Hydrogeology, Water Quality, and Ecology of Anderton Branch near the Quail Hollow Landfill, Bedford County, Tennessee, 1995-99

By James J. Farmer

Prepared in cooperation with the
Bedford County Solid Waste Authority

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Conversion Factors, Abbreviated Units, Datums, and Site-Numbering System

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.6048	kilometer (km)
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
	Flow	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06308	liter per second (L/s)

Temperature in degree Fahrenheit (^oF) can be converted to degree Celsius (^oC) in the following manner: $^oC = 5/9 \times (^oF-32)$

Abbreviated Units

µm	micrometer
g	gram
mL	milliliter
mg/L	milligrams per liter
µg/L	micrograms per liter
µS/cm	microsiemens per centimeter
µg/g	micrograms per gram

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29); horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

Site-Numbering System: In this report, sites are identified with four-digit numbers in which the first digit designates the drainage basin and the remaining digits designate the unique site. Within a basin, site numbers increase upstream, accounting for tributaries before continuing up the main stem. Numbers are commonly separated by five in order to allow for additional sites.

Hydrogeology, Water Quality, and Ecology of Anderton Branch near the Quail Hollow Landfill, Bedford County, Tennessee, 1995-99

By James J. Farmer

Abstract

The Quail Hollow Landfill, located in southeastern Bedford County on the Highland Rim overlooking the Central Basin karst region of Tennessee, is constructed on the gravelly, clay-rich residuum of the Fort Payne Formation of Mississippian age. A conceptual hydrologic model of the landfill indicated that Anderton Branch was at risk of being affected by the landfill. Ground water flowing beneath the landfill mixes with percolating rainwater that has passed through the landfill and discharges to the surface from numerous weeps, seeps, and springs present in the area. Anderton Branch, adjacent to the landfill site on the north and east, receives most of the discharge from these weeps, seeps, and springs. Anderton Branch also receives water from the Powell Branch drainage basin to the west and south because of diverted flow of ground water through Harrison Spring Cave. The U.S. Geological Survey, in cooperation with the Bedford County Solid Waste Authority, conducted a study to evaluate the effect of the Quail Hollow Landfill on ground- and surface-water quality.

During storm runoff, specific conductance was elevated, and cadmium, iron, manganese, lead, and nickel concentrations in Anderton Branch frequently exceeded maximum contaminant levels for drinking water for the State of Tennessee. High chloride inputs to Anderton Branch were detected at two locations—a barnyard straddling the stream and a tributary draining a pond that receives water directly from the landfill. The chloride inputs probably contribute to chloride load levels that are three times higher for Anderton Branch than for the control stream Anthony Branch. Although toxic volatile organic compounds were detected in water from monitoring wells at the landfill, no organic contaminants were detected in domestic water wells adjacent to the landfill or in Anderton Branch.

Sons Spring, a karst spring near the landfill, has been affected by the landfill as indicated by an increase in chloride concentrations from 4 milligrams per liter in 1974 to 59 milligrams per liter in 1996. Analysis of water samples from Sons Spring detected concentrations of nickel that exceeded primary drinking-water standards and Tennessee Department of Environment and Conservation fish and aquatic life chronic standards. Trichloroethene, 1,1-dichloroethene, and 1,1-dichloroethane also were detected at Sons Spring. The presence of these chlorinated solvents imply the landfill origin of the contaminants in Sons Spring. Continuous monitoring at Sons Spring indicated a pattern of decreased specific conductance and lower contaminant concentrations after a storm. Contaminant concentrations increased with specific conductance to pre-storm levels after several days.

The benthic macroinvertebrate community in Anderton Branch adjacent to the landfill was not different from the communities at control sites upstream and in Anthony Branch. Sons Spring, however, has low abundance and numbers of benthic macroinvertebrate taxa. Toxicity studies using *Ceriodaphnia dubia* indicated no toxicity in the base flow or storm water in Anderton Branch or in a tributary draining a pond that receives water from the landfill and Sons Spring; however, water collected from Sons Spring resulted in 100 percent mortality to all organisms within 48 hours.

High concentrations of nickel were detected in crayfish tissue from control sites and Anderton Branch. Analysis of sediment samples also indicates nickel concentrations are high at control sites upstream of the landfill. Increased levels of the biomarker metallothionein detected in crayfish from Anderton Branch likely are not caused by nickel or cadmium because the levels present in the tissue are not correlated with metallothionein levels.

Despite the high levels of certain metals in Anderton Branch during storm flow, the lack of toxicity and the health of the benthic community imply no detectable negative effect from the landfill to the stream. Sons Spring, however, is toxic and almost devoid of organisms. A high chloride concentration in the water from Brinkley tributary indicates the landfill as the origin of this water; however, the lack of contamination and toxicity in this water imply that biologic activity and filtering occurring in Brinkley Pond is improving the water quality. The overall negative effect from landfill-contaminated water appears to be localized to the area in the immediate vicinity of Sons Spring and in short reaches of Anderton Branch adjacent to the landfill.

Introduction

In August 1994, the Bedford County Solid Waste Authority (BCSWA) entered into a cooperative agreement with the U.S. Geological Survey (USGS) to obtain background water-quality data near the Quail Hollow Landfill because of suspected contamination of regional ground- and surface-water resources. As part of a reconnaissance study, background water-quality data were collected from streams in nine drainage basins in the vicinity of the landfill. Several areas were identified close to the landfill and were characterized by low diversity and abundance of benthic macroinvertebrates, high specific conductance, high concentrations of chloride, iron, manganese, and unidentified organic compounds (Hollyday and Byl, 1995). Because of the environmental concerns of the BCSWA and the USGS's continuing scientific research into contaminant transport in karst terranes, the study was expanded to include the spatial and temporal distribution of landfill-associated contaminants in the karst system and to assess possible risk to the ecology of the area.

Water-quality deterioration associated with landfills has been well documented (Merz and Stone, 1968; Hughes and others, 1971; Borden and Yanoschak, 1990). Borden and Yanoschak (1990) determined that water samples near 53 percent of the landfills in a North Carolina study contained concentrations of heavy metals and organic compounds that exceeded drinking-water standards. Landfill leachate, formed by rainwater percolating through the landfill waste, is the primary cause of ground-water contamination according to Chain and DeWalle (1976). Increases in concentrations of chloride, iron, and manganese along with elevated alkalinity and specific conductance in both surface and ground water have been attributed to the effect of landfill leachate (Falwell and others, 1990; Heck and others, 1992; Parks and Mirecki, 1992; Helgesen and others, 1993; Myers and others, 1993; Mack, 1994; Rasmussen and others, 1994; Ferrell and Smith, 1995; Nielsen and others, 1995). The concentrations of contaminants in surface and ground water near a landfill are usually several orders of magnitude lower than contaminants in landfill leachate due to dilution (Borden and Yanoschak, 1990). Even with dilution, concentrations of contaminants can remain high enough to pose a potential risk to human health and the ecology. Soil erosion from landfills also can produce detrimental quantities of sediment. Belval and others (1992) concluded that sediment produced by erosion from a landfill was the primary factor that resulted in negative effects on the abundance and taxa richness to the benthic community of a stream associated with a landfill.

Purpose and Scope

From 1995 to 1998, a study was conducted to characterize the hydrology and water quality of Anderton Branch, a stream adjacent to the Quail Hollow Landfill in Bedford County, Tennessee. During this time, the chemistry and toxicity of water during base-flow and storm conditions and the health of the benthic community were evaluated. This report summarizes the chemical and biologic effects of the landfill on surface and ground water in a karst area.

Approach

The effect of the Quail Hollow Landfill on the biota and the surface- and ground-water quality near the landfill was evaluated through a three phase approach: problem formulation, analyses, and risk characterization (U.S. Environmental Protection Agency, 1992). The reconnaissance study conducted in nine surface-water basins near the landfill (Hollyday and Byl, 1995) provided the data to identify and formulate the potential problem associated with the landfill. Two locations near the landfill had high chloride (>20 mg/L) concentrations and specific conductance (>500 μS/cm). A low abundance and diversity of organisms were identified in Sons Spring and in reaches of Anderton Branch adjacent to the east side of the landfill (fig. 1, near Yellow Boy 1).

The analysis phase of the investigation included the development of a conceptual model of water and contaminant movement and sample collection to test the model and to evaluate the temporal and spatial effects of the landfill on ground- and surface-water quality and on the aquatic biota. Water samples were collected from local domestic wells and springs to evaluate the effect of the landfill on ground water. The results of these analyses were compared to the analyses of samples collected from landfill monitor wells. Surface-water quality data were collected under base-flow and storm conditions. Biological samples were collected to evaluate the abundance and diversity of the benthic community. Toxicity studies were conducted using *Ceriodaphnia dubia* to evaluate the toxicity of water from Sons Spring and Anderton Branch. Results from this type of study have been shown to correlate with other instream biologic indicators (Eagleson and others, 1990). Crayfish were collected to conduct biomarker studies evaluating the response of enzymes or other biologic markers to stress induced as a result of exposure to contamination. Samples were collected from Anderton Branch at sites upstream (control site), adjacent to, and downstream of the landfill (fig. 1). Sites on Anthony Branch and other nearby streams were used as additional control sites for biological and storm-water sampling. The type of sampling conducted and the sampling sites are listed in table 1.

The risk characterization phase of the study incorporated the potential problems associated with the landfill and the results of the data collection and analyses to determine the overall ecological risk. Concentrations of the inorganic compounds in the stream and sediment were compared to the State of Tennessee Department of Environment and Conservation criteria for fish and aquatic life (Tennessee Department of Environment and Conservation, 1999). The concentrations of organic and inorganic compounds also were compared to the primary and secondary maximum contaminant levels established for drinking water by the Tennessee Department of Environment and Conservation (1999).

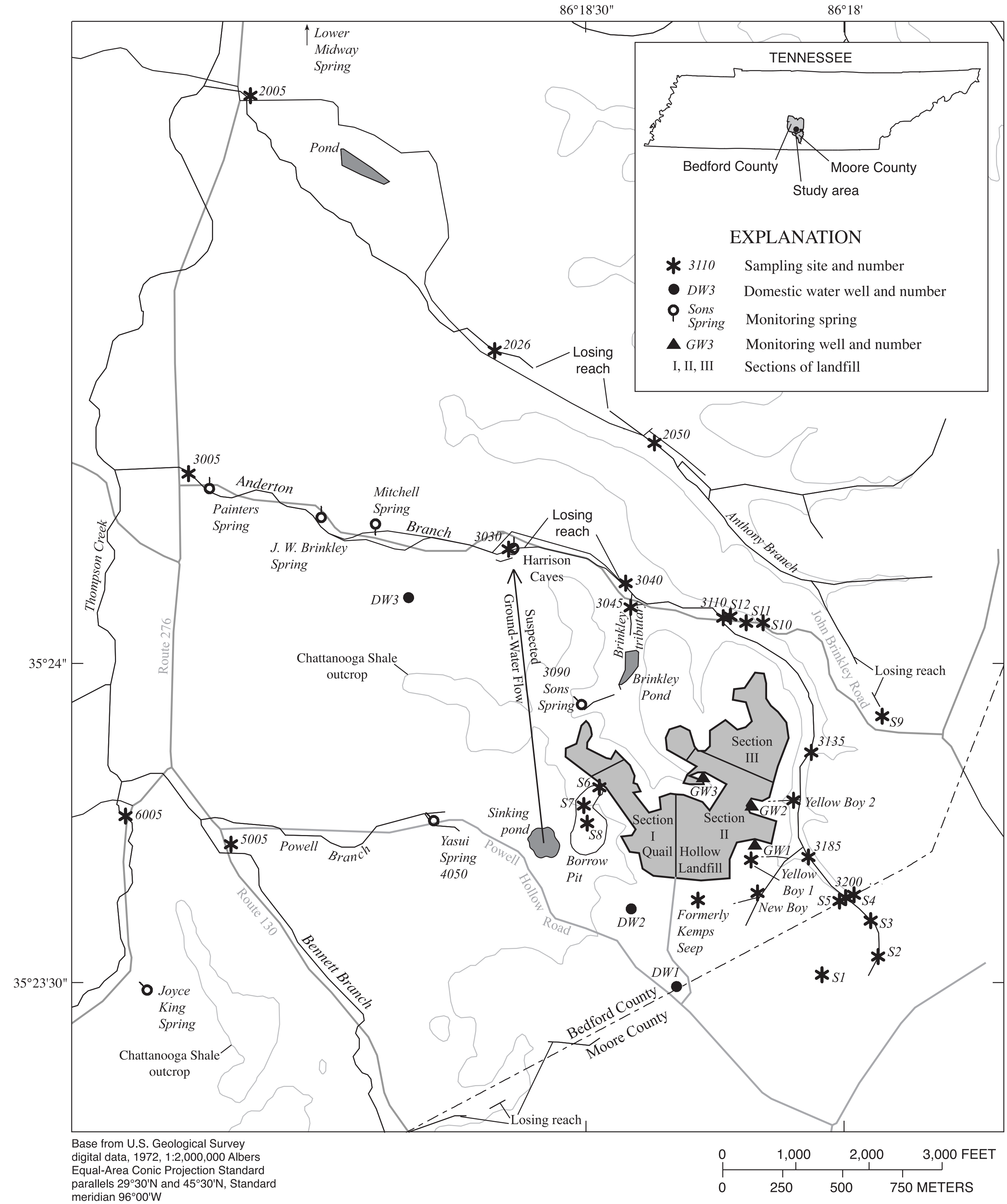


Figure 1. Location of study area and sampling sites at the Quail Hollow Landfill, Bedford County, Tennessee.

Table 1. Site number, site description, and type of sampling performed for sampling sites near Quail Hollow Landfill, Bedford County, Tennessee.

[B, Biomarkers; Cs, Control site; Be, Benthic macroinvertebrates; Ss, Storm sampling; T, Toxicity study; G, Gaging station; C, Chemistry; Sa, Soil or sediment analysis]

Site No.	Description	Type of sampling
2005	Riffle	B, Cs
2026	Riffle	Be, Cs
2050	Culvert	Ss, T, Cs
3005	Riffle	B, Be
3040	Riffle	Be, Cs
3045	Culvert	T
3090	Riffle	G, Ss, T, Be
3185	Riffle	Be
3135	Riffle	Be
3110	Riffle	B, Be, C, G, Ss, Sa, T
3200	Riffle	B, Be, Sa
4050	Spring house	Cs, Ss, T
5005	Pool	Be
6005	Pool	Be
S1	Field	Sa
S2	Pond bank	Sa
S3	Stream bank	Sa
S4	Stream	Sa
S5	Stream bank	Sa
S6	Borrow pit	Sa
S7	Borrow pit	Sa
S8	Borrow pit	Sa
S9	Road cut	Sa
S10	Road cut	Sa
S11	Road cut	Sa
S12	Stream	Sa

Description of Study Area

The Quail Hollow Landfill is located in southeastern Bedford County, Tennessee, on 352 acres, of which 77 acres are permitted for waste disposal as a Class I Sanitary landfill. Springs and streams adjacent to the landfill may be adversely affected by landfill operations or leachate migration. The landfill was originally permitted by Bedford County and operated as a commercial landfill. During the first several years of operation, the landfill received a variety of municipal, commercial, and industrial wastes. The landfill was permitted in three sections (fig. 1); sections I and II are the oldest sections and are not underlain by a liner. Vertical expansion of Section II resulted in leachate migrating from the landfill proper onto adjacent, privately owned land. The migrating leachate apparently was associated with the death of numerous deciduous trees along the south-southeastern segment of the landfill perimeter. In 1998, a vertical clay barrier was constructed down to bedrock to prevent additional migration of leachate off the landfill property along this segment of the perimeter. After the construction of the clay barrier, a geomembrane cap was placed on top of Section II and covered with soil. Vertical expansion of Section III resulted in waste being deposited on top of a liner to a depth near the top of the Chattanooga Shale. A leachate collection system was installed with this expansion. Landfill operations were discontinued at the Quail Hollow Landfill in 1998.

Land use in the area around the landfill may have an effect on water quality. Land adjacent to both Anderton and Anthony Branches is used predominantly for cattle grazing and hay farming, and the areas between the pastures are deciduous forest. A few homes with septic systems are present next to both streams, and residential developments with septic systems are common on the Highland Rim above the springs that form the headwaters of Anthony and Anderton Branches. During the period of the study, the surface of the landfill was mostly bare with only a thin grass cover.

The landfill is located in the Duck River drainage basin and is positioned on a spur of the Highland Rim overlooking the Central Basin, both physiographic regions of Tennessee (Miller, 1974) (fig. 2). The elevation in the study area ranges from about 1,100 feet above NGVD 29 on the Highland Rim to about 900 feet above NGVD 29 on Anderton Branch north of the landfill. Two streams border the landfill, Powell Branch to the southwest and Anderton Branch to the north, northeast, and east (fig. 1). Powell Branch drains an area of approximately 0.7 mi^2 and has a gradient of approximately 160 ft/mi. Powell Branch flows on the surface exposure of the Ordovician Leipers and Catheys Formations and the Cannon Limestone. The topography suggests that surface water leaving the southwest side of the landfill flows into Powell Branch and eventually into Bennett Branch and Thompson Creek. However, on May 6, 1998, water released from a holding pond at the landfill borrow-pit area (fig. 1) entered a sinking pond near the headwaters of Powell Branch and flowed under a surface divide through solution cavities and discharged into Anderton Branch. The water from the pond contained large amounts of suspended red clay, which served as a natural tracer, clearly indicating the connection between the pond in the Powell Branch drainage basin and the resurgence at Harrison Spring Cave in the Anderton Branch drainage basin. This natural tracer demonstrates that drainage from the southwest and west, as well as from the east and north, flows into Anderton Branch through karst solution channels.

Anderton Branch, with a drainage area of approximately 2 mi^2, flows off the Highland Rim and has a gradient of 170 ft/mi. As the stream moves onto the Central Basin, the gradient changes to 150 ft/mi. Anderton Branch originates from springs in the Fort Payne Formation. Anderton Branch historically sank into a swallet shortly after flowing onto the surface exposure of the Cannon Limestone and then flowed underground for approximately 1,500 ft before resurging. Stream channel modifications since the study began, however, have resulted in approximately two-thirds of the stream flow remaining on the surface. Anthony Branch, which generally parallels Anderton Branch in the adjacent drainage basin to the north, was used as a control stream because of its similarity to Anderton Branch. Anthony Branch drains 1.97 mi^2, flows over similar geology, and has a similar losing reach (fig. 1).

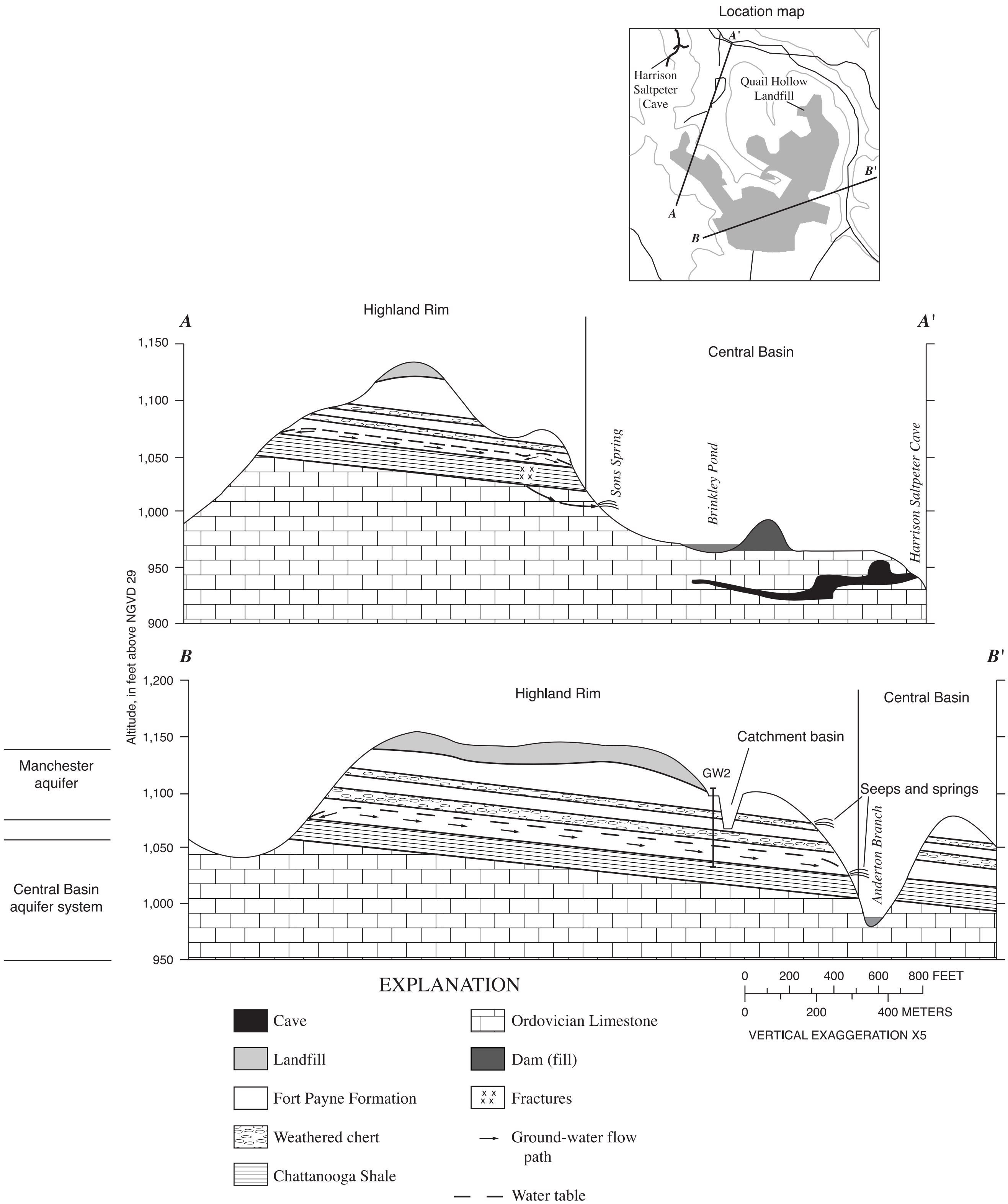


Figure 2. Geologic sections through Quail Hollow Landfill showing relations among the fill, the regolith, the rock units, water table, springs, and streams. Harrison Saltpeter Cave projected approximately 1,200 feet east into the line of section A-A'; Sons Spring projected approximately 400 feet east into the line of section A-A'.

Karst Hydrogeology

The primary geologic formations, in descending order from the land surface, are the Mississippian Fort Payne Formation, the Devonian Chattanooga Shale, and the Ordovician Leipers and Catheys Formations, Cannon Limestone, and the Hermitage Formation. The two aquifers potentially affected by the landfill are the Manchester aquifer and the Central Basin aquifer system (fig. 2).

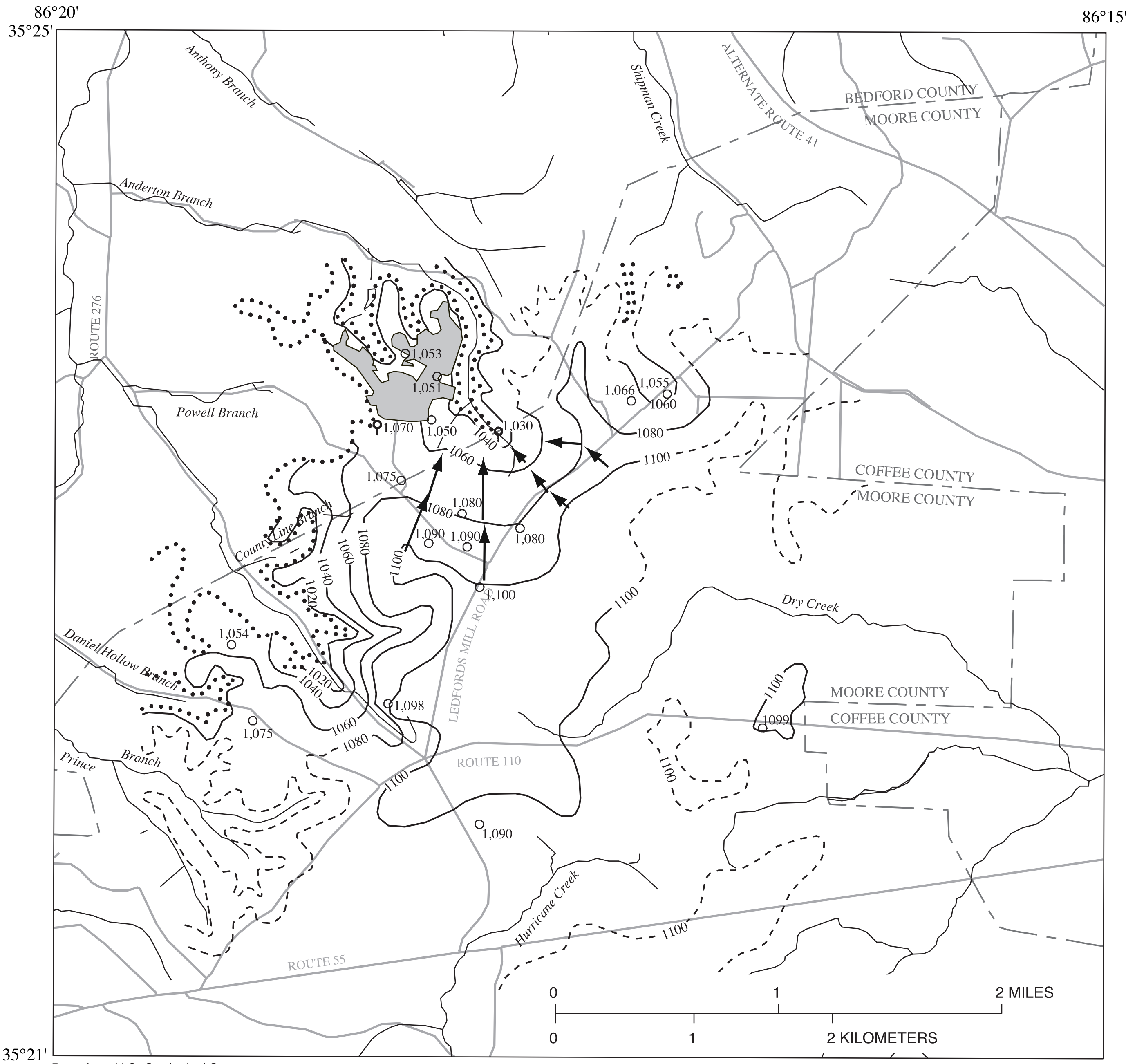
The Quail Hollow Landfill is developed in the gravels and residuum of the Manchester aquifer and weathered Fort Payne Formation (fig. 2). The thick residuum of the Fort Payne Formation has been considered a good location for landfills because the residuum acts as a thick filter medium (Miller and Maher, 1972) and it overlies the Chattanooga Shale, a regional confining layer. The Ordovician formations underlie the Chattanooga Shale and have numerous karst features including disappearing stream reaches in Anderton and Anthony Branches, springs, sinkholes, and interconnected cave systems.

The Manchester aquifer is a regional aquifer composed of chert (gravel to silt-sized) particles in the residuum of the upper part of the Fort Payne Formation and solution openings in the bedrock (Burchett and Hollyday, 1974). The Fort Payne Formation bedrock is predominantly soluble dolomitic limestone with 50 percent or greater insoluble residue of silt, clay, and blocky chert. Manganese oxides present in this formation are reported to contain up to 2 percent nickel and 4 percent cobalt (Larson, 1970). In the area of the landfill, the Fort Payne Formation is weathered to the degree that no carbonate bedrock is present. In the area around the landfill, the residuum contains layers of insoluble chert. Locally, the water in the aquifer can become perched above the chert layers. Regionally, the Manchester aquifer receives diffuse recharge from rainfall on the Highland Rim. A recent study by Farmer and Williams (2001) includes long-term monitoring data that confirm the diffuse-flow recharge characteristic of this aquifer. The potentiometric surface of the Manchester aquifer is lower at the landfill than within the Highland Rim to the south and east of the landfill (fig. 3). The potentiometric surface in the Manchester aquifer indicates a general direction of ground-water flow to the north under the landfill.

The Late Devonian and Early Mississippian Chattanooga Shale underlies the Fort Payne Formation. Chattanooga Shale is a regional layer that divides the Central Basin from the Highland Rim (Miller and Maher, 1972). The unweathered Chattanooga Shale, predominantly an insoluble, dense, black, carbonaceous shale with some sandy zones, is a major confining unit in Tennessee (Burchett, 1977). The landfill is located on the northeast edge of a Chattanooga Shale structural high with a structural dip of about 1.5 ^{o} northeast (NE) (C.W. Wilson, Tennessee Division of Geology, unpublished structure maps). Detailed mapping confirms a northeast dip of approximately 1^{o} NE (fig. 4). Water percolating through the landfill mixes with ground water moving along the Chattanooga Shale. The combined flow exits as seeps and springs along the outcrop (fig. 2). Fracturing and weathering near the outcrop of the shale, however, can result in water moving vertically through this confining unit into the Central Basin aquifer system (fig. 2, line of section A-A'). In some sites, the very thin (less than 3 ft) Maury Shale may be present at the top of the Chattanooga Shale. Hydrologically, the Maury Shale is part of the regional confining layer.

The Central Basin aquifer system is separated from the Manchester aquifer by the Chattanooga Shale regional confining unit (Brahana and Bradley, 1986) (fig. 2). Several Ordovician limestones comprise this aquifer system. The first formations below the Chattanooga Shale are the Leipers and Catheys Formations; soluble, thin-bedded, silty, clay-rich limestones that weather to a thin residuum (Miller and Maher, 1972) and are considered to be poor aquifers (E.F. Hollyday, U.S. Geological Survey, written commun., 1997). Soils associated with the Leipers and Catheys Formations in control areas not associated with the landfill (site S11, table 2) contain as much as 38.7 µg/g of nickel. These high concentrations may indicate that nickel has leached from the Fort Payne or the Maury Formations (Basseler, 1932), or both, and precipitated in soils formed from the Leipers and Catheys Formations (table 2). Below the Leipers and Catheys Formations is the Cannon Limestone (Wilson, 1990), a soluble coarse-grained, dark, dense, medium- to thick-bedded limestone with less than 10 percent insoluble residue. The Cannon Limestone is considered to be an excellent aquifer (E.F. Hollyday, U.S. Geological Survey, written commun., 1997). Beneath the Cannon Limestone is the laminated Argillaceous Limestone Member of the Hermitage Formation. The lithology of this unit is limestone with a greater than 49 percent fine-grained insoluble residue and is a major confining unit in Middle Tennessee (Tucci and others, 1990). Because much of the Hermitage Formation is a confining unit, ground water influenced by the landfill is unlikely to migrate into older and deeper formations. The Hermitage Formation is considered to be the base of ground-water hydrology near the landfill.

The Central Basin aquifer system is a karst aquifer (Wolfe and others, 1997). Regional recharge is from rainfall in the Central Basin and from sinking streams primarily in, or near, the Highland Rim escarpment area. The potentiometric surface of the Central Basin aquifer system (fig. 5) has more than twice the relief of the Manchester aquifer (fig. 3). The degree of karst development is well indicated in the area. Sinkholes have developed at the headwaters of Powell Branch. A large swallet has developed at Brinkley Pond where water from the pond disappears underground. In the vicinity of the landfill, several caves are developed near the top of the Cannon Limestone. Parts of the caves have been mapped (fig. 4) and recorded (Nashville Grotto, American Speleological Society, written commun. 1997). Losing reaches are present on both Anderton and Anthony Branches, and karst springs are present at several locations (fig. 1). In May 1998, turbid water was released from a borrow pit to a sinking pond. The water flowed through solution openings in the aquifer to the cave system and was discharged to Anderton Branch at the mouth of Harrison Spring Cave. The turbid water acting as a natural dye tracer indicates that the



Base from U.S. Geological Survey digital data, 1972, 1:2,000,000 Albers Equal-Area Conic Projection Standard parallels 29°30'N and 45°30'N, Standard meridian 96°00'W

EXPLANATION

- Quail Hollow Landfill disposal area
- —1100– – Potentiometric surface contour and altitude of approximate potentiometric surface in the Manchester aquifer, March 1996. Contour interval 20 feet. Dashed where inferred. Datum is NGVD 29
- Outcrop of top of Chattanooga Shale
- 1,080 Well with altitude of water level, in feet
- 1,070 Spring with altitude of water level, in feet
- Direction of ground-water flow

Figure 3. Altitude of the potentiometric surface of the Manchester aquifer in the area of Quail Hollow Landfill, Bedford and Moore Counties, Tennessee, March 1996.

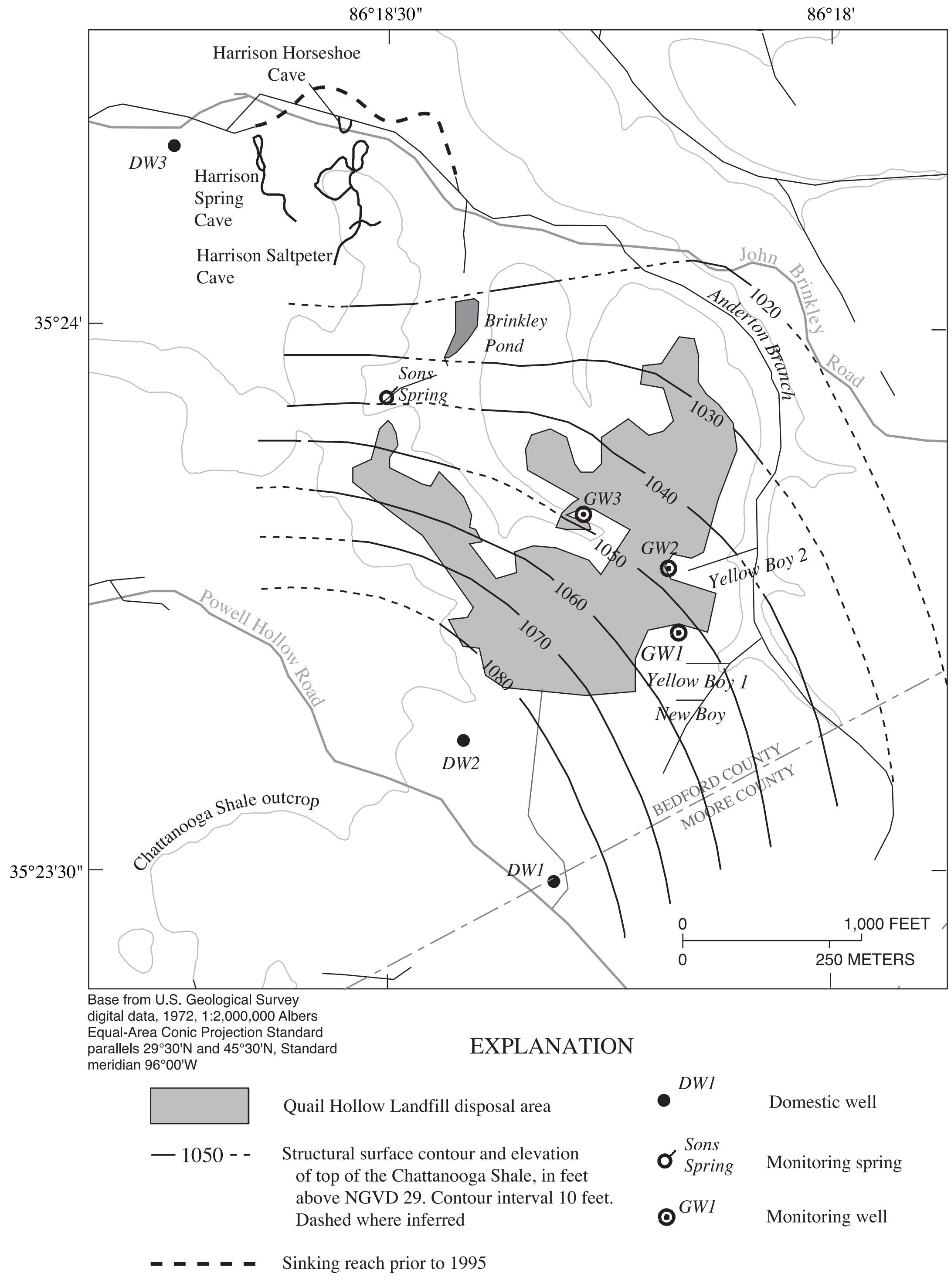
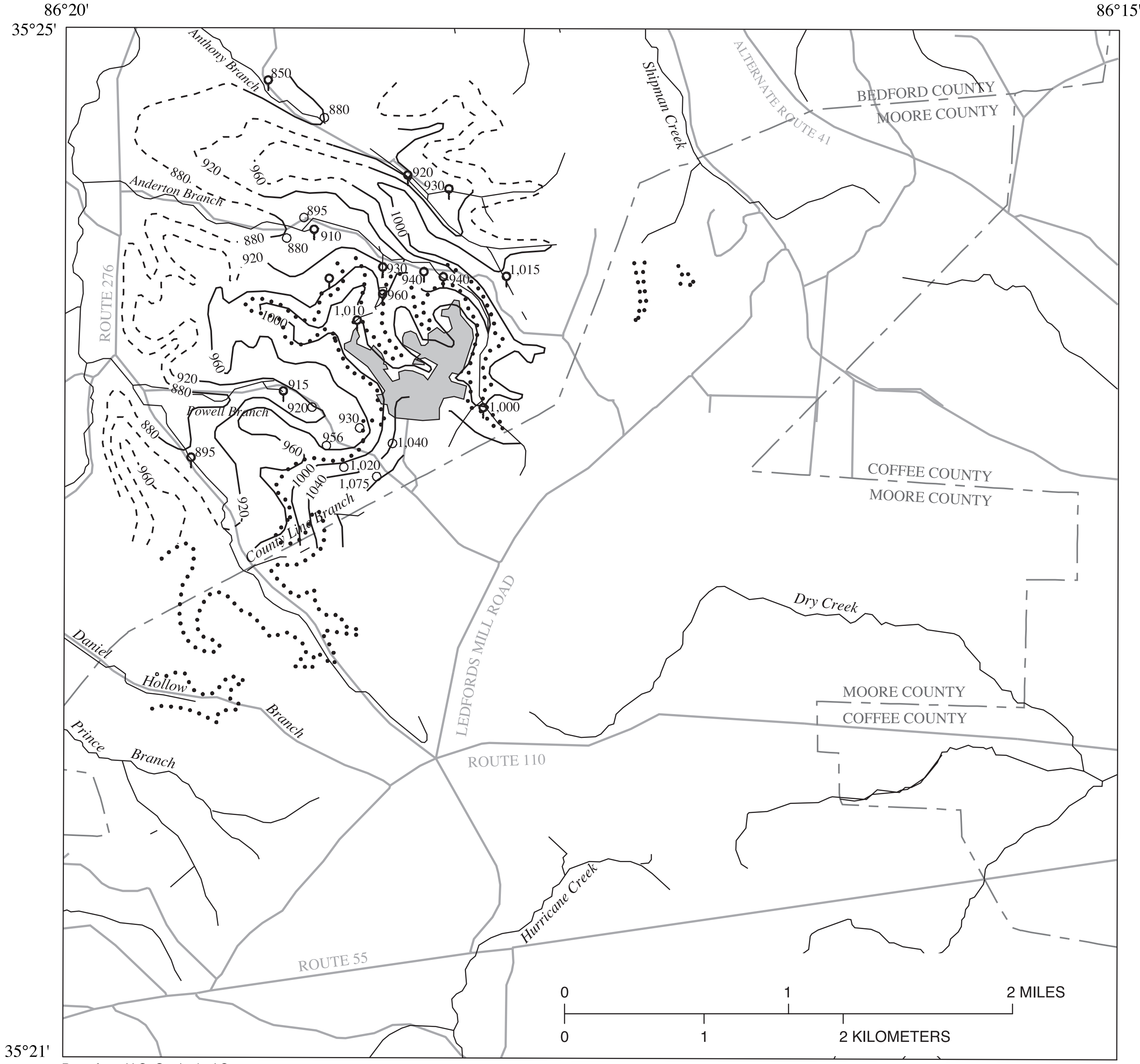


Figure 4. Structure of the top of the Chattanooga Shale underlying the Quail Hollow Landfill.



Base from U.S. Geological Survey digital data, 1972, 1:2,000,000 Albers Equal-Area Conic Projection Standard parallels 29°30'N and 45°30'N, Standard meridian 96°00'W

EXPLANATION

Quail Hollow Landfill disposal area

920 — Potentiometric surface contour and altitude of approximate potentiometric surface in the Central Basin aquifer system, March 1996. Contour interval 40 feet. Dashed where approximately located. Datum is NGVD 29

Outcrop of top of Chattanooga Shale

880 Well with altitude of water level, in feet

1,000 Spring with altitude of water level, in feet

Figure 5. Altitude of the potentiometric surface of the Central Basin aquifer system in the area of Quail Hollow Landfill, Bedford and Moore Counties, Tennessee, March 1996.

Table 2. Nickel concentrations in soil or sediment samples at selected locations near Quail Hollow Landfill, Bedford County, Tennessee.

[OWQL, duplicate sample analyzed at the U.S. Geological Survey Water Quality Laboratory, Ocala, Fla.; --, Not applicable]

Site		Nickel concentrations, in micrograms per liter				
No. (see fig. 1)	Description	Replicate 1	Replicate 2	Replicate 3	Mean	OWQL
S1	Soil from Kemps pasture—Warsaw Formation	2.0	2.2	2.3	2.2	--
S2	Near Kemps pond from base of fallen tree—Fort Payne Formation	6.8	--	--	--	--
	Northeast pond bank—Fort Payne Formation	--	15.5	--	--	--
	South pond bank—Fort Payne Formation	--	--	10.0	10.8	--
S3	Anderton Branch stream bank—500 feet upstream from Kemps pool	6.3	9.7	12.1	9.4	--
S4	Anderton Branch stream sediments near base of Fort Payne Formation—Maury Shale	45.2	--	--	--	44.1
		--	66.6	--	--	47.3
		--	--	30.0	47.3	--
S5	Anderton Branch stream bank near base of Fort Payne Formation—Maury Shale	27.0	15.0	28.3	23.4	--
S6	Borrow pit area near base of landfill material—Fort Payne Formation	14.9	63.0	89.3	55.7	--
S7	Borrow pit area—weathered Chattanooa Shale	1.2	5.2	2.3	2.9	--
S8	From borrow pit just below Chattanooga Shale—Catheys and Leipers Formations	124	--	--	--	129.4
		--	30.4	9.8	54.7	--
S9	Brinkley Road, road cut, near top of Highland Rim—Fort Payne Formation	25.7	--	50.2	34.0	--
		--	26.1	--	--	30.6
S10	Brinkley Road, road cut—weathered Chattanooga Shale	10.5	9.0	11.3	10.3	--
S11	Brinkley Road, road cut—Catheys and Leipers Formations	276	--	53.0	125.9	--
		--	48.7	--	--	38.7
S12	Anderton Branch stream sediment	39.1	--	--	--	40.8
		--	29.0	31.7	32.7	--

Harrison cave system and connected solution openings extend for 4,200 ft on the west side of the landfill. The existence of such a large cave system near the landfill leads to the hypothesis that water percolating through the landfill and surface runoff from the landfill in the Powell Branch drainage basin could possibly enter this system and discharge into Anderton Branch.

Data Collection

The study at Quail Hollow Landfill includes the collection of a wide range of hydrologic and biologic data at several sampling sites (table 1). Water-quality samples were collected from domestic wells, landfill monitoring wells, and from springs in the area. Surface-water flow was monitored and water-quality samples were collected during base-flow and storm-flow conditions. Because biologic indicators are excellent integrators of environmental conditions, the benthic macroinvertebrate community was evaluated as an indicator of stream health; water toxicity studies with the water flea, *Ceriodaphnia dubia*, were conducted; and biomarkers in crayfish were analyzed as the most sensitive indicator of water quality. Soil and sediment samples were collected at selected locations and analyzed for nickel content to supplement the biomarker results.

Ground-Water Data

Samples were collected at domestic wells located closest to the landfill to evaluate the quality of ground water near the landfill. Three domestic water wells (fig. 1) were sampled in May 1996 and May 1998 according to the method outlined by Wood (1976). Samples were sent to the USGS laboratory at Ocala, Fla., for analysis of selected inorganic constituents (table 3). Three landfill monitoring wells and Sons Spring were sampled in June and September 1996 to evaluate the effect of the landfill on ground water in the vicinity of the landfill. This sampling was conducted according to the methods of Wood (1976), and samples were sent to the USGS laboratory for analysis of selected inorganic constituents. Organic analyses were conducted at the laboratories of Quanterra Environmental Services.

Surface-Water and Rainfall Data

Streamflow gaging stations were established at site 3110 on Anderton Branch and at site 3090 (Sons Spring) (fig. 1) in February 1996, according to the procedures described by Carter and Davidian (1968). Site 3110, a continuous-stage recorder, as described by Buchanan and Somers (1969), was used to collect

Table 3. Major ions and selected metals analyzed and detection limits.

[mg/L, milligrams per liter; µg/L, micrograms per liter]

Description	Detection limits
Major ions	
Calcium (dissolved and total)	0.02 mg/L
Magnesium (dissolved and total)	0.03 mg/L
Sodium (dissolved and total)	0.1 mg/L
Potassium (dissolved and total)	0.1 mg/L
Chloride (dissolved)	0.1 mg/L
Sulfate (dissolved)	0.2 mg/L
Fluoride (dissolved)	0.1 mg/L
Metals	
Arsenic (total)	1 µg/L
Barium (total)	0.5 µg/L
Beryllium (total)	0.5 µg/L
Cadmium (dissolved and total)	0.5 µg/L
Chromium (dissolved and total)	1 µg/L
Cobalt (dissolved and total)	1 µg/L
Copper (total)	2 µg/L
Iron (dissolved and total)	2 µg/L
Lead (dissolved and total)	1 µg/L
Manganese (dissolved and total)	1 µg/L
Nickel (dissolved and total)	1 µg/L
Silver (total)	1 µg/L
Vanadium (total)	1 µg/L
Zinc (dissolved and total)	2 µg/L
Antimony (total)	1 µg/L
Aluminum (dissolved)	3 µg/L
Selenium (total)	1 µg/L

stage (water-level) data in 0.01-ft increments at 15-minute intervals. Discharge measurements were made for several stages following procedures described by Buchanan and Somers (1969), and a discharge rating was developed following procedures described by Kennedy (1983). This rating was applied to the continuous-stage data to produce continuous-discharge records. Periodic discharge measurements, instead of continuous-discharge measurements, were made at site 3090. Rainfall data were recorded with a tipping-bucket rain gage and data recorder at a site west of site 3090.

Field measurements of water quality were made at sites 3110 and 3090 according to the general procedures described by Wood (1976). Field measurements of specific conductance and temperature were made at 30-minute intervals at both sites by using a multiparameter data recorder. Instruments were calibrated using standard reference solutions and procedures recommended by the manufacturer at approximately 1-month intervals and were recalibrated as necessary.

Water samples were collected at selected sites during base-flow conditions and sent to the USGS laboratory to be analyzed for major ions and selected inorganic constituents (table 3). Storm-water samples were collected at sites 3110 and 3090 near the landfill. During selected storms, water samples were collected at site 3110 every 15 minutes, either as grab samples or by using an automatic sampler. Samples collected during peaks in specific conductance were sent to the USGS laboratory for analysis of selected inorganic constituents. During a storm in December 1996, control sites 2050 (Anthony Branch) and 4050 (Yasui Spring) were monitored at 15-minute intervals for specific conductance and temperature following procedures described by Wood (1976). The sites were selected to provide background water-quality values. During the same storm, samples were collected at Sons Spring (site 3090) every 3 hours with an automatic sampler to evaluate the possible range in concentrations in a karst spring. Samples representing approximately the high, low, and medium specific-conductance measurements were sent to the USGS laboratory for analysis of selected inorganic constituents.

Specific conductance and temperature were measured in Anderton Branch between sites 3110 and 3005. Changes in specific conductance and temperature identified spring discharges to Anderton Branch. Discharge was measured (Buchanan and Somers, 1969) above and below the spring, and grab samples (Wood, 1976) were collected and analyzed for chloride concentrations (Hach, 1992). Discharge data and chloride concentrations were used to calculate instantaneous chloride loads at each site, and daily loads were estimated from these calculations. Grab samples for the analysis of volatile organic compounds (VOCs) were collected at sites 3110 and 3090 by dipping 40-milliliter VOC vials into the water by hand. These samples were analyzed for selected organic compounds (table 4) by Quanterra Environmental Services, Denver, Colo.

Biologic Data

In May, September, and December 1996 and May 1997, benthic macroinvertebrates were sampled at sites 2026, 3005, 3040, 3090, 3110, and 3200 and again in December 1998 at site 3005 using artificial substrates. Sampling was conducted using a 15x15x5-centimeter plastic-covered wire basket filled with local substrate. Flat substrate was used to construct three sampling layers in each basket. A Hester-Dendy style multiplate artificial substrate sampler was attached to each basket by a 1-meter length of nylon cord. Minimums of three replicates of each sampling device were collected at each site on four dates between 1996 and 1997. At each harvest, a 250-µm mesh “D” net was first placed downstream of the sampling device to catch organisms displaced as the device was removed. The baskets and multiplate samplers were disassembled and handpicked for organisms. Organisms were preserved in the field in 80 percent ethanol and were later identified to genus where appropriate by using a variable power dissecting microscope and a taxonomic key (Merritt and Cummins, 1996). The numbers of organisms on the multiplate samplers and rock baskets were converted into organism density using a conversion

Table 4. Volatile organic compound analytes and reporting limits.

[All reporting limits in micrograms per liter]

Volatile organic compound analyte	Reporting limits
Benzene	1.0
Bromodichloromethane	1.0
Bromoform	1.0
Bromomethane	2.0
Carbon disulfide	1.0
Carbon tetrachloride	1.0
Chlorobenzene	1.0
Chlorodibromomethane	1.0
Chloroethane	2.0
Chloroform	1.0
Chloromethane	2.0
1,1-Dichloroethane	1.0
1,2-Dichloroethane	1.0
1,1-Dichloroethene	1.0
Cis-1,2-Dichloroethene	0.50
Trans-1,2-Dichloroethene	0.50
1,2 -Dichloropropane	1.0
Cis-1,3-Dichloropropene	1.0
Trans-1,3-Dichloropropene	1.0
Ethylbenzene	1.0
2-Hexanone	5.0
Methylene chloride	1.0
4-Methyl-2-pentanone	5.0
Styrene	1.0
1,1,2,2-Tetrachloroethane	1.0
Tetrachloroethane	1.0
Toluene	1.0
1,1,1-Trichloroethane	1.0
1,1,2-Trichloroethane	1.0
Trichloroethene	1.0
Vinyl chloride	2.0
Xylenes (total)	1.0
2-Butanone	5.0

factor based on surface area of each device. The organism densities from the multiplate samplers and the rock baskets at each site were compared with Student's *t* test at a 0.05 level of significance (Zar, 1996). No differences were found; therefore, the data from both devices at each site were treated as equal replicates. Differences in taxa richness and total abundance of macroinvertebrates were determined by analysis of variance at a 0.05 level of significance. Data were log-transformed, and comparisons of these differences were computed using the Ryan-Einot-Gabriel-Welsh Multiple Range Test (SAS Institute Inc., 1990).

Separate 2-L water samples were collected during base flow on October 31, 1996, and during storm flow on December 12, 1996. The water samples were tested for toxicity using *Ceriodaphnia dubia* as a test organism according to the USEPA method 1002.0 (Lewis and others, 1994). The chronic *C. dubia* test begins with a neonate less than 24 hours old and follows it through three reproductive cycles lasting at least 7 days. In this study, the numbers of offspring reproduced in water from each site during the toxicity tests were compared to offspring spawned in moderately hard water (negative control) using Dunnett's test at a 0.05 level of significance (Zar, 1996).

The contaminants near Quail Hollow Landfill most likely to affect the indicator organisms were organic solvents and trace metals (Hollyday and Byl, 1995). The concentrations of the biomarker cytochrome P450 in hepatopancreas (primitive liver) tissue of crayfish were evaluated to indicate the potential effect of organic solvents. Specific contaminants induce specific isomers of cytochrome P450 in fish livers (Stegeman, 1989; Stegeman and Lech, 1991). Because of the lack of research on isomers of crayfish cytochrome P450, total cytochrome P450 was evaluated in this study. The biomarker metallothionein, a peptide which is induced in organisms to bind to metals and render them biologically inactive, was evaluated as an indication of the environmental stress caused by cadmium and nickel.

From August 1998 to August 1999, crayfish were collected from selected sites on Thompson Creek, and Bennett, Anderton, and Anthony Branches (sites 2005, 3005, 3110, 3200, 5005, and 6005) using baited traps. At each harvest, crayfish were removed from the traps, and the hepatopancreas of each crayfish was removed and frozen immediately in liquid nitrogen. A set of control crayfish was captured at site 5005. The control crayfish were purged for 2 weeks in moderately hard water (Lewis and others, 1994) in the laboratory at Middle Tennessee State University, Murfreesboro, Tenn., and the hepatopancreas tissue was then removed and frozen in liquid nitrogen. Samples of hepatopancreas tissue were extracted from the frozen tissue and digested in nitric acid. The digested tissue samples were analyzed for nickel and cadmium concentrations using an absorption spectrophotometer equipped with a Zeeman graphite furnace module.

Crayfish tissue were prepared and centrifuged according to the procedures described by Ashley and others (1996). Total cytochrome P450 levels in the microsomal preparations were determined by carbon monoxide difference spectroscopy (Omura and Sato, 1962), and total microsomal protein was determined by the Lowery Method (Lowery and others, 1951). Supernatant resulting from the centrifuge process was analyzed to determine levels of metallothionein present in the hepatopancreas tissue. Metallothionein concentrations were determined by the cadmium-hemoglobin affinity assay (Eaton and Toal, 1982). Concentrations of nickel, cadmium, cytochrome P450, and metallothionein present in crayfish from each site were compared using analysis of variance at a significance level of 0.05.

Soil and Sediment Data

In October 1999, soil and sediment samples from 12 sites (sites S1-S12, fig. 1) were analyzed for cadmium and nickel concentrations. At each sampling location, five separate samples were collected and thoroughly mixed. Three 100-g replicate samples were taken from each mixture. A 0.5-g sample was taken from each replicate and digested in heated nitric acid for 24 hours. Digested samples were diluted appropriately and analyzed on an atomic absorption spectrophotometer at Middle Tennessee State University. For quality control, six duplicate samples were sent to the USGS National Water Quality Laboratory, Denver, Colo., for analysis.

Results and Discussion

Contaminant movement in the vicinity of the Quail Hollow Landfill is influenced by the complex hydrogeology of the Highland Rim, the escarpment, and the Central Basin. Recharge to the ground-water system, stream and spring flow, and ground-water movement and occurrence are affected by the karst hydrogeology of the study area.

A conceptual model of water movement in the vicinity of the landfill indicates that rainfall recharges the ground-water system and can transport contaminants to surface and ground water. Rain falling on the landfill during storms results in sheet flow off the landfill and percolation of water through the landfill to seeps and fractures. Sheet flow enters Anderton Branch on the east and north sides through several tributaries that drain the landfill (fig. 1). Brinkley tributary carries surface runoff from the landfill and water from Sons Spring to the middle reaches of Anderton Branch. Surface water moving to the Powell drainage basin can intercept sinkholes and can be diverted to Anderton Branch through karst conduits.

During base-flow conditions, flow to Anderton Branch is supplied by ground water issuing from seeps and springs primarily along the trunk stream and from seeps in sediment-catchment basins adjacent to the landfill. The flow is small but perennial, except in the dry or losing reaches on Anderton Branch. Water from these springs and seeps could be contaminated as precipitation percolating through the landfill commingles with landfill refuse to form leachate. The leachate is either deflected by chert layers in the Fort Payne regolith or continues downward through fractures in the chert beds or by flowing off the edge of a discontinuous chert layer. Leachate that is deflected by the chert moves along the top of the chert layer and returns to the surface at seeps or springs along the outcrop of the bed. Leachate that continues downward is diluted by mixing with ground water migrating along the top of the Chattanooga Shale. The contaminated ground water moves downgradient and re-enters the surface-water system as seeps and springs along the outcrop of the Chattanooga Shale.

Ground water at the top of the Chattanooga Shale also can move downward through fractures into the Central Basin aquifer system. Water entering the Central Basin aquifer system in this manner discharges to the surface as springs along minor confining units in this area of steep hydraulic gradient along the Highland Rim escarpment (fig. 5). Sons Spring (fig. 2) is an example of this type of contaminated spring. The other types of springs and seeps have all been observed in the vicinity of the landfill. Kemps seep (fig. 1) emerged at the top of a chert layer, and a large sheet flow spring was observed on the east fork of Anderton Branch (Hollyday and Byl, 1995, site 3195).

The landfill is positioned on a spur of the Highland Rim bordered on the south by Powell Branch and on the north by Anderton Branch. Although both streams appear to have the potential to be affected by contaminant movement in the vicinity of the landfill, the conceptual model indicates that Anderton Branch is the stream most likely to be affected.

Ground-Water Quality

Ground-water quality in the area of the landfill was evaluated by analyzing water samples from the landfill monitoring wells and several domestic water wells near the landfill (fig. 1). Domestic well DW1 upgradient of the landfill is completed near the base of the Manchester aquifer in a stratigraphic position similiar to monitoring wells GW1, GW2, and GW3 at the landfill. Domestic well DW2, also upgradient of the landfill, is completed near the top of the Central Basin aquifer system. Domestic well DW3 downgradient from the landfill is completed stratigraphically deeper in the Central Basin aquifer system than the discharge point for Sons Spring. Monitoring wells GW1, GW2, and GW3 are downgradient of the landfill and are completed in the Manchester aquifer at a depth close to the top of the Chattanooga Shale. The monitoring wells are positioned for sampling ground water almost directly beneath the landfill. Sons Spring issues from the top of the Central Basin aquifer system in a stratigraphic position similar to DW2. Results of analyses of water samples from monitoring wells GW1, GW2, and GW3 and domestic wells DW1, DW2, and DW3 were used to evaluate local ground-water quality (tables 5 and 6). The analytical results are compared to maximum contaminant levels for public drinking waters established by the Tennessee Department of Environment and Conservation (TDEC) (1999) and to acute and chronic criteria for fish and aquatic life (Tennessee Department of Environment and Conservation, 1999).

The results of quarterly sampling between March 1995 and September 1996 for monitoring wells GW1, GW2, and GW3 and for Sons Spring were evaluated to identify potential contaminants. Total concentrations of cadmium, nickel, and thallium occasionally exceeded primary maximum contaminant levels (PMCLs), and total iron and manganese exceeded secondary maximum contaminant levels (SMCLs) (E.F. Hollyday, U.S. Geological Survey, written commun., 1997). Additional samples were collected at other springs and domestic wells to evaluate background conditions and to identify possible contamination (table 5). Cadmium exceeded PMCLs and TDEC fish and aquatic life chronic standards in GW3 (E.F. Hollyday,

Table 5. Inorganic constituents in and physical properties of water from surface water, springs, and wells in the Quail Hollow Landfill area, Bedford County, Tennessee.

[mg/L, milligrams per liter; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter; <, less than detection limit; NA, not analyzed for; PMCL, primary maximum contaminant level for drinking water; SMCL, secondary maximum contaminant level for drinking water; fish and aquatic life standards based on water hardness range of 50 to 200 mg/L; Sp., spring; Br., branch; trib., tributary]

U.S. Geological Survey Identification No.	Site No.	Date	Time	Conditions	pH
PMCL (Tennessee Department of Environment and Conservation, 1999)					
SMCL (Tennessee Department of Environment and Conservation, 1999)					6.5-8.5
Fish and aquatic life acute standards (Tennessee Department of Environment and Conservation, 1999)					
Fish and aquatic life chronic standards (Tennessee Department of Environment and Conservation, 1999)					6.5-9.0
352351086183701	Sons Sp. Site 3090	3/22/1995			6.1
352351086183701	Sons Sp. Site 3090	4/25/1995			6.7
352351086183701	Sons Sp. Site 3090	6/10/1996			7.0
352351086183701	Sons Sp. Site 3090	9/26/1996			6.7
352351086183701	Sons Sp. Site 3090	6/4/1998			7.1
352351086183701	Sons Sp. Site 3090	6/5/1998	0811	Storm flow	7.1
352351086183701	Sons Sp. Site 3090	6/6/1998	0211	Storm flow	6.8
352351086183701	Sons Sp. Site 3090	1/28/1999	1700	Storm flow	7.1
352351086183701	Sons Sp. Site 3090	1/30/1999	0500	Storm flow	6.9
352351086183701	Sons Sp. Site 3090	1/31/1999	1100	Storm flow	6.6
352351086183701	Sons Sp. Site 3090	3/13/1999	0330	Storm flow	7.0
352351086183701	Sons Sp. Site 3090	3/14/1999	1830	Storm flow	7.0
352351086183701	Sons Sp. Site 3090	3/14/1999	2130	Storm flow	6.5
35977607	Anderton Br. Site 3110	12/12/1996	0815	Storm flow	7.8
35977607	Anderton Br. Site 3110	12/12/1996	1015	Storm flow	7.9
35977607	Anderton Br. Site 3110	4/28/1998	1415	Base flow	7.8
35977607	Anderton Br. Site 3110	4/30/1998	1600	Storm flow	7.5
35977607	Anderton Br. Site 3110	5/6/1998	1152	Base flow	7.7
35977607	Anderton Br. Site 3110	5/7/1998	1540	Storm flow	7.5
35977607	Anderton Br. Site 3110	6/4/1998	1032	Storm flow	7.6
35977607	Anderton Br. Site 3110	1/20/1999	1530	Base flow	7.7
35977607	Anderton Br. Site 3110	1/22/1999	2100	Storm flow	7.4
35977607	Anderton Br. Site 3110	3/19/1999	1000	Storm flow	7.4
3597766	Anderton Br. Site 3006	5/6/1998	1350	Base flow	7.9
3597764	Anderton Br. Site 3030	5/6/1998	1515	Base flow	7.4
3597764	Anderton Br. Site 3030	5/7/1998	1400	Pond release	7.2
352413086185001	Anderton Br. Site 3031	5/6/1998	1300	Base flow	7.6
3597762	Brinkley trib. Site 3045	5/6/1998	1455	Base flow	8.1
352418086194101	Painters Sp.	5/6/1998	1625	Base flow	7.4
3597765	J.W. Brinkley Sp.	5/19/1998	1610	Base flow	7.2
35977645	Mitchell Sp. No. 3	5/19/1998	1639	Base flow	7.4
3597754	Joyce King Sp.	5/19/1998	1050	Base flow	7.4
352544086192501	Lower Midway Sp.	5/7/1998	1010	Base flow	7.1
352411086185701	Well DW3	5/7/1996		Base flow	7.2
352411086185701	Well DW3	5/6/1998		Base flow	7.7
352411086185701	Well DW3	5/6/1998		Base flow	7.5
352324086182801	Well DW2	5/7/1996		Base flow	7.5
352313086182001	Well DW1	5/7/1996		Base flow	5.7
352329086181101	Monitoring well GW1	6/10/1996		Base flow	6.0
352329086181101	Monitoring well GW1	9/26/1996		Base flow	5.9
352338086180901	Monitoring well GW2	6/10/1996	1045	Base flow	5.1
352338086180901	Monitoring well GW2	9/26/1996	1426	Base flow	5.1
352343086181801	Monitoring well GW3	6/10/1996		Base flow	5.2
352343086181801	Monitoring well GW3	9/26/1996		Base flow	5.1

Table 5. Inorganic constituents in and physical properties of water from surface water, springs, and wells in the Quail Hollow Landfill area, Bedford County, Tennessee.—Continued

Site No.	Hardness, total (mg/L as $CaCO_3$)	Specific conductance (µS/cm)	Calcium, dissolved (mg/L as Ca)	Magnesium, total (mg/L as Mg)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)
PMCL	None	None	None	None	None	None
SMCL	None	None	None	None	None	None
Fish and aquatic life acute standards	None	None	None	None	None	None
Fish and aquatic life chronic standards	None	None	None	None	None	None
Sons Sp. Site 3090	200	617	NA	NA	NA	NA
Sons Sp. Site 3090	NA	532	77	NA	6.1	20
Sons Sp. Site 3090	270	660	96	NA	8	21
Sons Sp. Site 3090	NA	784	NA	9	NA	NA
Sons Sp. Site 3090	180	483	63	5.7	5.6	18
Sons Sp. Site 3090	110	261	38	3.2	3.2	7.3
Sons Sp. Site 3090	130	330	44	4	3.9	11
Sons Sp. Site 3090	190	520	69	5.8	5.4	14
Sons Sp. Site 3090	160	462	57	5.1	5	14
Sons Sp. Site 3090	120	329	40	3.9	3.9	9.8
Sons Sp. Site 3090	190	500	67	5.5	5.4	16
Sons Sp. Site 3090	120	350	43	3.8	3.9	10
Sons Sp. Site 3090	100	280	35	3.4	3.4	8.8
Anderton Br. Site 3110	47	210	24	5	NA	6.4
Anderton Br. Site 3110	65	218	26	5	NA	10
Anderton Br. Site 3110	36	80	12	NA	1.5	1.7
Anderton Br. Site 3110	60	119	21	3.4	1.8	2.8
Anderton Br. Site 3110	36	83	12	NA	1.4	1.8
Anderton Br. Site 3110	44	100	15	1.6	1.6	1.2
Anderton Br. Site 3110	69	163	24	2.4	2.3	2.5
Anderton Br. Site 3110	39	96	13	NA	1.6	1.9
Anderton Br. Site 3110	60	102	21	2.7	1.9	2.3
Anderton Br. Site 3110	44	105	15	1.8	1.7	2
Anderton Br. Site 3006	99	216	35	NA	2.7	1.9
Anderton Br. Site 3030	96	203	34	2.8	2.7	2.5
Anderton Br. Site 3030	110	194	38	3.2	3.1	2.6
Anderton Br. Site 3031	57	135	20	NA	1.7	2.8
Brinkley trib. Site 3045	130	263	46	NA	3	4.2
Painters Sp.	150	290	55	NA	2.1	0.4
J.W. Brinkley Sp.	130	230	45	NA	3.3	1.6
Mitchell Sp. No. 3	150	265	54	NA	4.6	1.5
Joyce King Sp.	110	230	41	NA	2.9	2.1
Lower Midway Sp.	160	289	53	NA	5.6	1.1
Well DW3	170	1,600	57	NA	7.9	100
Well DW3	260	3,020	74	NA	19	470
Well DW3	170	345	61	NA	5	5.1
Well DW2	83	221	28	NA	3.2	4.7
Well DW1	13	42	3.9	NA	0.7	1.7
Monitoring well GW1	18	265	4	NA	2	23
Monitoring well GW1	NA	157	NA	1	NA	NA
Monitoring well GW2	7	32	1.1	NA	1	2.7
Monitoring well GW2	NA	29	NA	1	NA	NA
Monitoring well GW3	6	151	1.1	NA	0.8	16
Monitoring well GW3	NA	148	NA	1	NA	NA

Table 5. Inorganic constituents in and physical properties of water from surface water, springs, and wells in the Quail Hollow Landfill area, Bedford County, Tennessee.—Continued

Site No.	Potassium, total (mg/L as K)	Potassium, dissolved (mg/L as K)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)	Arsenic, total (µg/L as As)	Barium, total (µg/L as Ba)
PMCL	None	None	None	None	50	2,000
SMCL	None	None	250	250	None	None
Fish and aquatic life acute standards	None	None	None	None	360	None
Fish and aquatic life chronic standards	None	None	None	None	190	None
Sons Sp. Site 3090	NA	NA	NA	NA	NA	NA
Sons Sp. Site 3090	NA	5.2	34	26	NA	NA
Sons Sp. Site 3090	NA	6.8	NA	NA	<1	NA
Sons Sp. Site 3090	6.7	NA	59	42	<1	29
Sons Sp. Site 3090	7.3	7.2	36	27	<1	42
Sons Sp. Site 3090	3.7	3.6	12	14	2	35
Sons Sp. Site 3090	4.8	4.3	18	16	<1	31
Sons Sp. Site 3090	5.3	5.2	35	29	<1	27
Sons Sp. Site 3090	5.7	6	30	27	<1	31
Sons Sp. Site 3090	4.3	4.5	18	18	<1	31
Sons Sp. Site 3090	4.8	4.8	34	27	<1	28
Sons Sp. Site 3090	3.8	3.8	19	17	<1	30
Sons Sp. Site 3090	3.2	3.3	15	14	<1	26
Anderton Br. Site 3110	7	4.4	NA	NA	<1	300
Anderton Br. Site 3110	7.2	6.5	NA	NA	<1	80
Anderton Br. Site 3110	NA	1	3	4.2	NA	NA
Anderton Br. Site 3110	5.4	2.7	NA	NA	4.8	82
Anderton Br. Site 3110	NA	0.8	2.9	3.6	NA	NA
Anderton Br. Site 3110	1.8	1.7	3.1	4.9	<1	13
Anderton Br. Site 3110	3.2	3.2	7.6	9.4	<1	17
Anderton Br. Site 3110	NA	1.2	4.4	5.5	NA	NA
Anderton Br. Site 3110	2.6	2.5	4.6	6.7	3.4	120
Anderton Br. Site 3110	1.3	1.4	3.8	5.2	<1	15
Anderton Br. Site 3006	NA	1.4	3.5	5.6	NA	NA
Anderton Br. Site 3030	1.2	1	3.8	6	<1	14
Anderton Br. Site 3030	3.9	1.4	3.1	7.2	5.9	84
Anderton Br. Site 3031	NA	1.4	4.5	4.8	NA	NA
Brinkley trib. Site 3045	NA	2	7.8	6.9	NA	NA
Painters Sp.	NA	0.5	1.6	3.1	NA	NA
J.W. Brinkley Sp.	NA	1	2.7	3.9	NA	NA
Mitchell Sp. No. 3	NA	0.8	2.1	5.1	NA	NA
Joyce King Sp.	NA	0.9	2.5	4.9	NA	NA
Lower Midway Sp.	NA	1.3	4.1	9.7	NA	NA
Well DW3	NA	2.6	220	240	NA	NA
Well DW3	NA	8.2	320	840	NA	NA
Well DW3	NA	1.2	3.6	10	NA	NA
Well DW2	NA	0.5	2.3	11	NA	NA
Well DW1	NA	0.1	2.3	1.5	NA	NA
Monitoring well GW1	NA	3.8	NA	NA	<1	NA
Monitoring well GW1	2	NA	21	0.3	<1	89
Monitoring well GW2	NA	0.3	NA	NA	<1	NA
Monitoring well GW2	0.2	NA	<0.1	<0.2	1.1	13
Monitoring well GW3	NA	1.2	NA	NA	<1	NA
Monitoring well GW3	1	NA	36	4.4	<1	130

Table 5. Inorganic constituents in and physical properties of water from surface water, springs, and wells in the Quail Hollow Landfill area, Bedford County, Tennessee.—Continued

Site No.	Barium, dissolved (µg/L as Ba)	Beryllium, total (µg/L as Be)	Cadmium, total (µg/L as Cd)	Cadmium, dissolved (µg/L as Cd)	Chromium, total (µg/L as Cr)	Cobalt, total (µg/L as Co)	Cobalt, dissolved (µg/L as Co)
PMCL	2,000	4	5	5	100	None	None
SMCL	None	None	None	None	None	None	None
Fish and aquatic life acute standards	None	None	None	1.8-8.6	None	None	None
Fish and aquatic life chronic standards	None	None	None	0.7-2.0	100	None	None
Sons Sp. Site 3090	NA	NA	NA	NA	NA	NA	NA
Sons Sp. Site 3090	NA	NA	NA	3.1	NA	NA	NA
Sons Sp. Site 3090	36	NA	NA	1.1	NA	NA	130
Sons Sp. Site 3090	NA	<0.5	1	NA	<1	140	NA
Sons Sp. Site 3090	NA	<0.5	1.5	2.6	<1	78	NA
Sons Sp. Site 3090	NA	<0.5	<0.5	0.8	<1	46	NA
Sons Sp. Site 3090	NA	<0.5	0.6	0.8	<1	42	NA
Sons Sp. Site 3090	NA	<0.5	1.3	1.4	<1	74	NA
Sons Sp. Site 3090	NA	<0.5	1.2	2.7	<1	65	NA
Sons Sp. Site 3090	NA	<0.5	1	1.6	<1	37	NA
Sons Sp. Site 3090	NA	<0.5	1.2	1.4	<1	68	NA
Sons Sp. Site 3090	NA	<0.5	1.3	1.9	<1	36	NA
Sons Sp. Site 3090	NA	<0.5	0.7	0.7	<1	29	NA
Anderton Br. Site 3110	NA	1.6	6	NA	45	50	NA
Anderton Br. Site 3110	NA	<0.5	2	NA	22	20	NA
Anderton Br. Site 3110	NA	<0.5	NA	0.7	NA	NA	NA
Anderton Br. Site 3110	NA	<0.5	<0.5	<0.5	8.1	9	NA
Anderton Br. Site 3110	NA	NA	NA	<0.5	NA	NA	NA
Anderton Br. Site 3110	NA	0.7	<0.5	<0.5	<1	<1	NA
Anderton Br. Site 3110	NA	0.5	<0.5	<0.5	<1	<1	NA
Anderton Br. Site 3110	NA	NA	NA	<0.5	NA	NA	NA
Anderton Br. Site 3110	NA	<0.5	<0.5	<0.5	4.3	20	NA
Anderton Br. Site 3110	NA	<0.5	0.5	<0.5	<1	1.5	NA
Anderton Br. Site 3006	NA	NA	NA	<0.5	NA	NA	NA
Anderton Br. Site 3030	NA	NA	<0.5	<0.5	<1	<1	NA
Anderton Br. Site 3030	NA	NA	<0.5	1.6	12	7.3	NA
Anderton Br. Site 3031	NA	NA	NA	<0.5	NA	NA	NA
Brinkley trib. Site 3045	NA	NA	NA	<0.5	NA	NA	NA
Painters Sp.	NA	NA	NA	<0.5	NA	NA	NA
J.W. Brinkley Sp.	NA	NA	NA	<0.5	NA	NA	NA
Mitchell Sp. No. 3	NA	NA	NA	<0.5	NA	NA	NA
Joyce King Sp.	NA	NA	NA	<0.5	NA	NA	NA
Lower Midway Sp.	NA	NA	NA	<0.5	NA	NA	NA
Well DW3	NA	NA	NA	<1.0	NA	NA	NA
Well DW3	NA	NA	NA	<0.5	NA	NA	NA
Well DW3	NA	NA	NA	<0.5	NA	NA	NA
Well DW2	NA	NA	NA	<1	NA	NA	NA
Well DW1	NA	NA	NA	<1	NA	NA	NA
Monitoring well GW1	15	<1	NA	<0.5	NA	NA	99
Monitoring well GW1	NA	<1	<0.5	NA	3.1	58	NA
Monitoring well GW2	17	<1	<0.5	<0.5	NA	NA	6
Monitoring well GW2	NA	<1	<0.5	NA	<1	2.3	NA
Monitoring well GW3	130	<1	NA	<0.5	NA	NA	10
Monitoring well GW3	NA	<1	<0.5	NA	2	7.2	NA

Table 5. Inorganic constituents in and physical properties of water from surface water, springs, and wells in the Quail Hollow Landfill area, Bedford County, Tennessee.—Continued

Site No.	Copper, total (µg/L as Cu)	Iron, total (µg/L as Fe)	Iron, dissolved (µg/L as Fe)	Lead, total (µg/L as Pb)	Lead, dissolved (µg/L as Pb)	Manganese, total (µg/L as Mn)	Manganese, dissolved (µg/L as Mn)
PMCL	None	None	None	5	None	None	None
SMCL	1,000	300	300		None	50	50
Fish and aquatic life acute standards	9.2-34.1	None	None	33.8-197	None	None	None
Fish and aquatic life chronic standards	6.5-21.4	None	None	1.3-7.7	None	None	None
Sons Sp. Site 3090	NA	NA	5,700	NA	NA	NA	NA
Sons Sp. Site 3090	NA	NA	80	NA	<1	NA	2,800
Sons Sp. Site 3090	1.3	NA	330	NA	<1	NA	4,800
Sons Sp. Site 3090	1.5	160	NA	<1	NA	4,500	NA
Sons Sp. Site 3090	16	483	17	<1	<1	2,600	2,600
Sons Sp. Site 3090	35	21,530	4.5	<1	<1	1,100	870
Sons Sp. Site 3090	17	1,600	3.6	<1	<1	1,500	1,400
Sons Sp. Site 3090	11	172	13	<1	<1	2,300	2,200
Sons Sp. Site 3090	8.4	161	8.4	<1	<1	2,100	2,000
Sons Sp. Site 3090	7.2	250	4.9	<1	<1	1,300	1,300
Sons Sp. Site 3090	20	310	4.8	<1	<1	2,300	2,200
Sons Sp. Site 3090	11	814	7.4	1.2	<1	1,300	1,300
Sons Sp. Site 3090	9.6	430	5.2	<1	<1	1,100	1,000
Anderton Br. Site 3110	59	72,000	NA	59	NA	2,900	NA
Anderton Br. Site 3110	39	17,000	NA	22	NA	1,100	NA
Anderton Br. Site 3110	NA	NA	10	NA	<1	NA	8.8
Anderton Br. Site 3110	15	12,294	10	8.2	<1	760	2.8
Anderton Br. Site 3110	NA	NA	20	NA	<1	NA	7.7
Anderton Br. Site 3110	<1	330	120	<1	4	63	47
Anderton Br. Site 3110	10	469	33	<1	<1	45	6.4
Anderton Br. Site 3110	NA	NA	13	NA	<1	NA	6.2
Anderton Br. Site 3110	24	8,100	254	17	<1	4,300	270
Anderton Br. Site 3110	7.9	850	68	1.6	<1	220	51
Anderton Br. Site 3006	NA	NA	120	NA	<1	NA	26
Anderton Br. Site 3030	<1	210	30	4.7	1	25	11
Anderton Br. Site 3030	7.1	10,874	280	5.7	9	260	150
Anderton Br. Site 3031	NA	NA	30	NA	<1	NA	16
Brinkley trib. Site 3045	NA	NA	150	NA	<1	NA	39
Painters Sp.	NA	NA	10	NA	<1	NA	3.7
J.W. Brinkley Sp.	NA	NA	5	NA	<1	NA	7.1
Mitchell Sp. No. 3	NA	NA	10	NA	1	NA	3.5
Joyce King Sp.	NA	NA	5	NA	<1	NA	3.5
Lower Midway Sp.	NA	NA	250	NA	2	NA	39
Well DW3	NA	NA	10	NA	1	NA	25
Well DW3	NA	NA	100	NA	<1	NA	72
Well DW3	NA	NA	40	NA	2	NA	13
Well DW2	NA	NA	10	NA	1	NA	41
Well DW1	NA	NA	620	NA	1	NA	870
Monitoring well GW1	NA	NA	440	NA	1	NA	24,000
Monitoring well GW1	2	55	NA	<1	1	12,000	NA
Monitoring well GW2	NA	NA	9	NA	1	NA	2,000
Monitoring well GW2	2	550	NA	3.2	NA	960	NA
Monitoring well GW3	NA	NA	1,200	NA	1	NA	6,500
Monitoring well GW3	1.7	1,200	NA	1.2	NA	5,300	NA

Table 5. Inorganic constituents in and physical properties of water from surface water, springs, and wells in the Quail Hollow Landfill area, Bedford County, Tennessee.—Continued

Site No.	Nickel, total (µg/L as Ni)	Nickel, dissolved (µg/L as Ni)	Vanadium, total (µg/L as V)	Zinc, total (µg/L as Zn)	Zinc, dissolved (µg/L as Zn)	Antimony, total (µg/L as Sb)	Aluminum, dissolved (µg/L as Al)
PMCL	100	100	None	None	None	6	None
SMCL	None	None	None	5,000	5,000	None	200
Fish and aquatic life acute standards	None	789-2,549	None	None	120	None	None
Fish and aquatic life chronic standards	None	87.7-283	None	None	106	None	None
Sons Sp. Site 3090	NA	NA	NA	NA	NA	NA	NA
Sons Sp. Site 3090	NA	110	NA	NA	64	NA	20
Sons Sp. Site 3090	NA	150	NA	NA	67	NA	NA
Sons Sp. Site 3090	170	NA	<1	78	71	<1	NA
Sons Sp. Site 3090	98	99	<1	66	27	<1	13
Sons Sp. Site 3090	56	38	<1	88	40	<1	11
Sons Sp. Site 3090	55	53	<1	43	NA	<1	8.7
Sons Sp. Site 3090	94	87	<1	85	100	<1	7
Sons Sp. Site 3090	83	81	<1	72	100	<1	7.2
Sons Sp. Site 3090	50	50	<1	43	58	<1	8
Sons Sp. Site 3090	88	88	<1	56	57	<1	16
Sons Sp. Site 3090	49	49	<1	43	53	<1	13
Sons Sp. Site 3090	41	41	<1	30	32	<1	12
Anderton Br. Site 3110	71	NA	110	210	NA	1	NA
Anderton Br. Site 3110	40	NA	34	140	NA	1	NA
Anderton Br. Site 3110	NA	1.5	NA	NA	3.8	<1	14
Anderton Br. Site 3110	22	1.3	19	59	1.8	1.8	31
Anderton Br. Site 3110	NA	1.9	NA	NA	4.6	NA	24
Anderton Br. Site 3110	2.1	1.8	<1	4.7	21	<1	84
Anderton Br. Site 3110	4.1	2.7	<1	12	13	<1	50
Anderton Br. Site 3110	NA	<1	NA	NA	5	NA	19
Anderton Br. Site 3110	35	3.7	1.2	58	6.2	<1	219
Anderton Br. Site 3110	5.3	3.4	<1	8.6	7.8	<1	75
Anderton Br. Site 3006	NA	<1	NA	NA	3.5	NA	39
Anderton Br. Site 3030	1.5	<1	<1	9.3	5.6	<1	28
Anderton Br. Site 3030	7.9	3.1	31	17	45	<1	890
Anderton Br. Site 3031	NA	1.2	NA	NA	15	NA	40
Brinkley trib. Site 3045	NA	<1	NA	NA	1.7	NA	51
Painters Sp.	NA	1.3	NA	NA	4	NA	16
J.W. Brinkley Sp.	NA	<1	NA	NA	5	NA	12
Mitchell Sp. No. 3	NA	<1	NA	NA	6.4	NA	10
Joyce King Sp.	NA	<1	NA	NA	5.6	NA	9.5
Lower Midway Sp.	NA	<1	NA	NA	9.1	NA	270
Well DW3	NA	<10	NA	NA	6	NA	<20
Well DW3	NA	1.2	NA	NA	8.6	NA	40
Well DW3	NA	2	NA	NA	5.4	NA	29
Well DW2	NA	10	NA	NA	5	NA	<20
Well DW1	NA	<1	NA	NA	30	NA	<20
Monitoring well GW1	NA	240	NA	NA	37	NA	NA
Monitoring well GW1	160	NA	<1	38	NA	<1	NA
Monitoring well GW2	NA	23	NA	NA	16	NA	NA
Monitoring well GW2	16	NA	<1	21	NA	<1	NA
Monitoring well GW3	NA	94	NA	NA	35	NA	NA
Monitoring well GW3	110	NA	<1	48	NA	<1	NA

Table 6. Volatile organic compounds from surface sites, springs, and wells near Quail Hollow Landfill, Bedford County, Tennessee, 1995-98.

[MCL, maximum contaminant level for drinking water as established by the State of Tennessee (Tennessee Department of Environment and Conservation, 1999); µg/L, micrograms per liter; e, estimated results below the reporting limit; ND, not detected; Sp., spring; Br., branch]

USGS site identification number	Site number	Date	Time	Conditions	Benzene (µg/L)	Chloro-benzene (µg/L)	1,4-Dichloro-benzene (µg/L)	Chloro-ethane (µg/L)	1,1-Dichloro-ethane (µg/L)	1,1-Dichloro-ethene (µg/L)	Cis-1,2-Dichloro-ethene (µg/L)	1,2-Dichloro-propane (µg/L)	Ethylben-zene (µg/L)
Primary maximum contaminant level					5	100	--	--	--	7	70	5	700
352351086183701	Sons Sp. Site 3090	3/22/1995			ND	ND	ND	ND	ND	ND	ND	ND	ND
352351086183701	Sons Sp. Site 3090	6/10/1996			ND	ND	ND	ND	7.2	ND	0.55	ND	ND
352351086183701	Sons Sp. Site 3090	9/26/1996			ND	ND	ND	ND	6.3	ND	1.1	ND	ND
352351086183701	Sons Sp. Site 3090	6/4/1998	2311		ND	ND	ND	ND	12	ND	0.32 e	ND	ND
35977607	Anderton Br. Site 3110	6/4/1998	1032	Storm flow	ND	ND	ND	ND	ND	ND	ND	ND	ND
352329086181101	Monitoring well GW1	6/10/1996		Base flow	2.9	0.27	1	4.8	17	0.40 e	4.4	ND	ND
352329086181101	Monitoring well GW1	9/26/1996		Base flow	1.7	ND	0.39 e	4.1	14	0.44 e	3.9	ND	ND
352338086180901	Monitoring well GW2	6/10/1996	1045	Base flow	0.78 e	ND	ND	3.9	5.6	0.45 e	1.1	ND	ND
352338086180901	Monitoring well GW2	9/26/1996	1426	Base flow	1.2	ND	ND	5.3	9	0.46 e	2.4	ND	ND
352343086181801	Monitoring well GW3	6/10/1996		Base flow	0.38 e	ND	ND	0.77 e	1.1	ND	ND	ND	0.26 e
352343086181801	Monitoring well GW3	9/26/1996		Base flow	0.33 e	ND	ND	ND	0.65 e	ND	ND	ND	ND

USGS site identification number	Site number	Date	Time	Conditions	Methylene chloride (µg/L)	Trichloro-fluoro-methane (µg/L)	Tetrachloro-ethene (µg/L)	1,1,1-Trichloro-ethane (µg/L)	Trichloro-ethene (µg/L)	Vinyl chloride (µg/L)	Xylenes, total (µg/L)	2-Butanone (µg/L)
Primary maximum contaminant level					5	--	5	200	5	2	10,000	
352351086183701	Sons Sp. Site 3090	3/22/1995			ND	ND	ND	ND	ND	ND	ND	ND
352351086183701	Sons Sp. Site 3090	6/10/1996			ND	ND	0.69 e	1.7	0.23 e	ND	ND	ND
352351086183701	Sons Sp. Site 3090	9/26/1996			ND	ND	0.55 e	0.83 e	0.29 e	ND	ND	ND
352351086183701	Sons Sp. Site 3090	6/4/1998	2311		ND	ND	0.73 e	6.4	0.29 e	ND	ND	ND
35977607	Anderton Br. Site 3110	6/4/1998	1032	Storm flow	ND	ND	ND	ND	ND	ND	ND	2.1 e
352329086181101	Monitoring well GW1	6/10/1996		Base flow	1.8	ND	1.7	0.87 e	1.8	5.3	ND	ND
352329086181101	Monitoring well GW1	9/26/1996		Base flow	1.9	0.86 e	2.3	1.5	2.2	3.7	ND	ND
352338086180901	Monitoring well GW2	6/10/1996	1045	Base flow	3.9	3.7	6.7	2.5	3.5	11	1	ND
352338086180901	Monitoring well GW2	9/26/1996	1426	Base flow	7.6	0.76	7.4	2.9	5	9.4	1.4	ND
352343086181801	Monitoring well GW3	6/10/1996		Base flow	ND	ND	0.21 e	0.21 e	ND	0.8e	ND	ND
352343086181801	Monitoring well GW3	9/26/1996		Base flow	ND	ND	ND	ND	ND	ND	0.32 e	ND

U.S. Geological Survey, written commun., 1997) but was not detected above detection limits at wells DW1, DW2, or DW3. Dissolved cobalt was detected in GW1 (99 µg/L) and Sons Spring (130 µg/L) but was not analyzed in the background wells (table 5). The USEPA does not presently have an ambient water-quality criterion for cobalt; however, research has indicated that the levels present in these waters are not toxic to fish and at times may exceed the no observable effect concentration for invertebrates (Diamond and others, 1992).

Dissolved manganese and iron often exceeded the SMCLs in samples collected from GW1, GW2, and GW3 with concentrations as high as 24,000 µg/L for dissolved manganese and 1,200 µg/L for dissolved iron. In Sons Spring, concentrations of these metals also exceeded SMCLs with 4,800 µg/L for dissolved manganese and 5,700 µg/L for dissolved iron. Dissolved manganese and iron concentrations were considerably less in the upgradient well DW1 with values of 870 µg/L for dissolved manganese and 620 µg/L for dissolved iron, which may reflect background concentrations in the area. Nickel concentrations exceeded the PMCL and TDEC fish and aquatic chronic criteria in samples collected from GW1, GW3, and Sons Spring, but was not detected above detection limits in the domestic wells (table 5). Thallium concentrations exceeded the PMCL at Sons Spring (E.F. Hollyday, U.S. Geological Survey, written commun., 1997). Chloride concentrations have increased from 3 to 59 mg/L in Sons Spring since the landfill began operating in 1974 (fig. 6). High concentrations of chloride were detected at DW3 on two occasions (table 5); however, these high concentrations are thought to be the result of inadequate purging as indicated by the duplicate samplings on May 6, 1998.

Among VOCs detected at the landfill, methylene chloride, tetrachloroethene (PCE), trichloroethene (TCE), and vinyl chloride equaled or exceeded PMCLs in ground water (table 6). Methylene chloride, a common laboratory solvent, was the only VOC detected in the samples of water from domestic wells; these results are not included in table 6. Methylene chloride detections were below PMCLs and probably were related to laboratory procedures rather than presence at the site. The organic compounds 1,1-dichloroethane (DCA) and 1,1-dichloroethene (DCE) also were detected (DCA in Sons Spring, GW1, GW2, and GW3 and DCE in GW1 and GW2). No PMCL has been established for DCA, and the levels of DCE are well below the PMCL (table 6). No fish and aquatic chronic criteria have been established for DCE or DCA by TDEC.

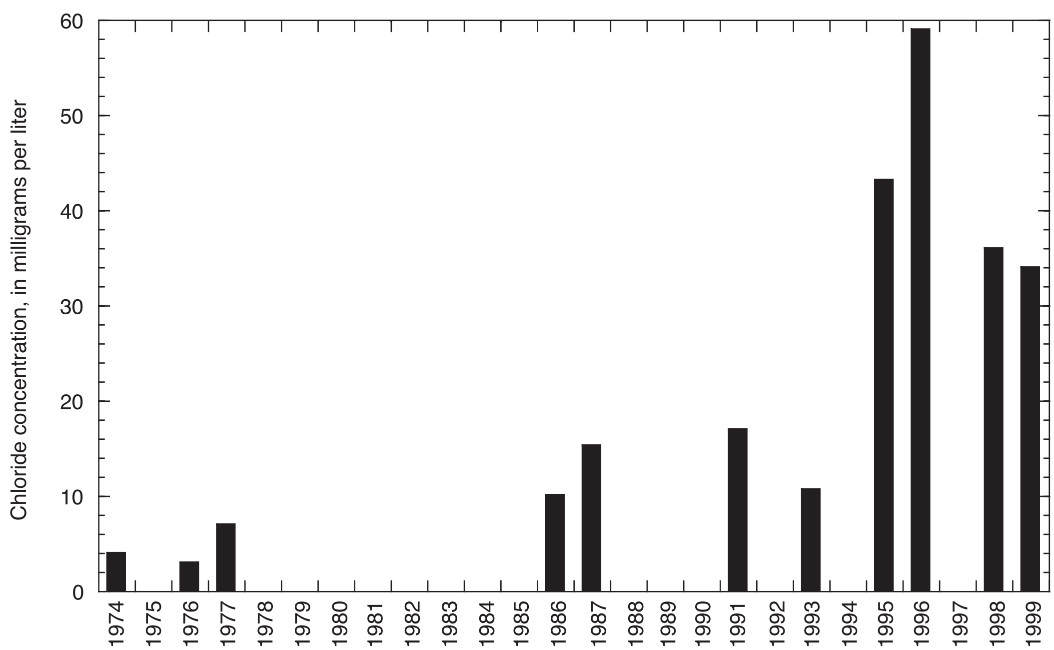


Figure 6. Chloride concentrations for selected water samples collected between 1974 and 1999 in Sons Spring, Bedford County, Tennessee. (E.F. Hollyday, U.S. Geological Survey, written commun., 1997.)

Surface-Water Quality

Surface-water quality near the landfill was monitored in Anderton Branch and Sons Spring. Water quality at these sites was compared to surface-water sites on Anthony Branch and Yasui Spring on Powell Branch. Continuous water-quality monitors were used to identify water-quality changes during storms. Water-quality samples were analyzed for major constituents, trace metals, and organic compounds. The analytical results are compared to maximum contaminant levels for public drinking water established by TDEC (1999) and are compared to acute and chronic criteria for fish and aquatic life (Tennessee Department of Environment and Conservation, 1999).

Anderton Branch

Continuous monitoring of Anderton Branch at site 3110 during 1996, 1998, and 1999 indicated increases in specific conductance associated with increased gage height after storms. During a storm on December 12, 1996 (fig. 7), the water in Anderton Branch changed from clear to a cloudy reddish color and the specific conductance increased from about 100 µS/cm to greater than 200 µS/cm. During the same storm, however, Anthony Branch showed no change in clarity or color, and the specific conductance decreased from about 160 to 120 µS/cm (fig. 7).

Water samples were collected from Anderton Branch during base- and storm-flow periods. Analysis of these samples indicated increased concentrations of iron, manganese, cadmium, lead, and nickel as compared with concentrations of these same metals detected during base flow (fig. 8). Concentrations of iron and manganese exceeded SMCLs on each

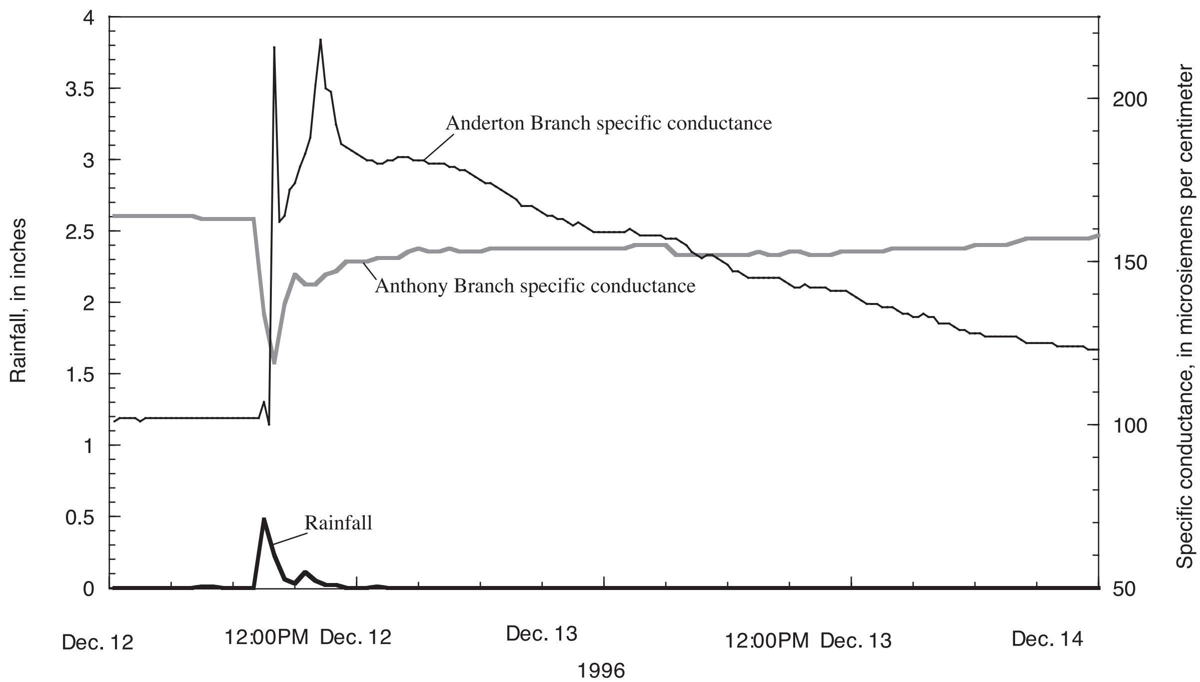


Figure 7. Comparison of specific conductance for Anderton and Anthony Branches, Bedford County, Tennessee, during a storm on December 12, 1996.

storm-flow sampling date with the exception of June 4, 1998, when the manganese concentration was only 5 µg/L below the SMCL. Lead concentration exceeded PMCLs and TDEC fish and aquatic life standards (table 5) in December 1996. Cadmium exceeded PMCLs in December 1996 and TDEC fish and aquatic life standards in May 1998, but showed levels as low as the base-flow concentrations on the remaining sampling dates (table 5 and fig. 8).

Analysis of samples for VOCs collected from Anderton Branch during a storm on June 4, 1998, indicated only the presence of 2-butanone at an estimated concentration (2.1 µg/L) below the reporting limit (table 6). The compound 2-butanone, a common laboratory contaminant, was not detected in any other sample and is not considered to be relevant to Anderton Branch.

Dissolved-solids concentrations in rainwater are low and storm runoff entering a stream typically is associated with a decrease in specific conductance. The increased metal concentrations detected in water samples from site 3110 during storm flow, along with increased specific conductance, leads to the hypothesis that a contaminant source upstream of the sampling site on Anderton Branch is being flushed by runoff from intense rains.

Chloride-load calculations indicate that Anderton Branch contains greater amounts of chloride than Anthony Branch. Studies of the stream indicate two point sources of chloride: Brinkley tributary, which drains a pond receiving water from both the landfill and Sons Spring; and a barnyard that straddles Anderton Branch (fig. 9). The discharge from Sons Spring flows a short distance on the surface before submerging into the gravel tributary that discharges into Brinkley Pond. Surface-water runoff from the landfill also discharges into and is detained in Brinkley Pond, which is a constructed pond that maintains a low water level because of a swallet in the northwestern corner of the pond. Because of the low water level, the pond resembles a wetland with ample amounts of vegetation present. Water escaping from the swallet, as well as seepage under the dam, results in a perennial tributary that drains into Anderton Branch. This tributary is a source of increased chloride load in Anderton Branch.

Sons Spring

Surface discharge from Sons Spring occurs about 10 ft below the Chattanooga Shale at a location approximately 300 ft from the toe of the landfill (fig. 2). Mean flow during the study period was 0.024 ft^3/s. Continuous monitoring during 1996, 1998, and 1999 indicated a distinct pattern of specific-conductance variations related to rainfall. Specific conductance shows an abrupt short-term increase beginning several hours after the onset of rainfall, followed by a sharp decrease (fig. 10). After the decrease, specific conductance gradually increases over the next several days and returns to pre-storm levels. Previous studies indicate that abrupt water-quality changes in response to storms are common to springs in mature karst environments (Quinlan and Alexander, 1987; Hess and White, 1988; Dreiss, 1989; Brown and Ewers, 1991; Ryan and Meiman, 1996; Farmer and Williams, 2001).

Comparisons of specific conductance to concentrations of total cobalt, dissolved manganese, dissolved nickel, dissolved chloride, dissolved iron, and dissolved magnesium during the storm flow and through the recovery period indicate a direct

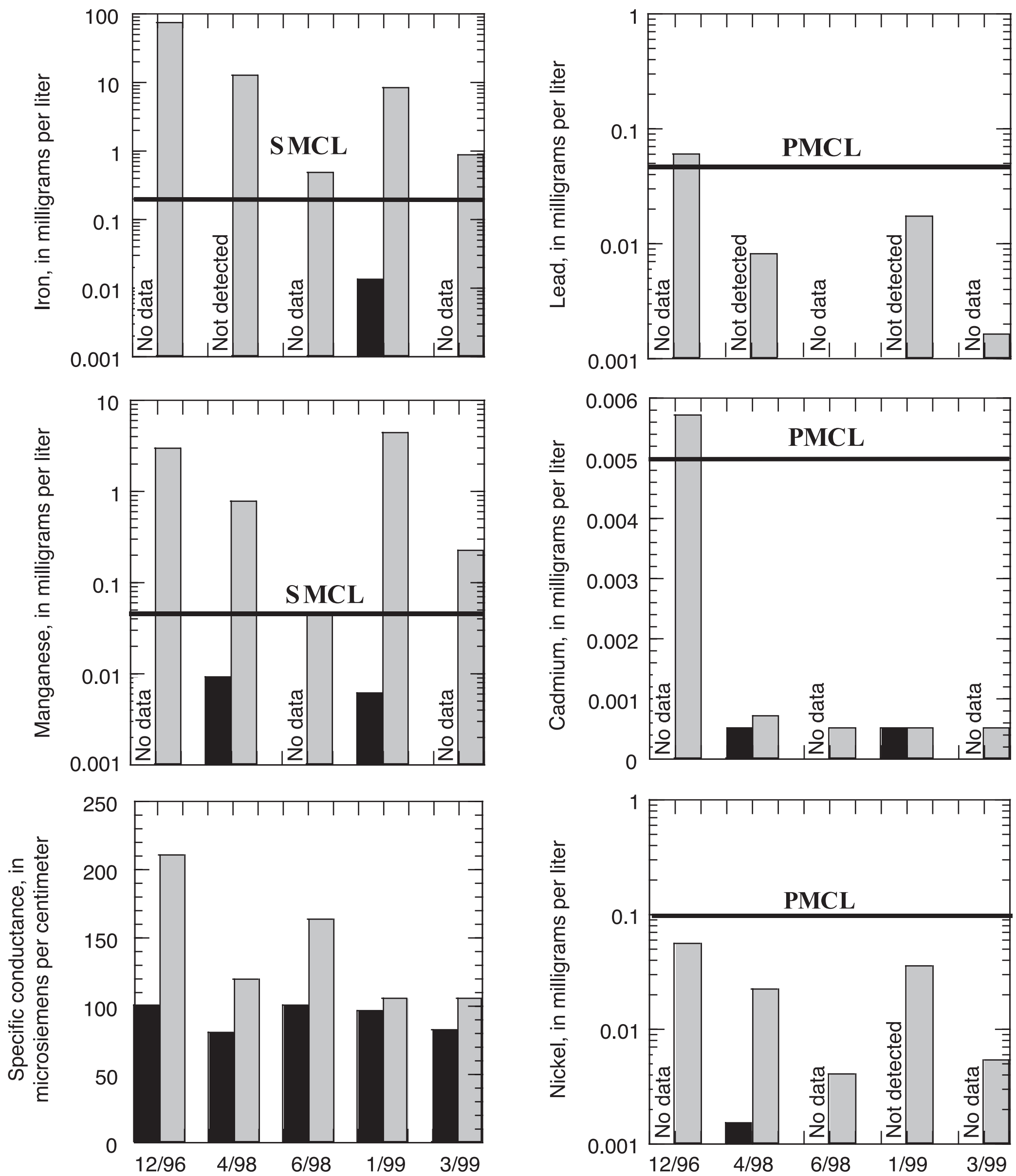


Figure 8. Concentrations of selected metals and specific conductance during storm flow and base flow on Anderton Branch, Bedford County, Tennessee. [Concentrations are analyzed as total solids for storm flow and dissolved solids for base flow. Primary (PMCL) and secondary (SMCL) maximum contaminant levels for drinking water are indicated. Base-flow data indicated in black, and storm data in gray.]

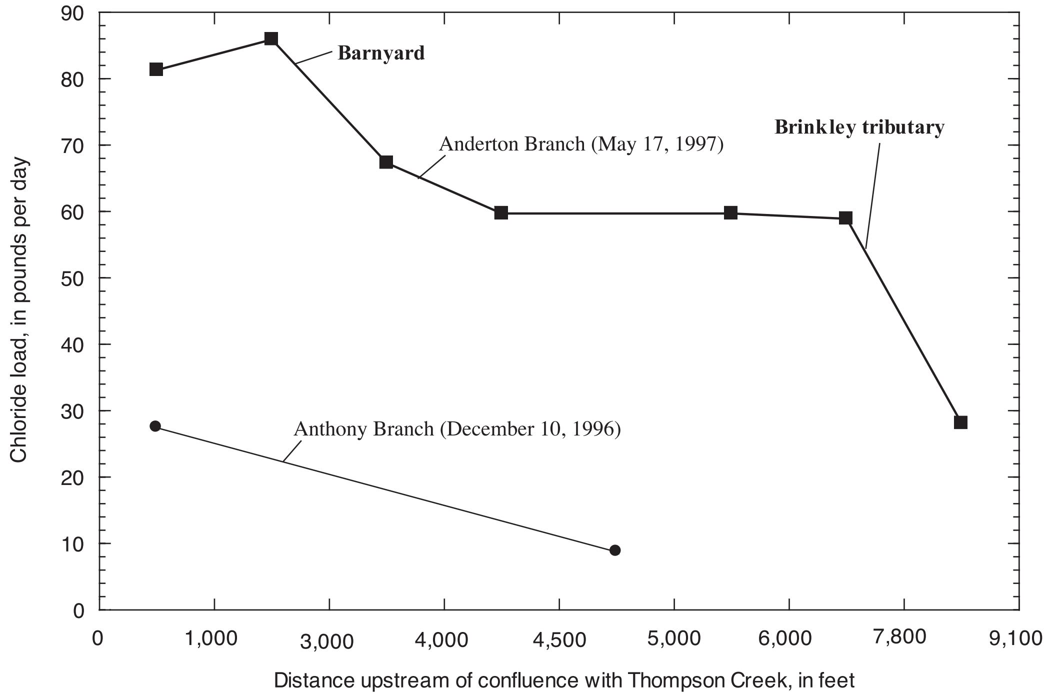


Figure 9. Chloride load calculations for Anthony and Anderton Branches, Bedford County, Tennessee.

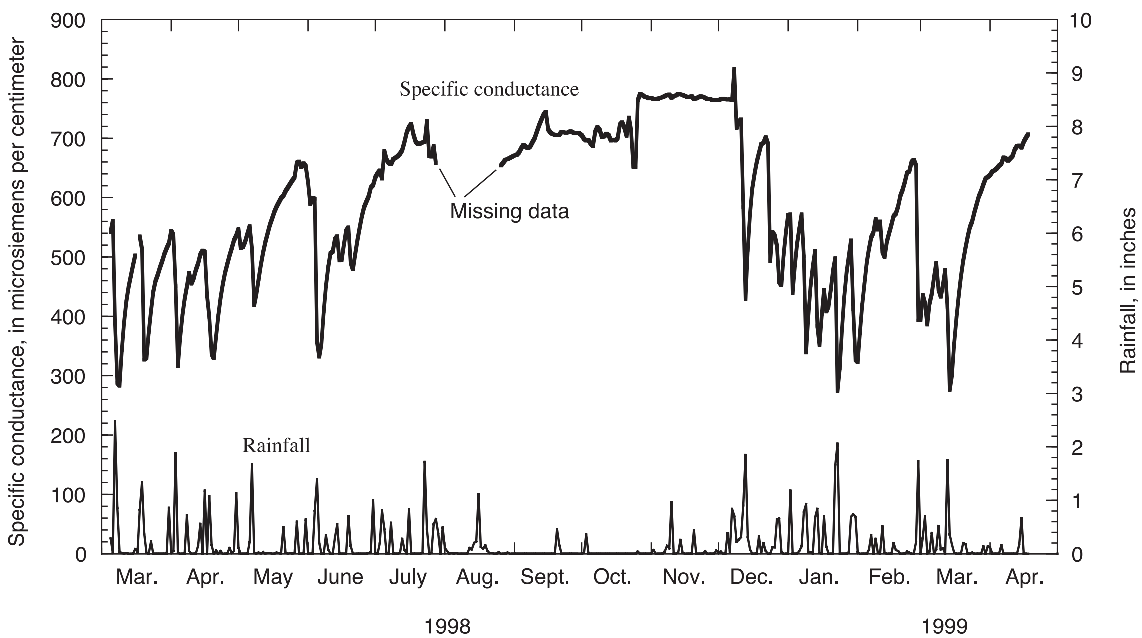


Figure 10. Specific conductance and rainfall at Sons Spring, Bedford County, Tennessee, March 1998 through May 1999.

correlation between concentrations of these constituents and the specific conductance (fig. 11). Total iron concentrations tend to have an opposite response (fig. 11). Dissolved iron showed a direct correlation with specific conductance for sampling dates in June 1998 and January 1999, but showed an increase and then a decrease for the March 1999 sampling date, which was identical to the response of total iron for this sampling date (fig. 11).

The contaminants identified at Sons Spring apparently are being diluted with the influx of rainwater. One possibility is that the recharge to Sons Spring during storms is through a solution channel or fracture near the face of the escarpment and not from water passing through the landfill. Another possibility is that the storm recharge is passing through the contaminants in the landfill without mobilizing them, causing dilution of contaminants already in the ground-water reservoir feeding the spring.

Chloride concentrations in samples not associated with storms at Sons Spring have increased from 3 mg/L in 1974 to 59 mg/L in 1996 (fig. 6). Specific conductance has increased

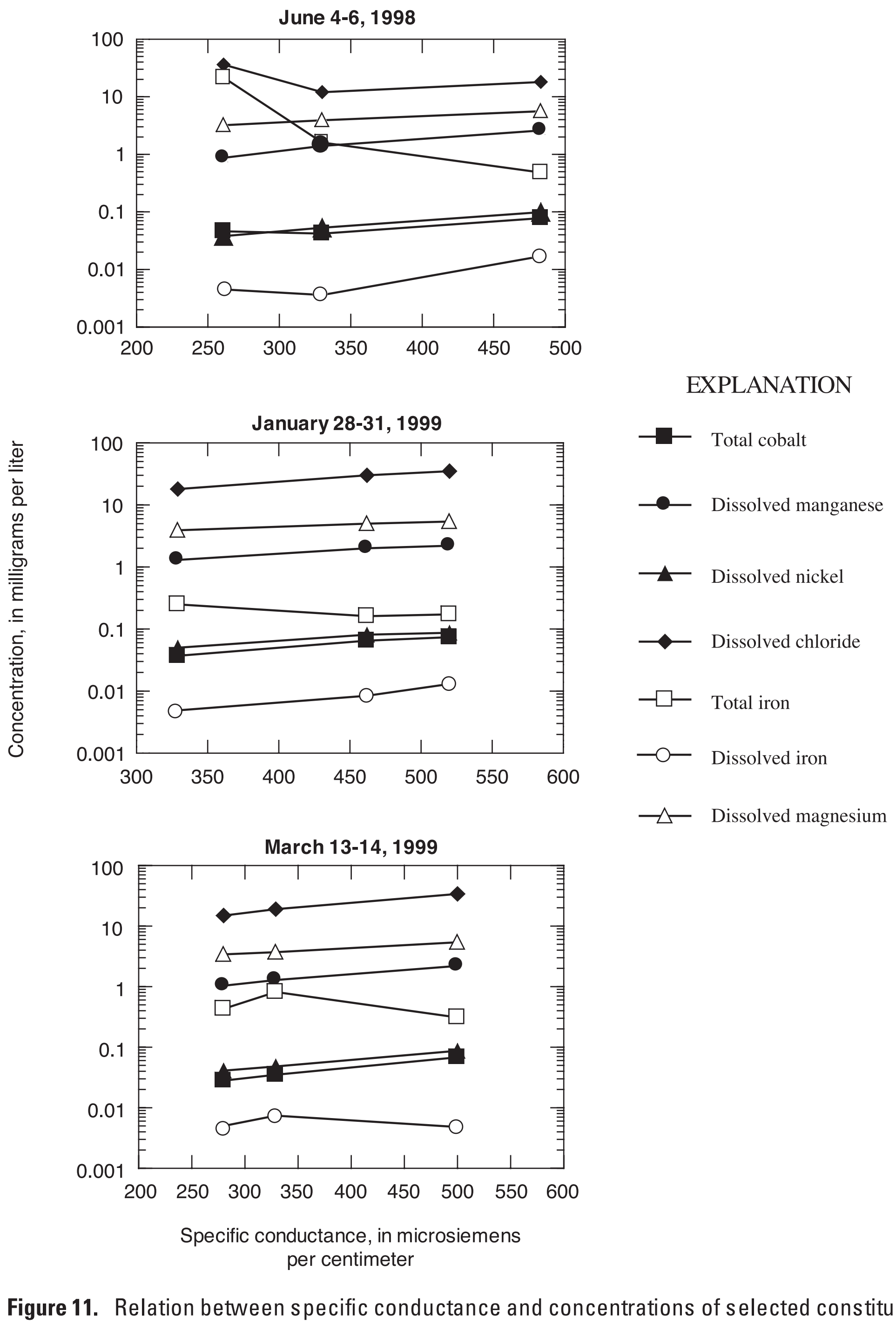


Figure 11. Relation between specific conductance and concentrations of selected constituents for three sampling events at Sons Spring, Bedford County, Tennessee.

from less than 300 to more than 800 µS/cm (fig. 10). The control spring, Yasui Spring (site 4050), had a specific conductance of 330 µS/cm and a chloride concentration of 8 mg/L in 1995, considerably lower than values at Sons Spring (Hollyday and Byl, 1995). The increased chloride concentrations and specific conductance values indicate the effect of the landfill on Sons Spring.

From 1995 through 1999, PMCLs of inorganic and trace constituents frequently were exceeded in samples from Sons Spring. Nickel concentrations exceeded PMCLs, and iron and manganese concentrations exceeded SMCLs. Dissolved zinc ranged from 27 to 100 µg/L. The 100-µg/L concentration approaches but does not exceed the TDEC fish and aquatic life standards. Total cobalt ranged from 29 to 140 µg/L, and dissolved cobalt was 130 µg/L on June 10, 1996 (table 5). No water-quality standards have been established for cobalt. Iron, manganese, and nickel (table 2) are present as natural constituents of the soil and sediments in the area. Analysis of water sampled during base flow in Anderton Branch (table 5) and at the control sites on Anthony Branch and Yasui Spring during the 1995 reconnaissance study (Hollyday and Byl, 1995) indicated low dissolved concentrations for these metals; iron less than 36 µg/L, manganese less than 25 µg/L, and nickel less than 10 µg/L. In Sons Spring during the current study, dissolved levels are high (iron 3.6 to 5,700 µg/L, manganese 870 to 4,800 µg/L, and nickel 38 to 150 µg/L) (table 5). Landfill activity may have caused increased mobilization of iron, manganese, and nickel from naturally occurring sources. The presence of chlorinated solvents in water samples from Sons Spring indicates that these contaminants originated in the landfill, but no detections exceeded PMCLs. TCE was detected four times and DCE six times (E.F. Hollyday, U.S. Geological Survey, written commun., 1997).

Benthic Macroinvertebrates

Benthic macroinvertebrates were collected at nine sites near the landfill to determine the abundance of organisms (fig. 12) and the number of different taxa at each site (fig. 13). The sites sampled included a control site on Anthony Branch (site 2026), sites on Anderton Branch upstream of the landfill (sites 3185 and 3200), sites on Anderton Branch adjacent to the landfill (sites 3040, 3110, 3135), Sons Spring (site 3090), Anderton Branch (site 3030) downstream of the resurgence of Anderton Branch and Harrison Cave Spring, and a location near the mouth of Anderton Branch (site 3005).

The high mean abundance (939 organisms per square meter) for May 1996 was at site 3030 downstream of the landfill. The mean abundance at site 3030 was not statistically different from all other sites except for Sons Spring (site 3090). The mean low abundance (47 organisms per square meter) was at site 3090, Sons Spring, and was statistically different from all other sites (fig. 12). The high mean taxa richness (nine taxa) was present at site 3135 and the low mean taxa richness (one taxa), at site 3090 (fig. 13). The mean taxa richness for site 3030 is lower than mean taxa richness at sites adjacent to (site 3135) and upstream of the landfill (site 3200); however, multiple comparison tests show that overlap occurs among these sites and all other sites upstream of, adjacent to, and downstream of the landfill (fig. 13).

An analysis of variance (95-percent confidence level) of abundance and taxa richness data from the sites upstream of, adjacent to, and downstream of the landfill indicated a statistical

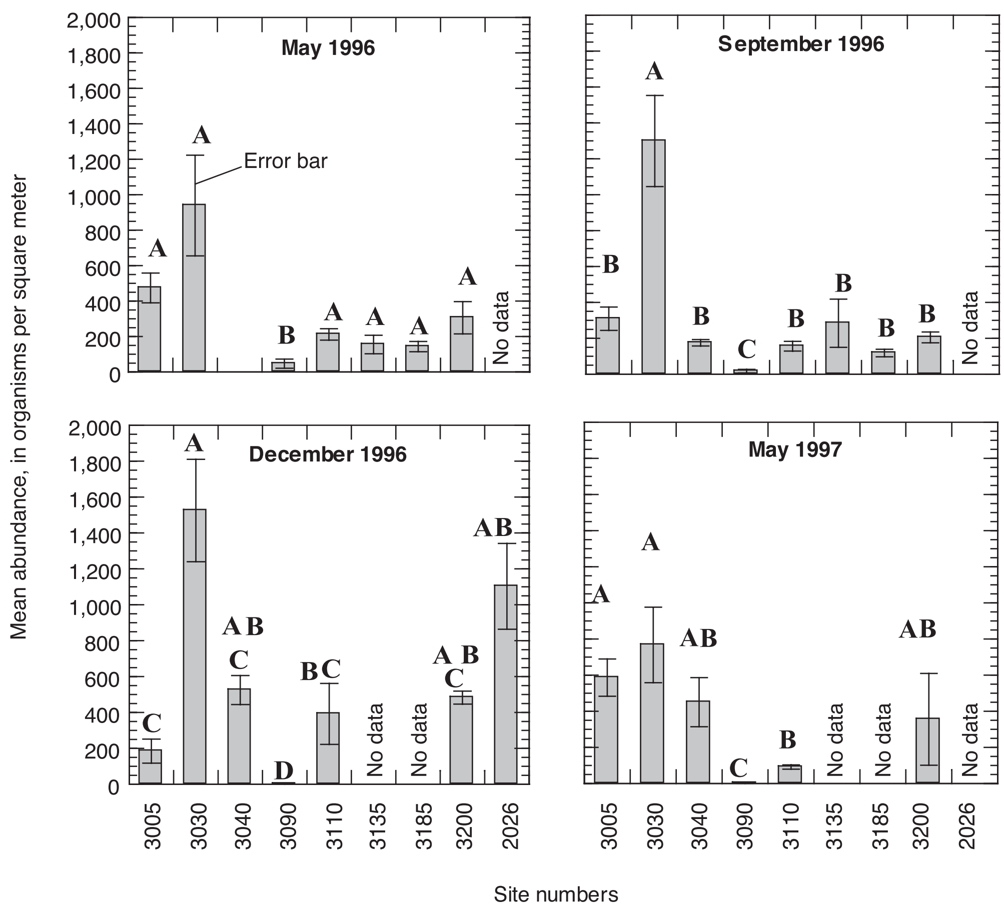


Figure 12. Mean abundance and standard error of benthic macroinvertebrates for Anderton Branch, Bedford County, Tennessee. [Site numbers increase upstream, where site 3090 is Sons Spring, and site 2026 is located on Anthony Branch. Sites with the same letter in each graph are not statistically different (∝ = 0.05).]

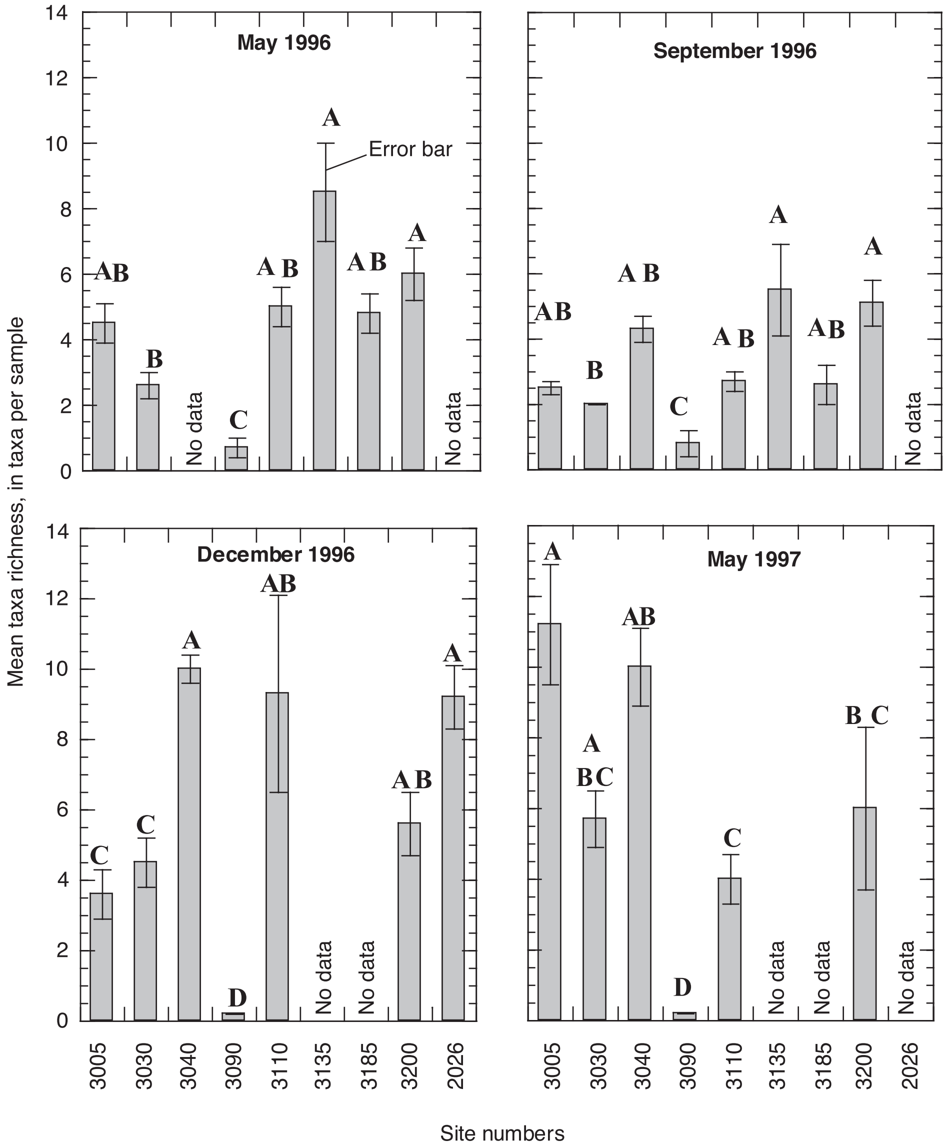


Figure 13. Mean taxa richness and standard error of benthic macroinvertebrates for Anderton Branch, Bedford County, Tennessee. [Site numbers increase upstream where site 3090 is Sons Spring, and site 2026 is located on Anthony Branch. Sites with same letter in each graph are not statistically different (∝ = 0.05).]

The high mean abundance (1,299 organisms per square meter) for September 1996 was present at site 3030 and the low mean abundance (170 organisms per square meter) at site 3090. The mean abundance for both of these sites is statistically different from all other sites, which are not statistically different and are grouped by the multiple comparison test into one category (fig. 12). The high mean taxa richness (six taxa) for September 1996 occurs at site 3135, which is not statistically different from site 3200. The low mean taxa richness (less than one organism) occurs at site 3090 (Sons Spring), and is statistically different from all other sites. The mean number of taxa is low for site 3030 but not statistically different from sites 3005, 3040, 3110, and 3185. The multiple comparison test indicates overlap occurs among sites 3005, 3040, 3110, and 3185 and among sites 3135 and 3200 (fig. 13).

The high mean abundance (1,525 organisms per square meter) for December 1996 was present again at site 3030, and the low mean abundance (2 organisms per square meter) again at site 3090. The mean abundance at site 3090, Sons Spring is statistically different from all other sites. Site 3030 is different from sites 3110 and 3005 but is not different from all other sites on Anderton Branch and the control site 2026 on Anthony Branch. The mean abundance at site 3005 is low but is not statistically different from sites adjacent to the landfill (sites 3040 and 3110) and upstream of the landfill (site 3200). The high mean taxa richness (10 taxa) for December 1996 was at site 3040, which was not different from the control site 2026 on Anthony Branch and site 3110 adjacent to the landfill or site 3200 upstream of the landfill. The lowest mean taxa richness (less than one) again occurred at site 3090, which is statistically different from all other sites. Sites 3005 and 3030 have mean taxa richness values in the middle range, and are different from all other sites (fig. 13).

The high mean abundance (767 organisms per square meter) for May 1997 was again present at site 3030. The mean abundance at this site was not different from site 3005, and both are not different from site 3040 adjacent to the landfill and site 3200 upstream of the landfill. The low mean abundance (three

difference at sites during different seasons. A multiple comparison test was used to group similar sites (not different statistically). Similar sites are designated on figures 12, 13, and 14 by the same letter label. Groups that are statistically different are assigned different letters. Some groups overlap, are similar to multiple groups, and are labeled with multiple letters. For example, abundance of macroinvertebrates in December 1996 (fig. 12) shows sites 3005, 3030, and 3090 to be statistically different and are designated C, A, and D, respectively. Site 3040 has an ABC designation indicating no difference between this site and sites 3005 (C), 3030 (A), 3110 (BC), 3200 (ABC), and 2026 (AB). Similarly site 2026 is designated AB indicating no difference statistically between site 2026 and sites 3030 (A), 3040 (ABC), 3110 (BC), and 3200 (ABC).

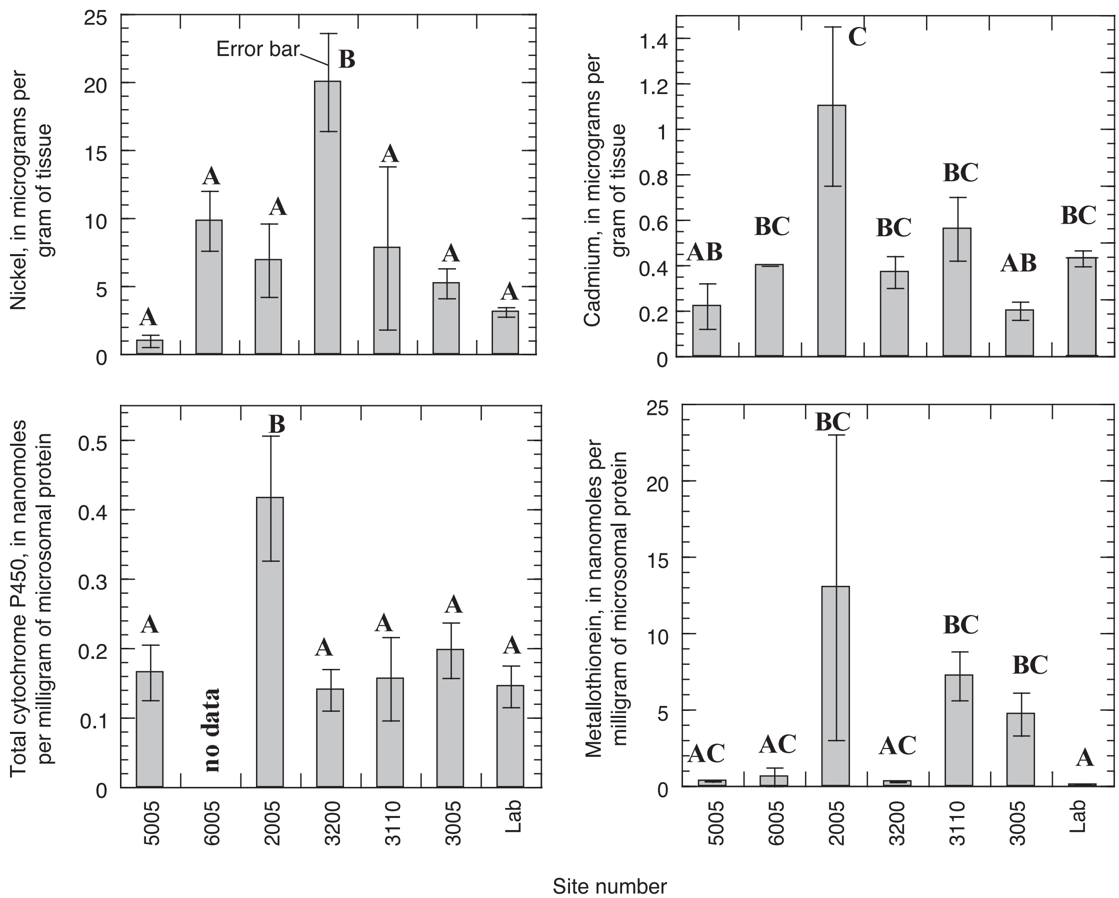


Figure 14. Mean concentrations of nickel, cadmium, cytochrome P450, and metallothionein present in hepatopancreas tissue from crayfish collected at sites near Quail Hollow Landfill, Bedford County, Tennessee. [Metallothionein and cytochrome P450 are reported relative to the amount of microsomal preparation present. Error bars are standard error, and sites with the same letter are not statistically different ($\propto$ = 0.05).]

organisms per square meter) at site 3090 was statistically different from all other sites. The mean abundance at site 3110 was statistically different from the lowest and the highest sites but was not statistically different from the remainder of the sites (fig. 12). The high mean taxa richness for May 1997 occurred at site 3005 near the mouth of Anderton Branch. The mean taxa richness at each site on Anderton Branch tends to increase downstream, but overlap exists among all of the sites except for site 3090. The low mean taxa richness (less than one) occurs at site 3090, Sons Spring, and is statistically different from all of the other sites (fig. 13).

Although seasonal variations exist, Sons Spring (site 3090) is consistently lower in mean abundance and mean taxa richness from all other sites. Sons Spring had the lowest mean abundance and lowest mean taxa richness during all four sampling events. Among the other sites some significant differences are apparent, but in general, the multiple comparison tests show that considerable overlap exists among the sites downstream of, adjacent to, and upstream of the landfill.

Site 3030 is high in abundance and low in taxa richness. Although low in taxa, this site is considered to be a healthy site. Physically different from the other sites, site 3030 is shady in spring, summer, and fall and has shallow water and a moss-covered substrate. The site also is downstream from the resurgence of Anderton Branch at Harrison Cave Spring where the water resurges from the upstream losing reach on Anderton Branch and mixes with the water from Harrison Spring Cave. The substrate is dominated by snails, and the moss contains high densities of the amphipod *Gammarus.*

Site 3005 (near the mouth of Anderton Branch) showed low values of taxa richness for the first three samplings; however, several samplers were lost during storm conditions. Because of the loss of samplers, the number of traps was increased in May 1997 for site 3005. The data collected in May 1997 are considered to be the most representative data for this site, having higher values of abundance and taxa richness than during the other sampling periods (figs. 12 and 13).

In October 1998, benthic invertebrate samples were collected near site 3005. Counts of abundance and taxa richness were statistically compared to the December 1996 sampling by using a Student's *t* test (significance 0.05). Results of this analysis indicated significant increases in abundance and richness. The increased number and diversity of benthic invertebrates present indicates an overall improvement in the water quality of Anderton Branch.

Laboratory Toxicity Studies

Chronic toxicity studies (Lewis and others, 1994) were conducted using the water flea, *Ceriodaphnia dubia,* as a test organism for water samples from a site on Anderton Branch adjacent to the landfill (site 3110), Brinkley tributary downstream of the landfill (site 3045), Sons Spring (site 3090), Anthony Branch (site 2050), and Yasui Spring (site 4050). The test detects toxicity by comparing the means of the number of offspring from parent organisms living in the water sample with the means of the number of offspring from parents living in the negative control water designed for ideal growth conditions (moderately hard water; Lewis and others, 1994). All parent organisms placed in storm- and base-flow water samples from Sons Spring died within 48 hours; therefore, no offspring were produced (table 7). All parent organisms also died within 48 hours when placed in the positive control (2,000 mg/L salt water, designed to kill the organisms).

Statistical comparison of the means of reproduction data (table 7) from all other sites tested (Dunnett's test, 95-percent confidence level) showed no difference in the toxicity for all sites as compared to the negative control, moderately hard water, including Brinkley tributary (site 3045), which contained water affected by the landfill as indicated by a chloride concentration of 7.8 mg/L (table 5). The toxicity study indicates that the contaminated water from the landfill and toxic water from Sons Spring is no longer toxic after flowing through the wetland in Brinkley Pond and discharging to Brinkley tributary. Although storm water in Anderton Branch (site 3110) contained higher levels of certain contaminants (table 5 and fig. 8) than base-flow water, no toxicity was detected in either sample.

Biomarkers

Crayfish hepatopancreas tissue was analyzed for nickel and cadmium concentrations, two metals that were detected in water samples from Anderton Branch. Nickel and cadmium exceeded TDEC criteria for fish and aquatic life (table 5).

Cadmium concentrations in crayfish hepatopancreas tissue ranged from a high of 1.1 µg/g of tissue (dry weight) in crayfish collected from the mouth of Anthony Branch (site 2005) (control site) to a low of 0.2 µg/g in crayfish collected from the mouth of Anderton Branch (site 3005) (fig. 14). Analysis of variance (95-percent confidence level) indicates cadmium concentrations in crayfish tissue from site 2005 are higher than concentrations in tissue from site 3005 and the control site on Bennett Branch (site 5005). Multiple comparison grouping analysis indicates considerable overlap occurs among most of the sites with the exception of site 2005 (fig. 14). Cadmium levels found in crayfish tissue are similar to background levels found in fish tissue in northern Bedford County (Knight and Powell, 2001).

Table 7. Results of toxicity tests on water collected from selected locations during base-flow and storm-flow conditions near Quail Hollow Landfill, Bedford County, Tennessee.

[Control +, Positive control (2,000 milligram per liter salt water designed to kill all organisms); Control–, Negative control (ideal water for growth and reproduction)]

Site location and number	Number of *Ceriodaphnia dubia* offspring Replicates 1	2	3	4	5	6	7	8	9	10	Mean	Live adults at end of test
Base-flow conditions, October 31, 1996												
Anderton Branch adjacent to landfill 3110	34	31	25	21	10	31	12	17	18	12	21	10
Anthony Branch 2050	25	31	28	29	31	28	16	28	20	17	25	10
Yasui Spring 4050	30	33	25	29	32	15	15	3	14	18	21	9
Sons Spring 3090	0	0	0	0	0	0	0	0	0	0	0	0
Control-	31	16	31	1	31	31	14	15	14	15	20	10
Control+	0	0	0	0	0	0	0	0	0	0	0	0
Storm-flow conditions, December 12, 1996												
Anderton Branch adjacent to landfill 3110-filtered	29	26	17	26	37	31	37	21	30	13	28.5	9
Anderton Branch adjacent to landfill 3110-unfiltered	37	32	6	24	24	24	0	20	10	25	20.2	8
Anthony Branch 2050	32	34	16	27	26	24	26	23	16	11	23.5	0
Yasui Spring 4050	27	16	14	16	21	22	24	30	11	20	20.1	9
Sons Spring 3090	0	0	0	0	0	0	0	0	0	0	0	0
Brinkley tributary 3045	28	28	12	21	33	31	28	18	25	22	24.6	9
Control-	10	4	17	21	20	30	7	23	11	20	16.3	9
Control+	0	0	0	0	0	0	0	0	0	0	0	0

Analysis of variance (95-percent confidence level) indicates nickel concentrations in crayfish hepatopancreas tissue were higher in samples from site 3200 (control site) in the headwaters of Anderton Branch than from all other sites (fig. 14). Naturally high nickel concentrations in the sediment from this site are the probable cause for these high nickel concentrations in crayfish collected from this site (site S4, table 2).

Organic compounds were detected in water samples from landfill monitoring wells and Sons Spring (table 6). Cytochrome P450 is a diverse family of enzymes that can be used as biomarkers and are induced by exposure to certain organic compounds. Analysis of variance (95-percent confidence level) indicates that cytochrome P450 concentrations in crayfish hepatopancreas tissue samples from control sites on Bennett Branch (site 5005), upstream of the landfill (site 3200), and the laboratory were not different from the samples from sites on Anderton Branch adjacent to (site 3110) and downstream of (site 3035) the landfill. The cytochrome P450 concentrations in tissue samples taken from control site 2005 on Anthony Branch were higher than in samples from all other sites (fig. 14). This high concentration may be caused by organic inputs from a facility near the sampling site or possibly from agricultural chemicals in use in the Anthony Branch drainage basin.

Metallothionein is a small peptide that reduces toxicity of some metals by binding the metals and making them less bioavailable. Metallothionein is induced by exposure to certain metals including nickel and cadmium. Analysis of variance (95-percent confidence level) indicates metallothionein concentrations in crayfish hepatopancreas tissue were lower in laboratory-purged crayfish than in tissue from crayfish from Anderton (sites 3005 and 3110) and Anthony Branches (site 2005) (fig. 14). The high concentrations of metallothionein present in tissue samples from crayfish collected on Anderton and Anthony Branches indicate that metallothionein may have been induced in the organisms tested. Because the cadmium and nickel concentrations in the purged crayfish are statistically not different from field crayfish collected at the sample sites, other metals may be present causing the induction of this biomarker.

Summary

Landfills can affect nearby ground-water and surface-water sources by increasing concentrations of chloride, heavy metals, and organic compounds in water. Increased turbidity caused by surface runoff over areas denuded of vegetation also can negatively affect the benthic community of streams draining landfills. From 1996 to 1998 the USGS, in cooperation with the Bedford County Solid Waste Authority, conducted a study to characterize the hydrology and water quality of Anderton Branch adjacent to the Quail Hollow Landfill.

Quail Hollow Landfill, located on the Highland Rim overlooking the Central Basin of Middle Tennessee, is constructed on the clay-rich gravelly residuum of the Fort Payne Formation above the Chattanooga Shale confining unit. Underlying the Chattanooga Shale are the Leipers and Catheys Formations, the Cannon Limestone, and the Hermitage Formation. The Cannon Limestone is characterized by sinking streams, sinkholes, and caves including the Harrison Cave system, an extensive network of solution channels of which the mapped portion is adjacent to the landfill. Evidence of the importance of this cave system to the hydrology of the area was obtained when a natural dye trace resulted from the release of impounded water that entered a sinking pond in the Powell Branch drainage basin and emerged overnight 4,200 feet away in the Anderton Branch drainage basin. This connection demonstrates that the karst solution channels can direct water from the south and west, as well as from the north and east, into Anderton Branch.

Surface- and ground-water data collected for this study from domestic and landfill monitoring wells, springs, and several streams in the landfill area were analyzed and compared with data collected during an earlier study of the landfill. Surface- and ground-water quality data were collected during base- and storm-flow conditions and were analyzed for specific conductance, metals, and organic and inorganic compounds. Abundance and taxa richness of the benthic community was sampled, and toxicity using *Ceriodaphnia dubia* was determined. Concentrations of nickel and cadmium and the biomarkers cytochrome P450 and metallothionein in crayfish hepatopancreas tissue were evaluated as more sensitive indicators of water quality.

Specific conductance and concentrations of iron, manganese, lead, and nickel increased in Anderton Branch during storm-flow conditions. Specific conductance at site 3110 in Anderton Branch increased from 100 to 200 µS/cm during storm flow. In contrast during the same storm, the specific conductance at site 2050 in Anthony Branch decreased from 160 to 120 µS/cm. Concentrations of total iron, manganese, lead, and nickel were greater (72,000, 2,900, 59, and 71 µg/L, respectively) during storm runoff in Anderton Branch than during base-flow conditions (17 and 34 µg/L, for iron and manganese, respectively, and no detections for lead and nickel). Concentrations of lead and nickel exceeded PMCLs (5 and 100 µg/L, respectively) and concentrations of iron and manganese exceeded SMCLs (300 and 50 µg/L, respectively) for drinking water. Cadmium also was detected during the December 1996 storm (6 µg/L, total) and again in May 1998 (0.7 µg/L, dissolved) at a concentration equal to the lowest TDEC fish and aquatic life standard, but its concentration remained below detection limits during other storms. Chloride-load levels in Anderton Branch are three times greater than for Anthony Branch. Chloride-load calculations in Anderton Branch established two point sources of chloride: Brinkley tributary, which drains Brinkley Pond that receives surface water and ground water from the landfill and ground water from Sons Spring, and a barnyard that is divided by Anderton Branch. Although volatile organic compounds were detected in the monitoring wells at the landfill and at Sons Spring, these contaminants were not detected in Anderton Branch or in domestic wells.

Sons Spring is a karst spring discharging about 10 feet below the Chattanooga Shale at a location approximately

300 feet from the toe of the landfill. Chloride concentrations at Sons Spring increased from 3 mg/L in 1974 to 59 mg/L in 1996. Specific conductance increased from 230 to 800 µS/cm during storm events. Both increases are indicators of the effect of the landfill on water quality at this spring. Water samples from Sons Spring contained concentrations of nickel that exceeded primary drinking-water standards and TDEC fish and aquatic life chronic criteria, and concentrations of iron and magnesium that exceeded secondary drinking-water standards. Cobalt also was detected at high concentrations.

Volatile organic compounds present in the ground water at the landfill included PCE, TCE, and vinyl chloride; each of these compounds equaled or exceeded PMCLs. Other volatile organic compounds detected at the ground-water monitoring wells at the landfill and in Sons Spring included DCA and DCE. The presence of these chlorinated solvents indicate the landfill origin of the contaminants in Sons Spring.

Analysis of variance (95-percent confidence level) of the data from benthic macroinvertebrate samples in Anderton Branch indicated some differences in abundance of organisms and number of taxa at sites upstream of the landfill as compared with sites adjacent to and downstream of the landfill as well as a control site on Anthony Branch. However, the ecological significance of these differences is doubtful because the multiple comparison tests indicate considerable overlap among many of these sites, and differences seen cannot be definitively attributed to landfill influence. As an example, even though site 3030 on Anderton Branch is low in taxa, this site is considered to be a healthy site because of the high abundance of organisms. The low number of taxa is probably not due to poor water quality, but rather to a unique environment. Sons Spring (site 3090) was statistically different from other sites and consistently had the lowest mean abundance and the lowest mean taxa richness. These differences do appear to be attributable to landfill influence. Annual monitoring and analysis of data from site 3005 on Anderton Branch in 1998 indicated that the number and types of benthic macroinvertebrates has increased at that site.

Toxicity studies evaluating the *Ceriodaphnia dubia*, water flea, indicated no toxicity in base flow or storm water from Anderton Branch. Water from Sons Spring resulted in 100-percent mortality to the test organisms within 48 hours for both base- and storm-flow water samples. Toxicity studies confirm results of benthic studies and are in agreement with the benthic studies in this project.

Biomarker studies indicated that cytochrome P450 was not induced in crayfish hepatopancreas tissue in samples from Anderton Branch. Cytochrome P450, however, was at statistically higher levels in tissue samples from the control stream Anthony Branch than in tissue samples from all the other sites studied. Metallothionein concentrations in crayfish hepatopancreas tissues showed increased levels in samples from Anderton Branch as compared with control samples, but the levels were not significantly increased. The increased levels of metallothionein were probably caused by the presence of other metals that were not studied because levels of nickel or cadmium detected in these same tissues were not different from control samples, which showed no metallothionein induction. Statistically high levels of nickel in crayfish hepatopancreas tissue detected in samples from an upstream control site probably were caused by naturally occurring high levels of nickel.

This study confirms the observations from the 1995 reconnaissance study that Sons Spring has been severely affected by the landfill; however, the overall effect of the landfill on water in Anderton Branch is minimal. Surface runoff and ground water from the landfill and ground water from Sons Spring flow into and through Brinkley Pond and then discharge through seeps into Brinkley tributary. High chloride concentrations detected in water from Brinkley tributary indicate that the water is affected by the landfill; however, the metal concentrations are not elevated and the water is not toxic. The lack of toxicity and metals in water from Brinkley tributary indicates that Brinkley Pond is reducing contaminant levels in the water received from the landfill. High concentrations of metals were detected in storm-water samples in Anderton Branch; however, this water was not toxic and the benthic community downstream of this site was not affected. These observations indicate that the overall effect of the Quail Hollow Landfill on the ecology of Anderton Branch is restricted primarily to Sons Spring and the short reaches on the east flank of the landfill identified in the 1995 study.

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