Water-Quality Trends and Effects of Lead and Zinc Mining on Upper Logan Creek and Blue Spring, Southeastern Missouri, 1925–2006

By John G. Schumacher

Chapter 7 of

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Abstract

Dye-tracing investigations have indicated a subsurface connection between a losing reach of Logan Creek downstream from an active lead mine (Sweetwater Mine) and Blue Spring, the seventh largest spring in Missouri. Blue Spring is an important source of water to the Current River within the Ozark National Scenic Riverways. Analyses of historical water-quality samples from Logan Creek (1965–2006) and Blue Spring (1925–2006) and streambed-sediment samples (1995–2002) were performed to characterize changes in water quality in the upper Logan Creek Basin resulting from a lead and zinc mine and the effects of these changes on the water quality of Blue Spring. These multiple lines of evidence from previous dye-trace investigations, water-quality sampling, and trace element and mineralogic composition of streambed-sediment samples indicate likely effects of mining on the water quality of Blue Spring.

Water samples from upper Logan Creek ranged from calcium-magnesium-bicarbonate type, typical of the Ozark region, to mixed sodium-magnesium-calcium-bicarbonate-sulfate type, indicating increased concentrations of sodium, chloride, and sulfate resulting from mining operations. After mine development in the 1960s, sulfate and chloride typically comprised more than 20 percent of the major anions in samples from Logan Creek as compared to less than 5 percent in baseline surface- and ground-water samples from the region. Concentrations of Mississippi Valley Type-related dissolved trace elements (arsenic, cadmium, cobalt, copper, lead, nickel, and zinc) in water samples collected from Logan Creek generally were small and near the reporting level. Zinc was the most commonly detected dissolved trace element and was detected above the reporting level in 30 of 68 samples collected; the maximum concentration of 90 micrograms per liter was detected from a sample collected during 1972. Depending on the quantity of runoff from the mine tailings impoundment and streamflow conditions, discharge from the mine complex and tailings impoundment comprised as much as 68 percent of the discharge in upper Logan Creek, which is lost into the subsurface and resurges at Blue Spring. Concentrations of major and trace constituents in Logan Creek decreased with increasing distance downstream from Adair Creek; however, concentrations of sodium, sulfate, chloride, and boron remained substantially greater than baseline concentrations as flow was lost into the subsurface.

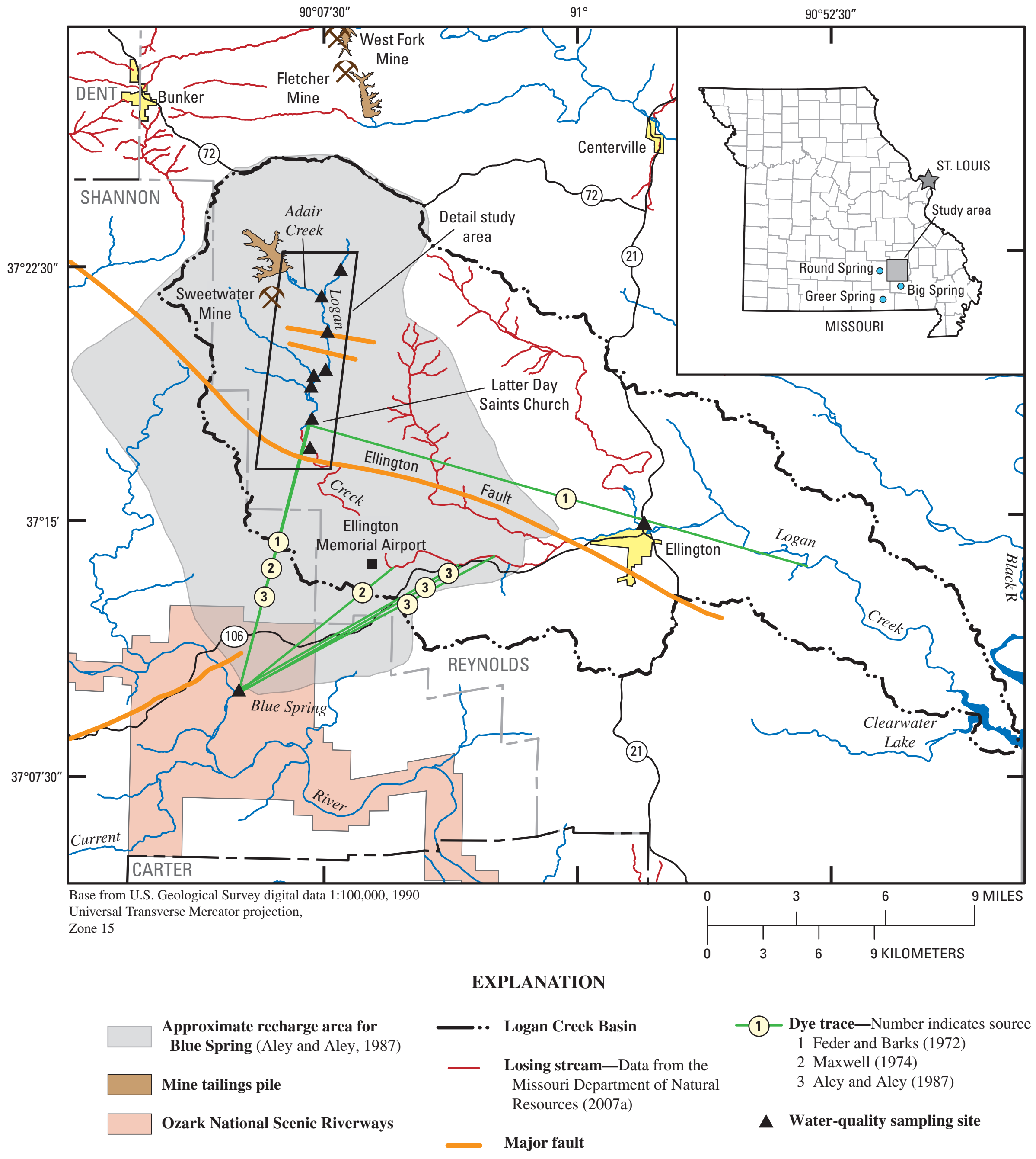
Mining in the Logan Creek Basin has resulted in changes in major ion chemistry of water discharged from Blue Spring. Mining also may have resulted in subtle changes in the mineralogy and concentrations of several trace elements in streambed-sediment samples from Blue Spring and the east side of the Current River downstream from the spring. Generally, water samples from Blue Spring had significantly larger sodium, sulfate, and chloride concentrations as compared to baseline concentrations represented by samples from Big Spring and Greer Spring. Results of a simple mixing model indicate that base-flow concentrations of major ions in an August 2006 sample from Blue Spring can be reasonably approximated by mixing of flow lost from Logan Creek with a baseline ground-water component. Mining effects at Blue Spring also were expressed as spikes in magnesium, sodium, and chloride concentrations and molar ratios of calcium to magnesium in samples collected between 1965 and 1974, and a generally steady increase in sulfate concentrations beginning in 1965. The spike in constituent concentrations and calcium to magnesium ratios coincides with the opening of the Sweetwater Mine exploration shaft during 1962 and initial development of the mine and corresponding increase in concentrations of these constituents in samples from Logan Creek during the same time.

Larger than baseline concentrations of cobalt and nickel (averages of 34 and 65 milligrams per kilogram in the fine (less than 0.063-millimeter size) fraction of streambed-sediment samples from Blue Spring may indicate subtle effects from mine tailings releases into Logan Creek during several breaches of a tailings impoundment at the mine during the 1970s. Mine tailings releases into Logan Creek also may be the source of lead and lead-ore minerals detected in the nonmagnetic heavy-mineral (C3) fraction of streambed-sediment samples from Blue Spring and the east side of the Current River downstream from Blue Spring.

Introduction

Blue Spring is an important source of water to the Current River, which is part of the Ozark National Scenic Riverways (fig. 1). Dye traces have confirmed a subsurface connection between Blue Spring and a losing reach of Logan Creek about 10 miles (mi) northeast of the spring orifice (Feder and Barks, 1972; Maxwell, 1974; Aley and Aley, 1987). Although near the Current River, much of the recharge area for Blue Spring is to the northeast along Logan Creek and within the Black River Basin (fig. 1). Whereas most of the Logan Creek Basin is sparsely populated and predominantly rural and forested, a lead and zinc mine known as the Sweetwater Mine is located along two tributaries in the upper reach of Logan Creek (fig. 1).

Blue Spring has an average discharge of about 130 cubic feet per second (ft^3/s) based on 115 discharge measurements [data on file at the U.S. Geological Survey (USGS) office in Rolla, Missouri] making it the seventh largest spring in Missouri (Miller and Vandike, 1997). The spring rises from a deep pool at the base of a dolostone bluff in Shannon County, Missouri, and flows along a branch about 0.25 mile (mi) to the



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Universal Transverse Mercator projection,
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Figure 1. Location of Logan Creek, Blue Spring, and the Ozark National Scenic Riverways.

Current River. The spring orifice is supplied by a near vertical tubular conduit that has been mapped to more than 300 feet (ft) deep, making it the deepest known spring in southern Missouri (Vineyard and Feder, 1982). A resort lodge previously was located at Blue Spring, and the site was a popular retreat until the 1960s when the spring and surrounding land were purchased by the Missouri Department of Conservation (MDC). The spring and adjacent 17 acres were designated the Blue Spring Nature Area in 1972 (Missouri Department of Conservation, 2008).

The Sweetwater Mine is the southernmost mine in the Viburnum Trend, a world-class lead and zinc ore producing subdistrict. The Viburnum Trend was opened in the early 1960s and became the largest producer of lead in the world by 1972, accounting for 15 percent of world production with more than 1 billion tons of reserves (Rueff, 1970). The initial discovery hole at the Sweetwater Mine was drilled in 1962 and production began at what was then called the Ozark Lead Company Mine in 1968 (Mouat and Clendenin, 1977) and later referred to as the "Adair Creek Mine" and eventually the Sweetwater Mine. Waste rock, called tailings, from the mining and milling of lead and zinc ore at the mine and effluent from the mill are discharged to an impoundment in the headwaters of Adair Creek where the tailings settle and excess water is discharged through a control structure and constructed wetlands into Adair Creek (fig. 2). The tailings impoundment was created by building a dam across Adair Creek, behind which mine tailings are placed using a slurry process. During 1977 and 1978, part of the Sweetwater Mine tailings pile was breached on three separate occasions, causing mine tailings to be released into Adair Creek and Logan Creek (Duchrow and others, 1980). Increased turbidity in response to the tailings releases extended more than 40 mi downstream in Logan Creek; Blue Spring also reportedly became turbid (Duchrow and others, 1980).

Purpose and Scope

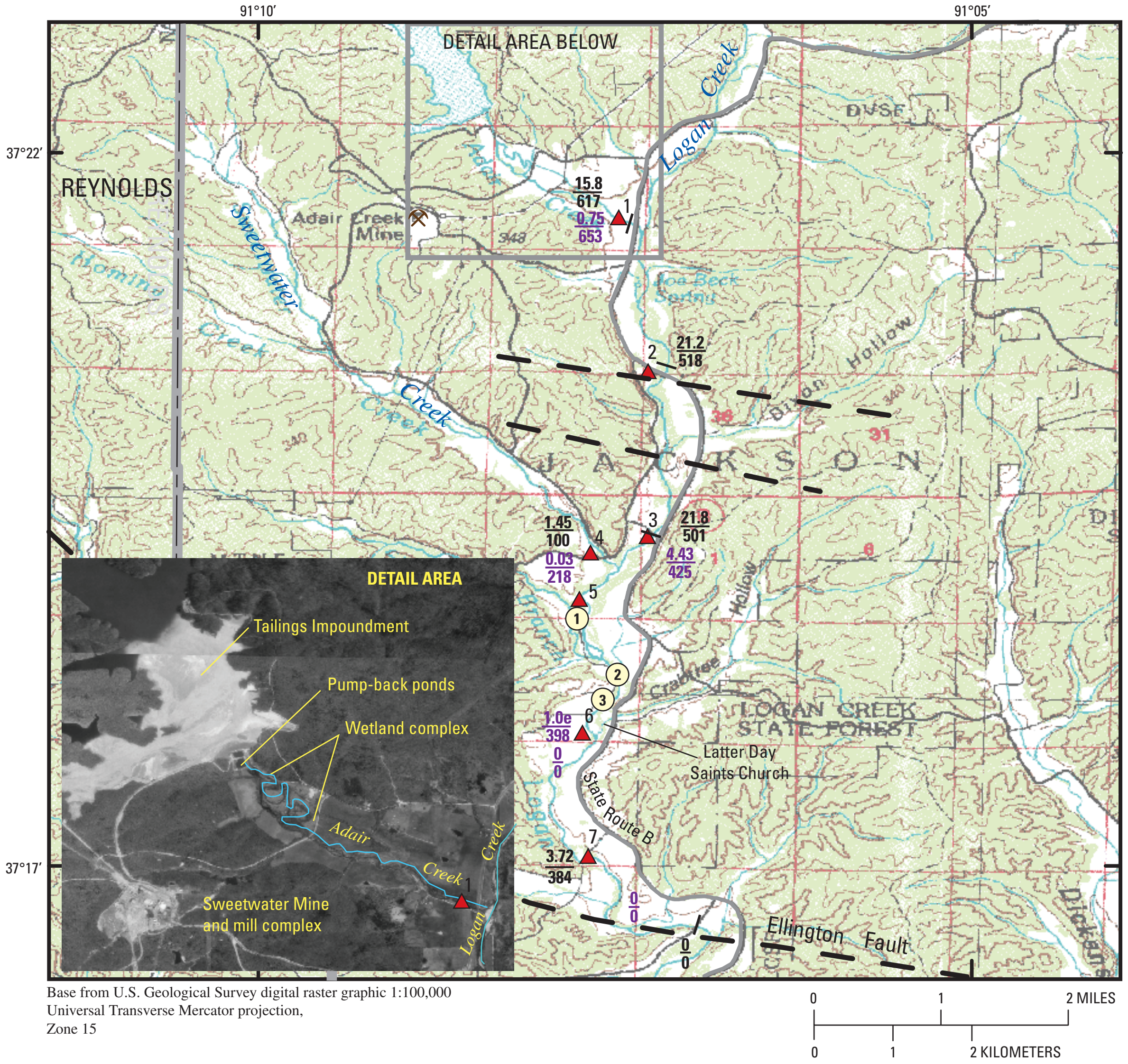
This chapter discusses the results of an analysis of water-quality trends and effects of lead and zinc mining based on water-quality sampling along Logan Creek, a tributary to the Black River, and at Blue Spring, an important source of water to the Current River within the Ozark National Scenic Riverways (ONSR). The analysis of historical (1925–2006) water-quality samples was done in an effort to characterize changes in water quality as a result of lead and zinc mining in the Logan Creek Basin and the effect of these changes on the water quality of Blue Spring. This report is part of a larger multi-discipline investigation of the effects of lead mining in the Viburnum Trend on ground- and surface-water quality and biota conducted by the USGS from 2000 through 2006. Results are presented from more than 60 water-quality samples collected by the USGS from two sites on Logan Creek from 1965 to 2002, base-flow water-quality sampling (6 samples) and a reconnaissance seepage run along upper Logan Creek during 2006, and more than 70 water-quality samples collected from Blue Spring by various agencies from 1925 through 2006. A discussion of results from five streambed-sediment samples collected from Blue Spring and the Current River upstream and downstream from Blue Spring also is presented, along with a summary of dye-tracing activities at Blue Spring.

Study Area Description

The study area focuses on a 7-mi reach of Logan Creek near the Sweetwater Mine and Blue Spring, about 10 mi to the southwest in the Current River Basin (fig. 1). Although Logan Creek flows near the Sweetwater Mine, all flow in Logan Creek is lost to the subsurface in the vicinity of the Ellington Fault (except during extreme runoff), which the creek crosses several miles downstream from the mine. The entire Logan Creek Basin has a surface area of about 200 square miles (mi^2) and the creek is about 50 mi long from its headwaters to its mouth with the Black River in Clearwater Lake (fig. 1). Logan Creek crosses the Ellington Fault twice, and the creek is a losing stream with flow seldom continuous along the 13-mi reach between these two fault crossings. The amount of flow lost along the reach between the two fault crossings can be substantial, such as during January 1969, when an estimated 200 ft^3/s of flow was lost to the subsurface along a 2-mi reach of the creek downstream from the upper Ellington Fault crossing (Feder and Barks, 1972). Topography is steep in the study area and land-surface altitudes range from about 1,250 ft in upland areas near the Sweetwater Mine to about 565 ft at the orifice of Blue Spring along the Current River (fig. 1). The land-surface altitude is about 865 ft in the streambed of Logan Creek in the vicinity of the upper Ellington Fault crossing. Most of the area is forested with scattered pasture along the creek valleys. The area contains small towns, such as Ellington, and the Sweetwater Mine complex. The area is underlain by dolostones of Cambrian and Ordovician age. Bedrock is exposed along the Current River and Blue Spring area and across much of the region; however, few exposures of bedrock occur in the losing part of the Logan Creek Basin because it is covered by a thick blanket of permeable cherty residuum.

Previous Investigations

From 1965 through 1975, the USGS collected water-quality samples from a network of stream monitoring sites in the vicinity of mines throughout the Viburnum Trend. Two sites in this historical network were along Logan Creek near the Sweetwater Mine—Logan Creek upstream from Sweetwater Creek (site 3, USGS station number 07061810) and Logan Creek below Sweetwater Creek (site 5, USGS station number 07061840) in the vicinity of the Sweetwater Mine (fig. 2). Monitoring at most historical sites was reduced or had ceased until the present USGS lead-mining-issues study began in 2000, when sampling resumed at several sites.



Base from U.S. Geological Survey digital raster graphic 1:100,000
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EXPLANATION

— — **Fault**

▲7 **Water-quality sampling site and number**

3.72/384 / **Seepage run site**—Top number is discharge in cubic feet per second; bottom number is specific conductance in microsiemens per centimeter at 25 degrees Celsius. Black values measured March 7, 2006; purple values measured August 15, 2006. "e" indicates estimated value

① **Dye injection site**—Number indicates source
1 Feder and Barks (1972)
2 Maxwell (1974)
3 Aley and Aley (1987)

⚒ **Mine**

Figure 2. Historical water-quality sampling sites and seepage-run measurements made at high base flow (March 7, 2006) and low base flow (August 15, 2006) along the upper reach of Logan Creek.

The USGS has made occasional discharge measurements at Blue Spring since 1923 and collected occasional water-quality samples since 1925. During 1970 and 1971, a continuous streamflow gaging station was installed at Blue Spring; however, because of frequent periods of backwater from the Current River, the record was rated poor, and the data were never published. During October 1969, Feder and Barks (1972) conducted a fluorescent dye trace from Logan Creek near the Latter Day Saints (LDS) Church to verify a suspected subsurface connection between Logan Creek and Blue Spring (Bridge, 1930). Dye recovery points included two locations along Logan Creek that were 17 and 22 mi downstream from the injection point and downstream from the town of Ellington and Powder Mill Spring and Blue Spring, both in the Current River Basin. Dye was recovered at Blue Spring and at the downstream-most site in Logan Creek between 3 and 10 days after injection (fig. 1).

Maxwell (1974) identified several sinkholes and caves along Logan Creek in the vicinity of the LDS Church where dye previously had been injected and recovered at Blue Spring during 1969 (Feder and Barks, 1972). Two small (about 6 ft wide, 20 ft long, and 3 ft deep) sinkholes were located in the channel of Logan Creek about 700 ft downstream from the LDS Church, as well as a sinkhole about 40 ft wide and 25 ft deep on the floodplain west of the Logan Creek channel and about 2,100 ft southwest of the LDS Church (Maxwell, 1974). The sinkhole had a 5-ft high cave entrance, referred to as “Latter Day cave” that extended about 50 ft below the surface of the floodplain. A small cave on the west bank of Logan Creek about 3,000 ft downstream from the LDS Church also was noted. Maxwell (1974) reported that during 1972, a sinkhole about 12 ft in diameter and 8 ft deep developed over 6 months in the sandy floor of the small cave. During a storm on April 11, 1972, Maxwell (1974) injected dye into Logan Creek about 0.25-mi upstream from the LDS Church and a second dye into a sinkhole near the Ellington Memorial Airport about 7 mi further downstream. Both dyes were recovered at Blue Spring (fig. 1) within 12 days.

Aley and Aley (1987) reported four successful dye traces to Blue Spring as part of a study to delineate recharge areas for several major springs in the ONSR (fig. 1). This study also provided a compilation of all dye-tracing activities to springs in the ONSR and mapping of potential water-quality hazards to springs in the ONSR. Of the four reported successful dye traces to Blue Spring, one was a confirmation of the previous 1969 Feder and Barks (1972) trace from the upper reach of Logan Creek; the other three traces were from a reach of Logan Creek or mouths of tributaries about 3 mi downstream from the Maxwell (1974) trace immediately south of Ellington Memorial Airport (fig. 1).

From 1965 through 1971, the USGS collected six water-quality samples from Blue Spring as part of a network of spring and surface water monitoring along the Current River (data on file at the USGS office in Rolla, Missouri). Barks (1978) collected four water-quality samples from Blue Spring during 1973 and 1974 and water-quality samples from several other springs and wells as part of a water-quality assessment of the Current River. Barks noted that springs contained larger concentrations of dissolved nitrite plus nitrate as nitrogen; [$NO_2 + NO_3$; average of 0.42 milligram per liter (mg/L)] compared to well samples (average of 0.22 mg/L). Barks (1978) also noted that springs in the upper Current River and Jacks Fork Basins contained larger $NO_2 + NO_3$ concentrations as compared to springs along the middle and lower part of the Current River Basin (Blue Spring, Big Spring, and Round Spring) (fig. 1), presumably because of differing land use in the spring recharge basins.

The MDC conducted an assessment of the effects of tailings releases from the Ozark Lead Company mine tailings pond (presently Sweetwater Mine) in 1978 (Duchrow and others, 1980). The MDC concluded that the tailings releases severely degraded water quality in Logan Creek as evidenced by decreased densities and diversity of invertebrates. They attributed the degradation to a combination of physical and chemical effects of the tailings in streambed sediments, although concentrations of heavy metals, except lead in one streambed-sediment sample, were less than sediment-quality guidelines established for aquatic life and concentrations of dissolved cadmium, copper, lead, and zinc in surface-water samples were small.

Methods

Data described in the following discussion include the analyses of water-quality samples collected over more than 80 years. The methods used to collect and analyze these samples varied with time; however, methods used were consistent with standard acceptable practices at the time of collection. Discharge, specific conductance, pH, temperature, and dissolved oxygen concentrations were determined onsite at the time of sampling. Samples collected during the 1920s were collected and analyzed by the Missouri Geological Survey [presently the Missouri Division of Geology and Land Survey (DGLS)]. Water-quality samples collected during the 1950s and later were analyzed by USGS laboratories. Samples collected by the USGS during the 1960s and 1970s were collected according to the methods described in Guy and Norman (1970) with subsequent samples collected according to the methods described in Ward and Harr (1990) and Wilde and others (1999). Specific sample collection and analytical methods used during 1973 and 1974 are discussed in Barks (1978).

A detailed description of methods used for the collection and analysis of streambed sediment samples is presented in chapter 3 of this report describing trace-metal concentrations and sulfide-mineral occurrence in streambed sediment of the Viburnum Trend Subdistrict and non-mining areas in southeastern Missouri. Generally, composite streambed-sediment samples were collected along cross sections on spring or stream channels. A plastic scoop was used to collect about 20 subsamples from the upper 2 inches (in.) of streambed sediment along each cross section. Because of high-water velocities and gravel and cobble bottoms, sampling usually was targeted to depositional areas downstream from large rocks or debris. All streambed-sediment samples were analyzed by the USGS mineralogy laboratory in Lakewood, Colorado, for grain-size distribution—coarse [(greater than 0.063 millimeter (mm)], silt (0.002 to 0.063 mm), and clay (less than 0.002 mm). Samples also were analyzed for bulk mineralogy of the less than 2 mm-size fraction using X-ray diffraction, inorganic chemical content of the fine (less than 0.063 mm-size) fraction by inductively coupled plasma atomic emission spectroscopy (ICP-AES) and mineralogy of the non-magnetic heavy mineral concentrate (hereinafter referred to as the C3-fraction) by bromoform separation and optical mineralogy. In addition, semi-quantitative emission spectrometry analysis of the C3 fraction was performed on the 1995 streambed-sediment samples collected from Blue Spring and the Current River.

The relations among major ionic constituents in water samples can be graphically displayed by grouping ions with similar chemical properties on a trilinear diagram (Hem, 1985). Major ions are expressed as percentages of milliequivalents per liter of major cations calcium, magnesium, sodium, and potassium and the major anions sulfate, bicarbonate, chloride, fluoride, and $NO_2 + NO_3$. Trilinear diagrams are useful in examining simple mixtures of solutions or dissolution or precipitation of simple salts. Because mine waters and infiltration percolating through mine tailings piles often produce chemical reactions that involve oxidation and subsequent dissolution of sulfide and carbonate minerals that affects concentrations of major ions, trilinear diagrams were used to examine water-quality changes and evolution of water chemistry in mining areas. Arsenic, cadmium, cobalt, copper, lead, nickel, and zinc are trace elements commonly associated with Mississippi Valley Type ore deposits and are referred to as MVT-related metals in this chapter.

Statistical analyses of water-quality data including summary statistics, distribution tests, correlations, box plots, and scatter plots were performed using the computer software SYSTAT (SYSTAT Software, Inc., 2002). A Shapiro-Wilk test was used to test distributions for normality. Hypothesis testing was done using the non-parametric Kruskal-Wallis test with the null hypothesis that no difference exists between the central tendency of groups being compared, and rejection is at a significance level (p-value) of 0.05 or less. For “censored” data where constituent concentrations were less than the laboratory reporting level and the concentration was reported as “less than the reporting level”, the reporting level was substituted for the censored value. This method was appropriate for most data sets examined because only one reporting level was listed. Insufficient data for statistical analysis were available for concentrations of dissolved trace elements at Blue Spring (only three samples). Statistical comparisons were made on concentrations of total lead and total zinc in water samples from Blue Spring to baseline concentrations represented by samples from the non-mining affected Big Spring and Greer Spring. About 50 percent of the values reported were censored and multiple reporting levels were listed; some of which were too large to be a practical value for statistical analysis. The multiple censoring levels generally were the result of changing analytical methods. For example, in the combined data set for Blue Spring, Big Spring, and Greer Spring, reporting levels for total lead (numbers in parenthesis are number of values in data set) were less than (<) 0.06 microgram per liter (µg/L, 4), <1 µg/L (72), <2 µg/L (2), <5 µg/L (5), <50 µg/L (1) and <200 µg/L (4). Censored values of <5, <50, and <200 µg/L were removed from the data set and censored values of <0.06, <1, and <2 µg/L were all set to a threshold of 2 µg/L for statistical analysis. A similar process was performed for total zinc concentrations where the minimum threshold value was <10 µg/L.

Water-Quality Trends and Effects of Mining

Because much of the recharge area for Blue Spring lies within the upper part of the Logan Creek Basin and flow lost within Logan Creek emerges at Blue Spring, a discussion of the water-quality of Logan Creek is presented followed by a discussion of the water-quality trends in Blue Spring. During March and August 2006, a reconnaissance seepage run and water-quality sampling effort was conducted along Logan Creek downstream from Adair Creek to provide additional information on the effect of mine water discharge on the more recent (2006) water quality of Blue Spring.

Upper Logan Creek

The establishment of monitoring sites on Logan Creek upstream (site 3; fig. 2) and downstream (site 5) from Sweetwater Creek during the 1965 to 1975 USGS water-quality monitoring of Black River Basin indicates that at the time of the initial sampling, Sweetwater Creek was the receiving stream for effluent from early operations at the Sweetwater Mine complex (fig. 2). However, at the time of the initial USGS sampling during 1965, the Sweetwater Mine complex had been in development for nearly 3 years and early samples may not represent “pre-mining conditions.”

Water samples from sites 3 and 5 have a mixture of major ions ranging from calcium-magnesium-bicarbonate (typical of Ozark streams and ground water) to sodium-magnesium-calcium-bicarbonate-sulfate and magnesium-calcium-bicarbonate-chloride, indicating disproportional amounts of sodium, sulfate, and chloride in some of the samples (fig. 3). The increased sodium, sulfate, and chloride in some surface-water samples is consistent with effects from the Sweetwater Mine as seep samples from mine faces within the Sweetwater Mine contained large proportions of sodium, sulfate, and chloride relative to calcium, magnesium, and bicarbonate (Lopaka Lee, U.S. Geological Survey written commun., 2006). In addition, oxidation of sulfide minerals within the mine tailings piles contributes to increased sulfate concentrations in seeps from

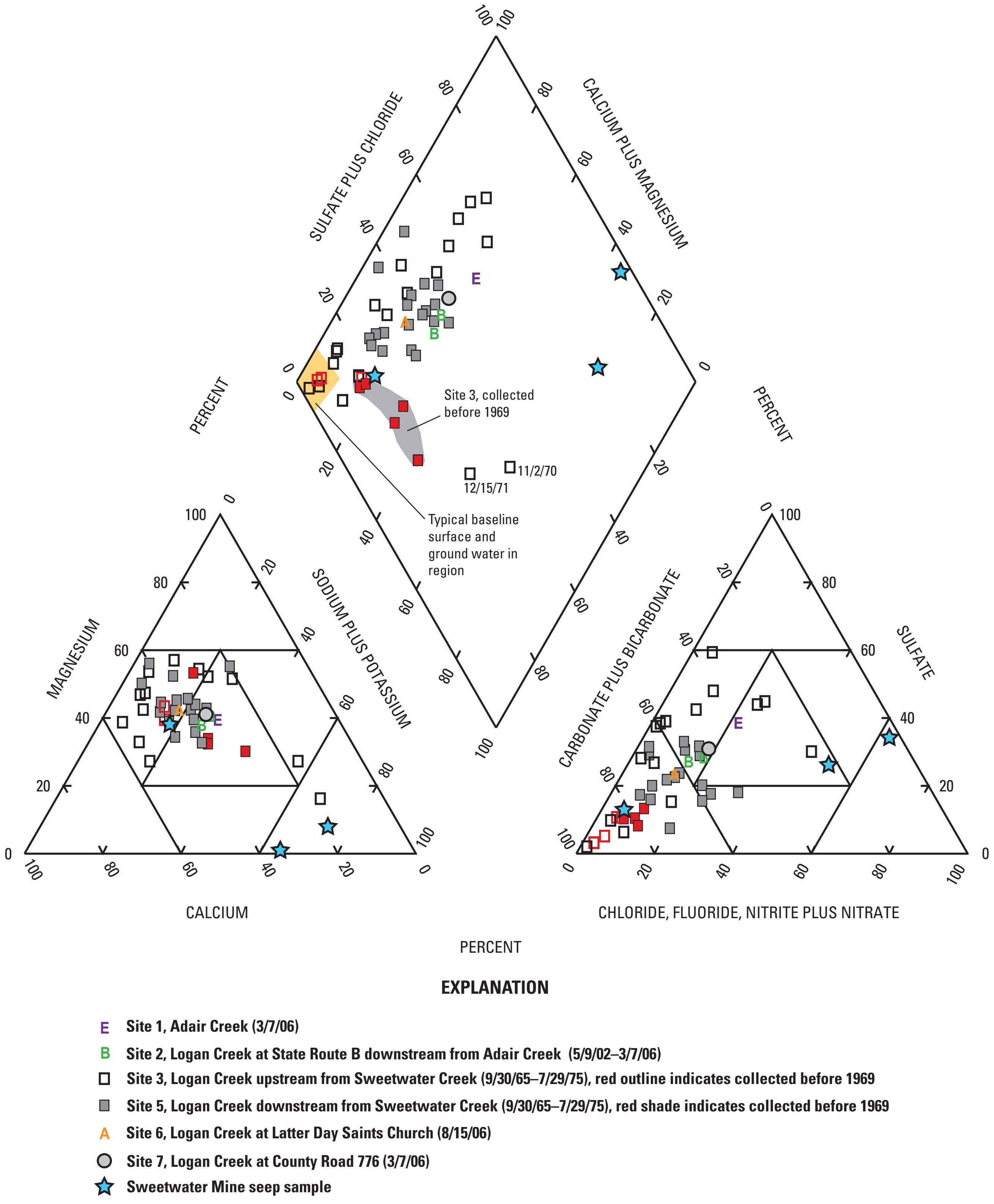

Figure 3. Trilinear diagram of water samples collected from upper Logan Creek, 1965–2006.

the piles (Schumacher and Hockanson, 1996). The presence of increased proportions of sodium, sulfate, and chloride in some of the surface-water samples indicates likely effects of mining operations on the water quality in upper Logan Creek as early as 1965. All samples from site 3 (upstream from Sweetwater Creek) collected before 1969 plot near the calcium plus magnesium-bicarbonate vertex typical of baseline surface and ground water in the region. However, samples collected from site 3 during 1969 and later typically plot trending toward the upper right of figure 3 with sulfate plus chloride generally comprising more than 20 percent of the major anions compared to less than 5 percent in baseline samples, indicating effects from mining operations. Unlike site 3, no samples from site 5 (downstream from Sweetwater Creek) collected before 1969 plot within the baseline range of regional surface and ground water, but plot in a band with increased sodium plus potassium and slightly increased proportions of sulfate and chloride (fig. 3). Samples collected from site 5 during and after 1969 trend toward increased proportions of sulfate plus chloride (greater than 20 percent of the major anions) as compared to earlier samples (fig. 3).

The differences in major ion chemistry between the upstream site (site 3) and downstream site (site 5) on Logan Creek before 1969, but similar chemistry after 1969 indicates changes in the composition of effluent from the mining operation or the location of the effluent discharge, or both. For mines typical of the period, the two major sources of discharge water were water pumped to dewater the mine workings and effluent from the mill complex. Both sources were initially derived from water pumped from the mine workings. Typically, mill effluent is used to slurry waste rock to the tailings impoundment where the tailings settle, and the water is partially recycled through the mill. At the Sweetwater Mine, excess water in the tailings impoundment and storm runoff is discharged through an overflow structure and flows through a constructed wetland meander system into Adair Creek. Based on the initial selection of the sampling site 3 and site 5, in 1965 most discharges during development of the mine shaft and mill complex probably went into Sweetwater Creek. This supposition is supported by the baseline distribution of major ions in the pre-1969 samples from site 3 and increased proportion of sodium, sulfate, and chloride in pre-1969 samples from site 5 (fig. 3). The trend of samples from site 3 away from the calcium plus magnesium-carbonate plus bicarbonate vertex toward more sulfate and chloride-rich water during and after 1969 probably is the result of discharges from the mine complex shifting to the mine-tailings pond on Adair Creek about 2.5 mi upstream from the sampling site 3 (fig. 2). However, apparently not all discharges from the facility had shifted to Adair Creek after production began because specific conductance values and concentrations of calcium, magnesium (not shown), sodium, chloride, sulfate, and alkalinity in post-1969 samples from site 5 were significantly larger (p-value <0.05 using the non-parametric Mann-Whitney test) than those in site 3 samples (fig. 4). By 1987 when National Pollution Discharge Elimination System (NPDES) permits were issued for the facility (chapter 1 of this report), all discharges from the facility apparently were to Adair Creek.

Although changes in major ion chemistry attributed to mining operations were evident as early as 1965 in upper Logan Creek, little, if any, effects were observed on concentrations of dissolved trace elements during sampling from 1965 through 1975. Most water samples from the two sites on upper Logan Creek (sites 3 and 5) were analyzed for a variety of trace elements such as barium, cadmium, chromium, cobalt, cupper, iron, lead, manganese, nickel, silver, and zinc. Several samples collected before September 1970 also were analyzed for boron, lithium, and strontium (table 1, at the back of this chapter). Concentrations of MVT-related metals and other trace elements in water samples collected from upper Logan Creek during 1965 through 1975 generally were small and near reporting levels in the 63 samples collected from sites 3 and 5. Zinc was the most commonly reported trace element, detected above reporting levels in 25 of the 54 samples in which it was analyzed, with a maximum concentration of 90 µg/L in two samples collected during 1972 (table 1). Cadmium and lead concentrations were less than the reporting level of 2 µg/L in all samples, chromium was detected in 4 samples (maximum concentration of 20 µg/L), cobalt was detected in 2 samples (maximum concentration of 40 µg/L), and copper was detected in 7 samples (maximum concentration of 20 µg/L) (table 1). The Mann-Whitney test indicated no significant differences in trace-element concentrations between site 3 and site 5. Only 4 of the 54 samples analyzed for zinc concentrations from these two upper Logan Creek sites indicated zinc concentrations that exceeded the current Missouri chronic standard based on water hardness for the protection of aquatic life (Missouri Department of Natural Resources, 2007b). These samples were collected from sites 3 and 5 during June and October 1972. Several samples from sites 3 and 5 contained unusually small values of specific conductance [less than 100 microsiemens per centimeter at 25 degrees Celsius (µS/cm)] and concentrations of calcium and magnesium less than 10 mg/L (table 1).

Results of the March and August 2006 seepage run and water-quality sampling effort along the upper reach of Logan Creek indicated that, depending on the quantity of runoff from the mine tailings impoundment and streamflow conditions, discharge from the mine complex and tailings impoundment comprised between about 17 to 68 percent of the discharge in upper Logan Creek that is lost into the subsurface. During high base-flow conditions on March 7, 2006, discharge and specific conductance were measured or estimated at six sites and water-quality samples were collected from three sites along Logan Creek, in addition to Blue Spring. Precipitation records from Ellington indicated that 0.2 in. of precipitation occurred in the area on March 5 and 6, 2006, and 0.15 in. of precipitation was recorded on March 7, 2006 (National Oceanic and Atmospheric Administration, 2007). Whereas no runoff was noted when discharge measurements and water-quality samples were collected on March 7, 2006, and the

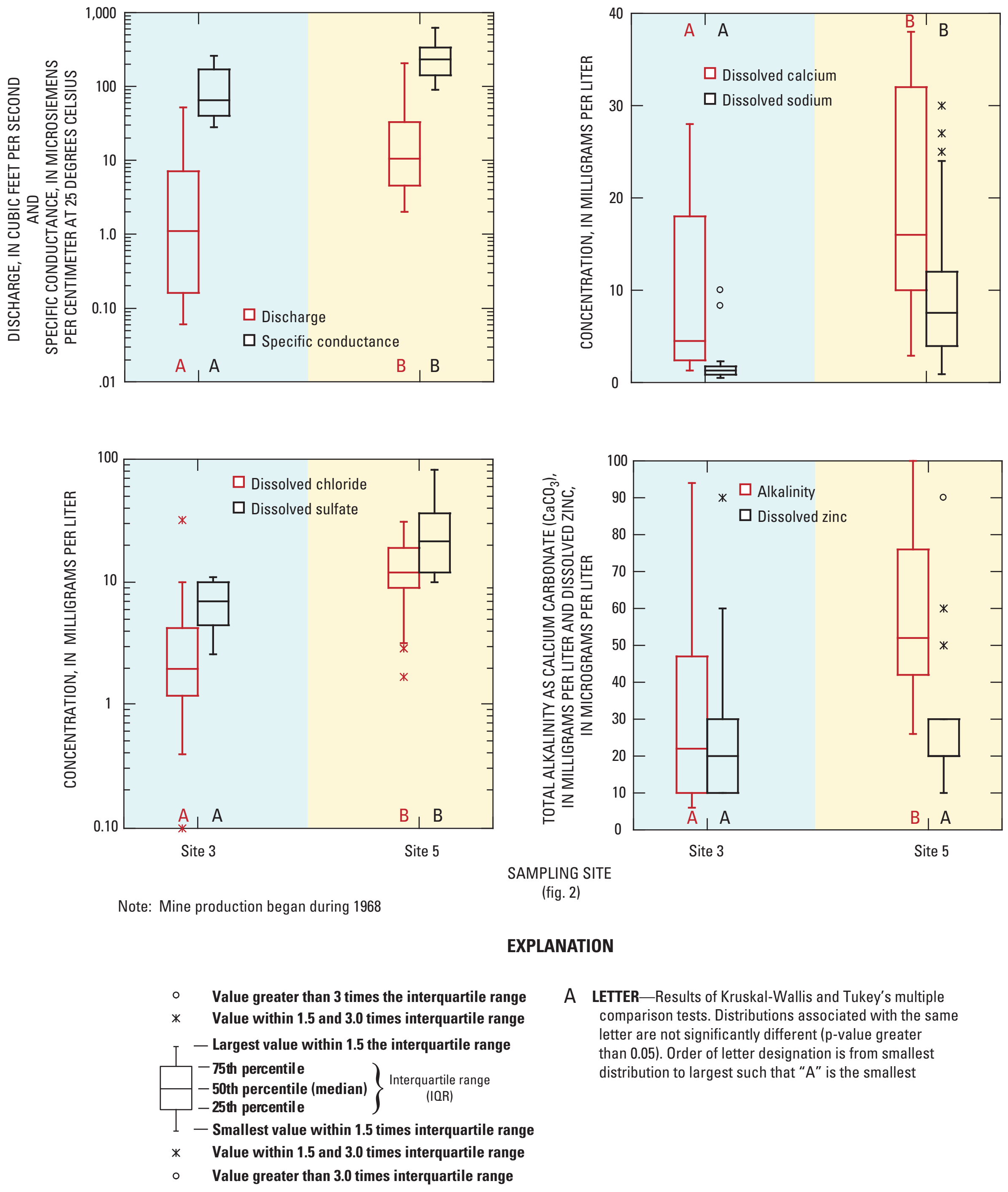

Figure 4. Discharge, specific conductance values, and concentrations of selected inorganic constituents in water samples collected from Logan Creek, 1969–1975.

streams were clear, puddles were observed along road sides and ditches, confirming recent rainfall in the area.

On March 7, 2006, the discharge from the mine complex and tailings impoundment of 15.8 ft^3/s was measured at site 1 at the mouth of Adair Creek (fig. 2). The discharges of Logan Creek downstream from Adair Creek at sites 2 and 3 were similar at 21.2 and 21.8 ft^3/s, indicating a maximum increase of 6 ft^3/s, most of which was inflow from several springs (such as Joe Beck Spring) upstream from site 2 and unmeasured flow in Logan Creek upstream from Adair Creek (fig. 2). Discharge decreased to 3.72 ft^3/s at site 7, indicating more than 80 percent (19.5 ft^3/s) of the discharge in Logan Creek was lost along the 3-mi reach between sites 3 and 7. This loss included a 1.45 ft^3/s inflow from Sweetwater Creek measured at site 4. No flow was observed at an unnamed gravel-road crossing about 1 mi downstream from site 7, indicating a total measured loss of 23.3 ft^3/s, of which about 70 percent (15.8 ft^3/s) was discharge from the mine complex and tailings impoundment. A discharge of 98.6 ft^3/s was measured at Blue Spring on March 7, 2006. Assuming that previous dye traces indicate that all flow lost in Logan Creek resurges at Blue Spring and that flow conditions in Adair Creek and Logan Creek were stable for at least the 10- to 12-day subsurface travel time from Logan Creek to Blue Spring, then flow lost in Logan Creek comprised about 23.3 ft^3/s of the 98.6 ft^3/s, or about 24 percent of the discharge measured at Blue Spring.

During low base-flow conditions on August 15, 2006, discharge was measured or estimated at five sites (including Blue Spring) and a water-quality sample was collected from Logan Creek at site 6 immediately upstream from where all flow was lost to the subsurface (fig. 2). Whereas 0.7 in. of precipitation was recorded at Ellington on August 15, 2006 (National Oceanic and Atmospheric Administration, 2007), no evidence of precipitation, such as damp ground, pools, or puddles along roads, was noted along upper Logan Creek. The discharge of Adair Creek at site 1 was 0.75 ft^3/s on August 15, 2006—considerably smaller than the 15.8 ft^3/s measured on March 7, 2006. The maximum discharge along Logan Creek was 4.43 ft^3/s at site 3. Most of this discharge, including an estimated 0.03 ft^3/s inflow from Sweetwater Creek, was lost into the subsurface by site 6, where a discharge of 1.0 ft^3/s was estimated, and all flow was lost within a few hundred feet downstream from site 6 (fig. 2). The 4.46 ft^3/s of flow lost along Logan Creek on August 15, 2006 (about 17 percent of which was from Adair Creek and mostly mine related), represents about 5 percent of the 88.4 ft^3/s measured at Blue Spring that same day.

Water samples collected during 2006 from Adair Creek (site 1) and three sites on Logan Creek at State Route B (site 2), near the LDS Church (site 6), and County Road 776 downstream from the LDS Church (site 7), all contained increased proportions of sodium plus potassium and sulfate plus chloride and plot within the range of samples collected during the 1960s and 1970s (fig. 3). During the March 7, 2006, sampling event, most of the 15.8 ft^3/s discharge from Adair Creek at site 1 probably was from the mine or mine tailings impoundment. The specific conductance value of 617 µS/cm and concentrations of sodium (40.2 mg/L), sulfate (114 mg/L), and chloride (49.1 mg/L) in the Adair Creek sample greatly exceeded baseline concentrations of sodium (1.5 mg/L), sulfate (4 mg/L), and chloride (3 mg/L) reported for area streams. The baseline concentrations were determined from the maximum values for non-mining sites in table 2, chapter 6 of this report. Concentrations of several MVT-related metals such as cobalt (2 µg/L), copper (3.2 µg/L), lead (11.7 µg/L), nickel (8.5 µg/L), and zinc (34 µg/L) in addition to manganese (330 µg/L) in Adair Creek (table 1) also exceeded baseline non-mining concentrations (table 2, chapter 6). The Adair Creek sample also contained a large concentration of boron at 125 µg/L compared to typical concentrations of 10 to 20 µg/L in surface and ground water in southern Missouri (Schumacher and Hockanson, 1996). Adair Creek comprised about 68 percent of the flow in Logan Creek during the March 7, 2006, sampling. Dilution and possibly geochemical reactions such as precipitation, cation exchange, or sorption resulted in smaller concentrations of sodium, sulfate, chloride, and trace elements at site 2, but concentrations remained substantially above baseline values (table 1). Concentrations of most MVT-related metals decreased to baseline concentrations at site 7; however, effects from mining were evident in the above-baseline concentrations of sodium, sulfate, chloride, and boron in the sample from site 7.

Concentrations of sodium (15.6 mg/L), sulfate (42.4 mg/L), chloride (18.5 mg/L), and boron (62 µg/L) in flow lost to the subsurface during low base-flow conditions approximated by the sample from Logan Creek at site 6 on August 15, 2006, were much smaller than during high base-flow conditions approximated by the sample from site 7 on March 7, 2006 (table 1). The smaller major ion concentrations during August 2006 were the result of the much smaller discharge from Adair Creek (0.75 ft^3/s) measured on August 15, 2006, compared to the 15.8 ft^3/s measured during high base-flow conditions in March 2006. A water-quality sample was not collected from Adair Creek during the August 2006 seepage study, but the specific conductance of 653 µS/cm measured on August 15, 2006, is similar to the 617 µS/cm measured on March 7, 2006, when a water-quality sample was collected, indicating that concentrations of major ions probably were of similar magnitude.

Blue Spring

A difficulty in documenting long-term effects of mining on the water quality of Blue Spring is the lack of a consistent sampling program for mining-related constituents. For example, although 77 water-quality samples have been collected from Blue Spring since 1925 (U.S. Geological Survey, 2007), these samples were collected for various agencies and generally focused on the recreational quality of the water (emphasis on nutrients and fecal bacteria) rather than an assessment of lead and zinc mining effects. Of the 77 water-quality samples collected from Blue Spring, 13 were analyzed for a complete set of major ions (table 2, at the back of this chapter), 3 were analyzed for a comprehensive suite of trace elements, and none were analyzed for organic compounds. Of the 13 samples analyzed for major ions, 2 samples (June 1925 and May 1952) were collected before development of the Sweetwater Mine began in 1962, 8 samples were collected from 1965 to 1973 during the early production years of the Sweetwater Mine, and 3 samples were collected after 2000 (May 2002, March 2006, and August 2006).

The following sections examine water-quality changes at Blue Spring and compares water and sediment data collected from Blue Spring to baseline spring sites in the region—Big Spring about 20 mi downstream along the Current River and Greer Spring about 30 mi southwest along the Eleven Point River. A meaningful comparison of trace-element data from Blue Spring with Big Spring and Greer Spring could not be performed because most trace-element data from Blue Spring was from unfiltered samples, with total concentrations reported in contrast to filtered or dissolved trace-element concentrations at Big Spring and Greer Spring. Although the discharges of Big Spring and Greer Spring (about 445 and 342 ft^3/s mean annual discharge; Hauck and Harris, 2006) are larger than Blue Spring, they have similar geologic settings to Blue Spring. Big Spring and Greer Spring have no lead and zinc mining in their known recharge areas. However, exploration for lead and zinc deposits has occurred within their recharge areas (Imes and others, 2007). Water-quality changes at Blue Spring, in response to mining, may provide insight to potential water-quality changes to Big Spring and Greer Spring if mining processes similar to those used in the Viburnum Trend were to occur in their respective recharge basins.

Water Quality

The measured discharge of Blue Spring ranged from 59.3 to 290 ft^3/s (115 measurements from 1923 through 2006, data on file at the USGS office in Rolla, Missouri) with a median of 108 ft^3/s and mean of 127 ft^3/s. Similar to most springs in southern Missouri, water samples collected from Blue Spring have moderate specific conductance values (118 to 350 μS/cm), near neutral pH values (6.9 to 8.2) and calcium, magnesium, and bicarbonate as the predominant ions (data on file at the USGS office in Rolla, Missouri). Five of the 13 samples from Blue Spring plot outside the baseline range for regional spring water caused by increased concentrations of sodium, sulfate, and chloride relative to calcium plus magnesium and bicarbonate (fig. 5). All five samples plotting outside the baseline range were collected after 1969 and after the Sweetwater Mine began operation within the Blue Spring recharge area (fig. 1). These five samples plot along a trend between baseline spring water samples and samples from mining-affected sites along upper Logan Creek. The increased concentrations of sodium, sulfate, and chloride in these samples are consistent with previous dye traces (Feder and Barks, 1972; Maxwell 1974; Aley and Aley, 1987), indicating that flow lost in Logan Creek downstream from the Sweetwater Mine emerges at Blue Spring.

To provide additional evidence that the increased sodium, sulfate, and chloride, in water samples from Blue Spring might be related to operations at the Sweetwater Mine, a simple two-component mixing model was constructed to simulate major ion concentrations in Blue Spring samples collected during the 2006 seepage-run study. The simple model was constructed using the following relations:

$$Qt*Ct = (Qb*Cb) + (QL*CL) \quad (1)$$

$$Qt = Qb + QL \quad (2)$$

where,

Qt is the measured discharge, in cubic feet per second at Blue Spring;

Ct is the measured constituent concentration, in milligrams per liter at Blue Spring;

Qb is the base flow (non-Logan Creek flow) component of discharge, in cubic feet per second of Blue Spring;

Cb is the baseline base-flow constituent concentration, in milligrams per liter in Blue Spring (approximated by median constituent concentrations in samples from Big Spring and Greer Spring);

QL is the total measured discharge lost, in cubic feet per second in Logan Creek between sites 3 and the unnamed gravel-road crossing downstream from site 7 (fig. 2); and

CL is the constituent concentration, in milligrams per liter in flow lost in Logan Creek (approximated using 2006 sample results from sites 6 and 7).

Equation 2 was solved for Ct for each constituent of interest. Initially, all flow lost in Logan Creek was assumed to contribute to the flow measured at Blue Spring. This assumption implies steady-state conditions of discharge and water-quality in Logan Creek and Blue Spring for at least the 10- to 12-day subsurface travel time between Logan Creek to Blue Spring estimated from previous dye traces.

Results of the simple mixing model indicated that concentrations of major ions measured in the March and August 2006 samples from Blue Spring can be reasonably approximated by the simple mixing of flow lost along Logan Creek with a baseline ground-water component (table 3). At low base-flow conditions in August 2006, this assumption resulted in reliably predicted concentrations of chloride and other constituents (table 3). Differences between measured and simulated major constituent concentrations generally were within 15 percent—an acceptable error based on an assumed 5 percent error in measured constituent concentrations and 5 to 8 percent error in discharge measurements. However, the initial

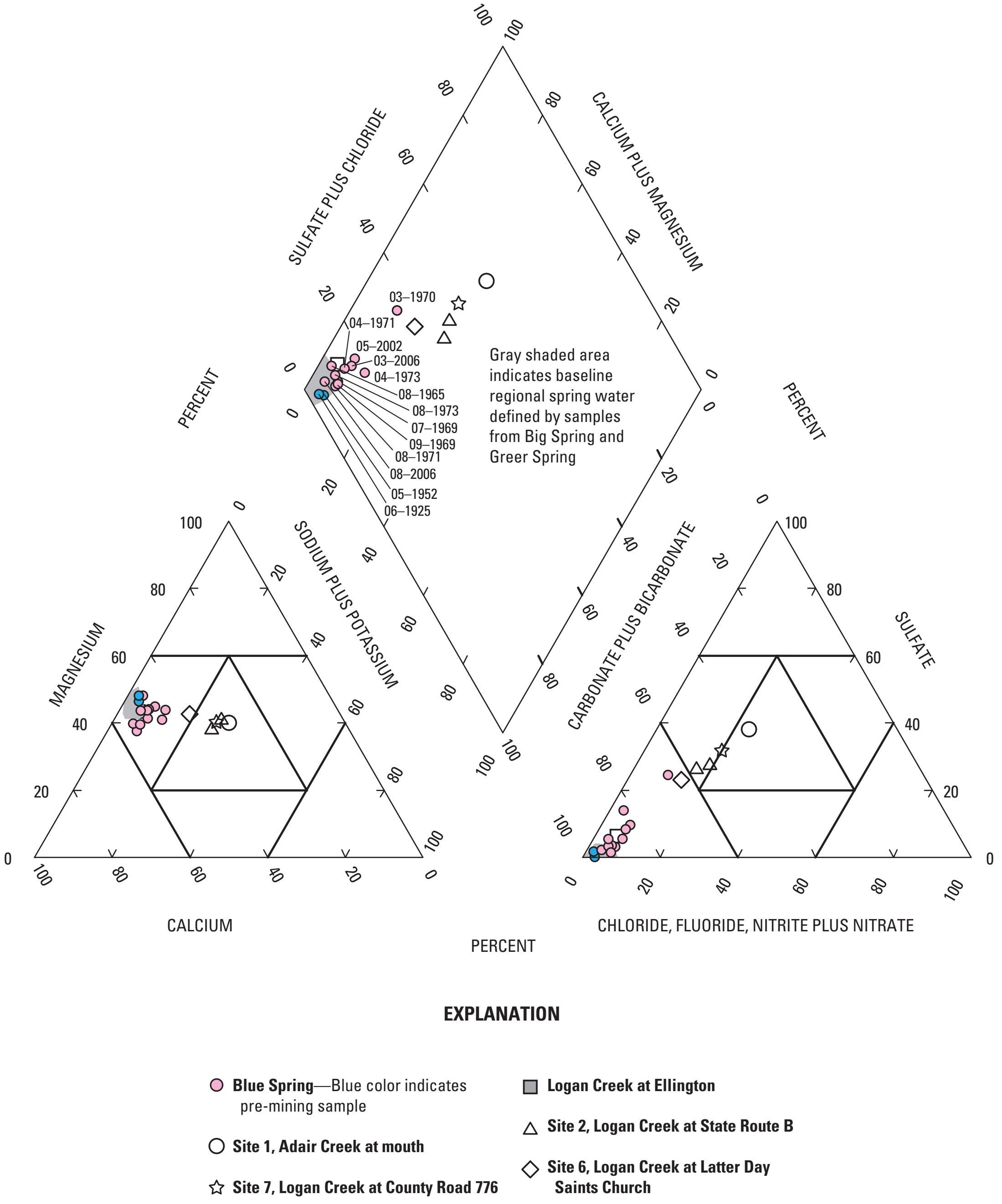

Figure 5. Trilinear diagram of water samples collected from Blue Spring (1925–2006) and water samples collected from upper Logan Creek during 2006.

simulated concentrations of chloride and other constituents in the March 2006 high base-flow simulation were greatly overestimated and the discharge of the Logan Creek component had to be reduced 23 percent from 23.3 ft^3/s (total discharge lost) to17.9 ft^3/s to balance the chloride concentration at Blue Spring. This reduction in discharge required in the high base-flow simulation probably indicates non-steady state conditions existed along upper Logan Creek—likely the result of precipitation and runoff affecting the discharge, water-quality, or both before the March 7, 2006, seepage run.

Significant differences (p-value < 0.05) in discharge, specific conductance, and concentrations of several major inorganic constituents were detected between Blue Spring and baseline concentrations represented by Big Spring and Greer Spring (fig. 6). Samples from Blue Spring had significantly smaller specific conductance values and dissolved concentrations of calcium and magnesium, but significantly larger concentrations of sodium, sulfate, and chloride as compared to Big Spring and Greer Spring (fig. 6). The significantly larger concentrations of sodium, sulfate, and chloride in Blue Spring

Table 3. Measured and simulated concentrations of selected constituents in water samples collected from Blue Spring in March and August 2006.

[ft^3/s, cubic feet per second; --, no data; Ca, calcium; Mg, magnesium; Na, sodium; K, potassium; Cl, chloride; SO_4, sulfate; HCO_3, total bicarbonate; B, boron; µg/L, micrograms per liter; all concentrations are dissolved in milligrams per liter unless noted otherwise; shade indicates percent difference greater than 15 percent]

	Base-flow component	Logan Creek component		Blue Spring high base flow (03/07/06)			Blue Spring low base flow (08/15/06)		
Constituent	Median Big Spring and Greer Spring	High base-flow site 7 (03/07/06)	Low base-flow site 6 (08/15/06)	Measured	Simulated (simulated with adjusted discharge)	Percent difference (with adjusted discharge)	Measured	Simulated	Percent difference
Discharge (ft^3/s)	--	23.3 [a](17.9)	[b]4.46	98.6	--	--	88.4	--	--
Ca	35	29.2	30.2	29.8	33.6 (33.9)	12.9 (13.9)	32.4	34.8	7.3
Mg	20	21.7	20.1	18.1	20.4 (20.3)	12.7 (12.2)	18.7	20.0	7.0
Na	1.6	25.3	15.6	6.3	7.2 (5.9)	14.9 (-6.3)	3.1	2.3	-26.8
K	.9	2.08	1.83	0.9	1.1 (1.0)	22.5 (14.7)	.7	.9	21.7
SO_4	2.4	73.5	42.4	16.0	19.2 (15.3)	20.0 (-4.3)	4.8	4.4	-8.0
Cl	2.5	31.4	18.5	7.7	9.3 [a](7.7)	20.7 (0)	3.4	3.3	-4.1
HCO_3	200	141	245	189	186 (189)	-1.6 (0.2)	185	197	9.3
B (µg/L)	8	72	62	17.3	23.2 (19.7)	36.4 (15.7)	11.1	10.7	-3.5

[a] Total discharge lost was 23.3 ft^3/s (21.8 ft^3/s measured at site 3 plus 1.45 ft^3/s measured at site 4); Logan Creek adjusted component reduced 23 percent to 17.9 ft^3/s to address mass balance of chloride at Blue Spring.

[b] Total discharge lost was 4.43 ft^3/s measured at site 3 plus an estimated 0.03 ft^3/s loss at site 4 (Sweetwater Creek).

likely are the result of water from the Sweetwater Mine and tailings impoundment that discharges into upper Logan Creek and emerges at Blue Spring. Samples of mine seeps within the Sweetwater Mine confirm large concentrations of sodium, sulfate, and chloride in water pumped from the mine (data on file at the USGS office in Rolla, Missouri). Concentrations of $NO_2 + NO_3$ in Blue Spring were similar to those in Big Spring, but significantly smaller than those in Greer Spring. It is noteworthy that concentrations of sodium, sulfate, chloride, $NO_2 + NO_3$, and fecal coliform densities (not shown) in Greer Spring were significantly larger than those in Big Spring (fig. 6). Although a sufficient number of samples from Big Spring and Greer Spring were analyzed for dissolved trace elements to establish baseline trace-element concentrations, only three samples from Blue Spring have been analyzed for dissolved trace elements, and no statistical comparison of these values to baseline concentrations was made. A Kruskal-Wallis non-parametric test indicated that concentrations of total lead and total zinc in water samples from Blue Spring were not significantly larger than baseline concentrations.

Because of the paucity of samples from Blue Spring for complete chemical analysis, especially before mining began in the Logan Creek Basin, insufficient data are available for detailed trend analysis. A Lowess smooth of historical data from Blue Spring using the software package SYSTAT (SYSTAT Software Inc., 2002) indicated that discharge tended to increase from the mid-1960s through the mid-1990s, then decreased thereafter (fig. 7). Specific conductance values, while variable for the period of record, exhibited no time trends. The period between 1965 and 1974 had noticeable spikes in concentrations of magnesium, sodium, chloride, and a relatively steady increase in sulfate concentrations (fig. 7). Concentrations of total dissolved solids (TDS) and molar ratios of calcium to magnesium (Ca:Mg) also tended to increase during this period (table 2). The spike in constituent concentrations and Ca:Mg ratios coincides with the opening of the exploration shaft during 1962 and initial development of the Sweetwater Mine complex and corresponding increase in concentrations of these constituents in samples from upper Logan Creek. Sampling density also may contribute to the

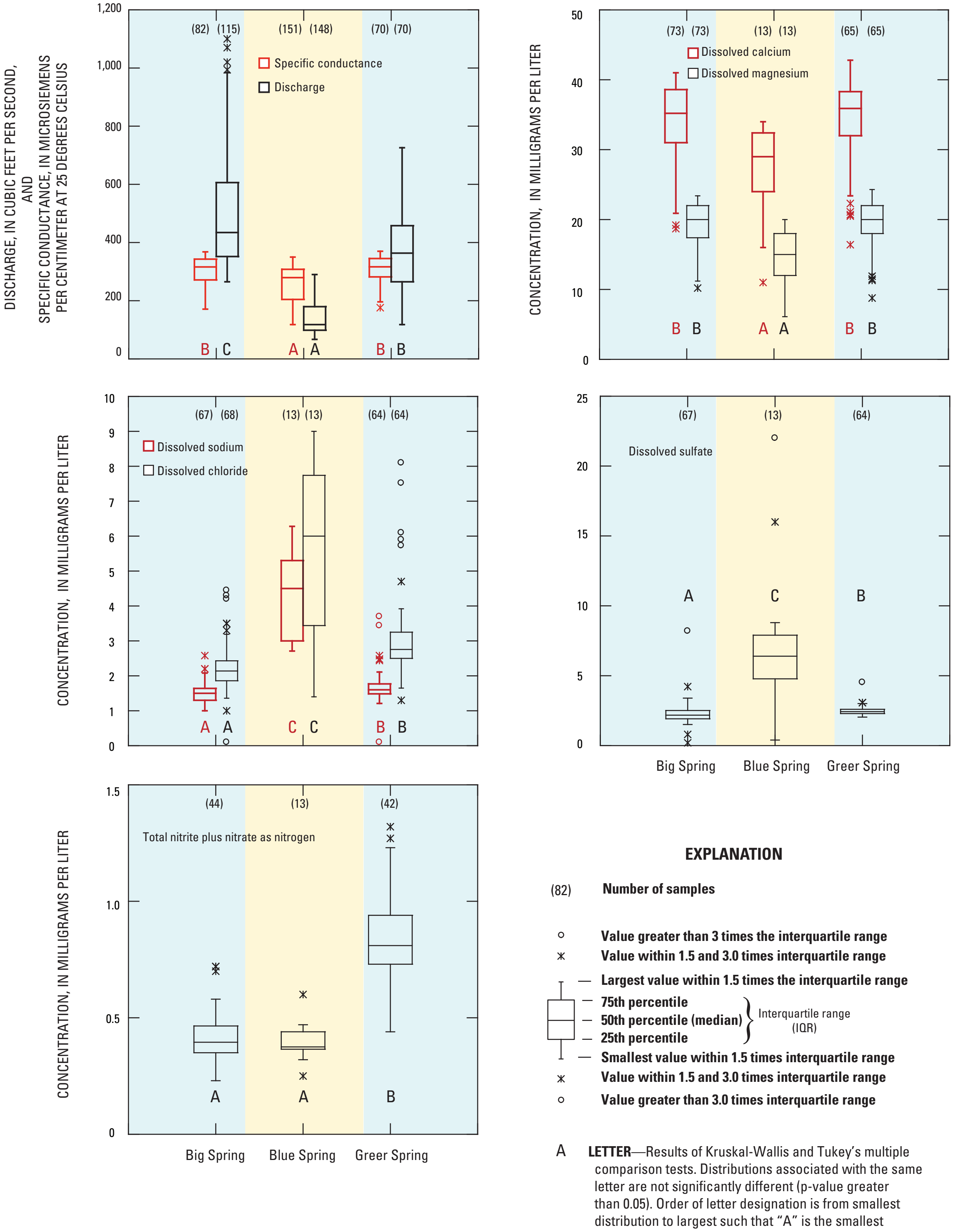

Figure 6. Concentrations of selected major ions and nitrate plus nitrate as nitrogen in water samples from Blue Spring, Big Spring, and Greer Spring and results of analysis of variance and multiple comparison tests on rank ordered data.

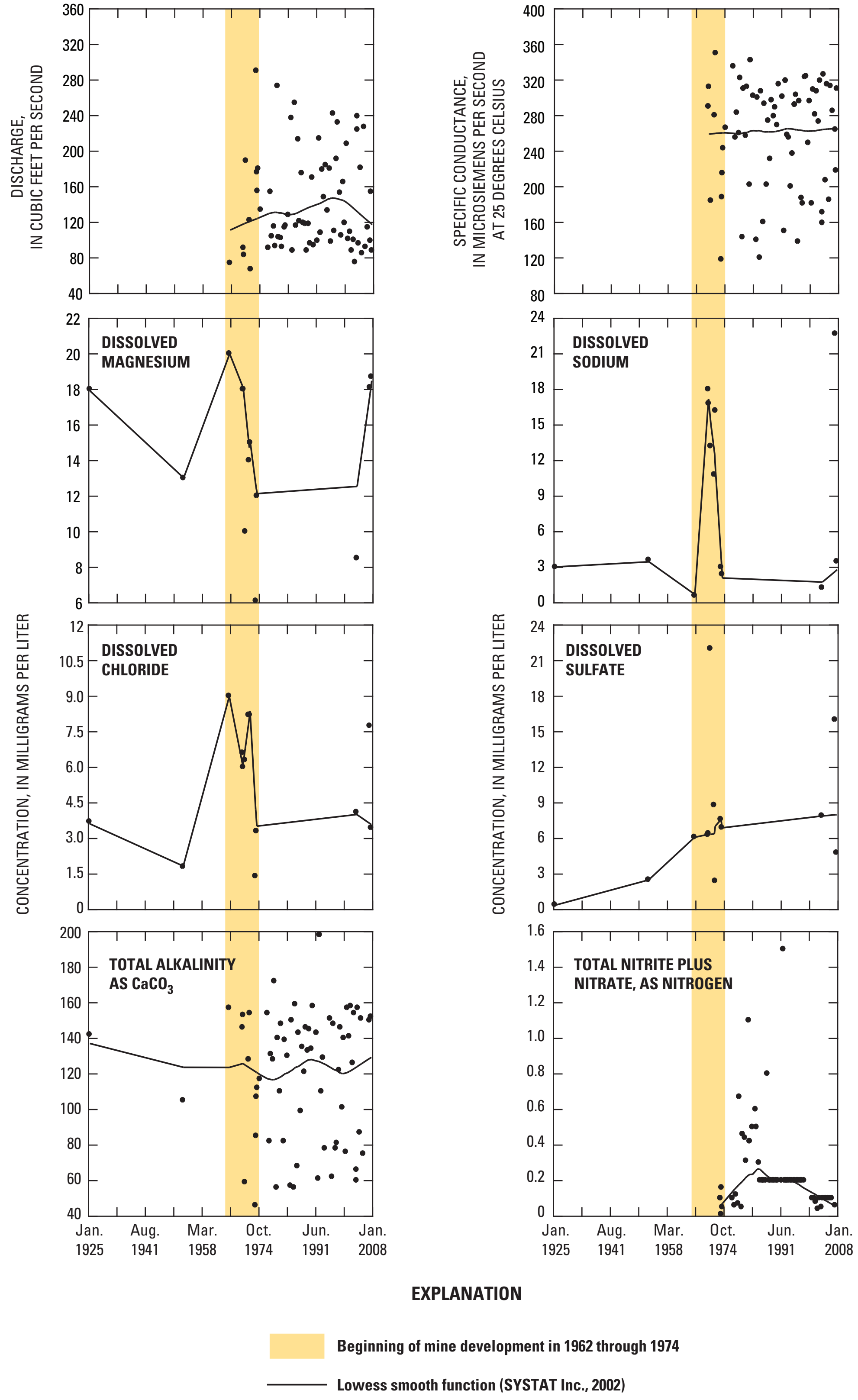

Figure 7. Discharge, specific conductance, and concentrations of selected chemical constituents with time in water samples from Blue Spring, 1925–2006.

observed spike in concentrations because more samples from Blue Spring were analyzed for these constituents during the 1960s and early 1970s than at any other time.

Streambed-Sediment Quality

Many mining-related constituents, such as lead, are considered insoluble and usually are not detected in the dissolved phase in surface water. Streambed-sediment samples were collected to determine if mine tailings releases into Logan Creek have resulted in increased concentrations of mining-related minerals and trace elements in streambed sediment from Blue Spring or the Current River downstream from Blue Spring.

During 1995, five composite streambed-sediment samples were collected; two from cross sections along Blue Spring branch (one about 20 ft downstream from the orifice referred to as the orifice and the other about 150 ft upstream from the spring branch mouth, referred to as the branch), one from a cross section on the Current River about 900 ft upstream from Blue Spring, and one each from the east and west sides of the Current River along a cross section about 100 ft downstream from Blue Spring. The Current River was about 250 ft wide at each cross section. The Blue Spring branch enters the Current River from the east bank. The section across the Current River downstream from Blue Spring branch was divided into an east one-half and a west one-half sample to document differences in mineralogy or chemistry of the streambed sediment. Streambed-sediment samples from 0 to 50 ft from each bank were collected as described in chapter 3 of this report and samples from the middle 150 ft of the channel were collected from a boat using a USGS BM-60 bed-sediment sampler. During 2002, an additional streambed-sediment sample was collected from a cross section about 20 ft downstream from the spring orifice as part of a larger streambed-sediment sampling effort along the Black River and adjacent streams described in chapter 3 in this report.

Concentrations of trace elements in streambed-sediment samples from Blue Spring were compared to results of streambed-sediment samples collected during 1997 and 2002 by the USGS from the baseline sites at Big Spring and Greer Spring (chapter 3). Comparisons focused on the MVT-related metals (arsenic, cadmium, cobalt, copper, lead, nickel, and zinc) in the fine fraction (less than 0.063-mm size) and the presence of lead-ore minerals such as galena (PbS) and cerrusite ($PbCO_3$). Because of the inherent heterogeneity in streambed sediment and difficulty in collecting representative samples, comparisons between single samples often are equivocal; comparisons are best made between groups of samples.

Streambed-sediment samples from Blue Spring, the Current River upstream and downstream from Blue Spring, and the baseline sites (Big Spring and Greer Spring) generally were coarse grained [more than about 90 percent sand-size (greater than 0.063 mm) or greater] and composed primarily of quartz and dolomite, with smaller amounts of amorphous silicates and oxides and other minerals (table 4, at the back of this chapter). Baseline sites tended to have larger quartz contents (74 to 93.1 percent by weight) and have less amorphous silicates and oxides and other minerals than samples from Blue Spring, which were composed of 59 to 69 percent quartz by weight. Dolomite generally was the predominant mineral in the C3-fraction at all sites and is present as a contaminant because its density [2.85 grams per cubic centimeter (gm/cm^3)] is similar to that of the bromoform (2.87 gm/cm^3) used to concentrate the heavy mineral fraction. Samples from Blue Spring and the Current River upstream and downstream from Blue Spring tended to have larger amounts of limonite and oxidized rock fragments (5 to 50 percent of the C3-fraction) compared to baseline sites that had 5 percent or less limonite and oxidized rock fragments (table 4).

Subtle effects from mine tailings releases into upper Logan Creek during the 1970s may be the source of significantly larger than baseline cobalt and nickel concentrations and the lead-ore minerals galena and cerrusite detected in streambed-sediment samples from Blue Spring. Concentrations of cobalt and nickel averaged 34 and 65 milligrams per kilogram (mg/kg) in the fine fraction of streambed sediments from the Blue Spring orifice or spring branch and were significantly larger (p-value < 0.05 using a Kruskal-Wallis test) than concentrations at Big Spring and Greer Spring, which had averages of 21 and 41 mg/kg (fig. 8; table 5, at the back of this chapter). The increased cobalt and nickel concentrations may be related to mine tailings releases into Logan Creek during the 1970s because cobalt- and nickel-rich minerals, such as siegenite [$(Co,Ni)_3S_4$] and millerite (NiS), are present within the Viburnum Trend ore deposits and, as described in chapter 3 of this report, cobalt and nickel are known to occur in increased concentrations in streambed-sediment samples downstream from Viburnum Trend mining areas. Concentrations of other MVT-related metals in Blue Spring streambed-sediment samples were not significantly larger than baseline concentrations and several, such as arsenic (all less than reporting level), lead, and zinc, were slightly smaller than baseline concentrations (fig. 8). The absence of elevated lead in the fine fraction of Blue Spring samples is unexpected considering that trace amounts of the lead-ore minerals galena and cerrusite were detected in the C3 fraction from three of the four samples from Blue Spring and on the east side of the Current River downstream from Blue Spring (table 4). The absence of elevated lead concentrations in the fine fraction of streambed-sediment samples from Blue Spring may indicate that much of the lead in this fraction is associated with minerals or particles other than the galena or cerrusite identified in the C3 fraction. Anthropogenic contamination in the C3 fraction was noted by the presence of metallic lead and zinc in the 1997 samples from Big Spring orifice and Big Spring branch, and trace amounts of glass were detected in a Big Spring orifice sample (table 4). This contamination may account for the significantly larger lead and zinc concentrations in baseline sites compared to Blue Spring. Brass contamination also was detected in the sample from the west side of the Current River sample downstream from Blue Spring.

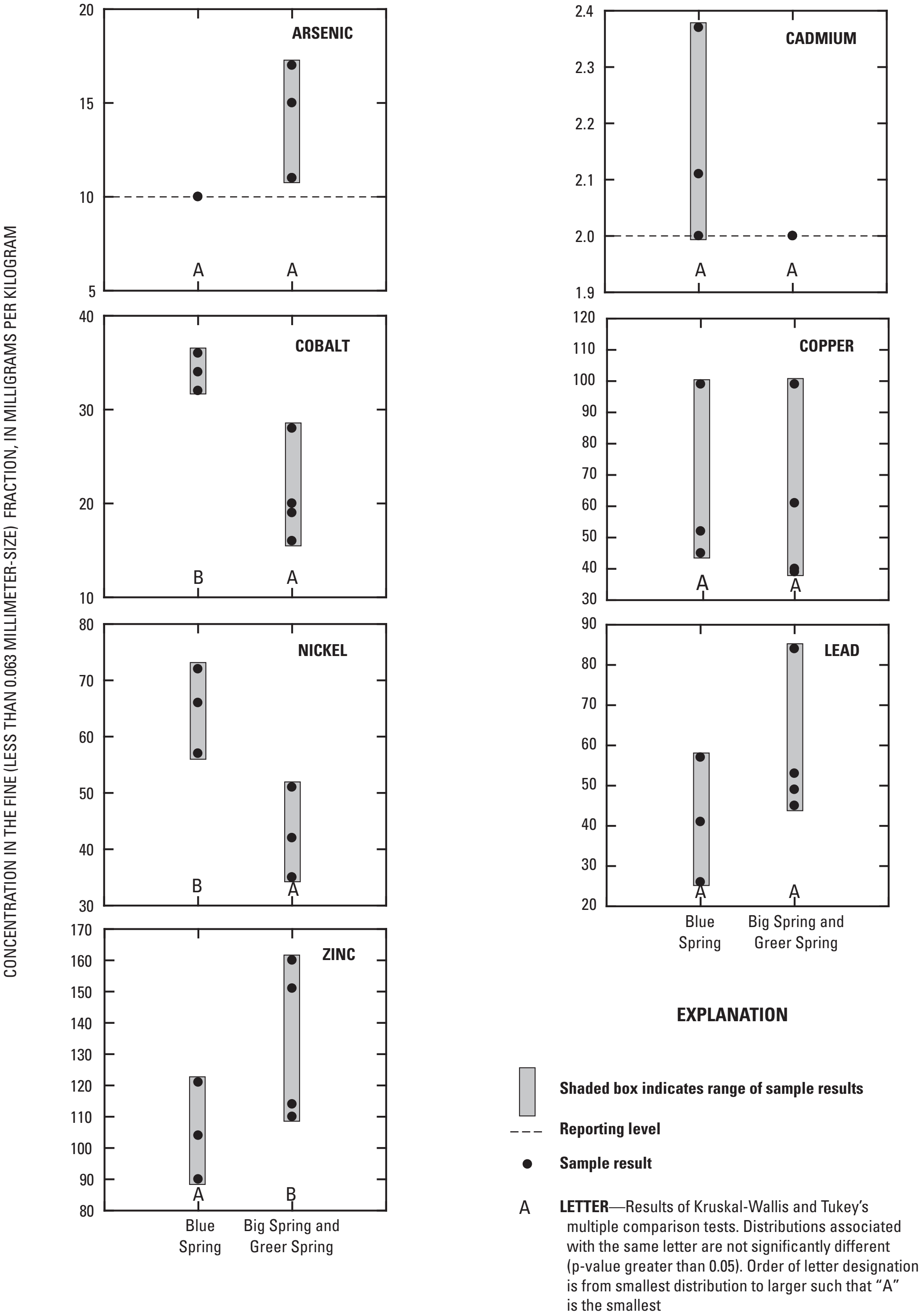

Figure 8. Concentrations of Mississippi Valley Type (MVT)-related metals in the fine (less than 0.063-millimeter size) fraction of streambed-sediment samples from Blue Spring and baseline concentrations from Big and Greer Springs, 1995–2002.

Comparison of MVT-related metals in the fine fraction in samples from Blue Spring and the Current River collected during 1995 and 2002 indicated generally larger trace element concentrations in Blue Spring (fig. 9). Using a Kruskal-Wallis non-parametric test and grouping the 1995 and 2002 samples from Blue Spring orifice and the 1995 spring branch sample together and comparing these against the three 1995 Current River samples indicated concentrations of cadmium, cobalt, nickel, and zinc in the fine fraction of streambed sediment from Blue Spring (fig. 9) were significantly larger (p-value < 0.05) than concentrations in the Current River streambed sediment. However, larger trace-element (copper, nickel, lead,

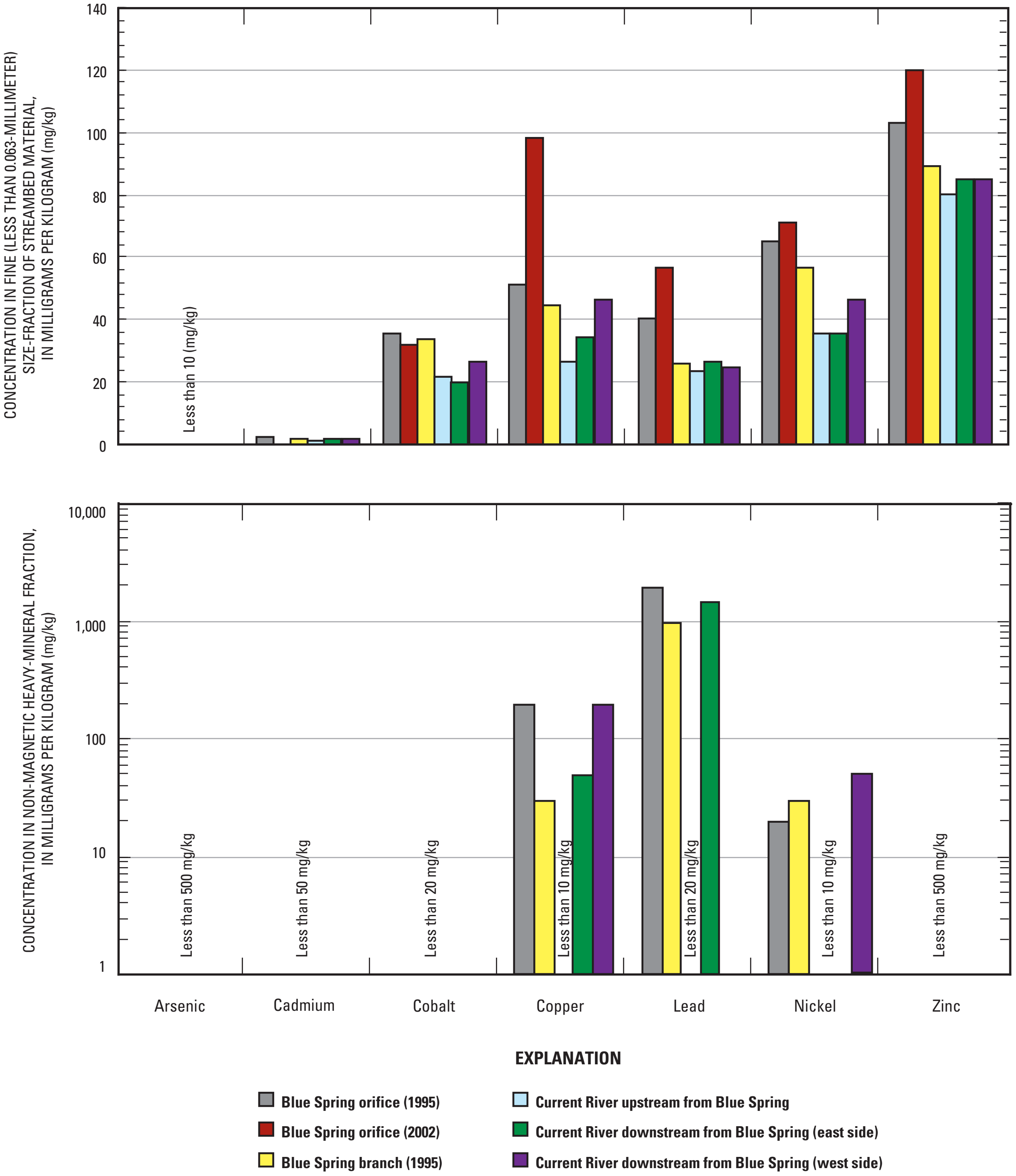

Figure 9. Maximum concentrations of Mississippi Valley Type (MVT)-related metals in the fine (less than 0.063-millimeter size) fraction by inductively coupled liquid plasma-atomic emmission spectrometry (ICP-AES) and semi-quantitative concentrations in the non-magnetic heavy mineral fraction by emmission spectrometry in streambed-sediment samples from Blue Spring and the Current River, 1995–2002.

and zinc) concentrations also were detected in samples from Big Spring and its spring branch as compared to the Current River upstream and downstream from Big Spring (table 5). The cause of the generally larger trace-element concentrations in streambed sediment in Blue Spring and Big Spring as compared to samples from the Current River is not known, but may be related to differences in geology of the spring recharge basins compared to that of the Current River. Both Blue Spring and Big Spring orifices have developed in the lower part of the Eminence Dolomite (Vineyard and Feder, 1982), and presumably streambed sediment in their orifices and spring branches are effected mostly by the Eminence Dolomite or underlying Potosi Dolomite. In contrast, streambed-sediment samples from the Current River are derived from rocks exposed upstream from either spring that include (from oldest to youngest) the Eminence Dolomite, Gasconade Dolomite, Roubidoux Formation, and Jefferson City Dolomite. In addition, streambed sediment in the Current River presumably has been transported further from its source and subjected to more weathering than streambed sediment in the spring orifices or spring branches. Indeed, streambed-sediment samples from the spring orifices and spring branches have larger quantities of dolomite and other carbonate material and much smaller quantities of quartz as compared to the Current River samples (table 4). Although significant differences were detected, results should be carefully considered, given the small sample sizes for the Blue Spring orifice and spring branch (three samples), the Big Spring orifice and spring branch, and Greer Spring (four samples) and the large variability in concentrations of some constituents between samples (fig. 9). A more important observation is that concentrations of MVT-related metals in the fine fraction of streambed sediment from the east side of the Current River downstream from Blue Spring were similar to those in the Current River sample upstream from Blue Spring (fig. 9), indicating no measurable effect from the 1970s mine tailings releases to Logan Creek on trace-element concentrations in the fine fraction of streambed sediment in the Current River.

Semi-quantitative concentrations of MVT-related metals in the C3 fraction of streambed-sediment samples from Blue Spring and the Current River also indicate subtle effects from historical mine tailings releases into Logan Creek. Because the C3 fraction tends to concentrate ore minerals and other mineral enriched in trace elements, trace-element concentrations in this fraction typically are larger than those in the fine fraction. The semi-quantitative trace-element concentrations in the C3 fraction are order-of-magnitude estimates and cannot be compared directly with concentrations in the fine fraction that were determined by quantitative ICP-AES. The mouth of Blue Spring branch is on the east bank of the Current River. Semi-quantitative concentrations of lead in the C3 fraction of streambed-sediment samples from Blue Spring (orifice and spring branch) and the east side of the Current River downstream from Blue Spring were estimated at about 1,000 to 2,000 mg/kg as compared to less than detection in samples from the Current River upstream from Blue Spring and on the west side of the Current River downstream from Blue Spring (fig. 9; table 6, at the back of this chapter). The large semi-quantitative concentrations of lead in the C3 fraction of streambed-sediment samples from Blue Spring and the east side of the Current River downstream from Blue Spring is consistent with the presence of the lead-ore minerals galena and cerrusite in the C3 fraction from these three sites.

Summary and Conclusions

Water-tracing investigations using fluorescent dye have indicated a subsurface connection between a losing reach of Logan Creek downstream from an active lead mine and Blue Spring, the seventh largest spring in Missouri. Blue Spring is about 10 miles southwest of Logan Creek and an important source of water to the Current River within the Ozark National Scenic Riverways. Logan Creek typically is dry several miles downstream from the mine, and previous investigations have indicated that as much as 200 cubic feet per second (ft^3/s) of discharge can be lost into the subsurface along this reach. An analysis of historical water-quality samples from upper Logan Creek and Blue Spring and streambed-sediment samples was performed to characterize changes in water- and streambed-sediment quality as a result of lead and zinc mining in the Logan Creek Basin and how those changes affect the water quality of Blue Spring. Multiple lines of evidence from results of dye-trace investigations, water-quality sampling, and trace-element and mineralogic composition of streambed-sediment samples indicate likely effects of mining on the water quality of Blue Spring.

Analysis of more than 70 water-quality samples collected by the U.S. Geological Survey from 1965 to 2006 along Logan Creek indicate effects from mining activities on major ion concentrations in Logan Creek. Water samples from Logan Creek ranged from calcium-magnesium-bicarbonate type, typical of the Ozark region, to mixed sodium-magnesium-calcium bicarbonate-sulfate type, indicating increased concentrations of sodium, sulfate, and chloride likely resulting from mining operations. Development of the Sweetwater Mine began in 1962, 3 years before the start of water-quality sampling along Logan Creek. Initial water-quality samples collected from a downstream site on Logan Creek contained increased proportions of sodium, sulfate, and chloride relative to other major ions. After the mine began production during 1968, the distribution of major ions at the upstream sampling site (site 3, Logan Creek above Sweetwater Creek) trended from the calcium-magnesium-bicarbonate vertex on a trilinear diagram toward increasingly sulfate and chloride-rich water as mill tailings began to be discharged to an impoundment on Adair Creek, a tributary to Logan Creek upstream from site 3. After mining began, sulfate and chloride typically comprised more than 20 percent of the major anions in Logan Creek compared to less than 5 percent in baseline surface- and ground-water samples from the region. Little, if any, effects of mine discharges were observed on concentrations of dissolved trace elements in Logan Creek. Historically, concentrations of Mississippi Valley Type (MVT)-related dissolved metals (arsenic, cadmium, cobalt, copper, lead, nickel, and zinc) and other dissolved trace elements in water samples collected from upper Logan Creek generally were small and near reporting levels in the 63 samples collected from sites 3 and 5. Dissolved zinc was the most commonly reported trace element being detected above reporting levels in 25 of the 54 samples in which it was analyzed, with a maximum concentration of 90 micrograms per liter (µg/L) detected in a sample collected during 1972. Dissolved zinc concentrations in four water samples (all collected during 1972) exceeded the current (2008) Missouri Department of Natural Resources chronic standard for the protection of aquatic life.

Results of a March and August 2006 stream seepage-run and water-quality investigation along the upper reach of Logan Creek indicated that, depending on the quantity of runoff from the mine tailings impoundment and streamflow conditions, discharge from the mine complex and tailings impoundment along Adair Creek comprised as much as 68 percent of the discharge in upper Logan Creek that is lost into the subsurface and resurges at Blue Spring. This finding is significant because at times, nearly all the flow in Adair Creek is from mining-related sources. On March 7, 2006, Logan Creek lost 23.3 ft^3/s of discharge downstream from the Sweetwater Mine in comparison to a discharge of 98.6 ft^3/s measured at Blue Spring that same day. On August 15, 2006, the discharge along Logan Creek was smaller, and about 4.46 ft^3/s of flow was lost (about 17 percent of which was from Adair Creek), which represented about 5 percent of the 88.4 ft^3/s measured at Blue Spring that same day. Water-quality samples collected during 2006 from Adair Creek and Logan Creek downstream from the mine all contained increased proportions of sodium, sulfate, and chloride as compared to other major ions. A March 7, 2006, sample from Adair Creek had a specific conductance value of 617 microsiemens per centimeter at 25 degrees Celsius (µS/cm) and concentrations of sodium [40.2 milligrams per liter (mg/L)], sulfate (114 mg/L), and chloride (49.1 mg/L) that exceeded baseline concentrations. This sample also contained above baseline concentrations of several MVT-related metals such as cobalt (2 µg/L), copper (3.2 µg/L), lead (11.7 µg/L), nickel (8.5 µg/L), and zinc (34 µg/L) and the trace elements boron (125 µg/L) and manganese (330 µg/L). Concentrations of major and trace constituents in Logan Creek decreased with increasing distance downstream from Adair Creek; however, concentrations of sodium, sulfate, chloride, and boron remained above baseline values until flow was lost into the subsurface.

Similar to water samples from most springs in southern Missouri, water samples collected from Blue Spring have moderate specific conductance values (118 to 350 µS/cm), near neutral pH values (6.9 to 8.2) and calcium, magnesium, and bicarbonate as the predominant ions. Effects of mining in the Logan Creek Basin have resulted in changes in major ion chemistry of the water discharged from Blue Spring and possibly subtle changes in the trace mineralogy and concentrations of several trace elements in streambed-sediment samples from the spring and east side of the Current River downstream from the spring. Although water samples from Blue Spring have calcium, magnesium, and bicarbonate as the predominant ions, 5 of the 13 samples from Blue Spring for which complete water-quality analyses are available plot outside the baseline range for area springs on a trilinear diagram and contain increased concentrations of sulfate, chloride, and sodium relative to bicarbonate and calcium plus magnesium. All five samples plotting outside the baseline range were collected after the Sweetwater Mine began operation, and they plot along a trend between baseline spring water samples and samples from Logan Creek downstream from the mine. The increased sulfate, chloride, and sodium concentrations in these samples are consistent with previous dye traces, indicating that flow lost in upper Logan Creek downstream from the mine emerges at Blue Spring. Results of a simple mixing model indicated that concentrations of major ions measured in the March and August 2006 samples from Blue Spring can be reasonably approximated by the mixing of flow lost along upper Logan Creek with a baseline ground-water component. The simple mixing model also is consistent with results from pervious dye-trace investigations.

Samples from Blue Spring had significantly smaller specific conductance values and calcium and magnesium concentrations, but significantly larger sodium, sulfate, and chloride concentrations as compared to baseline concentrations represented by samples from Big Spring and Greer Spring. The significantly larger sodium, chloride, and sulfate concentrations in Blue Spring likely are the result of loss of discharge from the mine complex into the subsurface along upper Logan Creek that resurges at Blue Spring. Samples of mine seeps within the Sweetwater Mine confirmed large concentrations of sodium, sulfate, and chloride in water pumped from the mine. Insufficient data were available for statistical comparisons of dissolved trace-element concentrations in Blue Spring to baseline concentrations; however, concentrations of total lead and total zinc in water samples from Blue Spring were not significantly larger than baseline concentrations. Samples collected from Blue Spring from 1965 to 1974 had spikes in concentrations of magnesium, sodium, chloride, and molar ratios of calcium to magnesium and a relatively steady increase in sulfate concentrations. The spike in constituent concentrations and calcium to magnesium ratios coincides with the opening of the exploration shaft during 1962 and initial development of the mine and corresponding increase in concentrations of these constituents in water samples from Logan Creek during the same period.

Mine tailings releases into Logan Creek from breaches in the mine tailings impoundment that occurred during the 1970s appear to be the source of significantly larger than baseline cobalt and nickel concentrations and the presence of the lead-ore minerals galena and cerrusite in streambed-sediment samples from Blue Spring. Concentrations of cobalt and nickel averaged 34 and 65 milligrams per kilogram (mg/kg) in the fine (less than 0.063 millimeter) fraction of streambed sediments from Blue Spring and its spring branch and were significantly larger (p-values less than 0.05 using a Kruskal-Wallis test) than in sediment from baseline sites that had average cobalt and nickel concentrations of 21 and 41 mg/kg. Cobalt and nickel-rich minerals, such as siegenite and millerite, are present within ore deposits in the Viburnum Trend and are a possible source of the increased cobalt and nickel concentrations in streambed-sediment samples from Blue Spring. Concentrations of MVT-related metals in streambed-sediment samples from the Current River downstream from Blue Spring were not significantly larger than baseline, indicating no measurable effect from the 1970s mine tailings releases into upper Logan Creek on trace-element concentrations in the fine fraction of streambed sediment in the Current River. However, mine tailings releases into Logan Creek may be the source of lead and lead-ore minerals detected in the non-magnetic heavy-mineral (C3) fraction of streambed-sediment samples from Blue Spring and the east side of the Current River downstream from Blue Spring.

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Tables

Table 1. Physical properties and concentrations of inorganic chemical constituents in water samples from upper Logan Creek, 1965–2006.

[All concentrations are dissolved and in milligrams per liter unless noted otherwise; ft^3/s, cubic feet per second; Cond, specific conductance in microsiemens per centimeter at 25 degrees Celsius; Temp, temperature in degrees Celsius; USGS, U.S. Geological Survey; --, no data; <, less than; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; ND, not detected; E, estimated value; µg/L, micrograms per liter]

Date	Time	Discharge (ft^3/s)	Cond	Temp	pH	Dissolved oxygen	Calcium	Magnesium	Sodium	Potassium
Site 1, Adair Creek at mouth (USGS station number 372128091072201)										
03/07/2006	0930	15.8	617	7.4	7.6	--	37	30	40	3.1
Site 2, Logan Creek at State Route B (USGS station number 372026091071101)										
05/29/2002	1530	16	313	19.6	7.7	--	21	14	17	2.0
03/07/2006	1030	21.2	518	7.7	7.7	--	33	26	31	2.6
Site 3, Logan Creek above Sweetwater Creek (USGS station number 07061810)										
09/30/1965	--	21	95	--	7.3	7.8	9.2	14	4.8	0.8
01/26/1966	--	7.1	100	--	7.5	13.9	11	6.1	4.1	.3
08/10/1966	--	3.8	160	--	7.5	7.0	16	10	5.2	1
10/24/1967	1615	.30	168	15	7.5	8.4	19	11	1.6	1.1
10/17/1968	0930	.17	180	18	7.2	6.5	20	12	1.5	1.1
01/14/1969	1530	2.5	30	10	7.1	12.5	4.0	1.5	.7	.5
07/15/1969	1600	.11	150	34	8.3	8.0	18	11	1.7	1
10/29/1969	1400	.15	237	11	7.4	10.3	27	22	2.3	.7
01/27/1970	--	.62	105	7	7.8	11.4	11	7.0	1.1	.8
04/29/1970	--	13	28	18	6.8	9.2	2.4	1.5	.5	.9
08/19/1970	--	.15	204	27	8.2	7.6	23	12	1.8	.7
11/02/1970	--	10	43	12	7.0	10.0	2.4	1.5	10	2.1
01/26/1971	--	3.5	40	1	7.8	12.7	2.4	2.4	8.3	1.3
04/21/1971	--	3.6	40	16	7.3	10.2	3.2	2.4	1.4	.7
07/14/1971	--	.06	110	23	7.5	6.4	11	6	1.4	1
11/09/1971	--	.10	260	10	7.0	10.4	28	17	2.3	.8
02/01/1972	--	.85	70	5	7.9	12.1	5.6	5.8	1.0	1
06/06/1972	--	1.1	65	25	6.8	9.4	5.0	6.0	1.0	.7
08/22/1972	--	.28	170	25	6.7	7.7	18	7.8	1.3	1.
10/17/1972	--	.13	210	16	7.5	8.2	18	11	1.5	.8
01/31/1973	--	10	45	6	6.3	12.4	1.6	1.9	.7	.6
05/15/1973	--	6	38	17	6.8	9.4	3.2	1.0	.7	.8

Table 1. Physical properties and concentrations of inorganic chemical constituents in water samples from upper Logan Creek, 1965–2006.—Continued

[All concentrations are dissolved and in milligrams per liter unless noted otherwise; ft^3/s, cubic feet per second; Cond, specific conductance in microsiemens per centimeter at 25 degrees Celsius; Temp, temperature in degrees Celsius; USGS, U.S. Geological Survey; --, no data; <, less than; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; ND, not detected; E, estimated value; µg/L, micrograms per liter]

Date	Time	Discharge (ft^3/s)	Cond	Temp	pH	Dissolved oxygen	Calcium	Magnesium	Sodium	Potassium
Site 3, Logan Creek above Sweetwater Creek (USGS station number 07061810)—Continued										
07/31/1973	--	3.3	46	24	7.4	8.7	1.3	4.1	1	.8
11/27/1973	1515	52	40	12	6.3	9.6	1.3	.12	.7	.6
03/05/1974	1725	9.7	32	12	6.3	11.2	1.6	1.9	.9	.7
05/14/1974	1725	13	30	15	5.8	9.0	1.6	2.4	1.8	.8
08/13/1974	--	.86	170	23	7.8	8.6	--	--	1.5	.8
10/30/1974	0815	.57	98	15	7.0	8.1	--	--	1.2	.6
01/07/1975	1440	8.4	38	6	7.0	11.8	--	--	.6	1
04/22/1975	--	2	55	15	7.0	10.4	--	--	.8	.8
07/29/1975	1445	.13	200	27	7.7	7.6	--	--	1.8	.8
Site 5, Logan Creek below Sweetwater Creek (USGS station number 07061840)										
09/30/1965	--	26	100	--	7.6	8.3	10	11	5.6	.8
01/26/1966	--	12	140	--	7.6	13.4	12	6.8	11	.3
08/10/1966	--	6.6	210	--	7.6	7.2	15	10	24	1.3
10/24/1967	1715	10	248	15	7.8	9.2	20	11	18	1.1
10/17/1968	0830	4.9	240	19	7.5	6.9	21	15	9.8	1.2
01/14/1969	1600	14	90	5	7.5	12.0	10	9.2	3.2	.8
04/08/1969	1200	36	105	16	7.7	9.8	9.6	6.3	3.2	.9
07/16/1969	0915	26	420	25	7.7	7.1	38	21	30	4.9
10/29/1969	1430	5.1	622	12	7.4	9.8	38	25	25	2.7
01/27/1970	--	9	342	6	8.0	11.8	30	21	14	1.7
04/30/1970	--	9.2	143	18	7.3	8.8	10	7.3	5.9	1.5
08/19/1970	--	3.7	439	27	8.0	6.9	34	20	24	2.6
11/02/1970	--	48	225	13	7.6	9.9	14	9.7	1.1	.8
01/26/1971	--	19	210	4	8.2	12.8	14	12	.9	.5
04/21/1971	--	12	225	18	8.0	8.9	16	12	8.6	1.5
07/14/1971	--	2.9	250	25	7.8	5.0	22	14	6.3	1.7
11/09/1971	--	2	320	12	7.0	9.5	35	16	7.6	1.5
02/01/1972	--	7	250	5	7.0	12.5	18	13	7.5	1.6

Table 1. Physical properties and concentrations of inorganic chemical constituents in water samples from upper Logan Creek, 1965–2006.—Continued

[All concentrations are dissolved and in milligrams per liter unless noted otherwise; ft^3/s, cubic feet per second; Cond, specific conductance in microsiemens per centimeter at 25 degrees Celsius; Temp, temperature in degrees Celsius; USGS, U.S. Geological Survey; --, no data; <, less than; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; ND, not detected; E, estimated value; µg/L, micrograms per liter]

Date	Time	Discharge (ft^3/s)	Cond	Temp	pH	Dissolved oxygen	Calcium	Magnesium	Sodium	Potassium
Site 5, Logan Creek below Sweetwater Creek (USGS station number 07061840)—Continued										
06/06/1972	--	4.2	240	27	7.2	8.2	16	12	7.5	1.8
08/23/1972	--	3.4	350	24	7.9	6.1	34	19	13	2.4
10/17/1972	--	6.9	550	16	7.7	8.6	34	28	27	4.3
01/31/1973	--	46	150	5	7.3	12.4	12	5.8	5.6	1.4
05/15/1973	--	39	102	19	7.5	8.7	9.6	5.8	2.6	1.2
07/31/1973	--	25	218	26	7.5	7.4	7.6	13	9.1	2.1
11/27/1973	1600	206	112	12	7.1	9.2	2.9	1.4	4.5	1.5
03/05/1974	1805	39	128	13	7.5	9.9	10	7.7	6.1	1.5
05/14/1974	1810	81	125	16	7.0	8.8	9.6	6.2	3.4	1.2
08/13/1974	--	2.4	280	26	8.2	8.3	--	--	8.1	2.2
10/30/1974	0740	7.1	330	15	7.5	8.7	--	--	11	1.9
01/07/1975	1520	30	140	6	6.7	12.0	--	--	3.4	1.1
04/22/1975	--	20	210	17	7.5	9.5	--	--	8.1	2
07/29/1975	1510	3	420	27	7.5	8.3	--	--	18	3.3
Site 6, Logan Creek at Latter Day Saints (LDS) Church (USGS station number 371754091073901)										
08/15/2006	1140	E1.0	398	26.6	8.3	--	30.2	20.1	15.6	1.8
Site 7, Logan Creek at County Road 776 (USGS station number 371703091074201)										
03/07/2006	1355	3.72	384	9	7.9	--	29.2	21.7	25.3	2.08

Table 1. Physical properties and concentrations of inorganic chemical constituents in water samples from upper Logan Creek, 1965–2006—Continued.

[All concentrations are dissolved and in milligrams per liter unless noted otherwise; ft^3/s, cubic feet per second; Cond, specific conductance in microsiemens per centimeter at 25 degrees Celsius; Temp, temperature in degrees Celsius; USGS, U.S. Geological Survey; --, no data; <, less than; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; ND, not detected; E, estimated value; µg/L, micrograms per liter]

Alkalinity, total as $CaCO_3$	Bicarbonate (total)	Sulfate	Chloride	Fluoride	Silica	Nitrite plus nitrate, total as N	Ammonia, total, as N	Phosphorus, dissolved as P	Orthophosphorus, as P
Site 1, Adair Creek at mouth (USGS station number 372128091072201)									
[a]120	[a]144	114	49.1	0.5	2.7	0.82	0.14	<0.04	<0.02
Site 2, Logan Creek at State Route B (USGS station number 372026091071101)									
77	95	39	19	0.3	2.8	--	--	<0.01	--
[a]200	[a]245	89.2	37.7	.38	3.5	0.65	0.06	<.04	<0.02
Site 3, Logan Creek above Sweetwater Creek (USGS station number 07061810)									
--	--	5.4	1.6	0.1	6.7	--	1.1	--	--
48	--	5.6	2.6	.2	5.0	--	1.4	--	--
80	--	4.6	2.4	.1	7.4	--	.9	--	--
84	--	4.0	1.6	ND	6.2	--	--	--	--
94	--	3.2	1.7	1.6	6.3	--	--	--	--
14	--	5.4	.8	.2	4.5	--	--	--	--
92	--	3.4	1.3	.3	6.6	--	--	--	--
134	--	2.6	1.1	ND	6.8	--	--	--	--
48	--	5.0	1.4	ND	4.9	--	--	--	--
6	--	9.6	.5	ND	5.8	--	--	--	--
--	--	3.2	1.4	ND	6.8	--	--	--	--
10	--	6	.1	.1	5.0	--	.1	--	--
26	--	10	.5	.1	6.0	--	.3	--	--
12	--	10	1.5	.1	0.8	--	--	--	--
46	--	10	7.4	.1	1.0	--	--	--	--
118	--	<10	--	--	9.6	--	--	--	--
22	--	<10	4.5	<.1	--	--	--	--	--
32	--	<10	--	--	7.0	--	--	--	--
72	--	5.0	5.0	.1	8.6	--	--	--	--
86	--	<10	3.4	.1	8.1	--	--	--	--
7	--	<10	4.0	.1	6.2	--	--	--	--
10	--	11	1.7	.28	5.8	--	--	--	--

Table 1. Physical properties and concentrations of inorganic chemical constituents in water samples from upper Logan Creek, 1965–2006—Continued.

[All concentrations are dissolved and in milligrams per liter unless noted otherwise; ft^3/s, cubic feet per second; Cond, specific conductance in microsiemens per centimeter at 25 degrees Celsius; Temp, temperature in degrees Celsius; USGS, U.S. Geological Survey; --, no data; <, less than; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; ND, not detected; E, estimated value; µg/L, micrograms per liter]

Alkalinity, total as $CaCO_3$	Bicarbonate (total)	Sulfate	Chloride	Fluoride	Silica	Nitrite plus nitrate, total as N	Ammonia, total, as N	Phosphorus, dissolved as P	Orthophosphorus, as P
Site 3, Logan Creek above Sweetwater Creek (USGS station number 07061810)—Continued									
16	--	<10	0.4	0.1	6.9	--	--	--	--
6	--	3.8	--	.03	--	--	--	--	--
8	--	9.0	9.7	.15	--	--	--	--	--
6	--	8.0	3.1	.04	--	--	--	--	--
92	--	7.0	4.0	--	--	--	--	--	--
40	--	7.0	32	--	--	--	--	--	--
10	--	4.0	10	--	--	--	--	--	--
22	--	5.0	2.3	--	--	--	--	--	--
102	--	4.0	3.1	--	--	--	--	--	--
Site 5, Logan Creek below Sweetwater Creek (USGS station number 07061840)									
46	--	5.8	1.9	0.1	6.6	--	1.2	--	--
57	--	9.6	5.4	.4	5.0	--	1.4	--	--
93	--	10	8.4	.5	7.0	--	.8	--	--
103	--	13	7.7	.4	5.7	--	--	--	--
110	--	14	6.2	.2	7.9	--	--	--	--
44	--	10	2.9	.2	4.4	--	--	--	--
36	--	10	3.2	.1	4.4	--	--	--	--
147	--	81	31	.6	4.5	--	--	--	--
132	--	69	29	ND	8.7	--	--	--	--
90	--	51	18	.2	3.7	--	--	--	--
40	--	21	5.6	ND	6.2	--	--	--	--
218	--	70	27	.3	5.9	--	--	--	--
50	--	30	12	.1	4.0	--	.1	--	--
58	--	21	9.0	.2	5.0	--	.6	--	--
66	--	23	10	.1	0.6	--	--	--	--
100	--	10	19	ND	1.2	--	--	--	--
122	--	12	--	--	7.5	--	--	--	--
72	--	18	20	.1	--	--	--	--	--

Table 1. Physical properties and concentrations of inorganic chemical constituents in water samples from upper Logan Creek, 1965–2006—Continued.

[All concentrations are dissolved and in milligrams per liter unless noted otherwise; ft^3/s, cubic feet per second; Cond, specific conductance in microsiemens per centimeter at 25 degrees Celsius; Temp, temperature in degrees Celsius; USGS, U.S. Geological Survey; --, no data; <, less than; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; ND, not detected; E, estimated value; µg/L, micrograms per liter]

Alkalinity, total as $CaCO_3$	Bicarbonate (total)	Sulfate	Chloride	Fluoride	Silica	Nitrite plus nitrate, total as N	Ammonia, total, as N	Phosphorus, dissolved as P	Orthophosphorus, as P
Site 5, Logan Creek below Sweetwater Creek (USGS station number 07061840)—Continued									
80	--	22	--	--	6.4	--	--	--	--
124	--	26	12	.9	8.6	--	--	--	--
120	--	66	16	<.10	6.4	--	--	--	--
34	--	12	15	.1	6.0	--	--	--	--
44	--	<10	2.9	.34	6.1	--	--	--	--
62	--	28	1.7	.1	5.6	--	--	--	--
26	--	11.2	--	.03	--	--	--	--	--
54	--	16	16	.14	--	--	--	--	--
36	--	12	9.2	.18	--	--	--	--	--
100	--	27	15	--	--	--	--	--	--
100	--	44	31	--	--	--	--	--	--
46	--	11	10	--	--	--	--	--	--
50	--	24	11	--	--	--	--	--	--
114	--	82	27	--	--	--	--	--	--
Site 6, Logan Creek at Latter Day Saints (LDS) Church (USGS station number 371754091073901)									
121	[a]245	42.4	18.5	0.2	7.0	E0.03	<0.01	<0.04	E0.004
Site 7, Logan Creek at County Road 776 (USGS station number 371703091074201)									
[a]120	[a]141	73.5	31.4	0.27	3.7	0.54	<0.04	<0.04	<0.02

Table 1. Physical properties and concentrations of inorganic chemical constituents in water samples from upper Logan Creek, 1965–2006—Continued.

[All concentrations are dissolved and in milligrams per liter unless noted otherwise; ft^3/s, cubic feet per second; Cond, specific conductance in microsiemens per centimeter at 25 degrees Celsius; Temp, temperature in degrees Celsius; USGS, U.S. Geological Survey; --, no data; <, less than; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; ND, not detected; E, estimated value; µg/L, micrograms per liter]

Antimony (µg/L)	Arsenic (µg/L)	Barium (µg/L)	Beryllium (µg/L)	Boron (µg/L)	Cadmium (µg/L)	Chromium (µg/L)	Cobalt (µg/L)	Copper (µg/L)	Iron (µg/L)	Lead (µg/L)	Lithium (µg/L)
Site 1, Adair Creek at mouth (USGS station number 372128091072201)											
0.34	0.87	52	<0.2	125	0.22	0.04	2	3.2	180	11.7	22
Site 2, Logan Creek at State Route B (USGS station number 372026091071101)											
<0.2	<1.0	50.3	<0.05	--	<2	<20	<2	<10	<50	<2	<6
.23	.54	46.3	E.1	95	.1	.1	1	2.5	131	7.18	15
Site 3, Logan Creek above Sweetwater Creek (USGS station number 07061810)											
--	--	--	--	--	--	--	--	--	--	--	--
--	--	--	--	--	--	--	--	--	--	--	--
--	--	--	--	--	--	--	--	--	--	--	--
--	--	--	--	--	--	--	--	--	--	--	--
--	--	ND	--	ND	ND	ND	ND	ND	--	ND	40
--	--	60	--	[b]1,000	--	--	--	--	--	--	ND
--	--	ND	--	ND	--	10	ND	ND	--	--	ND
--	--	ND	--	50	<2	<20	ND	<10	170	ND	ND
--	--	1,000	--	30	<2	<20	ND	10	50	<2	<6
--	--	140	--	ND	<2	<20	40	<10	40	<2	ND
--	--	800	--	20	ND	<20	ND	10	50	ND	ND
--	--	ND	--	--	ND	20	<2	20	120	ND	--
--	--	ND	--	--	ND	<20	<2	<10	100	ND	--
--	--	ND	--	--	ND	ND	ND	ND	ND	<2	--
--	--	ND	--	--	ND	<20	<2	<10	60	<2	--
--	--	ND	--	--	ND	ND	ND	<10	110	ND	--
--	--	ND	--	--	ND	ND	ND	<10	20	<2	--
--	--	ND	--	--	ND	ND	ND	--	40	<2	--
--	--	200	--	--	<2	ND	<2	<10	80	<2	--
--	--	<100	--	--	ND	ND	<2	<10	40	ND	--
--	--	<100	--	--	ND	<20	<2	<10	<10	ND	--
--	--	200	--	--	ND	<20	<2	<10	<10	ND	--

Table 1. Physical properties and concentrations of inorganic chemical constituents in water samples from upper Logan Creek, 1965–2006—Continued.

[All concentrations are dissolved and in milligrams per liter unless noted otherwise; ft^3/s, cubic feet per second; Cond, specific conductance in microsiemens per centimeter at 25 degrees Celsius; Temp, temperature in degrees Celsius; USGS, U.S. Geological Survey; --, no data; <, less than; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; ND, not detected; E, estimated value; µg/L, micrograms per liter]

Antimony (µg/L)	Arsenic (µg/L)	Barium (µg/L)	Beryllium (µg/L)	Boron (µg/L)	Cadmium (µg/L)	Chromium (µg/L)	Cobalt (µg/L)	Copper (µg/L)	Iron (µg/L)	Lead (µg/L)	Lithium (µg/L)
Site 3, Logan Creek above Sweetwater Creek (USGS station number 07061810)—Continued											
--	--	<100	--	--	ND	ND	<2	<10	70	<2	--
--	--	<100	--	--	ND	ND	ND	<10	30	<2	--
--	--	<100	--	--	ND	ND	<2	10	<10	<2	--
--	--	<100	--	--	ND	ND	ND	ND	40	<2	--
--	--	--	--	--	<2	--	--	<10	--	<2	--
--	--	--	--	--	ND	--	--	ND	--	<2	--
--	--	--	--	--	<2	--	--	<2	--	<2	--
--	--	--	--	--	ND	--	--	<2	--	<2	--
--	--	--	--	--	<2	--	--	<2	--	<2	--
Site 5, Logan Creek below Sweetwater Creek (USGS station number 07061840)											
--	--	30	ND	30	--	ND	ND	ND	--	ND	--
--	--	35	--	40	--	ND	ND	<10	--	<2	<6
--	--	--	--	--	--	--	--	--	--	--	--
--	--	60	--	70	--	ND	ND	ND	ND	ND	ND
--	--	ND	--	ND	ND	ND	ND	ND	--	<2	30
--	--	ND	--	ND	ND	ND	ND	ND	--	ND	ND
--	--	ND	--	ND	ND	20	ND	ND	--	ND	ND
--	--	ND	--	170	ND	ND	ND	ND	--	ND	ND
--	--	ND	--	70	<2	<20	ND	10	20	ND	ND
--	--	ND	--	40	<2	<20	ND	<10	20	<2	<6
--	--	ND	--	10	<2	ND	20	<10	40	ND	ND
--	--	ND	--	90	ND	<20	ND	<10	20	ND	ND
--	--	ND	--	--	<2	10	<2	<10	380	<2	--
--	--	300	--	--	ND	<20	ND	<10	120	ND	--
--	--	ND	--	--	ND	ND	ND	ND	ND	ND	--
--	--	1,700	--	--	ND	<20	<2	<10	20	ND	--
--	--	3,300	--	--	ND	<20	ND	<10	ND	ND	--
--	--	ND	--	--	<2	<20	ND	<10	ND	<2	--

Table 1. Physical properties and concentrations of inorganic chemical constituents in water samples from upper Logan Creek, 1965–2006—Continued.

[All concentrations are dissolved and in milligrams per liter unless noted otherwise; ft³/s, cubic feet per second; Cond, specific conductance in microsiemens per centimeter at 25 degrees Celsius; Temp, temperature in degrees Celsius; USGS, U.S. Geological Survey; --, no data; <, less than; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; ND, not detected; E, estimated value; µg/L, micrograms per liter]

Antimony (µg/L)	Arsenic (µg/L)	Barium (µg/L)	Beryllium (µg/L)	Boron (µg/L)	Cadmium (µg/L)	Chromium (µg/L)	Cobalt (µg/L)	Copper (µg/L)	Iron (µg/L)	Lead (µg/L)	Lithium (µg/L)
Site 5, Logan Creek below Sweetwater Creek (USGS station number 07061840)—Continued											
--	--	ND	--	--	ND	ND	ND	--	ND	<2	--
--	--	ND	--	--	<2	ND	<2	<10	20	<2	--
--	--	<100	--	--	ND	ND	ND	<10	<10	<2	--
--	--	<100	--	--	ND	<20	<2	<20	20	<2	--
--	--	<100	--	--	ND	<20	<2	<10	<10	ND	--
--	--	<100	--	--	ND	ND	ND	<10	50	<2	--
--	--	<100	--	--	ND	ND	ND	20	40	<2	--
--	--	<100	--	--	ND	ND	<2	10	30	<2	--
--	--	<100	--	--	<2	ND	ND	<10	50	<2	--
--	--	--	--	--	ND	--	--	<10	--	<2	--
--	--	--	--	--	ND	--	--	ND	--	<2	--
--	--	--	--	--	ND	--	--	<10	--	<2	--
--	--	--	--	--	ND	--	--	<10	--	<2	--
--	--	--	--	--	<2	--	--	<10	--	<2	--
Site 6, Logan Creek at Latter Day Saints (LDS) Church (USGS station number 371754091073901)											
<0.20	0.32	58.5	<0.2	62	E0.03	0.05	E0.03	E0.37	<6	0.09	4
Site 7, Logan Creek at County Road 776 (USGS station number 371703091074201)											
E0.13	0.18	49.2	E0.2	72	0.06	0.07	0.3	1.5	<6	0.17	9

Table 1. Physical properties and concentrations of inorganic chemical constituents in water samples from upper Logan Creek, 1965–2006—Continued.

[ft^3/s, cubic feet per second; Cond, specific conductance in microsiemens per centimeter at 25 degrees Celsius; Temp, temperature in degrees Celsius; --, no data; <, less than; E, estimated value; $CaCO_3$, calcium carbonate; N, Nitrogen; P, phosphorus; µg/L, micrograms per liter; Ca:Mg, molar ratio of calcium to magnesium; ND, not detected; all concentrations are dissolved and in milligrams per liter unless noted otherwise]

Manganese (µg/L)	Molybdenum (µg/L)	Nickel (µg/L)	Selenium (µg/L)	Silver (µg/L)	Strontium (µg/L)	Thallium (µg/L)	Vanadium (µg/L)	Zinc (µg/L)
Site 1, Adair Creek at mouth (USGS station number 372128091072201)								
330	5.2	8.5	E0.05	<0.2	168	E0.03	<2	34
Site 2, Logan Creek at State Route B (USGS station number 372026091071101)								
260	2	<2	<1	<3	80	<0.1	0.4	20
138	3.6	4.97	.09	<.2	135	E.02	<2	21
Site 3, Logan Creek above Sweetwater Creek (USGS station number 07061810)								
ND	--	--	--	--	--	--	--	--
ND	--	--	--	--	--	--	--	--
ND	--	--	--	--	--	--	--	--
--	--	--	--	--	--	--	--	--
30	--	<2	--	--	70	--	--	10
--	--	--	--	--	--	--	--	--
40	--	--	--	--	100	--	--	ND
100	--	<2	--	30	70	--	--	10
20	--	<2	--	ND	70	--	--	10
<10	--	<2	--	7	70	--	--	10
60	--	ND	--	ND	--	--	--	10
80	--	<2	--	2	--	--	--	20
10	--	ND	--	ND	--	--	--	30
10	--	<2	--	ND	--	--	--	ND
60	--	<2	--	1	--	--	--	30
40	--	<2	--	ND	--	--	--	ND
10	--	<2	--	4	--	--	--	ND
50	--	<2	--	ND	--	--	--	[c]90
50	--	<2	--	ND	--	--	--	ND
30	--	<2	--	<2	--	--	--	[c]60
<10	--	ND	--	ND	--	--	--	<20
<10	--	<2	--	ND	--	--	--	ND

Table 1. Physical properties and concentrations of inorganic chemical constituents in water samples from upper Logan Creek, 1965–2006—Continued.

[ft³/s, cubic feet per second; Cond, specific conductance in microsiemens per centimeter at 25 degrees Celsius; Temp, temperature in degrees Celsius; --, no data; <, less than; E, estimated value; $CaCO_3$, calcium carbonate; N, Nitrogen; P, phosphorus; µg/L, micrograms per liter; Ca:Mg, molar ratio of calcium to magnesium; ND, not detected; all concentrations are dissolved and in milligrams per liter unless noted otherwise]

Manganese (µg/L)	Molybdenum (µg/L)	Nickel (µg/L)	Selenium (µg/L)	Silver (µg/L)	Strontium (µg/L)	Thallium (µg/L)	Vanadium (µg/L)	Zinc (µg/L)
Site 3, Logan Creek above Sweetwater Creek (USGS station number 07061810)—Continued								
20	--	<2	--	ND	--	--	--	50
<10	--	<2	--	ND	--	--	--	ND
10	--	ND	--	ND	--	--	--	ND
<10	--	ND	--	ND	--	--	--	<20
50	--	--	--	--	--	--	--	ND
20	--	--	--	--	--	--	--	20
20	--	--	--	--	--	--	--	<20
<10	--	--	--	--	--	--	--	ND
90	--	--	--	--	--	--	--	<20
Site 5, Logan Creek below Sweetwater Creek (USGS station number 07061840)								
ND	--	ND	--	--	--	--	ND	30
ND	--	<2	--	--	30	--	--	--
--	--	--	--	--	--	--	--	--
ND	--	ND	--	--	50	--	--	--
10	--	ND	--	--	90	--	--	10
20	--	ND	--	--	20	--	--	ND
20	--	ND	--	--	ND	--	--	ND
30	--	<2	--	--	180	--	--	--
20	--	<2	--	12	140	--	--	<20
10	--	<2	--	ND	90	--	--	<20
10	--	<2	--	7	90	--	--	20
10	--	ND	--	ND	--	--	--	10
20	--	<2	--	5	--	--	--	<20
<10	--	<2	--	ND	--	--	--	20
10	--	<2	--	ND	--	--	--	ND
30	--	<2	--	ND	--	--	--	20
ND	--	<2	--	ND	--	--	--	ND
ND	--	<2	--	2	--	--	--	ND
30	--	<2	--	ND	--	--	--	[c]90

Table 1. Physical properties and concentrations of inorganic chemical constituents in water samples from upper Logan Creek, 1965–2006—Continued.

[ft^3/s, cubic feet per second; Cond, specific conductance in microsiemens per centimeter at 25 degrees Celsius; Temp, temperature in degrees Celsius; --, no data; <, less than; E, estimated value; $CaCO_3$, calcium carbonate; N, Nitrogen; P, phosphorus; µg/L, micrograms per liter; Ca:Mg, molar ratio of calcium to magnesium; ND, not detected; all concentrations are dissolved and in milligrams per liter unless noted otherwise]

Manganese (µg/L)	Molybdenum (µg/L)	Nickel (µg/L)	Selenium (µg/L)	Silver (µg/L)	Strontium (µg/L)	Thallium (µg/L)	Vanadium (µg/L)	Zinc (µg/L)
Site 5, Logan Creek below Sweetwater Creek (USGS station number 07061840)—Continued								
30	--	ND	--	ND	--	--	--	ND
40	--	<2	--	<2	--	--	--	[c]60
120	--	<2	--	ND	--	--	--	50
40	--	<2	--	ND	--	--	--	<20
40	--	<2	--	ND	--	--	--	20
80	--	<2	--	ND	--	--	--	<20
130	--	<2	--	ND	--	--	--	30
50	--	<2	--	ND	--	--	--	20
20	--	--	--	--	--	--	--	ND
<10	--	--	--	--	--	--	--	30
20	--	--	--	--	--	--	--	ND
160	--	--	--	--	--	--	--	ND
20	--	--	--	--	--	--	--	ND
Site 6, Logan Creek at Latter Day Saints (LDS) Church (USGS station number 371754091073901)								
1.6	1.8	0.14	E0.07	<0.2	102	<0.04	<2	1.2
Site 7, Logan Creek at County Road 776 (USGS station number 371703091074201)								
2.7	2.2	1.44	0.08	<0.2	107	<0.04	<2	3.7

[a] Concentration determined from a filtered sample.

[b] Concentration is suspect, and cannot be verified.

[c] Shade and footnote indicates concentration exceeded the 2007 Missouri Department of Natural Resources chronic standard for the protection of aquatic life (Missouri Department of Natural Resources, 2007b).

Table 2. Water-quality samples from Blue Spring analyzed for major and trace inorganic constituents, 1925–2006.

[All concentrations are dissolved and in milligrams per liter unless noted otherwise; ft^3/s, cubic feet per second; Cond; specific conductance in microsiemens per centimeter at 25 degrees Celsius; Temp, temperature in degrees Celsius; $CaCO_3$, calcium carbonate; --, no data; f, analysis on filtered sample; N, nitrogen; P, phosphorus; µg/L, micrograms per liter; <, less than; E, estimated value; u, analysis on unfiltered sample; Ca:Mg, molar ratio of calcium to magnesium]

Date	Time	Discharge (ft^3/s)	Cond	Temp	pH	Hardness	Calcium	Magnesium	Sodium	Potassium	Alkalinity, total as $CaCO_3$	Bicarbonate (total)	Sulfate
06/01/1925	--	--	--	--	--	150	29	18	[a]3.0	[b]3.8	142	173	0.4
05/23/1952	--	--	--	--	7.6	110	24	13	[a]3.1	[b]3.9	105	128	2.5
08/24/1965	--	73.6	--	--	8.2	160	33	20	[a]2.3	[b]3.3	157	192	6.1
07/24/1969	--	90.9	290	13	7.8	150	32	18	5.5	.8	146	178	6.3
09/17/1969	--	83	312	13	7.8	160	33	18	5.3	.8	153	187	6.4
03/30/1970	--	189	184	10.5	7.5	81	16	10	4.7	1	59	72	22
04/27/1971	--	122	280	13	7.7	--	29	14	4.3	.7	128	156	8.8
08/17/1971	--	66.7	350	13.5	7.6	150	34	15	5.2	.7	154	188	2.4
04/06/1973	1430	290	118	11.5	7.1	52	11	6.1	3.0	1.1	46	56	7.6
08/01/1973	1730	155	215	14.5	7.5	110	26	12	2.9	.9	110	130	6.9
05/30/2002	1130	--	171	14	7.0	76	16.4	8.5	2.7	1.2	65	81	7.9
03/07/2006	1540	98.6	264	12.4	7.5	150	29.8	18.1	6.3	.91	150	189 f	16
08/15/2006	1315	88.4	310	14.1	7.8	160	32.4	18.7	3.1	.7	152	185 f	4.78

Date	Time	Chloride	Fluoride	Silica	Total dissolved solids	Nitrite plus Nitrate, total as N	Ammonia, total, as N	Phosphorus, dissolved as P	Phosphorus, total as P	Orthophosphorus as P	Antimony (µg/L)	Arsenic (µg/L)	Barium (µg/L)
06/01/1925	--	3.7	--	5.6	146	0.11	--	--	--	--	--	--	--
05/23/1952	--	1.8	--	2.6	116	.38	--	--	--	--	--	--	--
08/24/1965	--	9.0	--	2.6	182	.2	--	--	--	--	--	--	--
07/24/1969	--	6.6	--	6.7	160	.41	--	--	--	--	--	--	--
09/17/1969	--	6	--	7.3	168	.29	--	--	--	--	--	--	--
03/30/1970	--	6.3	0.1	4.6	103	.63	--	--	--	--	--	--	--
04/27/1971	--	8.2	--	6.9	161	.25	--	--	--	--	--	--	--
08/17/1971	--	8.2	.1	8.0	181	.23	--	--	--	--	--	--	--
04/06/1973	1430	1.4	<.1	6.1	70	.38	<0.01	<0.010	<0.010	--	--	<10	<100 u
08/01/1973	1730	3.3	<.1	7.1	134	.52	.07	<.010	.02	--	--	5	400 u
05/30/2002	1130	4.1	<.08	3.6	--	2.8 f	--	<.010	--	--	<0.1	--	33.3
03/07/2006	1540	7.7	.12	7.0	--	.46 f	<.04 f	<.04	--	<0.02	<.2	--	31.6
08/15/2006	1315	3.4	.06 E	7.49	--	.39 f	<.01 f	<.04	--	.008	<.2	--	30.4

Table 2. Water-quality samples from Blue Spring analyzed for major and trace inorganic constituents, 1925–2006.—Continued

[All concentrations are dissolved and in milligrams per liter unless noted otherwise; ft^3/s, cubic feet per second; Cond; specific conductance in microsiemens per centimeter at 25 degrees Celsius; Temp, temperature in degrees Celsius; $CaCO_3$, calcium carbonate; --, no data; f, analysis on filtered sample; N, nitrogen; P, phosphorus; µg/L, micrograms per liter; <, less than; E, estimated value; u, analysis on unfiltered sample; Ca:Mg, molar ratio of calcium to magnesium]

Date	Time	Beryllium (µg/L)	Bismuth (µg/L)	Boron (µg/L)	Cadmium (µg/L)	Cerium (µg/L)	Chromium (µg/L)	Cobalt (µg/L)	Copper (µg/L)	Gallium (µg/L)	Germanium (µg/L)	Iron (µg/L)	Lanthanum (µg/L)
06/01/1925	--	--	--	--	--	--	--	--	--	--	--	--	--
05/23/1952	--	--	--	--	--	--	--	--	--	--	--	--	--
08/24/1965	--	--	--	--	--	--	--	--	--	--	--	60	--
07/24/1969	--	--	--	--	--	--	--	--	--	--	--	<10	--
09/17/1969	--	--	--	--	--	--	--	--	--	--	--	70	--
03/30/1970	--	--	--	--	--	--	--	--	--	--	--	20	--
04/27/1971	--	--	--	--	--	--	--	--	--	--	--	60	--
08/17/1971	--	--	--	--	--	--	--	--	--	--	--	60	--
04/06/1973	1430	--	--	--	--	--	<20 u	6 u	--	--	--	30	--
08/01/1973	1730	--	--	--	<20 u	--	20 u	<20 u	<20	--	--	160	--
05/30/2002	1130	<0.05	<0.01	--	<.02	0.03	1.3	.04	<.5	<0.02	<0.02	<50	0.03
03/07/2006	1540	.2 E	--	17.3	.03 E	--	.3	.12	.9	--	--	<6	--
08/15/2006	1315	<.2	--	11.1	<.04	--	.3	<.04	<.4	--	--	<6	--

Date	Time	Lead (µg/L)	Lithium (µg/L)	Manganese (µg/L)	Mercury (µg/L)	Molybdenum (µg/L)	Nickel (µg/L)	Niobium (µg/L)	Rubidium (µg/L)	Scandium (µg/L)	Selenium (µg/L)	Silver (µg/L)	Strontium (µg/L)
06/01/1925	--	--	--	--	--	--	--	--	--	--	--	--	--
05/23/1952	--	--	--	--	--	--	--	--	--	--	--	--	--
08/24/1965	--	--	--	<10	--	--	--	--	--	--	--	--	--
07/24/1969	--	--	--	<10	--	--	--	--	--	--	--	--	--
09/17/1969	--	--	--	<10	--	--	--	--	--	--	--	--	--
03/30/1970	--	--	--	10	--	--	--	--	--	--	--	--	--
04/27/1971	--	--	--	<3	--	--	--	--	--	--	--	--	--
08/17/1971	--	--	--	5	--	--	--	--	--	--	--	--	--
04/06/1973	1430	2 u	--	<10	<0.5	--	6 u	--	--	--	--	<2 u	--
08/01/1973	1730	650 u	--	<10	<.5	--	<20 u	--	--	--	--	200 u	--
05/30/2002	1130	<.05	0.5	0.4	--	0.2	.5	<0.02	1	1	<1	<3	30
03/07/2006	1540	.17	1 E	<.2	--	.4	.9	--	--	--	01	<.20	41.2
08/15/2006	1315	<.08	<2	.2	--	.4 E	.11	--	--	--	.1	<.20	33.3

Table 2. Water-quality samples from Blue Spring analyzed for major and trace inorganic constituents, 1925–2006.—Continued

[All concentrations are dissolved and in milligrams per liter unless noted otherwise; ft³/s, cubic feet per second; Cond; specific conductance in microsiemens per centimeter at 25 degrees Celsius; Temp, temperature in degrees Celsius; $CaCO_3$, calcium carbonate; --, no data; f, analysis on filtered sample; N, nitrogen; P, phosphorus; µg/L, micrograms per liter; <, less than; E, estimated value; u, analysis on unfiltered sample; Ca:Mg, molar ratio of calcium to magnesium]

Date	Time	Thallium (µg/L)	Thorium (µg/L)	Titanium (µg/L)	Vanadium (µg/L)	Yttrium (µg/L)	Zinc (µg/L)	Zircon (µg/L)	Ca:Mg
06/01/1925	--	--	--	--	--	--	--	--	0.98
05/23/1952	--	--	--	--	--	--	--	--	1.12
08/24/1965	--	--	--	--	--	--	--	--	1.00
07/24/1969	--	--	--	--	--	--	--	--	1.08
09/17/1969	--	--	--	--	--	--	--	--	1.11
03/30/1970	--	--	--	--	--	--	--	--	.97
04/27/1971	--	--	--	--	--	--	--	--	1.26
08/17/1971	--	--	--	--	--	--	--	--	1.37
04/06/1973	1430	--	--	--	--	--	30 u	--	1.09
08/01/1973	1730	--	--	--	--	--	1,400 u	--	1.31
05/30/2002	1130	<0.1	<0.005	<0.1	0.5	0.1	2	<0.1	1.17
03/07/2006	1540	<.04	--	--	<2	--	1.5	--	1.00
08/15/2006	1315	<.04	--	--	<2	--	.9	--	1.05

[a] Sodium concentration estimated as 80 percent of reported combined sodium plus potassium.

[b] Reported value is combined Na (sodium) plus K (potassium), in milligrams per liter.

Table 4. Grain-size, semi-quantitative bulk mineralogy, and optical mineralogy of the non-magnetic heavy mineral (C3) fraction of streambed-sediment samples from Blue Spring, Big Spring, and Greer Spring, 1995–2002.

[All values are in percent, percent should not be used as absolute number, but rather as relative from one sample site to another; relative standard deviation is at best plus or minus 20 percent; --, not detected]

	Blue Spring			Current River			Big Spring			Current River		Greer Spring
	Orifice	Orifice	Branch	Upstream Blue Spring	Downstream Blue Spring (east side)	Downstream Blue Spring (west side)	Orifice	Orifice	Branch	Upstream Big Spring	Downstream Big Spring	Branch
Constituent	6/20/95	5/30/02	6/20/95	6/20/95	6/20/95	6/20/95	10/16/97	6/11/02	10/16/97	10/16/97	10/16/97	6/10/02
Grain size (percent by weight)												
Coarse	89.2	92.3	93.4	97.7	98.2	99.5	98	95	99.1	98.5	98.6	98
Silt	4.1	5.6	3.2	1.1	.6	.3	1	4	.4	1	.8	1.6
Clay (by difference)	6.7	2.1	3.4	1.2	1.2	.2	1	1	.4	.5	.6	.4
Bulk mineralogy (less than 2 millimeter size fraction)												
Quartz	59	69	65	72	72	72	74	93.1	92	98	95	80.6
Dolomite	11	29.6	9	2	6	1	26	6.4	3	1	2	18.7
Kaolinite	16	--	14	8	10	11	--	--	--	--	--	--
Amorphous silicates and oxides	5–10	--	5–10	5–10	5–10	5–10	--	--	--	--	--	--
Potassium feldspar	7	--	6	8	6	8	--	--	5	1	3	--
Plagioclase feldspar	--	.3	--	4	--	--	--	--	--	--	--	--
Hornblende	--	.8	--	--	--	--	--	.5	--	--	--	.7
Calcite	--	.3	--	--	--	1	--	--	--	--	--	--
Other carbonates including kutnahorite and ankerite	--	--	--	1	--	--	--	--	--	--	--	--
Optical mineralogy of the non-magnetic heavy-mineral (C3) fraction												
Dolomite[a]	80	90	75	10	40	30	6	99	2	--	7	90
Limonite/oxidized rock fragments	10	10	15	10	5	50	4	--	3	5	4	5
Zircon	--	--	5	50	40	10	1	--	1	1	1	--
Apatite	--	--	1	2	1	1	8	Trace	--	--	11	5
Rutile	1	--	1	20	4	5	2	--	7	2	2	--
Tourmaline	1	--	2	5	10	--	3	--	4	4	3	--
Anatase	--	--	1	--	--	--	--	--	--	--	10	--
Pyrite	Trace	Trace	Trace	Trace	Trace	Trace	7	--	5	6	6	--
Barite	--	--	--	--	Trace	Trace	5	--	6	--	5	--
Cassiterite	Trace	--	--	--	Trace	--	--	--	--	8	--	--
Sphene	--	--	--	--	--	--	--	--	--	3	--	--
Cerrusite	Trace	--	Trace	--	Trace	--	--	--	--	--	--	--
Galena	Trace	--	Trace	--	Trace	--	--	--	--	--	--	--
Hematite	--	--	--	--	--	--	--	Trace	--	--	--	Trace
Anthropogenic contamination												
Lead	--	--	--	--	--	--	9	--	8	--	8	--
Zinc (silvery metal)	--	--	--	--	--	--	10	--	9	7	9	--
Brass	--	--	--	--	--	Trace	--	--	--	--	--	--
Glass	--	--	--	--	--	--	--	Trace	--	--	--	--

[a] Dolomite probably is present as a contaminant because its density [2.85 grams per cubic centimeter (gm/cm^3)] is similar to that of the bromoform (2.87 gm/cm^3) used to concentrate the heavy mineral fraction.

Table 5. Concentrations of major and trace elements in the fine (less than 0.063-millimeter size) fraction of streambed-sediment samples from Blue Spring, Current River, Big Spring, and Greer Spring, 1995–2002.

[<, less than]

	Blue Spring			Current River			Big Spring			Current River		Greer Spring
	Orifice	Orifice	Branch	Upstream Blue Spring	Downstream Blue Spring (east side)	Downstream Blue Spring (west side)	Orifice	Orifice	Branch	Upstream Big Spring	Down-stream Big Spring	Branch
Constituent	**06/20/95**	**05/30/02**	**06/20/95**	**06/20/95**	**06/20/95**	**06/20/95**	**10/16/97**	**06/11/02**	**10/16/97**	**10/16/97**	**10/16/97**	**06/10/02**
Major elements, in percent by weight												
Aluminum	6.6	5.9	5.9	5.3	4.9	5.7	6.0	4.7	4.2	4.7	4.4	4.6
Calcium	1.82	2.8	1.47	1.28	1.44	.79	2.6	.77	1.8	.89	1.1	1.4
Iron	3.3	3.0	3.0	2.3	2.6	2.7	3.3	2.3	2.2	2.5	2.4	2.6
Potassium	1.17	1.0	1.11	.99	1.02	1.09	1.1	1.0	.86	1	.89	1.0
Magnesium	1.44	1.9	1.12	.95	.82	.59	1.8	.53	1.2	.47	.59	.8
Sodium	.08	.05	.14	.15	.19	.19	.09	.2	.13	.19	.16	.14
Phosphorus	.08	.08	.09	.09	.1	.08	.13	.08	.1	.07	.09	.09
Titanium	.26	.24	.26	.25	.24	.33	.28	.31	.23	.32	.29	.33
Mississippi Valley Type-related trace elements, in milligrams per kilogram												
Arsenic	<10	<10	<10	<10	<10	<10	17	11	11	<10	10	15
Cadmium	2.40	<2	2.10	1.60	1.70	1.20	<2	<2	<2	<2	<2	<2
Cobalt	36	32	34	20	27	22	28	16	19	26	31	20
Copper	52	99	45	35	47	27	40	61	39	29	31	99
Lead	41	57	26	27	25	24	53	49	45	33	35	84
Nickel	66	72	57	36	47	36	51	35	35	29	34	42
Zinc	104	121	90	86	86	81	160	114	110	74	87	151
Other trace elements, in milligrams per kilogram												
Barium	272	272	336	278	369	386	230	402	220	370	310	438
Beryllium	3.6	3.6	3.10	2.3	2.1	2.3	3	2.2	2	2	2	2.2
Bismuth	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Cesium	93	89	85	64	70	78	95	85	77	84	78	97
Chromium	55	48	52	58	74	62	61	54	54	60	60	66
Europium	<2	2.5	<2	<2	<2	<2	2	<2	<2	<2	<2	<2
Gallium	17	12	15	13	11	14	24	10	14	12	13	9.9
Gold	<8	<8	<8	<8	<8	<8	<8	<8	<8	<8	<8	<8

Table 5. Concentrations of major and trace elements in the fine (less than 0.063-millimeter size) fraction of streambed-sediment samples from Blue Spring, Current River, Big Spring, and Greer Spring, 1995–2002.—Continued

[<, less than]

	Blue Spring			Current River			Big Spring			Current River		Greer Spring
	Orifice	Orifice	Branch	Upstream Blue Spring	Downstream Blue Spring (east side)	Downstream Blue Spring (west side)	Orifice	Orifice	Branch	Upstream Big Spring	Down-stream Big Spring	Branch
Constituent	06/20/95	05/30/02	06/20/95	06/20/95	06/20/95	06/20/95	10/16/97	06/11/02	10/16/97	10/16/97	10/16/97	06/10/02
Other trace elements, in milligrams per kilogram—Continued												
Holmium	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4
Lanthanum	54	48	49	40	38	45	57	43	42	42	42	46
Lithium	49	38	44	40	32	37	43	26	28	31	29	27
Manganese	1,630	2,120	1,490	390	1,580	840	1,300	1,190	750	1,600	1,500	2,210
Molybdenum	<2	3.6	<2	<2	<2	<2	2	<2	<2	<2	<2	2.9
Neodymium	60	55	53	42	34	41	67	40	49	41	41	38
Niobium	15	5.5	13	13	12	16	12	11	10	17	16	5.7
Scandium	12	11	10	8.9	7.9	9.7	12	8.5	8	8	8	7.6
Silver	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2
Strontium	46	39	50	45	57	48	40	39	38	43	40	37
Tantalum	<40	<40	<40	<40	<40	<40	<40	<40	<40	<40	<40	<40
Thorium	12.4	8.3	11.9	11.3	9.1	11.9	11	6.5	6	10	9	7.3
Tin	<5	11	<5	<5	<5	<5	<5	7.3	<5	<5	<5	18
Uranium	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100
Vanadium	97	83	89	76	72	81	90	66	62	70	68	74
Ytterbium	4.6	4.4	3.8	2.1	2.5	3	4	2.8	3	3	3	2.7
Yttrium	48	46	42	31	26	30	44	30	32	28	28	31

Table 6. Semi-quantitative concentrations of major and trace elements in the non-magnetic heavy mineral (C3) fraction of streambed-sediment samples from Blue Spring and the Current River near Blue Spring, 1995.

[All concentrations semi-quantitative; <, less than; >, greater than]

Constituent	Blue Spring		Current River		
	Orifice 06/20/95	Branch 06/20/95	Downstream Blue Spring (east side) 06/20/95	Downstream Blue Spring (west side) 06/20/95	Upstream Blue Spring 06/20/95
Percent by weight					
Calcium	10	7	7	1	1
Iron	2	3	.5	5	1.5
Magnesium	7	7	3	.5	1.5
Phosphorous	.7	.7	.5	.7	.5
Sodium	<.5	<.5	<.5	<.5	<.5
Titanium	.5	.7	2	>2	>2
Mississippi Valley Type-related trace elements, in milligrams per kilogram					
Arsenic	<500	<500	<500	<500	<500
Cadmium	<50	<50	<50	<50	<50
Cobalt	<20	<20	<20	<20	<20
Copper	200	30	50	200	<10
Lead	2,000	1,000	1,500	<20	<20
Nickel	20	30	<10	50	<10
Zinc	<500	<500	<500	<500	<500
Other trace elements, in milligrams per kilogram					
Antimony	<200	<200	<200	<200	<200
Barium	200	200	200	700	100
Beryllium	<2	<2	<2	<2	<2
Bismuth	<20	<20	50	<20	<20
Boron	100	200	1,000	300	1,000
Chromium	50	50	100	50	30
Gallium	<10	<10	<10	<10	<10
Germanium	<20	<20	<20	<20	<20
Gold	<20	<20	<20	<20	<20
Lanthanum	<100	<100	100	<100	<100
Manganese	700	300	150	500	150
Molybdenum	<10	<10	<10	<10	<10
Niobium	<50	<50	<50	<50	<50
Palladium	<5	<5	<5	<5	<5
Platinum	<20	<20	<20	<20	<20
Scandium	15	10	100	10	70
Silver	<1	<1	100	5	20
Strontium	<200	<200	<200	<200	<200
Thorium	<200	<200	<200	<200	<200
Tin	200	<20	1,000	<20	<20
Tungsten	<50	<50	<50	<50	<50
Vanadium	50	70	100	150	70
Yttrium	50	50	200	100	100
Zirconium	2,000	>2,000	>2,000	>2,000	>2,000

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