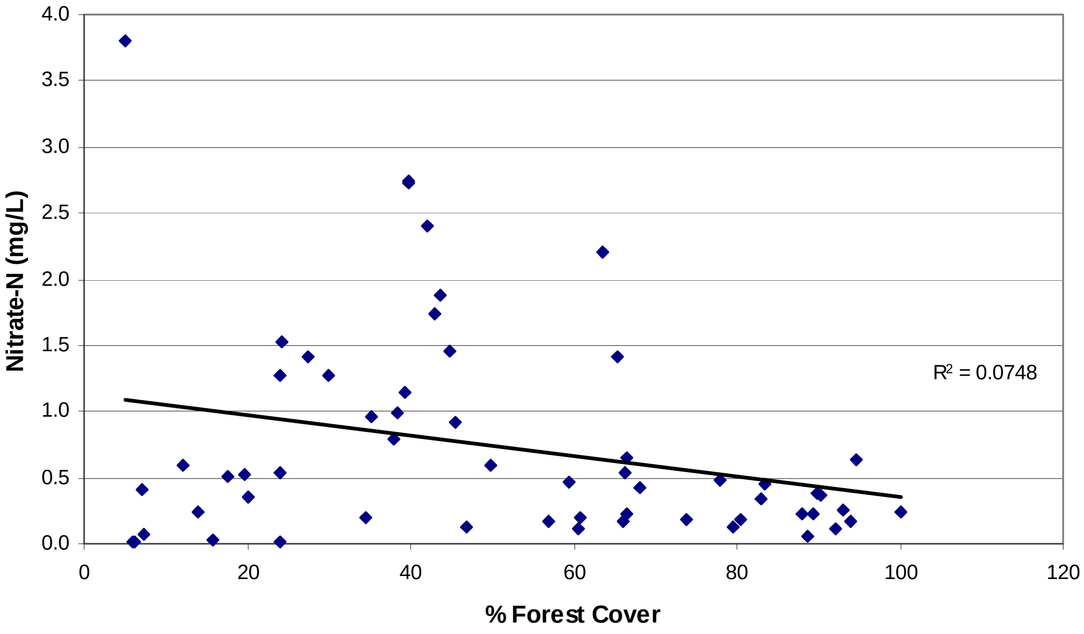

Figure 11. A graph of NO_3-N concentrations versus percent forest land cover. NO_3-N concentrations greater than 6.0 mg/L (four data points) have been removed. Goodness of fit represented by R^2 value.

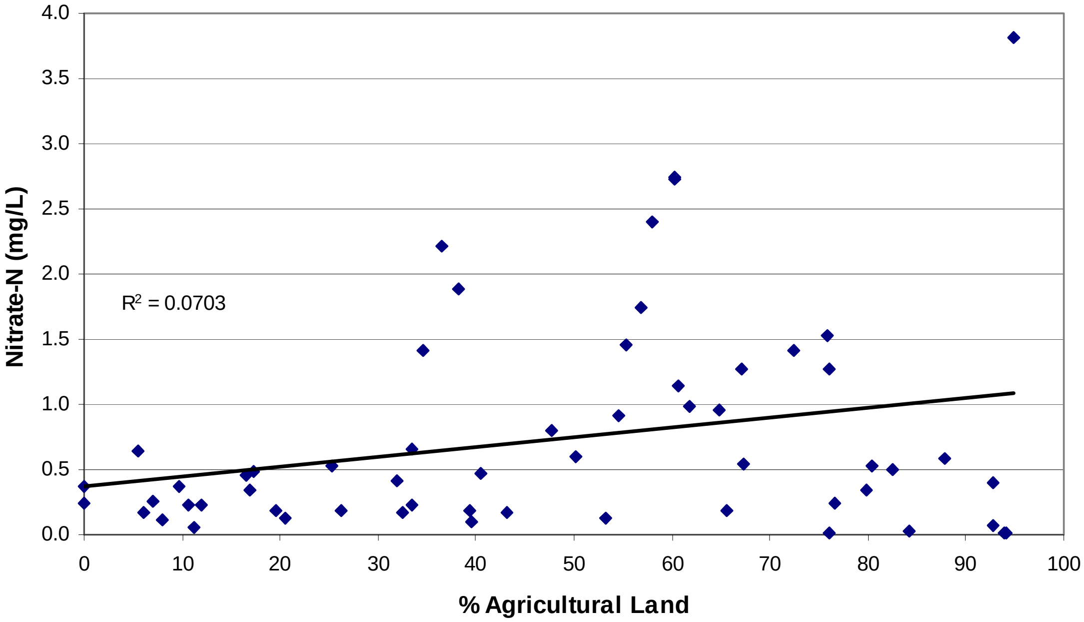

Figure 12. A graph of NO_3-N concentrations versus percent agricultural land use. NO_3-N concentrations greater than 6.0 mg/L have been removed. Goodness of fit represented by R^2 value.

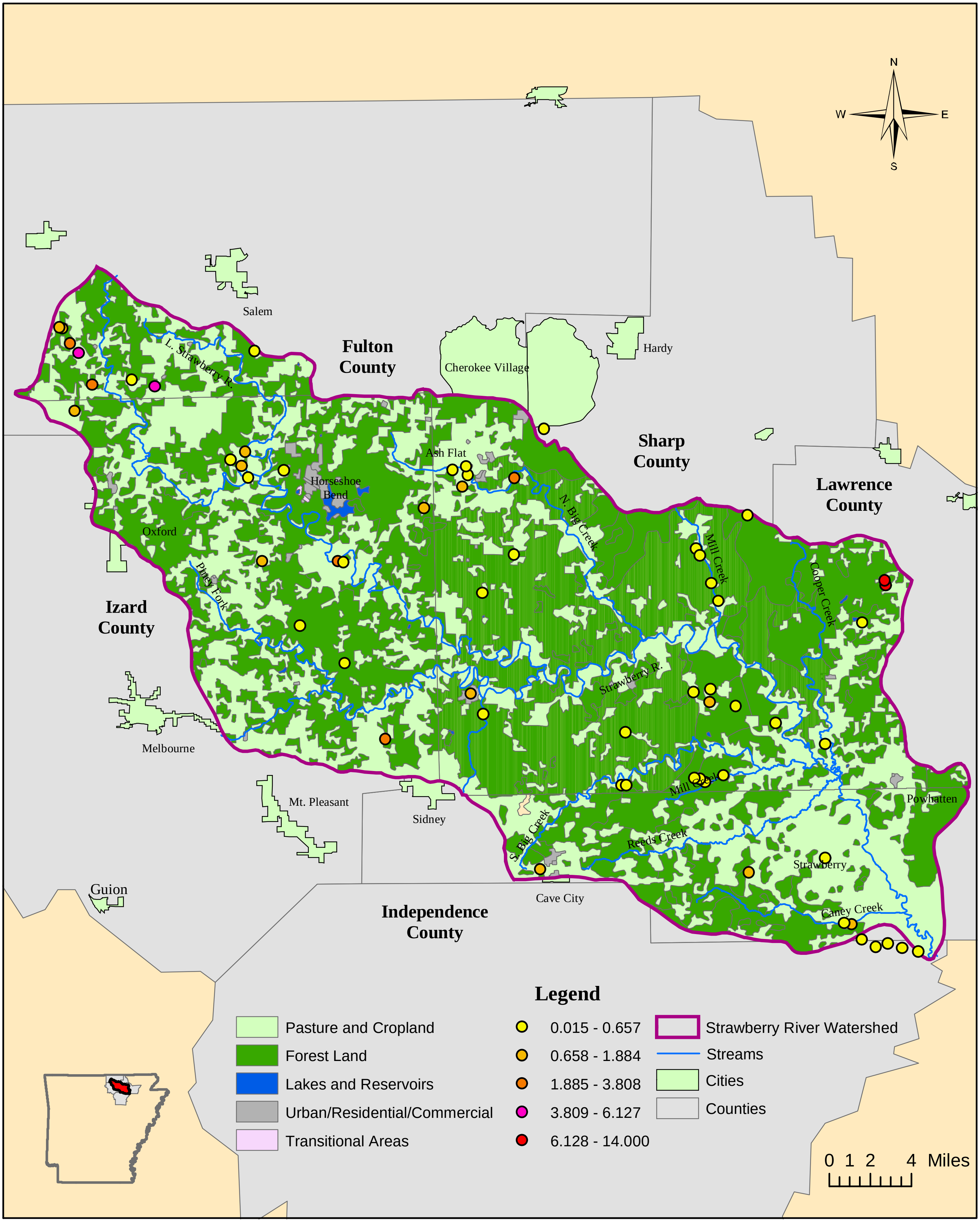

Figure 13. Map showing distribution of ranges for nitrate-N concentrations from the Strawberry River watershed ground-water database

Table 5. USGS Schedule 1433 Wastewater Scan Parameters

1,4–Dichlorobenzene	Caffeine-C13 (surrogate)	Metalaxyl
1–Methylnaphthalene	Camphor	Methyl Salicylate
17–beta-Estradiol	Carbaryl	Metolachlor
2,6-Dimethylnaphthalene	Carbazole	N,N-diethyl-meta-toluamide (DEET)
2-Methylnaphthalene	Chlorpyrifos	Naphthalene
3-beta-Coprostanol	Cholesterol	Nonylphenol, diethoxy- (total)
3-Methyl-1H-indole	Cotinine	Octylphenol, diethoxy-
3-tert-Butyl-4-hydroxy anisole (BHA)	d-Limonene	Octylphenol, monoethoxy-
4-Cumylphenol	Decafluorobiphenyl	p-Cresol
4-n-Octylphenol	Diazinon	Para-Nonylphenol (total)
5-Methyl-1H-benzotriazole	Dichlorvos	Pentachlorophenol
Acetophenone	Equilenin	Phenanthrene
Acetyl hexamethyl tetrahydronaphthalene (AHTN)	Estrone	Phenol
Anthracene	Ethynyl estradiol	Prometon
Anthraquinone	Fluoranthene	Pyrene
Benzo[a]pyrene	Fluoranthene, d10 (surrogate)	Tetrachloroethylene
Benzophenone	Hexadydrohexamethyl-cyclopentabenzopyran (HHCB)	Tri(2-butoxyethyl)phosphate
beta-Sitosterol	Indole	Tri(2-chloroethyl)phosphate
beta-Stigmastanol	Isoborneol	Tributyl phosphate
Bisphenol A	Isophorone	Triclosan
Bisphenol A, d3 (surrogate)	Isopropylbenzene	Triethyl citrate (ethyl citrate)
Bromoform	Isoquinoline	Triphenyl phosphate
Caffeine	Menthol	Tris(dichlorisopropyl)phosphate

Sampling locations were also selected near confined animal operations in the watershed. A total of six wells were sampled that supplied water to chicken houses; two wells were sampled that supplied water to dairy facilities; and one sample was taken from a spring located in a field used as a pasture for cattle. Mean and median NO_3-N concentrations for these nine samples were 1.5 mg/L and 0.6 mg/L, respectively, as compared to 1.3 mg/L and 0.5 mg/L, respectively, for all samples. As such, there was no significant difference between samples collected next to animal facilities versus random locations within the watershed. The two samples which contained NO_3-N concentrations greater than 12.0 mg/L were in the northeast portion of the watershed. Although one owner raises dogs in a pasture behind his house, there are no confined animal operations in the area. The elevated NO_3-N concentrations strongly suggest contamination from onsite septic systems, but there is no definitive evidence for the source at the present time, and the Schedule 1433 Wastewater Scan analyses provided no additional information. Plans are underway to conduct a series of dye tests in both households, using two different dyes during concurrent time frames. Information gained from the dye traces will assist the residents in protecting their drinking water source.

CONCLUSIONS

Ground-water quality was assessed in the Strawberry River watershed by the sampling and analysis of water from 53 wells and 9 springs. Ground water is very important to residents in the four-county area encompassing the watershed, which includes Fulton, Izard, Sharp and Lawrence counties, and accounts for 99% of the total drinking-water use in these counties, including both domestic wells and municipal-supply systems. Ground water is extracted almost entirely from the Ozark aquifer, which serves as the dominant source of ground water in the Ozarks of northern Arkansas and southern Missouri. Domestic wells are generally less than 300 feet in depth, although some can extend to 600 feet or greater, and extract water almost entirely from the exposed Ordovician formations in the watershed including the St. Peter and Everton Formations, the Powell Formation, and the Jefferson City and Cotter Dolomites. Municipal systems most often derive their water from the Lower Ordovician rocks, which include the Roubidoux Formation and the Gunter Sandstone member of the Gasconade Formation, and wells completed in these formations generally range from 1500 to 2700 feet in depth. Four wells were sampled from irrigation wells completed in Quaternary-age alluvial sediments, which occupy a small area in the southeast portion of the watershed.

Ground water flows in a southeastward direction across the watershed, through faults, fractures and bedding plans in the Ozark aquifer, and discharges as baseflow into local streams and springs. The ground water is generally a Ca,Mg-HCO_3 type water, with Ca accounting for over 50 % of the total equivalent cation concentration in 46 of the 58 samples from the Ozark aquifer. Calcium averages 51.6 % of the total cations, whereas Mg averages 45.4% of the total cations and is the dominant cation in 12 of the 58 samples. Ground-water quality in the watershed is good as compared to national drinking-water criteria. The main problem for domestic and municipal-supply users is the high hardness concentrations in the ground water associated with the elevated Ca and Mg concentrations. The water was classified as very hard in 57 of the 62 analyses for the present study.

Secondary maximum contaminant levels for Fe and Mn were exceeded in three of the four alluvial aquifer samples. High Fe and Mn concentrations are ubiquitous throughout the alluvial aquifer, as the result from the dissolution of metal-oxide coatings on the sand grains under reducing conditions. The alluvial aquifer samples also contained elevated TDS, Na, Cl and SO_4 concentrations as compared to the Ozark aquifer. Elevated salts are associated with upward leakage from saline water at depth in the rock units underlying the alluvial aquifer. However, the alluvial aquifer contained significantly-lower NO_3-N concentrations than water from the Ozark aquifer, the cause of which is attributed to denitrification in the alluvial aquifer.

Statistical analysis of the water-quality data revealed differences in water chemistry between the three groups of Ordovician formations exposed at the surface within the watershed, which include, from south to north in the watershed, the St. Peter and Everton Formations (Ose), the Powell Dolomite (Op), and the Cotter and Jefferson City Dolomites (Ocjc). Concentrations of TDS, Ca, Mg, and HCO_3 increase from south to north, although a mechanism has not been identified to explain the increase. Ca/Mg ratios are higher in the Ose versus both the Op and Ocjc, as a result of the higher percentage of limestone in the St. Peter Sandstone. No significant differences were noted between springs and wells in the Ozark aquifer within the watershed.

Two of the samples from wells completed in the Ozark aquifer contain NO_3-N concentrations which exceed the maximum contaminant level of 10 mg/L. A preliminary assessment of the two wells indicates septic-tank effluent as the source for the elevated nitrates. Eighteen of the 62 well-water samples contain NO_3-N concentrations exceeding 1.0 mg/L, which has been derived as a background concentration for NO_3-N in the Ozarks of Arkansas. Identification of the source of elevated nitrates is complicated by the numerous potential sources of nutrients and bacteria in the watershed, which include confined animal operations (animal-waste lagoons, stacked waste, etc.), land application of dry and wet animal waste, fertilizers, bat guano, and septic systems. Nine samples were taken from sites that dominantly housed confined animals, including poultry and dairy operations. Mean and median concentrations of NO_3-N for these nine samples exhibited no differences as compared to mean and median NO_3-N for the general population of samples. Effects of land use on water quality was evaluated by calculating the percent forest cover and the percent pasture land use within a one-mile radius of each well. Concentrations of NO_3-N initially revealed very poor correlations when compared to either percent forest and/or pasture land use. However, removal of four samples with NO_3-N concentrations greater than 6.0 mg/L resulted in a negative correlation between NO_3-N concentrations versus forest cover, and a positive correlation of NO_3-N concentrations versus percent pasture land use. The R^2 values for both regressions were very poor, and the correlations can only be viewed as general trends rather than an absolute cause and effect relationship.

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Appendix I

General and Inorganic Ground-Water Analyses

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Station_ID	Longitude	Latitude	Depth (feet)	pH	Temp. deg. C	Conductance µS/cm	Aluminum µg/L	Arsenic µg/L	Barium µg/L	Beryllium µg/L
FUL100	-91.960703	36.274686	400	8.26	16.9	251	<127	<1.0	12.4	<0.11
FUL101	-91.945215	36.293131	280	5.90	16.0	58	<127	<1.0	12.6	<0.11
FUL102	-91.956683	36.315454	134	7.90	15.8	513	<127	<1.0	28.5	<0.11
FUL103	-91.964195	36.322513	142	7.82	15.8	527	<127	<1.0	39.2	<0.11
FUL104	-91.910371	36.296520	207	7.92	15.9	465	<127	<1.0	20.6	<0.11
FUL105	-91.890877	36.291274	175	7.58	16.2	652	<127	<1.0	24.9	<0.11
FUL106	-91.803347	36.315615	260	8.30	15.2	409	<127	<1.0	23.0	<0.11
IZA110	-91.825470	36.239224	107	7.99	15.6	567	<127	<1.0	25.6	<0.11
SHA124	-91.618822	36.071833	Spring	7.59	19.4	451	<127	<1.0	34.8	<0.11
SHA125	-91.375685	36.194869	218	8.10	15.4	518	<127	<1.0	27.6	<0.11
SHA126	-91.421135	36.171861	158	7.69	16.1	625	<127	<1.0	21.5	<0.11
SHA127	-91.417881	36.167033	Spring	7.65	19.0	557	<127	<1.0	27.0	<0.11
SHA128	-91.485269	36.043034	Spring	7.78	15.5	515	<127	<1.0	24.3	<0.11
LAW107	-91.291651	35.904671	400	7.93	17.0	571	<127	<1.0	46.6	<0.11
LAW108	-91.277718	36.117533	200	8.06	16.5	592	<127	<1.0	31.3	<0.11
LAW109	-91.257035	36.143590	300	7.61	15.9	583	<127	<1.0	87.5	<0.11
SHA129	-91.380062	35.942729	115	7.43	16.0	236	<127	<1.0	10.3	<0.11
LAW102	-91.248327	35.887480	65	7.02	16.4	716	<127	<1.0	473.2	<0.11
LAW103	-91.234166	35.884816	75	7.14	16.0	1264	<127	1.4	343.5	<0.11
LAW104	-91.271044	35.888762	53	7.56	15.8	581	<127	<1.0	72.7	<0.11
LAW105	-91.260794	35.890742	57	7.45	16.1	593	<127	1.7	309.0	<0.11
LAW106	-91.282979	35.894020	600	7.40	16.8	645	<127	<1.0	43.5	<0.11
SHA112	-91.354785	36.047803	278	7.52	17.3	651	<127	<1.0	22.4	<0.11
SHA113	-91.489327	36.005664	400	7.75	17.4	448	<127	<1.0	17.2	<0.11
SHA114	-91.485178	36.005709	Spring	7.92	16.4	373	<127	<1.0	13.7	<0.11
SHA115	-91.416758	36.006961	Spring	7.74	16.8	461	<127	<1.0	18.3	<0.11
SHA116	-91.400680	36.011402	Spring	7.82	15.9	362	<127	<1.0	15.3	<0.11
SHA117	-91.421086	36.009264	2200	7.59	17.4	461	<127	1.1	76.4	<0.11
SHA118	-91.425823	36.009805	2200	7.70	17.4	454	<127	<1.0	30.5	<0.11
SHA119	-91.608617	36.057322	Spring	8.01	16.8	353	<127	<1.0	15.5	<0.11
SHA120	-91.607922	36.142616	308	7.45	16.9	476	<127	<1.0	22.1	<0.11
SHA121	-91.578481	36.223559	288	7.41	15.5	614	<127	<1.0	27.0	<0.11

Appendix I. General and Inorganic Ground-Water Analyses

Station_ID	Longitude	Latitude	Depth (feet)	pH	Temp. deg. C	Conductance µS/cm	Aluminum µg/L	Arsenic µg/L	Barium µg/L	Beryllium µg/L
SHA122	-91.618860	36.226301	293	7.53	16.1	496	<127	<1.0	16.2	<0.11
SHA123	-91.657617	36.203167	263	7.20	15.8	720	<127	<1.0	28.3	<0.11
IZA105	-91.766977	36.121344	230	7.60	16.3	452	<127	<1.0	23.5	<0.11
IZA106	-91.779148	36.231220	?	7.40	17.1	569	<127	<1.0	30.7	<0.11
IZA107	-91.815923	36.234601	Spring	7.29	16.2	550	<127	<1.0	27.3	<0.11
IZA108	-91.812449	36.244577	263	7.40	15.8	558	<127	<1.0	25.6	<0.11
IZA109	-91.810006	36.226492	?	7.66	16.0	440	<127	<1.0	16.5	<0.11
SHA100	-91.560754	35.947133	188	7.26	16.6	254	<127	<1.0	12.0	<0.11
SHA101	-91.579603	36.169447	218	7.47	16.9	701	<127	<1.0	28.5	<0.11
SHA102	-91.620220	36.232259	180	7.56	15.8	450	<127	<1.0	27.9	<0.11
SHA103	-91.632045	36.229889	203	7.50	16.0	557	<127	<1.0	26.0	<0.11
SHA104	-91.623746	36.217877	220	7.66	16.3	434	<127	<1.0	16.4	<0.11
SHA105	-91.551787	36.257809	165	7.80	15.6	399	<127	<1.0	29.7	<0.11
SHA106	-91.402524	36.134449	173	7.06	15.4	740	<127	<1.0	37.5	<0.11
SHA107	-91.408499	36.147013	293	7.23	16.3	645	<127	<1.0	20.4	<0.11
SHA108	-91.425680	36.070605	150	7.30	NA	512	<127	<1.0	43.4	<0.11
SHA109	-91.410761	36.072487	188	7.75	16.2	399	<127	<1.0	21.0	<0.11
SHA110	-91.411564	36.063330	?	7.56	16.3	486	<127	<1.0	21.7	<0.11
SHA111	-91.389008	36.060286	134	7.50	16.1	363	<127	<1.0	22.8	<0.11
LAW100	-91.311811	36.032428	?	7.25	16.8	636	<127	<1.0	32.5	<0.11
LAW101	-91.313687	35.952055	188	7.70	17.4	349	<127	<1.0	19.5	<0.11
IZA100	-91.693670	36.040741	150	7.34	17.9	366	<127	<1.0	18.4	<0.11
IZA101	-91.728258	36.094543	147	7.41	16.2	536	<127	<1.0	22.9	<0.11
IZA102	-91.798866	36.167251	105	7.44	15.9	229	<127	<1.0	19.6	<0.11
IZA103	-91.733124	36.166441	70	7.16	16.5	576	<127	<1.0	41.7	<0.11
IZA104	-91.728239	36.165884	600	7.55	17.5	510	<127	<1.0	28.1	<0.11
FUL107	-91.970499	36.333050	Spring	7.08	15.0	496	282	<1.0	25.1	<0.11
FUL108	-91.973150	36.333824	284	7.31	17.0	555	314	<1.0	26.1	<0.11
LAW110	-91.257696	36.147195	80	7.75	16.2	686	293	<1.0	47.1	<0.11
LAW111	-91.298151	35.905708	145	7.46	16.9	456	295	<1.0	34.3	<0.11

Appendix I. General and Inorganic Ground-Water Analyses

Station_ID	Boron µg/L	Cadmium µg/L	Calcium mg/L	Chromium µg/L	Cobalt µg/L	Copper µg/L	Iron µg/L	Lead µg/L	Magnesium mg/L	Manganese µg/L
FUL100	<4.5	<0.14	27.4	0.5	<0.5	0.9	20.0	0.6	15.0	<0.5
FUL101	<4.5	<0.14	4.6	<0.4	<0.5	2.2	186.0	0.5	2.2	25.6
FUL102	<4.5	<0.14	55.0	1.2	<0.5	0.6	70.4	<0.4	32.2	<0.5
FUL103	<4.5	<0.14	59.5	1.4	<0.5	1.5	73.8	<0.4	33.9	<0.5
FUL104	<4.5	<0.14	52.0	1.2	<0.5	2.1	66.3	<0.4	31.9	1.1
FUL105	<4.5	<0.14	75.0	1.7	<0.5	3.1	108.0	<0.4	41.8	4.6
FUL106	<4.5	<0.14	46.6	1.1	<0.5	2.1	49.3	<0.4	25.2	<0.5
IZA110	<4.5	<0.14	66.9	1.4	<0.5	6.4	96.7	<0.4	38.4	<0.5
SHA124	7.0	<0.14	52.9	1.3	<0.5	2.0	52.7	<0.4	26.9	9.1
SHA125	<4.5	<0.14	59.4	1.2	<0.5	1.7	55.5	<0.4	30.4	1.7
SHA126	<4.5	<0.14	83.4	1.6	<0.5	3.5	74.8	<0.4	39.9	<0.5
SHA127	<4.5	<0.14	68.4	1.6	<0.5	0.9	67.7	<0.4	36.0	<0.5
SHA128	<4.5	<0.14	62.3	1.5	<0.5	0.8	62.8	<0.4	33.8	<0.5
LAW107	11.5	0.2	73.8	1.4	<0.5	1.3	57.7	<0.4	33.1	<0.5
LAW108	<4.5	<0.14	75.1	1.4	<0.5	5.0	70.1	<0.4	38.7	<0.5
LAW109	<4.5	<0.14	58.1	0.8	<0.5	4.5	46.9	<0.4	27.9	<0.5
SHA129	<4.5	<0.14	29.1	0.7	<0.5	5.5	<15.0	0.7	12.4	<0.5
LAW102	<4.5	<0.14	75.4	<0.4	<0.5	0.5	6830.0	<0.4	35.6	983.0
LAW103	112.1	<0.14	90.7	<0.4	<0.5	2.0	6090.0	0.9	40.8	649.5
LAW104	5.3	<0.14	64.0	<0.4	<0.5	<0.5	275.0	<0.4	30.4	22.6
LAW105	<4.5	<0.14	70.7	<0.4	<0.5	<0.5	2610.0	<0.4	33.2	1053.0
LAW106	22.3	<0.14	80.3	<0.4	<0.5	2.3	73.0	<0.4	39.0	<0.5
SHA112	<4.5	0.18	78.1	<0.4	<0.5	4.5	76.5	<0.4	44.4	7.8
SHA113	<4.5	0.25	52.7	<0.4	<0.5	4.9	49.7	1.6	27.9	<0.5
SHA114	<4.5	<0.14	43.6	<0.4	<0.5	<0.5	41.7	<0.4	22.7	<0.5
SHA115	<4.5	0.19	54.7	<0.4	<0.5	<0.5	60.4	<0.4	28.4	<0.5
SHA116	<4.5	<0.14	42.1	<0.4	<0.5	<0.5	41.4	<0.4	22.2	<0.5
SHA117	14.8	<0.14	53.7	<0.4	<0.5	1.1	52.7	<0.4	28.4	<0.5
SHA118	7.6	<0.14	52.0	<0.4	<0.5	0.8	58.4	<0.4	27.9	<0.5
SHA119	<4.5	<0.14	41.7	<0.4	<0.5	0.7	42.6	<0.4	20.8	<0.5
SHA120	15.1	<0.14	59.9	<0.4	<0.5	5.4	69.3	<0.4	33.6	<0.5
SHA121	4.8	<0.14	74.2	<0.4	<0.5	4.0	76.6	<0.4	37.9	<0.5

Appendix I. General and Inorganic Ground-Water Analyses

Station_ID	Boron µg/L	Cadmium µg/L	Calcium mg/L	Chromium µg/L	Cobalt µg/L	Copper µg/L	Iron µg/L	Lead µg/L	Magnesium mg/L	Manganese µg/L
SHA122	<4.5	<0.14	54.6	<0.4	<0.5	7.3	69.7	<0.4	32.8	<0.5
SHA123	<4.5	<0.14	84.6	<0.4	<0.5	2.4	96.5	<0.4	47.6	<0.5
IZA105	146.3	<0.14	46.3	<0.4	<0.5	0.8	70.5	<0.4	29.3	<0.5
IZA106	<4.5	<0.14	65.3	<0.4	<0.5	6.4	78.0	<0.4	37.7	<0.5
IZA107	<4.5	<0.14	59.6	<0.4	<0.5	<0.5	84.8	<0.4	36.8	9.3
IZA108	<4.5	<0.14	61.2	<0.4	<0.5	3.0	82.3	<0.4	37.9	<0.5
IZA109	<4.5	<0.14	47.7	<0.4	<0.5	0.8	62.1	<0.4	28.3	<0.5
SHA100	<4.5	<0.14	30.3	<0.4	<0.5	4.3	32.7	<0.4	14.6	2.4
SHA101	7.0	<0.14	89.4	<0.4	<0.5	3.1	91.9	<0.4	44.5	<0.5
SHA102	<4.5	<0.14	51.2	<0.4	<0.5	4.2	67.1	<0.4	29.1	<0.5
SHA103	<4.5	<0.14	68.4	<0.4	<0.5	4.2	81.7	<0.4	36.6	<0.5
SHA104	<4.5	<0.14	51.2	<0.4	<0.5	1.1	63.8	<0.4	27.8	<0.5
SHA105	<4.5	<0.14	44.5	<0.4	<0.5	6.6	73.3	<0.4	26.1	2.9
SHA106	<4.5	<0.14	101.3	2.9	<0.5	14.7	127.0	0.5	57.9	<0.5
SHA107	7.4	<0.14	82.7	<0.4	<0.5	2.0	89.2	<0.4	40.3	<0.5
SHA108	<4.5	0.57	53.6	<0.4	<0.5	5.8	79.8	<0.4	31.3	<0.5
SHA109	<4.5	<0.14	46.5	<0.4	<0.5	3.9	66.2	<0.4	26.1	<0.5
SHA110	<4.5	0.41	57.2	<0.4	<0.5	0.7	71.7	<0.4	30.3	<0.5
SHA111	<4.5	0.62	41.0	<0.4	<0.5	0.9	67.5	<0.4	23.8	0.9
LAW100	30.4	<0.14	76.8	<0.4	<0.5	<0.5	137.0	<0.4	40.9	2.3
LAW101	<4.5	<0.14	48.8	<0.4	<0.5	<0.5	51.3	<0.4	21.3	<0.5
IZA100	<4.5	<0.14	43.9	<0.4	<0.5	0.9	51.8	<0.4	19.2	<0.5
IZA101	7.3	<0.14	65.8	<0.4	<0.5	1.1	90.6	<0.4	34.7	<0.5
IZA102	<4.5	<0.14	22.1	<0.4	<0.5	4.7	106.0	<0.4	12.4	40.3
IZA103	<4.5	<0.14	71.1	<0.4	<0.5	2.5	84.3	<0.4	33.6	<0.5
IZA104	<4.5	<0.14	61.1	<0.4	0.52	<0.5	2880.0	<0.4	31.6	26.6
FUL107	<4.5	<0.14	57.4	1.4	<0.5	<0.5	72.2	<0.4	32.0	<0.5
FUL108	<4.5	<0.14	64.9	1.4	<0.5	2.4	81.1	<0.4	36.0	<0.5
LAW110	<4.5	0.17	57.8	1.4	<0.5	1.7	73.7	<0.4	31.4	<0.5
LAW111	6.0	<0.14	54.2	1.5	<0.5	0.9	61.1	<0.4	26.0	<0.5

Appendix I. General and Inorganic Ground-Water Analyses

Station_ID	Nickel µg/L	Potassium mg/L	Selenium µg/L	Sodium mg/L	Vanadium µg/L	Zinc µg/L	Hardness mg/L $CaCO_3$	Silica mg/L	Alkalinity mg/L as $CaCO_3$
FUL100	<2.0	<0.46	<3.0	1.8	<1.0	79.6	130	11.0	126
FUL101	11.6	0.7	<3.0	1.4	<1.0	389.4	20	9.5	11
FUL102	2.2	0.6	<3.0	2.5	<1.0	22.0	270	10.3	226
FUL103	2.0	1.0	<3.0	3.1	<1.0	22.3	288	10.1	264
FUL104	3.2	<0.46	<3.0	1.2	<1.0	15.9	261	8.5	245
FUL105	3.0	0.5	<3.0	2.7	<1.0	56.2	360	10.4	301
FUL106	<2.0	<0.46	<3.0	3.5	<1.0	30.9	220	12.4	198
IZA110	2.7	0.7	<3.0	1.2	<1.0	15.1	325	10.9	312
SHA124	2.6	1.5	<3.0	3.6	<1.0	8.9	243	11.9	224
SHA125	2.2	1.0	<3.0	6.0	1.0	4.5	273	12.2	226
SHA126	2.8	0.6	<3.0	0.7	<1.0	10.7	372	9.9	328
SHA127	2.6	1.0	<3.0	1.4	<1.0	5.5	319	10.3	297
SHA128	2.4	0.5	<3.0	0.9	<1.0	9.3	295	10.4	277
LAW107	3.8	1.1	<3.0	6.0	<1.0	64.5	321	16.2	275
LAW108	2.4	0.8	<3.0	2.3	<1.0	16.5	347	11.2	317
LAW109	2.8	1.2	<3.0	21.9	<1.0	50.4	260	16.1	184
SHA129	<2.0	4.1	<3.0	3.0	<1.0	17.1	124	13.2	118
LAW102	<2.0	0.8	<3.0	26.7	<1.0	<1.0	335	29.1	320
LAW103	<2.0	1.8	<3.0	116.0	2.5	14.6	394	23.5	360
LAW104	<2.0	<0.46	<3.0	14.2	1.8	18.6	285	23.4	254
LAW105	<2.0	<0.46	<3.0	9.2	<1.0	14.2	313	25.3	274
LAW106	<2.0	0.6	<3.0	5.4	<1.0	42.5	361	20.8	336
SHA112	<2.0	<0.46	<3.0	1.3	<1.0	68.0	378	9.5	352
SHA113	<2.0	<0.46	<3.0	1.1	<1.0	415.9	246	9.8	241
SHA114	<2.0	<0.46	<3.0	1.0	<1.0	<1.0	202	9.7	204
SHA115	<2.0	<0.46	<3.0	1.4	<1.0	35.1	253	10.4	248
SHA116	<2.0	<0.46	<3.0	1.3	<1.0	17.9	196	12.0	199
SHA117	<2.0	<0.46	<3.0	1.4	<1.0	16.5	251	10.8	246
SHA118	<2.0	<0.46	<3.0	1.4	<1.0	222.1	245	10.4	242
SHA119	<2.0	<0.46	<3.0	1.2	<1.0	<1.0	190	9.3	194
SHA120	<2.0	0.6	<3.0	1.5	<1.0	7.2	288	11.2	282
SHA121	<2.0	<0.46	<3.0	2.2	<1.0	52.6	341	11.9	326

Appendix I. General and Inorganic Ground-Water Analyses

Station_ID	Nickel µg/L	Potassium mg/L	Selenium µg/L	Sodium mg/L	Vanadium µg/L	Zinc µg/L	Hardness mg/L $CaCO_3$	Silica mg/L	Alkalinity mg/L as $CaCO_3$
SHA122	<2.0	<0.46	<3.0	1.3	<1.0	26.7	271	10.0	263
SHA123	2.4	<0.46	<3.0	1.5	<1.0	38.7	407	9.2	370
IZA105	<2.0	4.8	<3.0	2.4	<1.0	13.7	236	10.5	241
IZA106	<2.0	<0.46	<3.0	2.0	<1.0	16.2	318	11.3	306
IZA107	<2.0	<0.46	<3.0	1.9	<1.0	3.4	300	10.8	291
IZA108	<2.0	<0.46	<3.0	1.0	<1.0	24.2	309	12.6	300
IZA109	<2.0	<0.46	<3.0	1.5	<1.0	8.6	236	10.1	235
SHA100	<2.0	0.8	<3.0	1.4	<1.0	15.7	136	11.3	136
SHA101	2.7	0.7	<3.0	1.3	<1.0	12.4	406	10.7	369
SHA102	2.1	1.3	<3.0	1.6	<1.0	24.5	248	11.7	244
SHA103	<2.0	0.6	<3.0	1.6	<1.0	12.8	321	13.5	303
SHA104	17.0	0.5	<3.0	1.1	<1.0	26.0	242	12.8	238
SHA105	<2.0	<0.46	<3.0	3.3	<1.0	5.6	219	14.5	215
SHA106	3.2	<0.46	<3.0	1.3	<1.0	23.9	491	12.2	458
SHA107	3.2	1.4	<3.0	1.2	<1.0	7.1	372	10.3	343
SHA108	<2.0	<0.46	<3.0	11.7	<1.0	136.4	263	12.2	257
SHA109	<2.0	0.9	<3.0	1.2	<1.0	41.0	224	13.3	226
SHA110	<2.0	<0.46	<3.0	2.9	<1.0	12.0	268	13.2	247
SHA111	2.2	<0.46	<3.0	1.6	<1.0	92.2	200	16.3	201
LAW100	2.9	2.2	<3.0	3.1	<1.0	17.2	360	12.2	336
LAW101	<2.0	<0.46	<3.0	2.1	<1.0	34.8	210	13.7	210
IZA100	<2.0	0.7	<3.0	3.3	<1.0	12.7	189	10.5	177
IZA101	2.3	1.3	<3.0	1.8	<1.0	45.4	307	11.3	287
IZA102	<2.0	<0.46	<3.0	5.1	<1.0	39.4	106	14.0	101
IZA103	4.0	1.1	<3.0	3.8	<1.0	47.7	316	11.9	277
IZA104	3.1	1.4	<3.0	1.6	<1.0	1808.0	283	10.1	271
FUL107	<2.00	0.8	<3.0	2.0	<1.0	52.8	275		272
FUL108	2.7	0.5	<3.0	1.3	<1.0	44.7	310		301
LAW110	2.0	<0.46	<3.0	31.2	1.2	71.7	274		203
LAW111	3.0	<0.46	<3.0	2.4	<1.0	34.0	242		245

Appendix I. General and Inorganic Ground-Water Analyses

Station_ID	Bicarbonate mg/L	Bromide mg/L	Chloride mg/L	Fluoride mg/L	Sulfate mg/L	Ammonia-N mg/L	Nitrate-N mg/L	Ortho-P mg/L	TDS mg/L
FUL100	154	0.02	2.2	0.08	1.49	<0.005	1.41	<0.005	145
FUL101	13	0.03	3.3	0.04	1.16	0.074	2.74	<0.005	57
FUL102	276	0.07	13.7	0.07	5.65	<0.005	5.99	<0.005	288
FUL103	322	0.03	5.7	0.06	5.76	<0.005	2.40	<0.005	293
FUL104	299	0.03	2.7	0.07	10.98	<0.005	0.17	<0.005	256
FUL105	367	0.11	17.3	0.10	2.99	<0.005	6.13	<0.005	359
FUL106	242	0.09	11.3	0.12	5.64	<0.005	0.45	<0.005	230
IZA110	381	<0.01	1.6	0.07	2.42	<0.005	0.13	<0.005	309
SHA124	273	0.03	6.1	0.09	5.00	<0.005	1.88	<0.005	256
SHA125	276	0.47	33.0	0.07	2.73	<0.005	0.25	<0.005	281
SHA126	400	<0.01	2.5	0.07	6.85	<0.005	0.66	<0.005	346
SHA127	362	<0.01	1.9	0.07	6.91	<0.005	0.13	<0.005	302
SHA128	338	<0.01	3.3	0.08	3.89	<0.005	0.26	<0.005	286
LAW107	336	0.05	10.7	0.09	14.90	<0.005	1.27	<0.005	327
LAW108	387	0.02	2.5	0.08	6.68	<0.005	0.17	<0.005	324
LAW109	224	0.23	35.3	0.07	15.73	<0.005	12.85	<0.005	343
SHA129	144	0.02	3.4	0.08	1.70	<0.005	0.91	<0.005	142
LAW102	390	0.4	26.2	0.18	27.96	0.372	0.07	0.012	413
LAW103	439	1.82	159.0	0.21	44.73	0.186	0.03	0.010	709
LAW104	310	0.5	33.9	0.15	17.17	0.006	0.41	0.042	344
LAW105	334	0.33	22.6	0.17	15.36	0.109	0.02	0.008	335
LAW106	410	0.16	10.0	0.18	10.29	<0.005	0.35	0.018	375
SHA112	429	<0.01	2.2	0.12	9.70	<0.005	0.60	<0.005	364
SHA113	294	<0.01	1.6	0.13	9.93	<0.005	0.11	<0.005	253
SHA114	249	0.04	1.9	0.15	5.37	<0.005	0.47	0.005	215
SHA115	303	<0.01	2.5	0.14	6.79	<0.005	0.37	0.005	259
SHA116	243	<0.01	2.1	0.14	4.27	<0.005	0.34	0.010	206
SHA117	300	0.04	2.1	0.16	11.55	<0.005	0.12	<0.005	259
SHA118	295	<0.01	2.1	0.15	7.29	<0.005	0.23	0.005	249
SHA119	237	<0.01	1.8	0.14	4.73	<0.005	0.48	0.007	200
SHA120	344	<0.01	3.5	0.14	8.95	<0.005	0.17	<0.005	297
SHA121	398	0.05	5.5	0.10	4.08	<0.005	2.21	<0.005	346

Appendix I. General and Inorganic Ground-Water Analyses

Station_ID	Bicarbonate mg/L	Bromide mg/L	Chloride mg/L	Fluoride mg/L	Sulfate mg/L	Ammonia-N mg/L	Nitrate-N mg/L	Ortho-P mg/L	TDS mg/L
SHA122	321	0.04	1.6	0.11	10.84	<0.005	0.54	<0.005	276
SHA123	451	<0.01	11.8	0.14	14.05	<0.005	1.46	<0.005	414
IZA105	294	<0.01	2.7	0.35	8.84	0.137	0.05	<0.005	252
IZA106	373	0.06	3.8	0.13	7.72	<0.005	0.53	0.008	320
IZA107	355	0.05	5.1	0.12	5.03	<0.005	1.53	<0.005	311
IZA108	366	<0.01	3.7	0.13	4.52	<0.005	0.96	<0.005	312
IZA109	287	<0.01	1.9	0.13	6.93	<0.005	0.53	<0.005	242
SHA100	166	<0.01	2.3	0.09	3.95	<0.005	0.79	0.010	146
SHA101	451	<0.01	4.0	0.15	19.60	<0.005	0.23	0.006	399
SHA102	298	<0.01	3.8	0.11	4.26	<0.005	0.25	0.007	248
SHA103	370	0.03	4.3	0.10	9.36	<0.005	0.50	0.007	310
SHA104	291	<0.01	2.5	0.11	1.67	<0.005	1.28	0.010	239
SHA105	262	0.04	2.6	0.13	7.23	<0.005	0.38	0.010	222
SHA106	559	0.04	2.5	0.08	9.58	0.006	0.18	0.005	465
SHA107	419	<0.01	2.7	0.10	13.00	<0.005	0.64	<0.005	361
SHA108	314	0.07	6.4	0.14	21.12	<0.005	0.42	0.006	286
SHA109	276	<0.01	1.8	0.11	3.44	<0.005	0.19	0.005	223
SHA110	302	<0.01	9.7	0.12	3.29	<0.005	1.41	0.009	264
SHA111	245	0.03	3.5	0.10	1.64	<0.005	0.23	0.008	202
LAW100	410	0.05	4.3	0.16	13.80	<0.005	0.02	<0.005	354
LAW101	256	0.04	3.4	0.13	3.00	<0.005	0.59	0.012	212
IZA100	216	<0.01	8.4	0.09	4.17	<0.005	2.73	0.005	205
IZA101	350	0.07	6.8	0.14	6.78	<0.005	0.18	<0.005	298
IZA102	123	0.08	9.6	0.11	2.42	<0.005	1.74	<0.005	134
IZA103	338	<0.01	12.9	0.09	8.73	<0.005	3.81	0.016	329
IZA104	331	0.03	1.7	0.12	9.40	<0.005	0.02	<0.005	277
FUL107	331	<0.01	5.4	0.09	4.49	<0.005	0.99	0.013	284
FUL108	367	<0.01	4.2	0.09	4.22	<0.005	1.15	0.013	314
LAW110	248	0.28	46.9	0.09	27.40	<0.005	14.00	0.018	406
LAW111	298	0.15	3.5	0.14	6.70	<0.005	0.19	0.020	263

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Appendix II

Estimated Penetrated Thicknesses of Formations for Strawberry River Watershed Study Wells

Appendix II. Estimated penetrated thicknesses of formations for Strawberry River watershed study wells.

Site Number	Well/Spring	Surface Elevation	Well Depth	Well Bottom Elevation	Surface Geology	Surface Geology Lower Contact Elevation	Qal Penetrated Thickness	K Penetrated Thickness	Ospe Penetrated Thickness	Oe Penetrated Thickness	Opw Penetrated Thickness	Oc Penetrated Thickness	Ojc Penetrated Thickness	Quadrangle Map
FUL100	well	882	400	482	Oe	790				92	100	208		Salem - 15 minute
FUL101	well	745	280	465	Opw	720					25	255		Salem - 15 minute
FUL102	well	825	134	691	Opw	800					25	109		Salem - 15 minute
FUL103	well	900	142	758	Opw	800					100	42		Salem - 15 minute
FUL104	well	775	207	568	Opw	720					55	152		Salem - 15 minute
FUL105	well	830	175	655	Opw	800					30	145		Salem - 15 minute
FUL106	well	885	260	625	Oc	(Upper) 900						260		Salem - 15 minute
FUL107	spring	900	N/A	N/A	Opw	N/A								Salem - 15 minute
FUL108	well	900	284	616	Opw	860					40	244		Salem - 15 minute
IZA100	well	595	150	445	Ospe	300			150					Sidney - 7.5 minute
IZA101	well	645	147	498	Opw	(Upper) 710					147			Sidney - 7.5 minute
IZA102	well	805	105	700	Oe	780				25	80			Melbourne - 15 minute
IZA103	well	530	70	460	Opw	525					5	65		Myron - 7.5 minute
IZA104	well	555	600	-45	Opw	525					30	400	170	Myron - 7.5 minute
IZA105	well	765	230	535	Oe	710				55	175			Melbourne - 15 minute
IZA106	well	705	unk.	unk.	Oc	unk.								Melbourne - 15 minute
IZA107	spring	590	N/A	N/A	Oc	N/A								Melbourne - 15 minute
IZA108	well	690	263	427	Opw	680					10	253		Melbourne - 15 minute
IZA109	well	665	unk.	unk.	Oc	unk.								Melbourne - 15 minute
IZA110	well	665	107	558	Oc	(Upper) 680						107		Melbourne - 15 minute
LAW100	well	305	unk.	unk.	Oe	250								Smithville - 7.5 minute
LAW101	well	285	188	97	Oe	-150				188				Strawberry - 7.5 minute
LAW102	well	235	65	170	Qal	unk.	65							Alicia - 15 minute
LAW103	well	235	75	160	Qal	unk.	75							Alicia - 15 minute
LAW104	well	240	53	187	Qal	unk.	53							Strawberry - 7.5 minute
LAW105	well	234	57	177	Qal	unk.	57							Strawberry - 7.5 minute
LAW106	well	318	600	-282	K	250		68		>250	?	?		Strawberry - 7.5 minute
LAW107	well	280	400	-120	K	260		20		>260	?	?		Strawberry - 7.5 minute
LAW108	well	455	200	255	Opw	315					140	60		Smithville - 7.5 minute
LAW109	well	605	300	305	Oe	550				55	200	45		Ravenden - 7.5 minute
LAW110	well	605	80	525	Oe	560				45	35			Ravenden - 7.5 minute
LAW111	well	265	145	120	K	260		5		140				Strawberry - 7.5 minute
SHA100	well	720	188	532	Ospe	(Upper) 740			188					Cave City - 7.5 minute
SHA101	well	665	218	447	Opw	640					25	193		Ash Flat - 7.5 minute
SHA102	well	620	180	440	Oc	370						180		Ash Flat - 7.5 minute

Appendix II. Estimated penetrated thicknesses of formations for Strawberry River watershed study wells.

Site Number	Well/Spring	Surface Elevation	Well Depth	Well Bottom Elevation	Surface Geology	Surface Geology Lower Contact Elevation	Qal Penetrated Thickness	K Penetrated Thickness	Ospe Penetrated Thickness	Oe Penetrated Thickness	Opw Penetrated Thickness	Oc Penetrated Thickness	Ojc Penetrated Thickness	Quadrangle Map
SHA103	well	625	203	422	Oc	370						203		Myron - 7.5 minute
SHA104	well	640	220	420	Oc	330						220		Ash Flat - 7.5 minute
SHA105	well	710	165	545	Oc	450						165		Stuart - 7.5 minute
SHA106	well	385	173	212	Opw	300					85	88		Sitka - 7.5 minute
SHA107	well	385	293	92	Opw	355					30	263		Sitka - 7.5 minute
SHA108	well	505	150	355	Opw	300					150			Poughkeepsie - 7.5 minute
SHA109	well	445	188	257	Opw	220					188			Poughkeepsie - 7.5 minute
SHA110	well	530	unk.	unk.	Oe	440								Poughkeepsie - 7.5 minute
SHA111	well	475	134	341	Oe	355				120	14			Poughkeepsie - 7.5 minute
SHA112	well	320	278	42	Oe	225				95	183			Smithville - 7.5 minute
SHA113	well	470	70	400	Oe	unk.				70				Poughkeepsie - 7.5 minute
SHA114	spring	485	N/A	N/A	Oe	N/A								Poughkeepsie - 7.5 minute
SHA115	spring	360	N/A	N/A	Oe	N/A								Sitka - 7.5 minute
SHA116	spring	315	N/A	N/A	Oe	N/A								Poughkeepsie - 7.5 minute
SHA117	well	395	1900	-1505	Oe	unk.								Poughkeepsie - 7.5 minute
SHA118	well	460	1850	-1390	Oe	unk.								Poughkeepsie - 7.5 minute
SHA119	spring	438	N/A	N/A	Oe	N/A								Evening Shade - 7.5 minute
SHA120	well	660	308	352	Opw	460					200	108		Ash Flat - 7.5 minute
SHA121	well	575	288	287	Oc	270						288		Ash Flat - 7.5 minute
SHA122	well	620	293	327	Oc	345						275	18	Ash Flat - 7.5 minute
SHA123	well	710	263	447	Opw	705					5	258		Myron - 7.5 minute
SHA124	spring	460	N/A	N/A	Oe	N/A								Evening Shade - 7.5 minute
SHA125	well	725	218	507	Opw	540					185	33		Sitka - 7.5 minute
SHA126	well	465	158	307	Opw	450					15	143		Sitka - 7.5 minute
SHA127	spring	415	N/A	N/A	Oc	N/A								Sitka - 7.5 minute
SHA128	spring	455	N/A	N/A	Oe	N/A								Sitka - 7.5 minute
SHA129	well	415	115	300	K/Oe contact	300				115				Grange - 7.5 minute

Stratigraphic Units

Qal - Quaternary alluvium
K - Cretaceous rocks
Ospe - St. Peter Sandstone and Everton Formation (undifferentiated)
Oe - Everton Formation
Opw - Powell Dolomite
Oc - Cotter Dolomite
Ojc - Jefferson City Dolomite

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Appendix III

Results of *z*-Test Statistical Analysis of Well-Water Data from Exposed Ordovician Formations

Appendix III. Results of z-Test statistical analysis of well-water data from exposed Ordovician formations.

z-Test: Two Sample for Means
Calcium: Op versus Ocjc

	Variable 1	*Variable 2*
Mean	56.94285714	63.62105263
Known Variance	478.3	170.4
Observations	21	19
Hypothesized Mean Difference	0	
z	-1.185288633	
P(Z<=z) one-tail	0.117951733	
z Critical one-tail	1.644853476	
P(Z<=z) two-tail	0.235903465	
z Critical two-tail	1.959962787	

z-Test: Two Sample for Means
Calcium: Op versus Ose

	Variable 1	*Variable 2*
Mean	56.94285714	46.35833333
Known Variance	478.3	98.5
Observations	21	12
Hypothesized Mean Difference	0	
z	1.901511302	
P(Z<=z) one-tail	0.02861747	
z Critical one-tail	1.644853476	
P(Z<=z) two-tail	0.057234939	
z Critical two-tail	1.959962787	

z-Test: Two Sample for Means
Calcium: Ocjc versus Ose

	Variable 1	*Variable 2*
Mean	63.62105263	46.35833333
Known Variance	170.4	98.5
Observations	19	12
Hypothesized Mean Difference	0	
z	4.165226817	
P(Z<=z) one-tail	1.55614E-05	
z Critical one-tail	1.644853476	
P(Z<=z) two-tail	3.11229E-05	
z Critical two-tail	1.959962787	

z-Test: Two Sample for Means
Magnesium: Op versus Ocjc

	Variable 1	*Variable 2*
Mean	31.42857143	34.64210526
Known Variance	140.6	36.6
Observations	21	19
Hypothesized Mean Difference	0	
z	-1.094435328	
P(Z<=z) one-tail	0.136882087	
z Critical one-tail	1.644853476	
P(Z<=z) two-tail	0.273764175	
z Critical two-tail	1.959962787	

z-Test: Two Sample for Means
Magnesium: Op versus Ose

	Variable 1	*Variable 2*
Mean	31.42857143	23.01666667
Known Variance	140.6	36.3
Observations	21	12
Hypothesized Mean Difference	0	
z	2.698086665	
P(Z<=z) one-tail	0.003487013	
z Critical one-tail	1.644853476	
P(Z<=z) two-tail	0.006974026	
z Critical two-tail	1.959962787	

z-Test: Two Sample for Means
Magnesium: Ocjc versus Ose

	Variable 1	*Variable 2*
Mean	34.64210526	23.01666667
Known Variance	36.6	36.3
Observations	19	12
Hypothesized Mean Difference	0	
z	5.22455173	
P(Z<=z) one-tail	8.7459E-08	
z Critical one-tail	1.644853476	
P(Z<=z) two-tail	1.74918E-07	
z Critical two-tail	1.959962787	

Appendix III. Results of z-Test statistical analysis of well-water data from exposed Ordovician formations.

z-Test: Two Sample for Means
Sodium: Op versus Ocjc

	Variable 1	*Variable 2*
Mean	4.913809524	2.03
Known Variance	24	1.64
Observations	21	19
Hypothesized Mean Difference	0	
z	2.601118139	
P(Z<=z) one-tail	0.004646056	
z Critical one-tail	1.644853476	
P(Z<=z) two-tail	0.009292113	
z Critical two-tail	1.959962787	

z-Test: Two Sample for Means
Chloride: Op versus Ocjc

	Variable 1	*Variable 2*
Mean	8.811904762	6.08
Known Variance	62.1	54.9
Observations	21	19
Hypothesized Mean Difference	0	
z	1.129830384	
P(Z<=z) one-tail	0.1292739	
z Critical one-tail	1.644853476	
P(Z<=z) two-tail	0.2585478	
z Critical two-tail	1.959962787	

z-Test: Two Sample for Means
Sodium: Op versus Ose

	Variable 1	*Variable 2*
Mean	4.913809524	1.893083333
Known Variance	24	0.99
Observations	21	12
Hypothesized Mean Difference	0	
z	2.728852223	
P(Z<=z) one-tail	0.003177812	
z Critical one-tail	1.644853476	
P(Z<=z) two-tail	0.006355624	
z Critical two-tail	1.959962787	

z-Test: Two Sample for Means
Chloride: Op versus Ose

	Variable 1	*Variable 2*
Mean	8.811904762	3.341666667
Known Variance	62.1	2.11
Observations	21	12
Hypothesized Mean Difference	0	
z	3.090492418	
P(Z<=z) one-tail	0.000999193	
z Critical one-tail	1.644853476	
P(Z<=z) two-tail	0.001998386	
z Critical two-tail	1.959962787	

z-Test: Two Sample for Means
Sodium: Ocjc versus Ose

	Variable 1	*Variable 2*
Mean	2.03	1.893083333
Known Variance	1.64	0.99
Observations	19	12
Hypothesized Mean Difference	0	
z	0.333234368	
P(Z<=z) one-tail	0.369478753	
z Critical one-tail	1.644853476	
P(Z<=z) two-tail	0.738957506	
z Critical two-tail	1.959962787	

z-Test: Two Sample for Means
Chloride: Ocjc versus Ose

	Variable 1	*Variable 2*
Mean	6.08	3.341666667
Known Variance	54.9	2.11
Observations	19	12
Hypothesized Mean Difference	0	
z	1.564045285	
P(Z<=z) one-tail	0.058903476	
z Critical one-tail	1.644853476	
P(Z<=z) two-tail	0.117806951	
z Critical two-tail	1.959962787	

Appendix III. Results of z-Test statistical analysis of well-water data from exposed Ordovician formations.

z-Test: Two Sample for Means
Sulfate: Op versus Ocjc

	Variable 1	*Variable 2*
Mean	8.59047619	7.261578947
Known Variance	28.8	18.5
Observations	21	19
Hypothesized Mean Difference	0	
z	0.867779794	
P(Z<=z) one-tail	0.192757402	
z Critical one-tail	1.644853476	
P(Z<=z) two-tail	0.385514803	
z Critical two-tail	1.959962787	

z-Test: Two Sample for Means
Sulfate: Op versus Ose

	Variable 1	*Variable 2*
Mean	8.59047619	4.958333333
Known Variance	28.8	2.14
Observations	21	12
Hypothesized Mean Difference	0	
z	2.917631445	
P(Z<=z) one-tail	0.001763572	
z Critical one-tail	1.644853476	
P(Z<=z) two-tail	0.003527145	
z Critical two-tail	1.959962787	

z-Test: Two Sample for Means
Sulfate: Ocjc versus Ose

	Variable 1	*Variable 2*
Mean	7.261578947	4.958333333
Known Variance	18.5	2.14
Observations	19	12
Hypothesized Mean Difference	0	
z	2.145906061	
P(Z<=z) one-tail	0.01594018	
z Critical one-tail	1.644853476	
P(Z<=z) two-tail	0.03188036	
z Critical two-tail	1.959962787	

z-Test: Two Sample for Means
Bicarbonate: Op versus Ocjc

	Variable 1	*Variable 2*
Mean	302.5849524	344.8041053
Known Variance	13716	3530
Observations	21	19
Hypothesized Mean Difference	0	
z	-1.457625808	
P(Z<=z) one-tail	0.072471895	
z Critical one-tail	1.644853476	
P(Z<=z) two-tail	0.14494379	
z Critical two-tail	1.959962787	

z-Test: Two Sample for Means
Bicarbonate: Op versus Ose

	Variable 1	*Variable 2*
Mean	302.5849524	251.3098333
Known Variance	13716	56.5
Observations	21	12
Hypothesized Mean Difference	0	
z	1.999138325	
P(Z<=z) one-tail	0.022796625	
z Critical one-tail	1.644853476	
P(Z<=z) two-tail	0.04559325	
z Critical two-tail	1.959962787	

z-Test: Two Sample for Means
Bicarbonate: Ocjc versus Ose

	Variable 1	*Variable 2*
Mean	344.8041053	251.3098333
Known Variance	3530	56.5
Observations	19	12
Hypothesized Mean Difference	0	
z	6.773919226	
P(Z<=z) one-tail	6.30307E-12	
z Critical one-tail	1.644853476	
P(Z<=z) two-tail	1.26061E-11	
z Critical two-tail	1.959962787	

Appendix III. Results of z-Test statistical analysis of well-water data from exposed Ordovician formations.

z-Test: Two Sample for Means

TDS: Op versus Ocjc

	Variable 1	*Variable 2*
Mean	284.2380952	300.6052632
Known Variance	8760	2830
Observations	21	19
Hypothesized Mean Difference	0	
z	-0.687908554	
P(Z<=z) one-tail	0.245755112	
z Critical one-tail	1.644853476	
P(Z<=z) two-tail	0.491510224	
z Critical two-tail	1.959962787	

z-Test: Two Sample for Means

TDS: Op versus Ose

	Variable 1	*Variable 2*
Mean	284.2380952	220.2083333
Known Variance	8760	45.4
Observations	21	12
Hypothesized Mean Difference	0	
z	3.12089324	
P(Z<=z) one-tail	0.000901584	
z Critical one-tail	1.644853476	
P(Z<=z) two-tail	0.001803169	
z Critical two-tail	1.959962787	

z-Test: Two Sample for Means

TDS: Ocjc versus Ose

	Variable 1	*Variable 2*
Mean	300.6052632	220.2083333
Known Variance	2830	45.4
Observations	19	12
Hypothesized Mean Difference	0	
z	6.505434233	
P(Z<=z) one-tail	3.89261E-11	
z Critical one-tail	1.644853476	
P(Z<=z) two-tail	7.78522E-11	
z Critical two-tail	1.959962787	

z-Test: Two Sample for Means

Ca/Mg ratio: Op versus Ocjc

	Variable 1	*Variable 2*
Mean	1.104597184	1.111320592
Known Variance	0.0061	0.0084
Observations	21	19
Hypothesized Mean Difference	0	
z	-0.24840565	
P(Z<=z) one-tail	0.401910332	
z Critical one-tail	1.644853476	
P(Z<=z) two-tail	0.803820665	
z Critical two-tail	1.959962787	

z-Test: Two Sample for Means

Ca/Mg ratio: Op versus Ose

	Variable 1	*Variable 2*
Mean	1.104597184	1.239609949
Known Variance	0.0061	0.0113
Observations	21	12
Hypothesized Mean Difference	0	
z	-3.846310124	
P(Z<=z) one-tail	5.99769E-05	
z Critical one-tail	1.644853476	
P(Z<=z) two-tail	0.000119954	
z Critical two-tail	1.959962787	

z-Test: Two Sample for Means

Ca/Mg ratio: Ocjc versus Ose

	Variable 1	*Variable 2*
Mean	1.111320592	1.239609949
Known Variance	0.0084	0.0113
Observations	19	12
Hypothesized Mean Difference	0	
z	-3.448723452	
P(Z<=z) one-tail	0.00028167	
z Critical one-tail	1.644853476	
P(Z<=z) two-tail	0.000563339	
z Critical two-tail	1.959962787	

Appendix III. Results of z-Test statistical analysis of well-water data from exposed Ordovician formations.

z-Test: Two Sample for Means
pH: Op versus Ocjc

	Variable 1	*Variable 2*
Mean	7.517619048	7.595789474
Known Variance	0.221	0.086
Observations	21	19
Hypothesized Mean Difference	0	
z	-0.637195091	
P(Z<=z) one-tail	0.261998823	
z Critical one-tail	1.644853476	
P(Z<=z) two-tail	0.523997647	
z Critical two-tail	1.959962787	

z-Test: Two Sample for Means
pH: Op versus Ose

	Variable 1	*Variable 2*
Mean	7.517619048	7.65
Known Variance	0.221	0.055
Observations	21	12
Hypothesized Mean Difference	0	
z	-1.077046201	
P(Z<=z) one-tail	0.140729847	
z Critical one-tail	1.644853476	
P(Z<=z) two-tail	0.281459693	
z Critical two-tail	1.959962787	

z-Test: Two Sample for Means
pH: Ocjc versus Ose

	Variable 1	*Variable 2*
Mean	7.595789474	7.65
Known Variance	0.086	0.055
Observations	19	12
Hypothesized Mean Difference	0	
z	-0.56797968	
P(Z<=z) one-tail	0.285024343	
z Critical one-tail	1.644853476	
P(Z<=z) two-tail	0.570048685	
z Critical two-tail	1.959962787	

z-Test: Two Sample for Means
Nitrate: Op versus Ocjc

	Variable 1	*Variable 2*
Mean	2.460857143	0.833631579
Known Variance	9.95	0.85
Observations	21	19
Hypothesized Mean Difference	0	
z	2.259716522	
P(Z<=z) one-tail	0.011919388	
z Critical one-tail	1.644853476	
P(Z<=z) two-tail	0.023838776	
z Critical two-tail	1.959962787	

z-Test: Two Sample for Means
Nitrate: Op versus Ose

	Variable 1	*Variable 2*
Mean	2.460857143	0.760083333
Known Variance	9.95	0.795
Observations	21	12
Hypothesized Mean Difference	0	
z	2.314332451	
P(Z<=z) one-tail	0.010324721	
z Critical one-tail	1.644853476	
P(Z<=z) two-tail	0.020649441	
z Critical two-tail	1.959962787	

z-Test: Two Sample for Means
Nitrate: Ocjc versus Ose

	Variable 1	*Variable 2*
Mean	0.833631579	0.760083333
Known Variance	0.85	0.795
Observations	19	12
Hypothesized Mean Difference	0	
z	0.220768227	
P(Z<=z) one-tail	0.412636489	
z Critical one-tail	1.644853476	
P(Z<=z) two-tail	0.825272977	
z Critical two-tail	1.959962787	