HYDROLOGIC ENVIRONMENTS AND WATER-QUALITY CHARACTERISTICS AT FOUR LANDFILLS IN MECKLENBURG COUNTY, NORTH CAROLINA, 1980-86

By Alex P. Cardinell, Charles R. Barnes,
W. Harold Eddins, and Ronald W. Coble

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 89-4035

Prepared in cooperation with the

CITY OF CHARLOTTE, NORTH CAROLINA, and

MECKLENBURG COUNTY, NORTH CAROLINA

Raleigh, North Carolina

1989

DEPARTMENT OF THE INTERIOR

MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information write to:

District Chief
U.S. Geological Survey
Post Office Box 2857
Raleigh, North Carolina 27602

Copies of this report can be purchased from:

U.S. Geological Survey
Books and Open-File Reports
Federal Center, Building 810
Box 25425
Denver, Colorado 80225

CONTENTS

	Page
Abstract	1
Introduction	2
Purpose and scope	4
Acknowledgments	4
Description of Mecklenburg County	7
Precipitation	7
Streams	8
Topography	8
Hydrogeologic setting	9
Landfill hydrologic environments	13
Harrisburg Road landfill	14
Holbrooks Road landfill	17
Statesville Road landfill	21
York Road landfill	26
Collection of water-quality data	30
Ground-water sites	30
Surface-water sites	35
Selected water-quality indicators	37
Inorganic indicators	39
Dissolved solids	39
Specific conductance	41
Chloride	44
Hardness	47
Manganese	49
Organic indicators	52
Total organic carbon	52
Specific organic compounds	53
Water-quality characteristics at landfills	55
Harrisburg Road landfill	55
Ground water	56
Surface water	56
Holbrooks Road landfill	58
Ground water	58
Surface water	60

Page

Statesville Road landfill 62

Ground water 62

Surface water 64

York Road landfill 66

Ground water 67

Surface water 70

Summary 72

References 75

ILLUSTRATIONS

Page

Figure 1. Map showing location of landfill study sites in Mecklenburg County 3

2. Sketch showing the conceptual structure of the Piedmont hydrogeologic framework 10

3. Diagram showing an idealized weathering profile through the regolith, showing relative permeability 11

4-11. Maps showing:

4. Location of monitoring wells, surface-water monitoring sites, and solid-waste disposal cells at or near Harrisburg Road landfill 15

5. Altitude of water table at Harrisburg Road landfill, March 1986 18

6. Location of monitoring wells, surface-water monitoring sites, and solid-waste disposal cells at or near Holbrooks Road landfill 19

7. Location of monitoring wells, surface-water monitoring sites, gaging station, and solid-waste disposal cells at or near Statesville Road landfill 22

		Page
	8. Location of borings and test pits and position of refuse with respect to the saturated zone at Statesville Road landfill, 1980	23
	9. Altitude of water table at Statesville Road landfill, 1980	25
	10. Location of monitoring wells, surface-water monitoring sites, gaging station, and solid-waste disposal cells at York Road landfill...............	27
	11. Altitude of water table at York Road landfill, November 1982	29
12-16.	Diagrams showing:	
	12. Water analysis for ground water and surface water at Harrisburg Road, Holbrooks Road, Statesville Road, and York Road landfills	40
	13. Summary of specific conductance data at Harrisburg Road, Holbrooks Road, Statesville Road, and York Road landfills	43
	14. Summary of chloride-concentration data at Harrisburg Road, Holbrooks Road, Statesville Road, and York Road landfills	46
	15. Summary of hardness data at Harrisburg Road, Holbrooks Road, Statesville Road, and York Road landfills	48
	16. Summary of manganese data at Harrisburg Road, Holbrooks Road, Statesville Road, and York Road landfills	51
17.	Map showing distribution of sites where water-quality indicators exceed background levels at Harrisburg Road landfill	57
18.	Map showing distribution of sites where water-quality indicators exceed background levels at Holbrooks Road landfill	59
19.	Graphs of specific conductance values and chloride concentrations at surface-water quality monitoring sites HRSW1 and HRSW2 at Holbrooks Road landfill	61

Page

20. Map showing distribution of sites where water-quality indicators exceed background levels at Statesville Road landfill 63
21. Graphs of specific conductance values and chloride and hardness concentrations at surface-water quality monitoring sites SRSW2, SRSW3, and SRSW11 at Statesville Road landfill 65
22. Map showing distribution of sites where water-quality indicators exceed background levels at York Road landfill 68
23. Graphs of annual average specific conductance values and concentrations of dissolved chloride, dissolved manganese, and total organic carbon at well YRW1, 1981-86, at York Road landfill 69
24. Graphs of specific conductance values and chloride and hardness concentrations at surface-water quality monitoring sites YRSW8, YRSW9 and YRSW9A at York Road landfill 71

TABLES

Page

Table 1. Water-quality analyses performed on ground- and surface-water samples 5
2. Specific conductance and pH of ground water at Statesville Road landfill 24
3. Description of ground-water monitoring wells 32
4. Description of surface-water quality monitoring sites 36

INCH-POUND TO INTERNATIONAL SYSTEM (SI) UNITS

The following factors may be used to convert inch-pound units published herein to metric (International System) units:

Multiply inch-pound unit	By	To obtain metric unit
Area		
acre	4047.0	square meter (m^2)
	0.4047	hectare (ha)
	0.004047	square kilometer (km^2)
square mile (mi^2)	2.590	square kilometer (km^2)
Length		
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Volume		
cubic inch (in^3)		milliliter (mL)
gallon (gal)	3.785	liter (L)
Flow		
cubic foot per second (ft^3/s)	28.32	liter per second (L/s)
	0.02817	cubic meter per second (m^3/s)
Temperature		
degree Fahrenheit (°F)	5/9 (°F-32)	degree Celsius (°C)
Hydraulic conductivity		
foot per day (ft/d)	0.3048	meter per day (m/d)

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Sea Level Datum of 1929."

HYDROLOGIC ENVIRONMENTS AND WATER-QUALITY CHARACTERISTICS AT FOUR LANDFILLS IN MECKLENBURG COUNTY, NORTH CAROLINA, 1980-86

By Alex P. Cardinell, Charles R. Barnes, W. Harold Eddins, and Ronald W. Coble

ABSTRACT

A water-quality study was conducted during 1980-86 at four landfills in Mecklenburg County, North Carolina. Each landfill has a three-layered hydrogeologic system typical of the Piedmont, consisting of (1) the regolith; (2) a transition zone; and (3) unweathered, fractured crystalline bedrock. As much as 7.6 inches per year of rainfall enters the ground-water system and has the potential to generate leachate within landfill cells. Ground water and leachate discharge to tributaries within the landfill sites or to streams adjacent to them.

Water-quality samples were collected from 53 monitoring wells and 20 surface-water sites. Samples were analyzed for selected physical and biological characteristics, major inorganic ions, nutrients, trace elements, and organic compounds. Selected indicators of water quality, including specific conductance; hardness; and concentrations of chloride, manganese, dissolved solids, total organic carbon, and specific organic compounds were analyzed to determine the effects of each landfill on ground- and surface-water quality.

Increases in concentrations of inorganic constituents above background levels were detected in ground water downgradient of the landfills. The increases were generally greatest in samples from wells in close proximity to the older landfill cells. In general, the increases in concentrations in downgradient wells were greater for calcium, magnesium, and chloride than for other major ions. Manganese exhibited the largest relative increase in concentration between upgradient and downgradient wells of any constituent, and manganese concentration data were effective in defining areas with extensive anaerobic biological activity.

Differences between upgradient and downgradient concentrations of total organic carbon and specific organic compounds generally were not as apparent. The most frequently identified organic contaminants were the herbicides 2,4-D and 2,4,5-T. Chlorofluoromethanes were identified in three of four ground-water samples analyzed for volatile organic compounds.

Landfills affected the water quality of several smaller streams but did not noticeably affect larger ones. Apparent effects on water quality were greatest at the oldest landfill, located on Statesville Road, where waste is in cells that are partly below the water table.

INTRODUCTION

Mecklenburg County is one of the most highly industrialized, rapidly growing areas in North Carolina. The county population was nearly 435,000 in 1985. Charlotte is the largest city in North Carolina and covers a large part of Mecklenburg County (fig. 1). Local officials are concerned about development-induced effects on the water quality of the area. In response to these concerns, the U.S. Geological Survey, in cooperation with the City of Charlotte and Mecklenburg County, began a 2-phase program in 1979 to evaluate the effects of urban development on the surface- and ground-water resources of the area.

Results of the first-phase reconnaissance study of surface-water quality in Mecklenburg County are described by Eddins and Crawford (1984). Results of that reconnaissance study indicate that a variety of both point and nonpoint sources affect the water quality of streams in the county and that runoff from nonpoint sources often appears to contribute more contaminants to streams than direct point-source effluents. The results also suggest that nonpoint seepage from landfills affects the water quality of streams draining those areas, especially during low flow when streamflow is derived primarily from ground-water discharge.

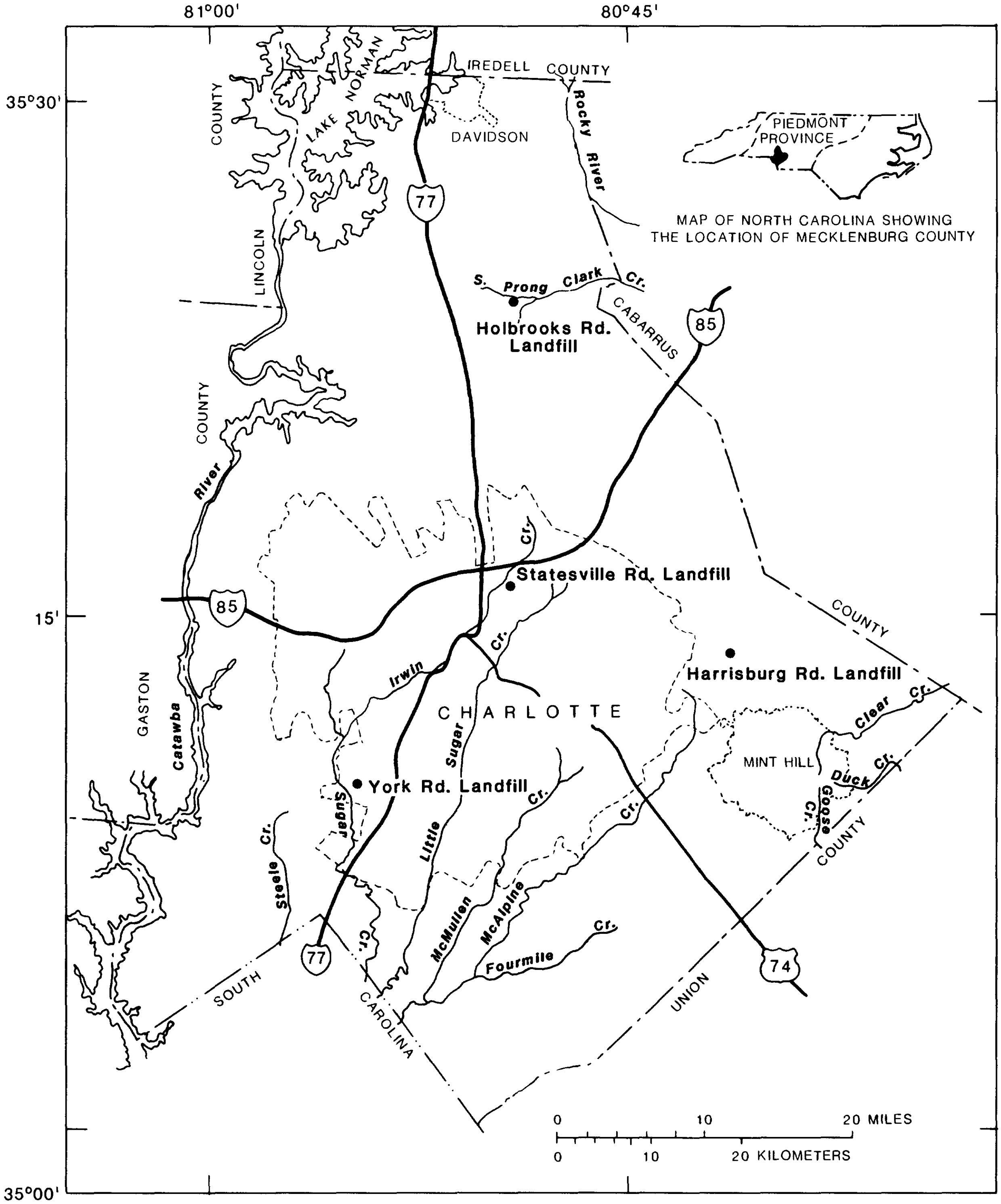

Figure 1.--Location of landfill study sites in Mecklenburg County.

As a consequence of the findings of Eddins and Crawford (1984) the second phase of the study specifically addressed water quality in the vicinity of county landfills.

Purpose and Scope

The purpose of this report is to describe the hydrologic environment at four landfills in Mecklenburg County and to summarize water-quality characteristics at each site in terms of selected constituents that may indicate the presence of leachate. The landfills included in this study are the Harrisburg Road, Holbrooks Road, Statesville Road, and York Road landfills (fig. 1).

Hydrologic data were collected at 53 observation wells and 20 surface-water sites, with emphasis on water-quality data. Ground- and surface-water samples were analyzed for 142 selected physical, chemical, and biological characteristics, including major inorganic ions, nutrients, trace elements, and organic compounds. A complete list of these constituents is given in table 1. Field measurements included specific conductance, alkalinity, temperature, and pH. Dissolved oxygen was measured in the field for surface-water samples.

The results of these analyses are summarized in diagrams and graphs in this report. The data are published in Eddins and Cardinell (1987).

Acknowledgments

Special appreciation is extended to Clarke D. Readling, City Engineer, City of Charlotte; Kenneth Hoffman, Director of Engineering, Mecklenburg County; and Dr. John M. Barry, Director, Mecklenburg County Environmental Health Department. All played key roles in planning and coordinating this study.

Table 1.--*Water-quality analyses performed on ground- and surface-water samples*

[+, analysis started in November 1985; *, priority pollutants (U.S. Environmental Protection Agency, 1976, 1984, 1986)]

Physical and biological characteristics	
Alkalinity	Fecal streptococci
Biological oxygen demand	Hardness
Chemical oxygen demand	pH
Color	Specific conductance
Dissolved oxygen	Temperature
Fecal coliform	Total dissolved solids

Major inorganic ions	
Bicarbonate	+Potassium
+Calcium	+Silica
Chloride	+Sodium
Fluoride	Sulfate
+Magnesium	

Nutrients
+Ammonia nitrogen (as N)
Nitrate
Phosphorus

Trace elements	
+Aluminum	*Lead
*Arsenic	Manganese
Barium	*Mercury
*Cadmium	*Selenium
*Chromium	*Silver
*Copper	*Zinc
Iron	

Base/neutral and acid extractable organic compounds	
*Acenaphthene	*Dibenzo(a,h)anthracene
*Acenaphthylene	*Diethyl phthalate
*Anthracene	*Dimethyl phthalate
*Benzidine	*Dinitromethylphenol
*Benzo(a)anthracene	*Fluoranthene
*Benzo(a)pyrene	*Fluorene
*Benzo(b)fluoranthene	*Hexachlorobenzene
*Benzo(g,h,i)perylene	*Hexachlorobutadiene
*Benzo(k)fluoranthene	*Hexachlorocyclopentadiene
*Butyl benzyl phthalate	*Hexachloroethane
Chloromethylphenol	*Indeno(1,2,3-c,d)pyrene
*Chrysene	*Isophorone
*Di-n-butyl phthalate	n-Nitrosodi-n-propylamine
*Di-n-octyl phthalate	*n-Nitrosodiphenylamine

Table 1.--*Water-quality analyses performed on ground- and surface-water samples*--Continued

[+, analysis started in November 1985; *, priority pollutants (U.S. Environmental Protection Agency, 1976, 1984, 1986)]

Base/neutral and acid extractable organic compounds--Continued	
*n-Nitrosodimethylamine	*2-Chlorophenol
*Naphthalene	*2-Ethylhexyl phthalate
*Nitrobenzene	*2-Nitrophenol
*Pentachlorophenol	*2,3,7,8-Tetrachloro dibenzo-p-dioxin
*Phenanthrene	*2,4-Dichlorophenol
*Phenol	*2-4-Dimethylphenol
*Pyrene	*2,4-Dinitrophenol
*1,2-Dichlorobenzene	*2-4-Dinitrotoluene
*1,2,4-Trichlorobenzene	*2,4,6-Trichlorophenol
*1,3-Dichlorobenzene	*2,6-Dinitrotoluene
*1,4-Dichlorobenzene	*3,3-Dichlorobenzidine
2-Chloroethyl methane	*4-Bromophenyl phenyl ether
*2-Chloroethyl vinyl ether	*4-Chlorophenyl phenyl ether
*2-Chloroisopropyl ether	*4-Nitrophenol
*2-Chloronaphthalene	

Pesticides	
*Aldrin	*Heptachlor epoxide
*Chlordane	*Lindane
*DDD	Methoxychlor
*DDE	Mirex
*DDT	Perthane
*Dieldrin	Silvex
*Endosulfan	*Toxaphene
*Endrin	2,4-D
*Gross PCB's	2,4-DP
Gross PCN's	2,4,5-T
*Heptachlor	

Volatile organic compounds	
*Benzene	*Trichloroethylene
*Bromoform (tribromomethane)	*Trichlorofluoromethane
*Carbon tetrachloride	*Vinyl chloride (chloroethane)
*Chlorobenzene	*1,1-Dichlorethylene
*Chlorodibromomethane	*1,1-Dichloroethane
*Chloroethane	*1,1,1-Trichloroethane
*Chloroform (trichloromethane)	*1,1,2-Trichloroethane
*Dichlorobromomethane	*1,1,2,2-Tetrochloroethane
*Dichlorodifluoromethane	*1,2-Dichloroethane
*Ethylbenzene	*1,2-Dichloropropane
*Methyl bromide	*1,3-Dichloropropane
*Methylene chloride	*1,2-trans-Dichloroethylene
*Tetrachloroethylene	*2-Chloroethyl vinyl ether
*Toluene	

Others who played key roles in the successful implementation and completion of this study are Tom Water, Keith O'Neal, John Gibson, and Jim Pascal with the Mecklenburg County Environmental Health Department; and Cary S. Saul, Ricky W. Gray, William S. Evans, Luther Bingham, and Eddie Allen with the Mecklenburg County Solid Waste Division.

Engineering and geotechnical studies of the Harrisburg Road, Statesville Road, and York Road sites were conducted for the City of Charlotte and Mecklenburg County by Law Engineering Testing Company of Charlotte. Several of the company's staff members were helpful during this investigation; Neil J. Gilbert and Jimmy N. Smith deserve special thanks.

Test-hole augering, split-spoon sampling, and observation-well construction were conducted at five sites at the Harrisburg Road and York Road landfill sites in November and December 1985 by Oscar Howard, Billy Casper, and Carl Jones of the drilling unit of the Groundwater Section of the North Carolina Department of Natural Resources and Community Development.

DESCRIPTION OF MECKLENBURG COUNTY

Precipitation

The Mecklenburg County area lies within a humid subtropical climate region. The temperatures in the study area are moderate, seldom dropping to 0 °F in the winter and occasionally rising above 100 °F in the summer. The coldest month is January (mean temperature 42 °F), and the warmest month is July (mean temperature 78 °F). The average annual precipitation in the study area is 45 in. (inches). Generally, the highest precipitation totals occur during the summer months, and the lowest totals occur during the autumn. Although rainfall is heaviest in the summer, evaporation and transpiration losses are also greatest during the summer, which coincides with the growing season in North Carolina. Consequently, there is a deficit of soil moisture, and little ground-water recharge occurs during summer months.

A water budget was developed for the Sugar Creek basin in southern Mecklenburg County for the period 1973-76 (C.C. Daniel, U.S. Geological Survey, written commun., 1986). This budget indicated that direct surface runoff to streams averaged 16.2 in., evapotranspiration accounted for 21.2 in., and recharge to the shallow ground-water system averaged 7.6 in. during the period.

Streams

The Catawba River and Rocky River systems, which drain Mecklenburg County, are separated by a broad dissected ridge which extends from Davidson to Mint Hill (fig. 1). The Catawba River and its tributaries, Steele, Sugar, Little Sugar, McAlpine, McMullen, and Fourmile Creeks, drain the western, central, and southern parts of the area. The Catawba River is dammed at several places to impound water to produce electric power. The Rocky River and its tributaries, Goose, Duck, and Clear Creeks, drain the northeastern and eastern corners of Mecklenburg County. Overall, there are more than 400 mi (miles) of streams in the county.

Topography

The topography of Mecklenburg County is that of a gently rolling Piedmont plain that slopes to the east and southeast. It consists of broad divides between incised streams. Most of the county lies between 600 and 700 ft (feet) above sea level. Relief is generally low, averaging less than 164 ft (Hack, 1982) with hills of greater relief being remnants of more erosion-resistant rocks. The present topography is, in part, related to erosion in response to ongoing, possibly periodic, uplift (Hack, 1982).

Hydrogeologic Setting

Mecklenburg County encompasses part of the Charlotte belt, which is one of several northeast-southwest oriented litho-tectonic belts in the North Carolina Piedmont (North Carolina Department of Natural Resources and Community Development, 1985). The basement rocks in the study area are composed of folded and fractured Precambrian- and Paleozoic-aged metamorphic and igneous rocks. These rocks may have undergone two or three regional metamorphic events and as many as four major deformation events from the Precambrian through the Paleozoic Period, as well as additional metamorphic events during the Early Mesozoic Period. More detailed discussions of recent hypotheses for these events can be found elsewhere (Gilbert and others, 1982; Goldsmith and others, 1982; Hack, 1982; Ragland and others, 1983; Farrar, 1985; Pavish, 1985; Russell and others, 1985; Wehr and Grove, 1985).

The near-surface geology consists of a 3-stage system that includes: (1) the surficial (or shallow) regolith, (2) an intermediate transition zone, and (3) the underlying fractured crystalline bedrock (fig. 2). The regolith consists of an unconsolidated or semiconsolidated mixture of clay and fragmental material ranging in size from silt and sand to boulders. Components of the regolith include saprolite and alluvium and the soil in the uppermost part of both the saprolite and alluvium. Saprolite is the dominant regolith material and is the unconsolidated product of in-place weathering of parent bedrock. Some of the textural features of bedrock are retained within the saprolite, and boulders of unweathered bedrock are often found within the saprolite. Alluvium deposits are unconsolidated sediments deposited by streams and rivers and are restricted to valleys. Soils in the study area are generally of the Ultisol order and have formed largely from saprolite (Daniels and others, 1984). Ultisols are characteristically very acid, highly weathered, and leached with subsoils of clay accumulation.

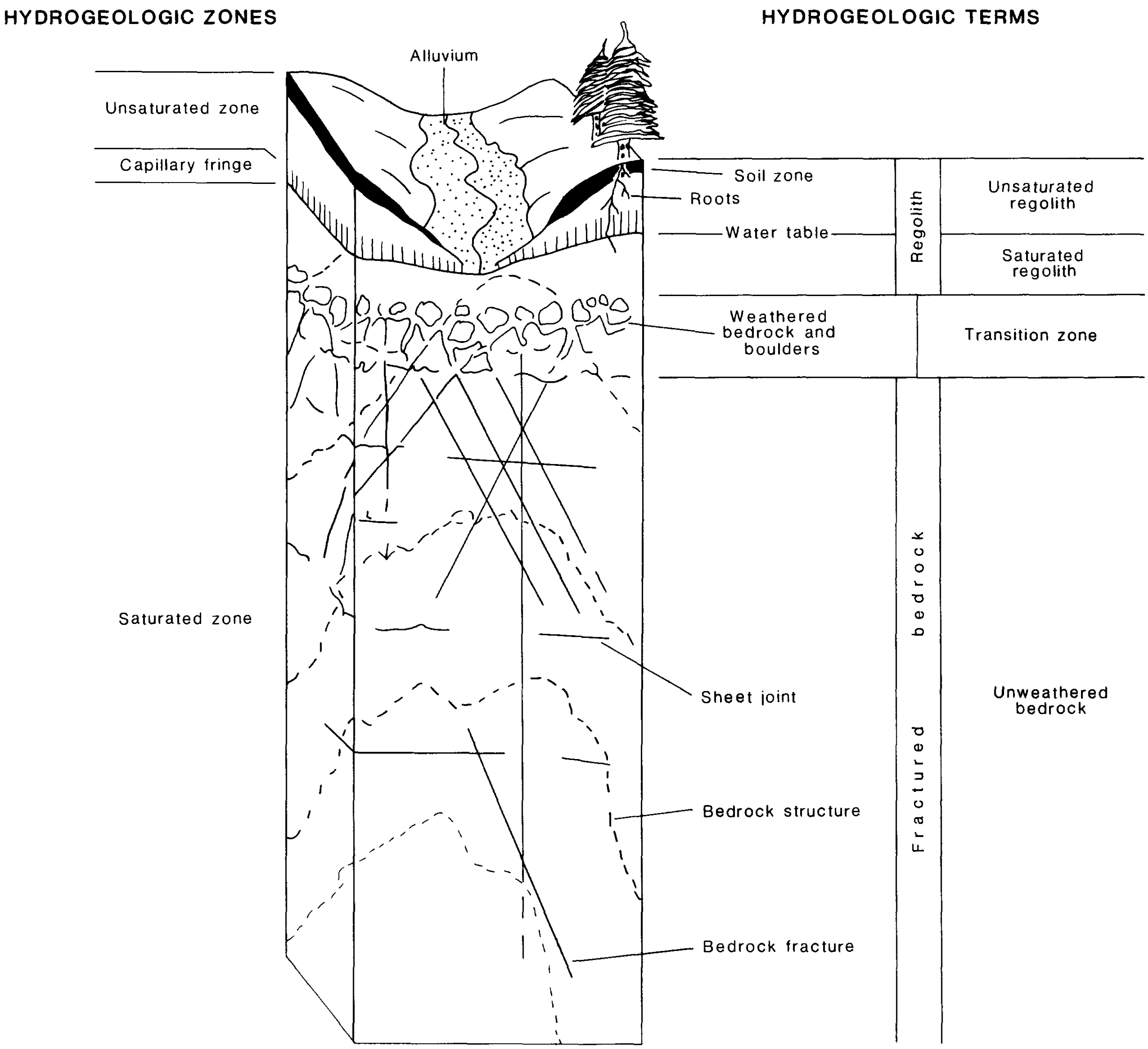

Figure 2.--The conceptual structure of the Piedmont hydrogeologic framework.

The permeability in the regolith is related to the degree of weathering (fig. 3). Heath (1980) indicates that saprolite, because of its anisotropic nature, has hydraulic conductivities in the range of 1 to 20 ft/d (feet per day). Alluvium, which usually contains considerable amounts of silt and sand, has hydraulic conductivities generally ranging from 1 to 100 ft/d.

Between the regolith and the fractured crystalline bedrock is a transition zone consisting of saprolite and partially-weathered bedrock where unconsolidated material grades into bedrock. Mechanical weathering has progressed only to a stage of minute fracturing of rock fabric, but the rock and rock minerals have not chemically weathered to clays. The thickness of this zone depends significantly on the texture and composition of the parent rock. The best defined transitional zones are usually associated with highly foliated metamorphic parent rock; whereas, those of massive igneous rocks are often poorly defined or nonexistent (C.C. Daniel, U.S. Geological Survey, oral commun., 1985). The transition zone has the highest permeability within the saprolite due to the less advanced chemical weathering (Stewart, 1962; Nutter and Otton, 1969). The higher permeability of the transition zone at the top of the bedrock results in a region of higher hydraulic conductivity within the ground-water flow system, and a large proportion of the ground-water moving through the system moves through the transition zone.

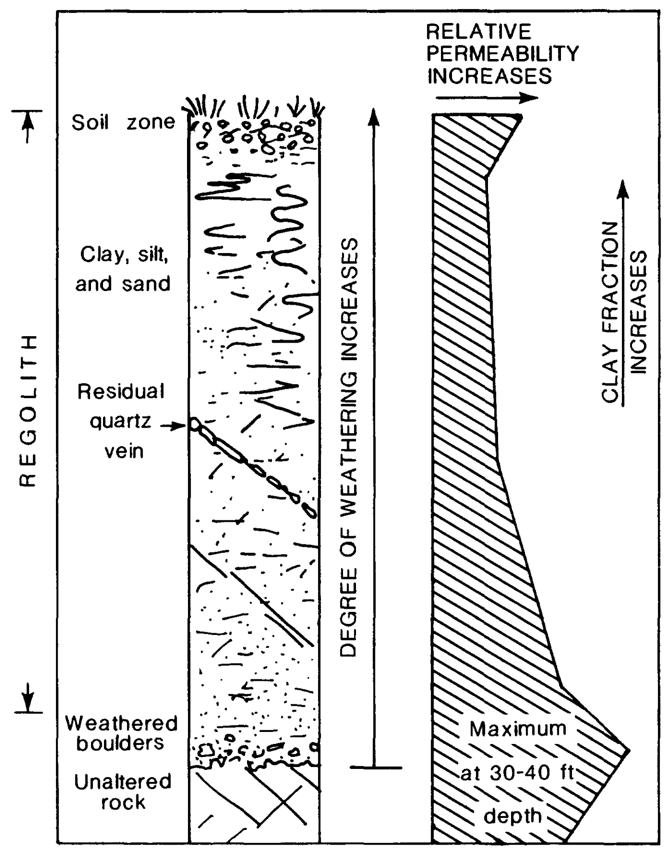

Figure 3.--An idealized weathering profile through the regolith, showing relative permeability (after Nutter and Otton, 1969).

Below the transition zone is the uppermost part of the Piedmont crystalline bedrock, which contains numerous closely-spaced stress-relief fractures formed in response to removal of overlying material. As a general rule, few of these fractures occur at depths greater than 400 ft (LeGrand, 1967). The bedrock in the Piedmont has relatively low porosity, 0.1 to 1.0 percent, although large, localized differences may occur due to fracturing. The hydraulic conductivity of the bedrock zone is generally 1 to 20 ft/d, reflecting the anisotropic nature of the fracture patterns.

Depth to the bedrock surface has been determined indirectly at study sites to range from 5 to 92 ft below land surface. The generally accepted procedure is to estimate the depth of bedrock to be at the depth of auger refusal, which is the point at which the earth materials are so dense or hard that auger-boring machines equipped with steel bits are unable to penetrate any deeper. At one site in the York Road landfill, an auger test hole was constructed adjacent to a deep water well. Data from a borehole geophysical log of the water well indicated that bedrock was within 1 ft of the depth of auger refusal in the test hole, thus giving additional confidence in using depth of auger refusal as an estimate of bedrock depth. However, caution needs to be exercised in making bedrock-depth estimates this way because boulders of resistant rock lying within the saprolite and pinnacles of bedrock protruding upward into the saprolite will also result in auger refusal, indicating the position of the bedrock surface to be above the actual bedrock surface.

Generally, three hydrogeologic zones are present in the regolith--an unsaturated zone, a capillary fringe, and a saturated zone. The unsaturated zone extends from the ground surface to the capillary fringe and usually ranges from 5 to 50 ft in thickness. In this zone, the intergranular pores are only partially filled with water. Water infiltrates down through this zone primarily by intergranular, gravity-driven flow through macropores and through passages left by burrows or decayed roots.

The capillary fringe is a narrow zone at the top of the saturated zone and is located immediately above the water table. Within this fringe, moisture is raised above the water table by capillary action alone; the small capillary-sized pores are full of water which is at a pressure head that is less than atmospheric pressure. Freeze and Cherry (1979, p. 44) use the more descriptive term, "tension-saturated zone," for the capillary fringe. The capillary fringe may range in thickness from a fraction of an inch to as much as 3 ft, and its depth fluctuates with changes in the water table.

At the base of the capillary fringe is the water table, a surface within the saturated zone where the ground water is at atmospheric pressure. Water levels in wells drilled a few feet into the saturated zone are at the same level as the water table in the adjacent regolith.

The saturated zone within the regolith provides the bulk of water storage within the Piedmont ground-water system. Drainable porosity values in this zone, which is composed primarily of saprolite, range from about 20 to 30 percent. Once water has reached the saturated zone below the water table, it flows in laminar fashion through intergranular pore spaces with limited mixing. The general direction of flow is toward discharge areas, which are the perennial streams; however, local flow may be affected by the anisotropy of the remnant bedrock textural features within the saprolite.

Although the water table is generally within the regolith, it is not unusual to find that the unsaturated zone extends into the bedrock. This situation most commonly occurs beneath relatively high bluffs in major stream valleys where the bedrock is close to the surface. This occurs at several locations in Mecklenburg County, including the area near the York Road landfill.

LANDFILL HYDROLOGIC ENVIRONMENTS

Current solid-waste disposal in Mecklenburg County is by sanitary landfilling. Brunner and Keller (1972) describe sanitary landfilling as an engineering method of disposing of solid waste on land by spreading, compacting to the smallest practical volume, and covering with soil each operating day in a manner designed to protect the environment. In modern sanitary landfills in the Piedmont, refuse is buried in the unsaturated zone, generally the saprolite of the regolith zone. Ideally, the bases of the refuse cells are at least 4 ft above the highest position of the water table. When a disposal area is discontinued, a final 2-foot soil cover is added. The final cover is constructed to maximize surface runoff and minimize infiltration.

Solid-waste disposal sites in operation before modern sanitary landfill design standards were instituted were commonly characterized by open burning and the lack of a soil covering. In addition, some solid wastes were occasionally buried in areas that were below the water table much of the time, leading to almost certain water-pollution problems.

The four landfills of this study were selected because of local concerns about potential effects of these landfills on local water quality. Three of the sites are sanitary landfills that were in operation throughout most of the study. Two of these, Harrisburg Road and York Road landfills, are relatively large (several hundred acres); the third, Holbrooks Road landfill, is smaller. The fourth site, Statesville Road landfill, is older than the other sites and was operated at one time as an open, burning dump. This dump was subsequently covered with soil.

This section describes the physical and hydrologic environment of each landfill and presents a brief history of excavation and fill. A later section reviews in detail the ground- and surface-water quality at each of these sites and discusses findings relative to leachate migration.

Harrisburg Road Landfill

The Harrisburg Road sanitary landfill (fig. 4) covers approximately 305 acres and is located in eastern Mecklenburg County about one mile east of the Charlotte city limits. The Harrisburg Road landfill is the most recently developed of the four study landfills and the only one still active (1987), receiving mixed (residential, commercial, and industrial) solid waste. The general surface-water drainage at this landfill is to the north.

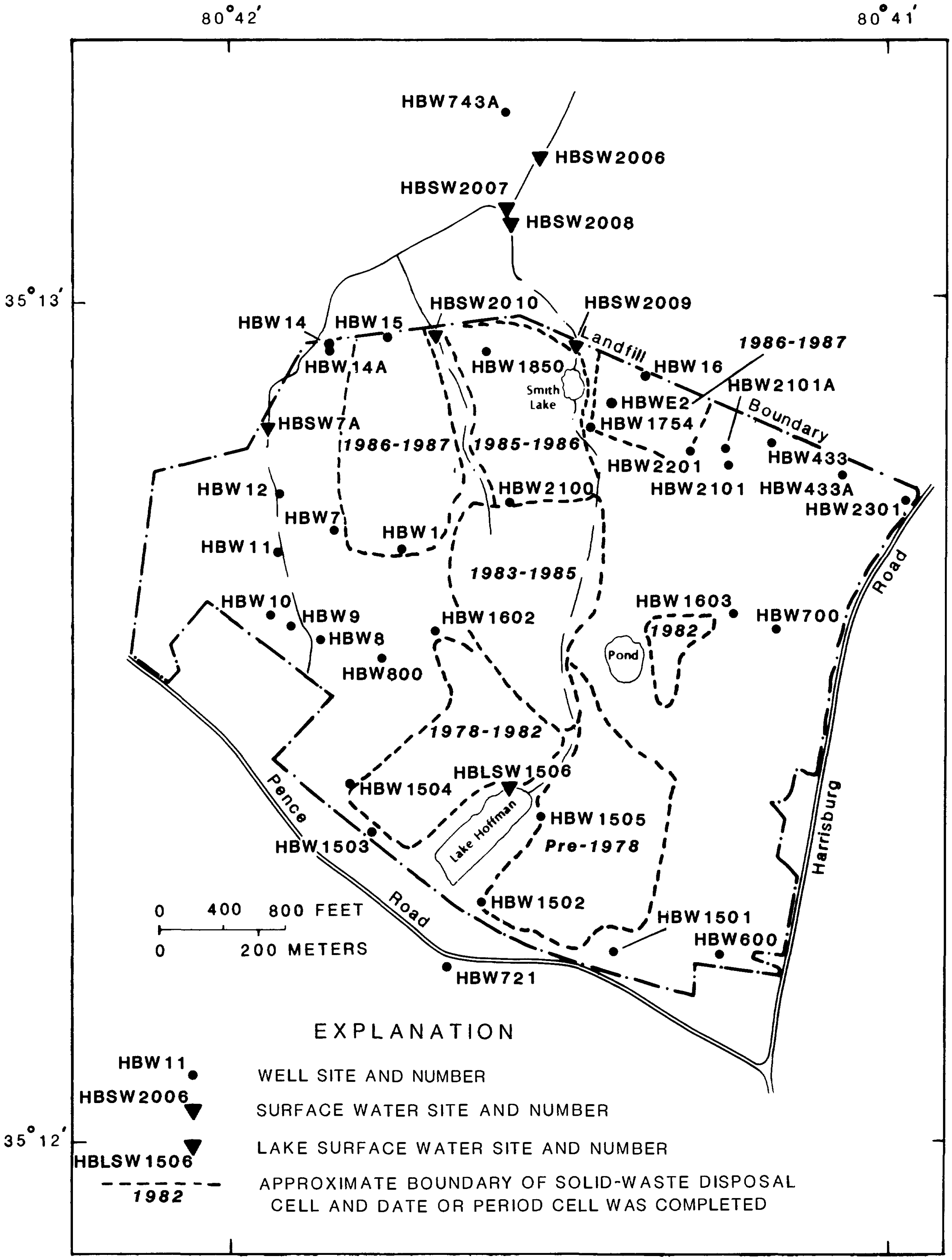

Figure 4.--Location of monitoring wells, surface-water monitoring sites, and solid-waste disposal cells at or near Harrisburg Road landfill.

Three small streams drain the landfill. The stream on the east, which drains Lake Hoffman and Smith Lake, and the one on the west edge of the landfill have perennial flow throughout most of their length. The short stream upstream from site HBSW2010 is intermittent. Topographic relief is 100 ft from an altitude of 780 ft above sea level along the southwestern edge and northeastern corner of the landfill to an altitude of 680 ft where streams draining the site flow across the northern boundary.

Landfilling at Harrisburg Road started in 1973 on its southern border, southeast of Lake Hoffman, and has progressed in a generally northern direction, with current (1987) activity centered in the northeastern corner. The landfill is unlined, and excavation and fill techniques are used, with disposal of solid wastes above the water table. A 6-inch soil cover is applied to fresh waste daily. As a result of the continued development of the landfill, several of the monitoring wells initially used for water-quality sampling were destroyed as new landfill cells were created. Where landfill activities have been completed, a 2-foot final cover has been added, and on one 100-acre completed segment, a 9-hole golf course is currently under construction.

Bedrock has been reached at only a few test sites in the landfill. Drillers' logs of some of the wells constructed along the southwestern edge of the landfill indicate bedrock at depths of 90 to 100 ft, or at an altitude of 680 to 690 ft. Attempts to construct an observation and monitoring well just east of the present well, HBW7, were unsuccessful because of rock at a depth of 12 ft (approximate altitude, 732 ft). This rock may be large boulders or pinnacles of bedrock extending into the general body of saprolite and may not be representative of the general bedrock position in this area. Auger and split-spoon samples collected near well HBW2201 show bedrock at a depth of 84 ft (altitude 656 ft), and new well HBW2301 bedrock occurs at a depth greater than 109 ft (below altitude 669 ft).

Bedrock beneath the landfill is metamorphosed diorite, quartz diorite, and tonalite (Goldsmith and others, 1982). Split-spoon samples collected to bedrock on the northeastern part of the landfill during an engineering study consist predominantly of silty clays and sandy-silty clays which reflect the high level of in-place chemical weathering that has occurred here.

The altitude of the water table during March 1986 is shown on figure 5. Ground water throughout the landfill discharges either into one of the streams traversing the site or moves northward discharging to the main stream. The water-table configuration indicates that ground water within the landfill boundaries does not move southward across Pence Road or eastward across Harrisburg Road.

The thickness of the unsaturated zone, as determined by the depth of the water-table, ranges from 30 to 40 ft along the southwestern edge of the site to 5 to 12 ft near the streams. The water table is within the saprolite throughout the landfill as evidenced by ground-water level and bedrock-depth data. The upper part of the saprolite is in the unsaturated zone, and the lower saprolite, transition zone, and bedrock are in the saturated zone. A possible exception is just east of well HBW7 where bedrock is 12 ft below the land surface and lies in the unsaturated zone.

Holbrooks Road Landfill

The Holbrooks Road sanitary landfill (fig. 6), which opened in 1968 and closed in 1986, is in north-central Mecklenburg County approximately 5 mi north of the Charlotte city limit. The landfill covers 65 acres within the Clark Creek basin. The landfill comprises about 5.5 percent of the watershed upstream from surface-water sampling site HRSW1 on the South Prong of Clark Creek.

The landfill is near the eastern end of a long ridge that parallels the South Prong of Clark Creek. Holbrooks Road, which forms the southwest border of the landfill, lies at an altitude of around 755 ft; the land surface altitude adjacent to the South Prong of Clark Creek along the

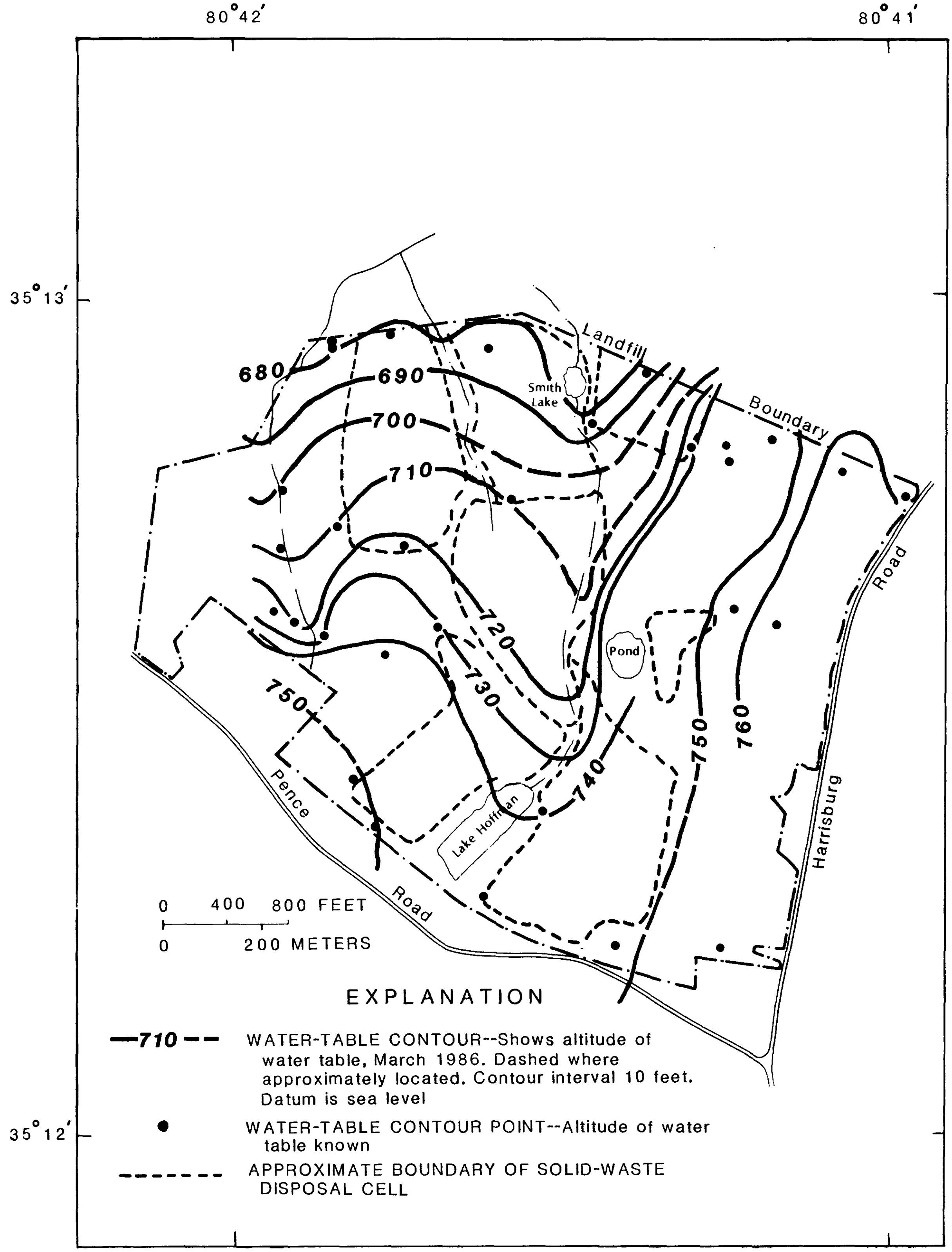

Figure 5.--Altitude of water table at Harrisburg Road landfill, March 1986.

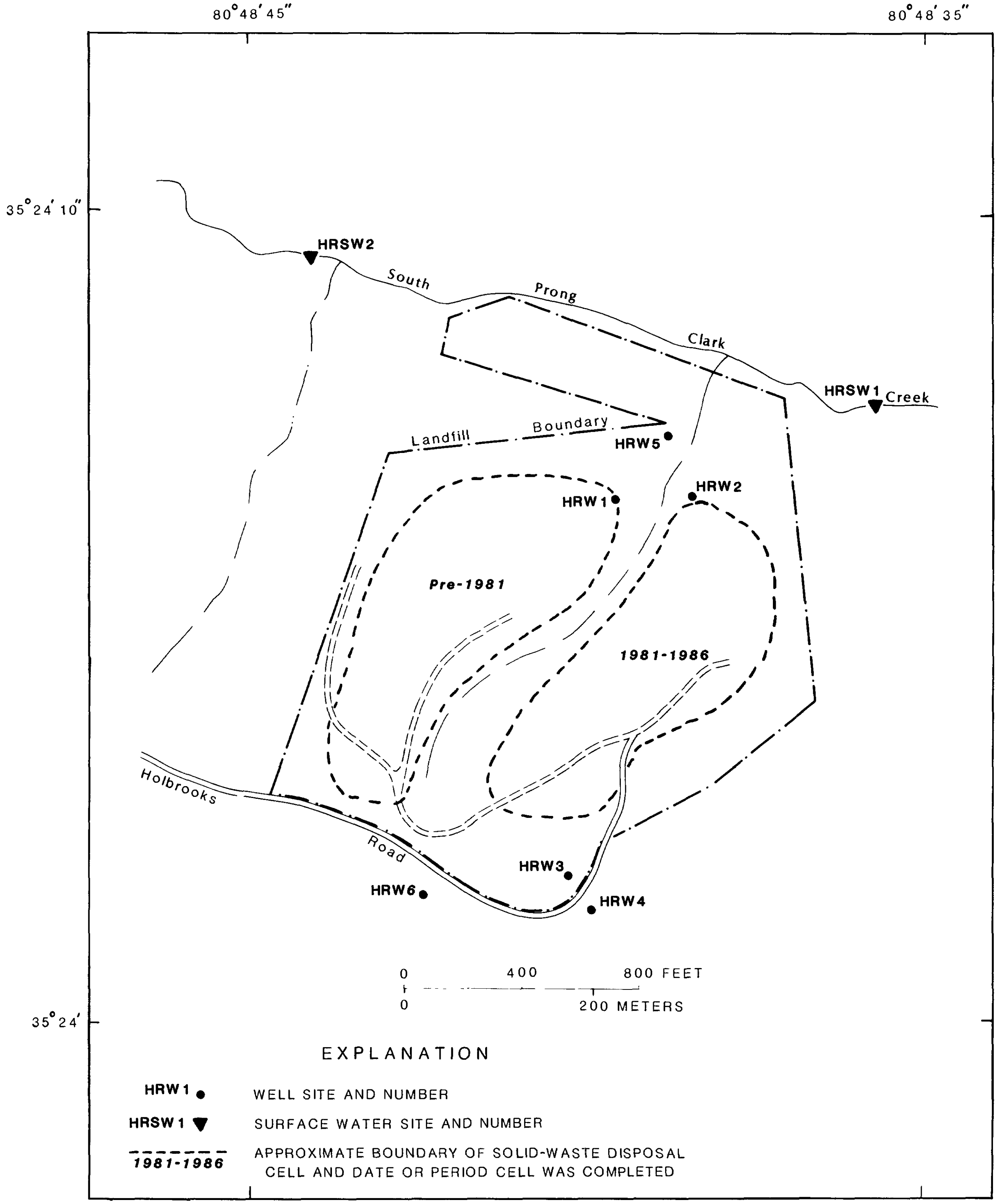

Figure 6.--Location of monitoring wells, surface-water monitoring sites, and solid-waste disposal cells at or near Holbrooks Road landfill.

northeast border is about 660 ft. A small area along the western side is nearly 780 ft above sea level. The site is bisected by a short draw which carries water only during extreme rainfall events; its channel lies from 50 to 70 ft below ridges on each side of it. A natural-gas pipeline is buried beneath this draw.

There are two landfill cells at the Holbrooks Road landfill, one on each side of the intermittent stream cutting through the landfill. The western landfill cell is the older disposal area. Excavation and fill techniques were used for disposal of mixed solid wastes above the water table, and a 6-inch soil cover was applied over each day's waste. The Holbrooks Road landfill was not lined with an impermeable layer. A 2-foot final cover of sandy-clay loam was placed over each landfill cell to inhibit infiltration of rainfall. Parts of this landfill are currently being used for a model-airplane recreational area.

No test-hole data were available concerning the depth to bedrock or bedrock lithology within the landfill cells, and outcrops of bedrock were observed at the landfill. However, the driller's log for well HRW3, which was constructed as a supply well for the landfill office, lists bedrock at a depth of 55 ft, or an altitude of about 680 ft. The driller described this material as gray and dark gray rock. Metamorphosed quartz diorite, diorite, and tonalite, which are locally porphyritic, underlie this area (Goldsmith and others, 1982). These rocks are similar to those at the other landfill sites.

The saprolite at the Holbrooks Road site contains granular quartz in a tan clay and silt matrix; this saprolite is different from the red and reddish brown sandy, silty clay saprolite commonly found throughout most of Mecklenburg County. The saprolite at the Holbrooks Road site may be derived from porphyritic quartz diorite or possible granitic material. The granular saprolite probably has a higher hydraulic conductivity than the more common red clay saprolite.

Periodic water-level measurements were made only in observation wells HRW1, HRW2, and HRW5 because the other wells are water-supply wells and were unaccessible for water-level measurements. The observation wells are all located in one small area; therefore, construction of a water-table map was not possible from these data. Measurements made in April and July 1987 indicate the water table ranged from 6.62 to 5.73 ft below land surface at these three wells.

Statesville Road Landfill

The Statesville Road landfill (fig. 7) is located in central Mecklenburg County in the northern part of Charlotte. This 140-acre disposal area, which opened in 1940 and closed in 1970, is the oldest of the four study sites. This site is located within the Irwin Creek basin, and this perennial stream cuts through the middle of the landfill. One refuse cell is located on each side of Irwin Creek. The drainage area upstream from gaging station SRSW11 is 5.97 mi^2 (square miles). Maximum topographic relief is nearly 100 ft (660- to 759-foot altitude) in the southeastern refuse area and 70 ft (660 to 730 ft) in the northwestern area. Land-surface slopes along Irwin Creek are relatively steep (20-percent slope).

The hydrologic setting at this landfill is believed to be similar to that of the other three study landfills; however, little is known about the depth to bedrock or thickness of the saprolite at this site. During a 1980 engineering study (Law Engineering Testing Company, 1980), partially-weathered rock or dense silty sand that could indicate nearness to the top of bedrock was found in borings B-9, B-11, and B-12 at depths of 15.0, 34.5, and 55.0 ft, respectively (fig. 8). This material lies at altitudes ranging from 668 to 675 ft, similar to that of the Irwin Creek channel in this area.

Throughout the major part of the Statesville Road landfill, refuse is buried in the saturated zone (fig. 8), hence the potential for ground-water contamination is great. Water samples from several borings, wells, and test pits constructed during the 1980 study were analyzed for specific conductance by the Mecklenburg County Department of Environmental Health and

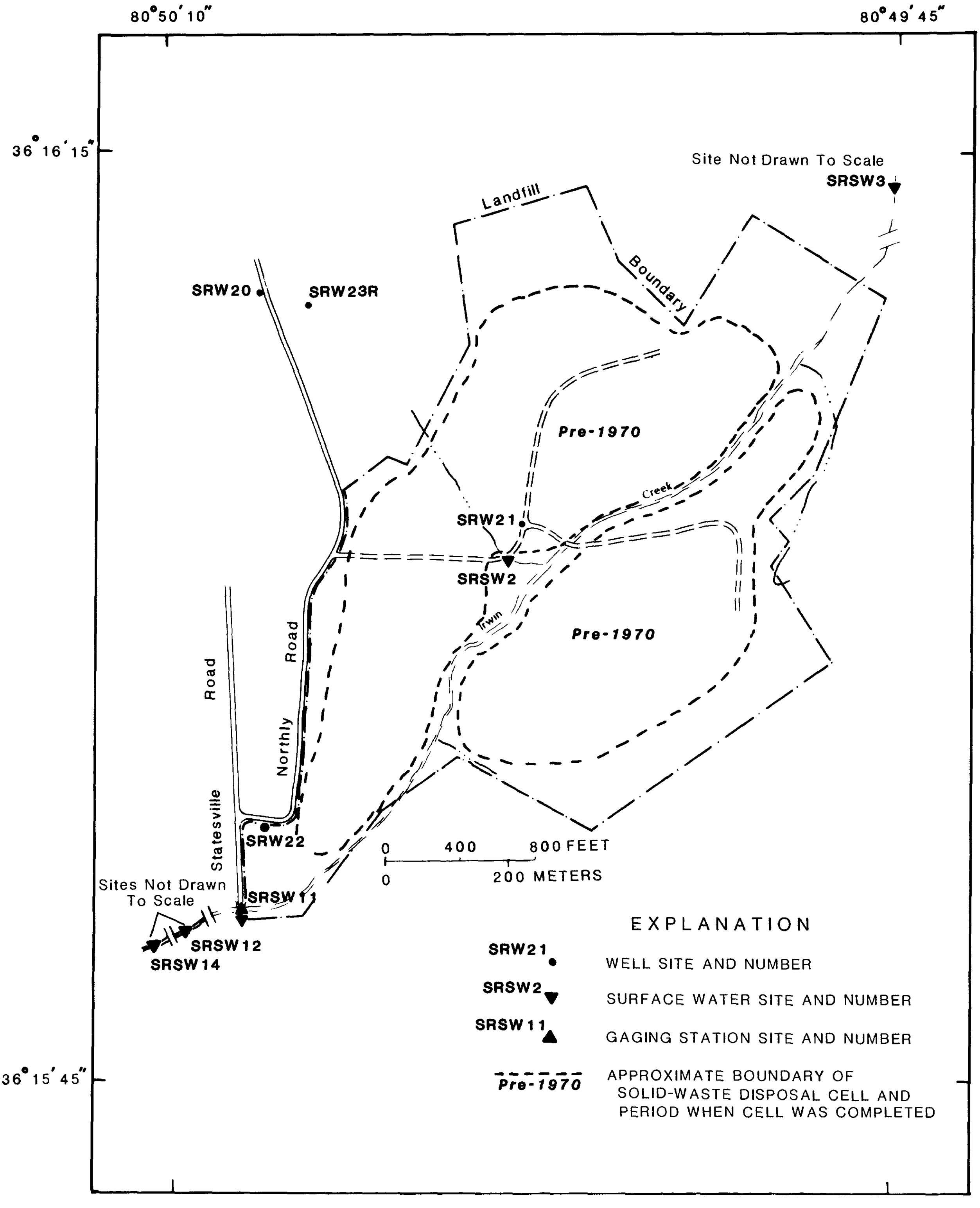

Figure 7.--Location of monitoring wells, surface-water monitoring sites, gaging station, and solid-waste disposal cells at or near Statesville Road landfill.

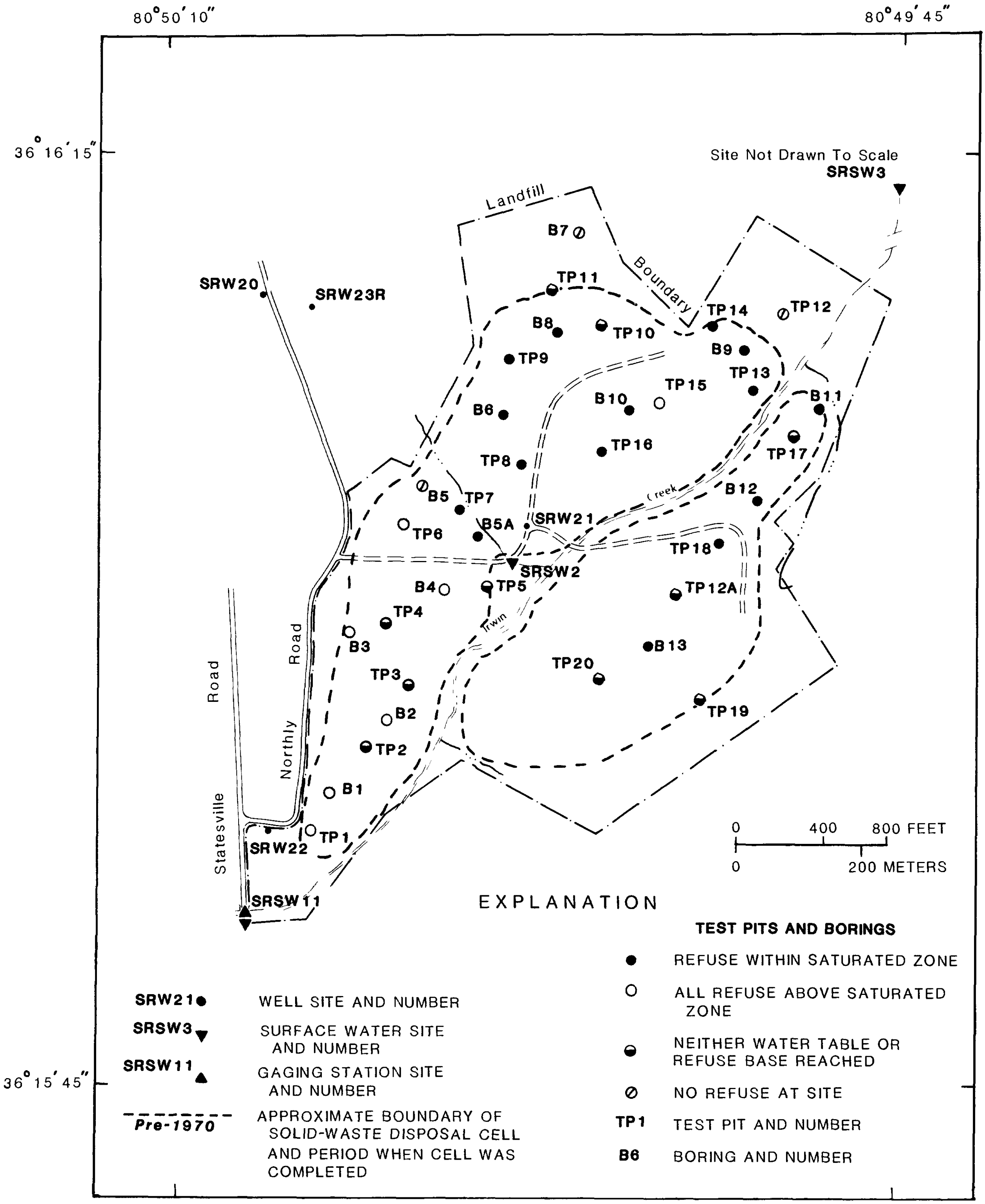

Figure 8.--Location of borings and test pits and position of refuse with respect to the saturated zone at Statesville Road landfill, 1980.

pH by the U.S. Geological Survey. Specific conductance values ranged from 1,000 to 8,000 µS/cm (microsiemens per centimeter at 25 °C) (table 2). These values are substantially higher than those measured at surface-water sites (600-800 µS/cm) within and immediately downstream of the landfill during low-flow periods (Eddins and Crawford, 1984).

Table 2.--*Specific conductance and pH of ground water at Statesville Road landfill*

[µS/cm, specific conductance in microsiemens per centimeter at 25 °C]

Site number	Depth (feet)	Date sampled	Specific conductance[1] (µS/cm)	pH[2] (standard units)
		Borings and wells		
Boring B-2	55.0	6-19-80	4,600	7.6
Boring B-8	35	6-19-80	4,000	6
Well B-8	25	2- 4-81	4,900	6.5
Boring B-12	55	6-19-80	7,100	6.5
Well B-12	29	2- 4-81	8,000	7
Boring B-13	70	6-19-80	4,200	7.2
Well B-13	45.2	2- 4-81	8,000	8.3
		Test pit		
TP-7	14	6-20-80	3,000	6.9
TP-8	13	6-20-80	1,500	6.4
TP-14	15	6-20-80	1,000	6.3
TP-18	19	6-20-80	3,400	6.9

[1]Measured by Mecklenburg County Department of Environmental Health.
[2]Measured by U.S. Geological Survey.

Ground-water level data collected in 1980 from borings, wells, and test pits and surface altitude data of Irwin Creek and small tributaries show the water table at the Statesville Road site slopes generally from both sides of the landfill toward Irwin Creek and to a lesser extent toward the small tributaries within and along the borders of the landfill (fig. 9). These ground-water levels indicate that reaches of these streams within the landfill are ground-water discharge areas, and the streams may receive landfill leachate.

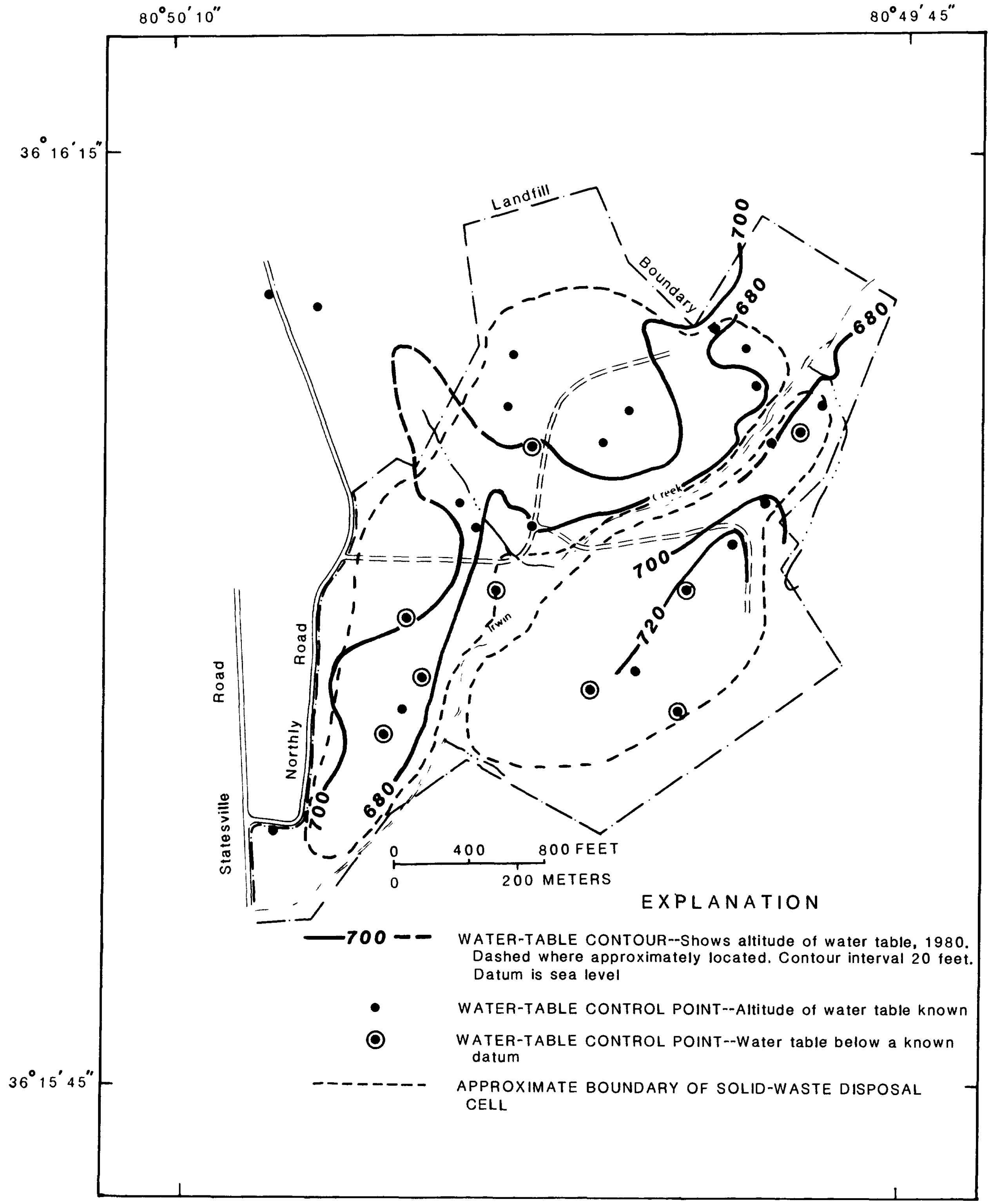

Figure 9.--Altitude of water table at Statesville Road landfill, 1980.

York Road Landfill

The York Road sanitary landfill is located in the Sugar Creek basin in southwestern Mecklenburg County (fig. 1). This 375-acre site, the largest of the study sites, was opened in 1968 and closed in 1986. An unnamed perennial stream in the southeastern part of the landfill collects most of the runoff from this landfill (fig. 10). The stream enters Sugar Creek about 600 ft below site YRSW9 and has a total drainage area of 1.02 mi^2. Another small perennial tributary to Sugar Creek drains the northwestern part of the landfill.

Maximum topographic relief is 112 ft, from about 692 ft above sea level near well YRWB12A in the northeastern corner to a little less than 580 ft above sea level along Sugar Creek. Remnants of the undissected Piedmont plain are represented by relatively flat upland with land-surface altitudes ranging between 660 and 690 ft. These upland areas include a ridge extending from just south of well YRWA to well YRWB12A, isolated areas around wells YRWB16 and YRWB20, and areas along York Road at the southeastern edge of the landfill.

Landfill operations in the unlined York Road landfill began in the southern part of the area and progressed to the north (fig. 10). A combination of excavation and fill- and ramp-disposal techniques was used for disposal of mixed (residential, commercial, and industrial) solid wastes in the unsaturated zone. A 6-inch soil cover was applied to fresh refuse daily. A 2-foot final cover has been added, and a recreational area, including softball fields and an 18-hole golf course, is currently (1987) being constructed on parts of this landfill.

An engineering study conducted by Law Engineering Testing Company (1982) showed that bedrock depth throughout the northern part of the landfill and north of the landfill ranges from 17 ft to more than 63 ft below land surface as estimated from the depths of auger refusal or failure to bore deep enough to reach refusal at borings YRWB1 through YRWB23 (fig. 10). Bedrock was determined to be at a depth of 68 ft at well YRWA by means

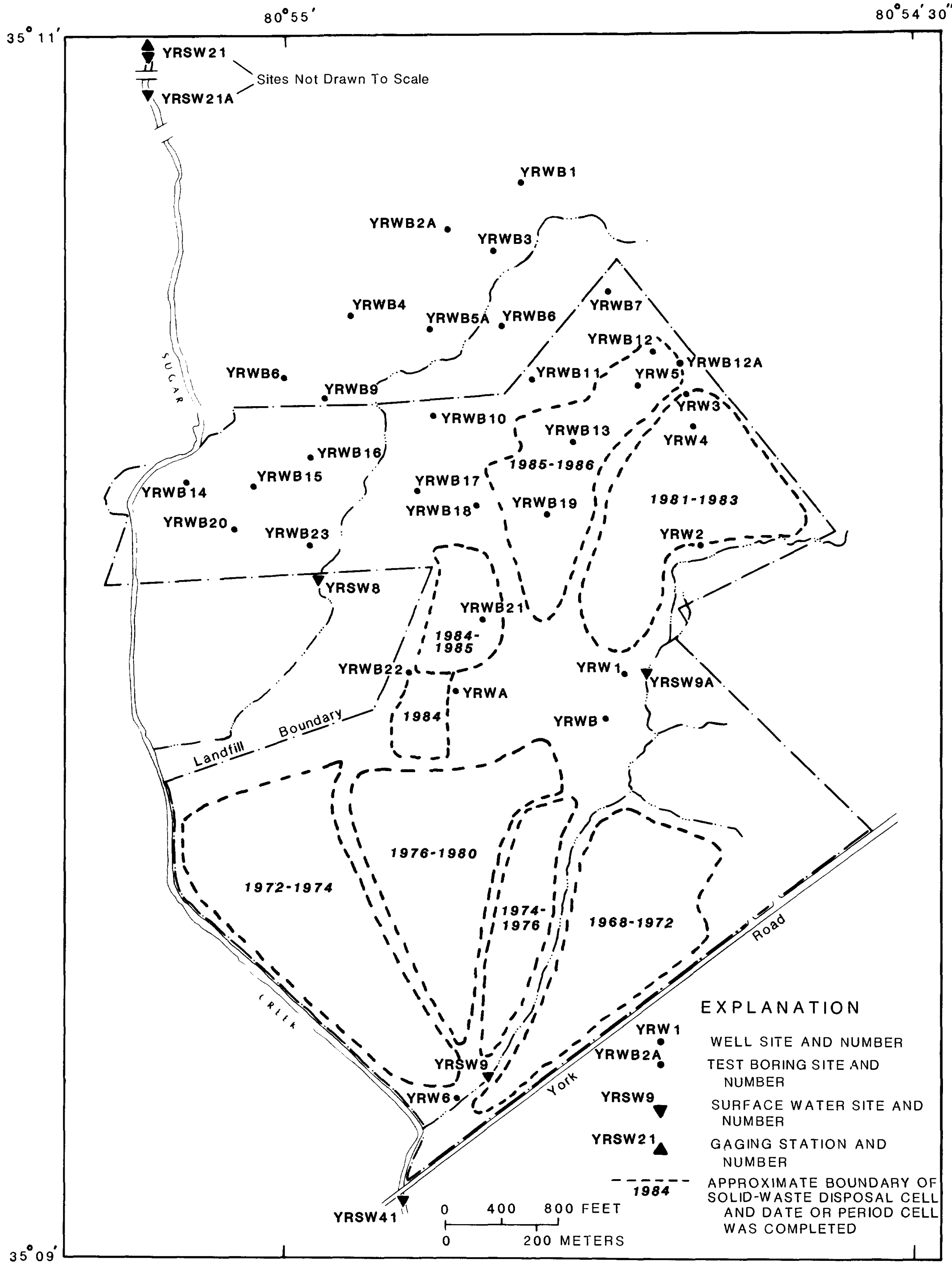

Figure 10.--Location of monitoring wells, surface-water monitoring sites, gaging station, and solid-waste disposal cells at York Road landfill.

of a neutron-density borehole geophysical log run by the U.S. Geological Survey. Auger refusal was at 69 ft in a test boring adjacent to well YRWA showing that, in this instance, depth of auger refusal is a good indication of depth to bedrock. Generally the altitude of the bedrock surface is higher in the eastern and northeastern parts of the landfill site than in the southern and western parts.

The predominant bedrock underlying the landfill has been mapped by Goldsmith and others (1982) as metamorphosed quartz diorite, diorite, and tonalite, which are locally porphyritic. Split-spoon samples collected near wells YRWA and YRWB in 1985 indicate a high degree of chemical weathering of the bedrock underlying the site. The majority of the saprolite samples collected there are silty clay to sandy and silty clays and silty sands. Samples collected near the points of auger refusal during the 1982 engineering study were partially-weathered rock, micaceous sand, or stiff micaceous, sandy, clayey silt.

The altitude of the water table in November 1982 is shown on figure 11. Water-level measurements for the northern two-thirds of the map area were made from piezometers installed during the engineering study. No data were available for the southern part of the area during 1982, and water-table altitudes were estimated for that area from measurements made in wells YRW1, YRW2, and YRW3 in April 1984 and in well YRW6 in 1986. Water levels in nine wells and piezometers measured in November 1982 generally were less than 4 ft lower than in April 1984. Measurements were made in well YRW6 soon after it was constructed in 1986; water levels in this well fluctuated less than 7 ft throughout 1986 and 1987. Thus, estimates of 1982 water levels in the southern area based on 1984 and 1986 data are considered reasonable.

The configuration of water-table contours in figure 11 indicates that ground-water movement generally is to the west and southwest. Most of the ground-water discharges from the landfill area are to the two tributary streams with the remainder discharging into Sugar Creek.

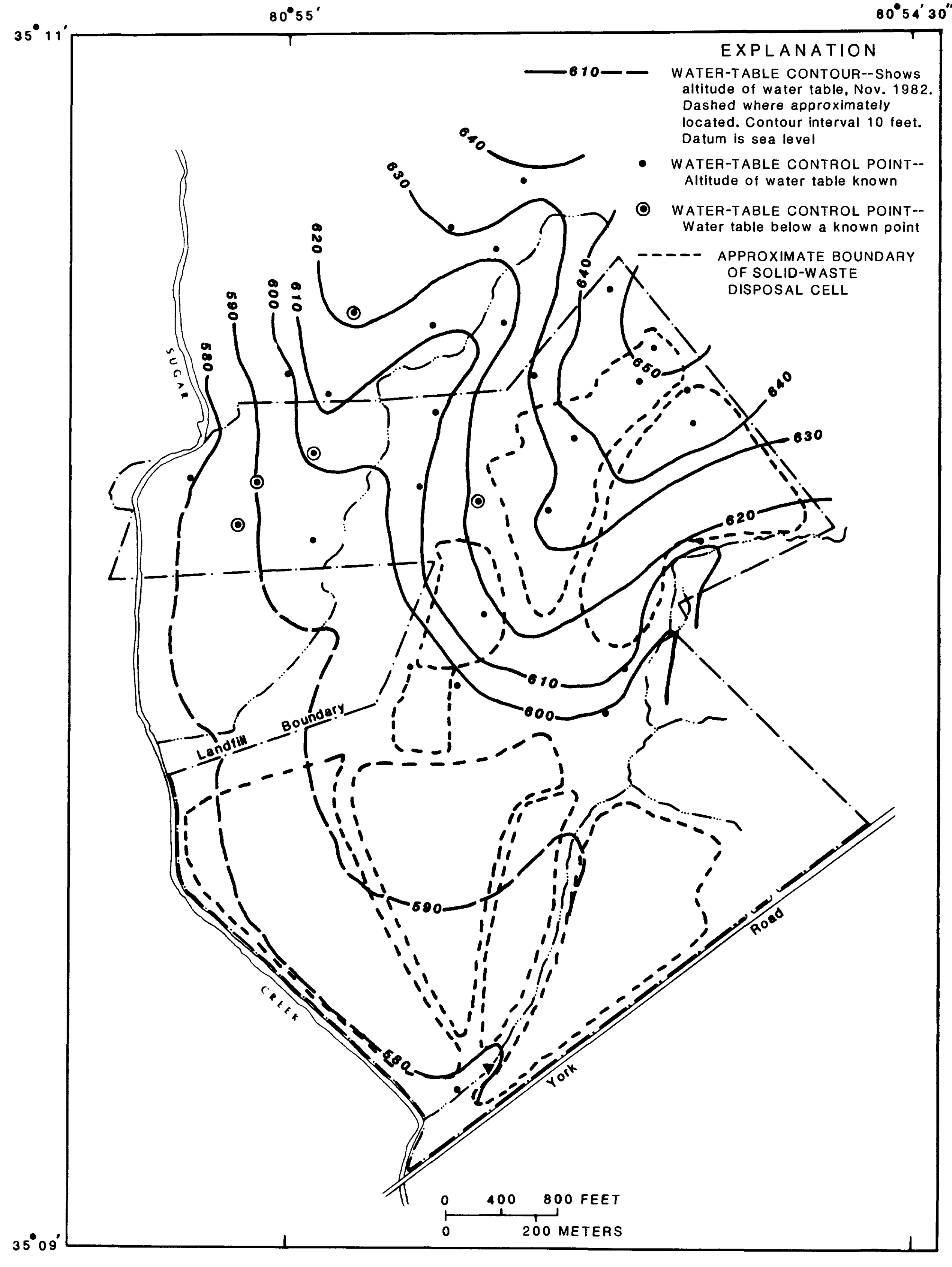

Figure 11.--Altitude of water table at York Road landfill, November 1982.

Measured water-table depths range from 2 ft near the streams draining the site to 52 ft beneath the upland area in the northeastern part of the landfill. The water table is within the saprolite throughout most of the site. However, it is within the bedrock in several areas where uplands are near the streams. At well YRWA on an upland ridge, bedrock is 68 ft below land surface, and the water table is 92 ft below land surface, indicating that 24 ft of the upper part of the bedrock was in the unsaturated zone. In several test borings, auger refusal occurred before the water table was reached. This situation was found at eight wells: YRWB4, YRWB15 through YRWB18, and YRWB20 through YRWB22.

COLLECTION OF WATER-QUALITY DATA

Water quality in the area of the four landfills was monitored during this investigation through a network of observation wells and surface-water sites. These sites are briefly reviewed in this section. The techniques used to collect and preserve the water samples for analysis are described in detail in Eddins and Cardinell (1987).

The numbering system used for the monitoring wells and surface-water sites in this report follows a preexisting numbering system used by Mecklenburg County. This system has been retained to maintain consistency with previous reports.

Ground-Water Sites

The ability to effectively use a monitoring well to detect the presence of a specific constituent in ground water depends on well location, depth of the well's intake interval, and the sampling procedure. The fact that various chemicals are attenuated within the hydrogeologic system to different degrees through adsorption and chemical interaction with other organic and inorganic constituents makes it difficult to predict the movement and fate of chemicals in ground water. Knowledge of the flow system is an essential precondition in assessing chemical contamination problems, and a monitoring program implemented without hydrogeologic information can give misleading results.

Sites for ground-water monitoring wells were selected upgradient, within, and downgradient of each of the four study landfills. Thirty-one existing wells, either residential or previously established monitoring wells, were used. Most of the ground-water monitoring wells were constructed during engineering studies conducted during the design of the sanitary landfills. A few observation wells were constructed later by or under the direction of U.S. Geological Survey investigators. These wells were constructed in or near areas where refuse cells were planned to monitor hydrologic changes caused by the operation of these cells. Considerable data at the Statesville Road landfill came from a feasibility study of possible recreational uses for the landfill site conducted about 10 years after waste disposal ceased in 1970.

An additional 23 monitoring wells were established as part of this study. Only three of these monitoring wells reach bedrock (Harrisburg Road landfill wells HBW1850 and HBW1 and York Road landfill well YRWA). Harrisburg Road and York Road landfills have the greatest number of monitoring wells (33 and 32, respectively) owing to the large number of wells previously established at those sites. Holbrooks Road and Statesville Road landfills had 6 and 4 wells, respectively, used for this study.

In addition to the ground-water quality sampling, water-level data were obtained at most wells for determining direction of ground-water movement. An inventory of ground-water monitoring wells included in this study is listed in table 3. Well locations are shown in figures 4, 6, 7, and 10.

Closely-spaced wells screened at different depths were not available during much of the study period at any of the landfill sites. One such group of wells was constructed adjacent to well YRW6 at York Road landfill at the end of this study. Each of these wells has a short screened interval so that leachate concentrations at various levels within the saturated saprolite could be determined.

Table 3.--*Description of ground-water monitoring wells*

[Location of wells shown in figures 4, 6, 7, and 10. USGS site ID number composed of latitude and longitude of well suffixed with a two-digit sequence number. Well depth, casing depth, and screen openings given in feet below land surface. PVC, polyvinyl chloride casing; GAL, galvanized steel casing. -, no data]

Mecklenburg County site number	USGS site ID number	Date installed	Well depth (feet)	Casing Type	Casing Diameter (inches)	Casing Depth (feet)	Screen opening From (feet)	Screen opening To (feet)	Well use	Number of samples Inorganic	Number of samples Organic	Owner of well
Harrisburg Road landfill												
HBW1	351321080414601	Sept. 1982	48.9	PVC	2	38.9	38.9	48.9	Monitoring	15	1	Mecklenburg County
HBW7	351322080415001	Sept. 1982	48.8	PVC	2	38.8	38.8	48.8	Monitoring	12	1	Mecklenburg County
HBW8	351317080414901	June 1983	23.3	PVC	2	18.3	18.3	23.3	Monitoring	6	1	Mecklenburg County
HBW9	351319080415101	May 1983	27.5	PVC	2	17.5	17.5	27.5	Monitoring	3	1	Mecklenburg County
HBW10	351320080415501	May 1983	48.2	PVC	2	38.2	38.2	48.2	Monitoring	16	3	Mecklenburg County
HBW11	351326080415501	June 1983	23.8	PVC	2	18.8	18.8	23.8	Monitoring	4	1	Mecklenburg County
HBW12	351330080415701	May 1983	23.4	PVC	2	18.4	18.4	23.4	Monitoring	10	2	Mecklenburg County
HBW14	351337080415001	May 1983	22	PVC	2	17	17	22	Monitoring	5	1	Mecklenburg County
HBW14A	351337080414801	Aug. 1983	23.5	PVC	2	18.5	18.5	23.5	Monitoring	16	8	Mecklenburg County
HBW15	351340080414901	Aug. 1983	39	PVC	2	29	29	39	Monitoring	19	6	Mecklenburg County
HBW16	351338080411201	Aug. 1983	44.5	PVC	2	34.5	34.5	44.5	Monitoring	16	6	Mecklenburg County
HBW433	351330080410801	Unknown	-	-	-	-	-	-	Domestic	2	2	Unknown
HBW433A	351327080410701	Unknown	-	-	-	-	-	-	Domestic	3	1	Unknown
HBW600	351258080412101	Unknown	-	-	-	-	-	-	Domestic	2	1	Mecklenburg County
HBW700	351317080411801	Unknown	-	-	-	-	-	-	Domestic	1	1	Mecklenburg County
HBW721	351257080414101	Unknown	-	-	-	-	-	-	Domestic	5	2	Unknown
HBW743A	351351080413701	Unknown	-	-	-	-	-	-	Domestic	5	3	Unknown
HBW800	351327080414601	Unknown	-	-	-	-	-	-	Domestic	14	3	Mecklenburg County
HBW1501	351258080412401	Sept. 1982	42	PVC	4	-	-	-	Monitoring	5	1	Mecklenburg County
HBW1502	351259080413001	Sept. 1982	21	PVC	4	-	-	-	Monitoring	2	-	Mecklenburg County
HBW1503	351258080413801	May 1980	46	PVC	4	-	-	-	Water levels	-	-	Mecklenburg County
HBW1504	351307080414601	Nov. 1982	43	PVC	4	-	-	-	Monitoring	18	3	Mecklenburg County
HBW1505	351306080413301	May 1980	8	PVC	4	-	-	-	Water levels	-	-	Mecklenburg County
HBW1602	351317080414101	Sept. 1982	39	PVC	4	-	-	-	Monitoring	7	2	Mecklenburg County
HBW1603	351319080411701	Sept. 1982	51	PVC	4	-	-	-	Monitoring	13	3	Mecklenburg County
HBW1754	351334080412901	Nov. 1982	10	PVC	2	-	-	-	Monitoring	5	1	Mecklenburg County
HBW1850	351340080413501	Oct. 1976	92	Steel	6	88	No screen		Monitoring	20	9	Mecklenburg County
HBW2100	351327080413501	Mar. 1983	59.2	PVC	2	49.2	49.2	59.2	Monitoring	2	2	Mecklenburg County

Table 3.--*Description of ground-water monitoring wells*--Continued

[Location of wells shown in figures 4, 6, 7, and 10. USGS site ID number composed of latitude and longitude of well suffixed with a two-digit sequence number. Well depth, casing depth, and screen openings given in feet below land surface. PVC, polyvinyl chloride casing; GAL, galvanized steel casing. -, no data]

Mecklenburg County site number	USGS site ID number	Date installed	Well depth (feet)	Casing Type	Casing Diameter (inches)	Casing Depth (feet)	Screen opening From (feet)	Screen opening To (feet)	Well use	Number of samples Inorganic	Number of samples Organic	Owner of well
					Harrisburg Road landfill--Continued							
HBW2101	351331080411601	Feb. 1983	53.7	PVC	2	43.7	43.7	53.7	Monitoring	13	3	Mecklenburg County
HBW2101A	351331080411603	Apr. 1984	33.7	PVC	4	28	28	33	Water levels	-	-	Mecklenburg County
HBW2201	351333080405501	Nov. 1985	32	PVC	4	22	22	32	Water levels	-	-	Mecklenburg County
HBW2301	351327080404401	Nov. 1985	55	PVC	4	35	35	55	Water levels	-	-	Mecklenburg County
HBWE2	351335080412801	Mar. 1983	28.9	PVC	2	-	-	-	Monitoring	5	-	Mecklenburg County
					Holbrooks Road landfill							
HRW1	352415080485601	Jan. 1983	11.3	PVC	2	6.3	6.3	11.3	Monitoring	15	4	Mecklenburg County
HRW2	352415080484901	Jan. 1983	6.10	PVC	2	1.10	1.10	6.10	Monitoring	14	4	Mecklenburg County
HRW3	352404080485401	Feb. 1983	60.4	-	-	-	-	-	Domestic	17	7	Mecklenburg County
HRW4	352402080485201	Feb. 1983	Unknown	-	-	-	-	-	Domestic	15	4	Carl Lynch
HRW5	352418080485101	Mar. 1983	12.5	PVC	2	7.5	7.5	12.5	Monitoring	15	3	Mecklenburg County
HRW6	352403080490001	Apr. 1983	Unknown	-	-	-	-	-	Domestic	12	3	Edwards Residence
					Statesville Road landfill							
SRW20	351615080501301	Feb. 1983	54.1	PVC	2	44.1	44.1	54.1	Monitoring	16	3	City of Charlotte
SRW21	351603080495801	Feb. 1983	24.2	PVC	2	19.2	19.2	24.2	Monitoring	17	3	City of Charlotte
SRW22	351547080501401	Feb. 1983	32.5	PVC	2	22.5	22.5	32.5	Monitoring	13	3	City of Charlotte
SRW23R	351614080501401	-	-	-	-	-	-	-	Domestic	12	3	Mrs. Cornelison
					York Road landfill							
YRW1	351028080543001	Nov. 1980	26.7	PVC	2	16.7	16.7	26.7	Monitoring	22	5	City of Charlotte
YRW2	351036080542301	Dec. 1980	16.8	PVC	2	6.8	6.8	16.8	Monitoring	22	2	City of Charlotte
YRW3	351046080542301	Nov. 1980	32.8	PVC	2	22.8	22.8	32.8	Monitoring	22	3	City of Charlotte
YRW4	351042080542501	June 1981	35.2	GAL	2	-	No screen		Domestic	6	-	City of Charlotte
YRW5	351047080542701	Unknown	-	PVC	2	-	-	-	Domestic	8	2	City of Charlotte
YRW6	351003080544201	Nov. 1984	23	PVC	3.5	18	18	23	Monitoring	7	-	City of Charlotte
YRWA	351026080544301	July 1970	350	Steel	6.5	45	No screen		Monitoring	7	1	City of Charlotte

Table 3.--*Description of ground-water monitoring wells*--Continued

[Location of wells shown in figures 4, 6, 7, and 10. USGS site ID number composed of latitude and longitude of well suffixed with a two-digit sequence number. Well depth, casing depth, and screen openings given in feet below land surface. PVC, polyvinyl chloride casing; GAL, galvanized steel casing. -, no data]

Mecklenburg County site number	USGS site ID number	Date installed	Well depth (feet)	Casing			Screen opening		Well use	Number of samples		Owner of well
				Type	Diameter (inches)	Depth (feet)	From (feet)	To (feet)		Inorganic	Organic	
York Road landfill--Continued												
YRWB	-	Sept. 1984	34.0	PVC	4	24.0	-	-	Water levels	-	-	City of Charlotte
YRWB1	351057080543301	Oct. 1982	23	PVC	2	13	13.0	23.0	Monitoring	1	-	City of Charlotte
YRWB2	351056080544601	Oct. 1982	38.5	PVC	2	28.5	28.5	38.5	Monitoring	1	1	City of Charlotte
YRWB3	-	Sept. 1984	34	PVC	2	25	-	-	Water levels	-	-	City of Charlotte
YRWB4	-	Oct. 1982	42	PVC	2	23	-	-	Water levels	-	-	City of Charlotte
YRWB5	351050080544901	Oct. 1982	23	PVC	2	13	13	23	Monitoring	2	2	City of Charlotte
YRWB6	-	Oct. 1982	42	PVC	2	42	-	-	Water levels	-	-	City of Charlotte
YRWB7	-	Oct. 1982	45	PVC	2	43.5	-	-	Water levels	-	-	City of Charlotte
YRWB8	-	Oct. 1982	35	PVC	2	33.5	-	-	Water levels	-	-	City of Charlotte
YRWB9	-	Oct. 1982	63.5	PVC	2	63.5	-	-	Water levels	-	-	City of Charlotte
YRWB10	351046080544801	Nov. 1982	27	PVC	2	17	17	27	Monitoring	-	-	City of Charlotte
YRWB11	-	Oct. 1982	50	PVC	2	47	-	-	Water levels	-	-	City of Charlotte
YRWB12	351052080543001	Oct. 1982	48.5	PVC	2	38.5	38.5	48.5	Monitoring	3	-	City of Charlotte
YRWB12A	351052080543002	Oct. 1982	40.5	PVC	2	30.5	30.5	40.5	Monitoring	7	2	City of Charlotte
YRWB13	351043080543601	Oct. 1982	18.5	PVC	2	8.5	8.5	18.5	Monitoring	1	1	City of Charlotte
YRWB14	351036080550501	Oct. 1982	49.5	PVC	2	39.5	39.5	49.5	Monitoring	2	1	City of Charlotte
YRWB15	-	Oct. 1982	22	PVC	2	20	-	-	Water levels	-	-	City of Charlotte
YRWB16	-	Oct. 1982	40.9	PVC	2	40	-	-	Water levels	-	-	City of Charlotte
YRWB17	-	Oct. 1982	30	PVC	2	28.5	-	-	Water levels	-	-	City of Charlotte
YRWB18	-	Oct. 1982	40	PVC	2	40	-	-	Water levels	-	-	City of Charlotte
YRWB19	-	Oct. 1982	57.7	PVC	2	57	-	-	Water levels	-	-	City of Charlotte
YRWB20	-	Oct. 1982	32	PVC	2	32	-	-	Water levels	-	-	City of Charlotte
YRWB21	351032080544601	Oct. 1982	17	PVC	2	7	7	17	Monitoring	1	1	City of Charlotte
YRWB22	-	Oct. 1982	57.5	PVC	2	57.5	-	-	Water levels	-	-	City of Charlotte
YRWB23	-	Oct. 1982	41	PVC	2	31	31	41	Water levels	-	-	City of Charlotte

Surface-Water Sites

The foundation for the collection of surface-water quality data at landfill sites has three aspects. First is the monitoring of overland runoff from refuse cells to determine how landfill operations at or near land surface affects stream quality. Sampling streams draining the landfill at high flows provides these data.

Second, the discharge of leachate-bearing ground water into streams can have an effect on stream quality. The analyses of samples taken from streams draining the landfill during low flows are representative of ground-water discharge and any unattenuated leachate constituents present.

The third aspect is the need for data against which to judge whether, or the degree to which, the landfills have affected stream quality. Sampling sites upstream from the landfills can provide background information on which to evaluate downstream water-quality data.

Ten surface-water quality monitoring sites were established on streams near the four landfills by Eddins and Crawford (1984), and ten additional monitoring sites were established upstream and downstream of the landfills as part of this investigation. These sites were on streams ranging in size from small, intermittent streams with drainage areas of less than 0.10 mi^2 to perennial streams with drainage areas in excess of 40 mi^2.

Two of the sites were established as continuous-record gaging stations--HBSW2009 at the Harrisburg Road landfill and SRSW11 at the Statesville Road landfill. Streamflow, specific conductance, and temperature were recorded continuously at these two stations. These data are in annual water-resources data reports for North Carolina published by the U.S. Geological Survey (1980-86). Surface-water sites included in this study are listed in table 4 and are shown in figures 4, 6, 7, and 10.

Table 4.--*Description of surface-water quality monitoring sites*

[Location of sites shown on figures 4, 6, 7, and 10. Record types: P, periodic sample collection; C, continuous discharge; S, continuous specific conductance and temperature; R, periodic stage]

Mecklenburg County site number	USGS station number[1]	Date established	Drainage area (square miles)	Record type	Number of samples: Inorganic	Number of samples: Organic
			Harrisburg Road landfill			
HBSW7A	0212429910	Sept. 1982	0.12	P	15	2
HBLSW1506	0212429935	Aug. 1983	.06	P	6	3
HBSW2006	0212429960	Dec. 1984	1	P	4	2
HBSW2007	0212429920	Nov. 1982	.44	P	15	2
HBSW2008	0212429940	Nov. 1982	.5	P	14	3
HBSW2009	0212429930	Oct. 1984	.39	C,P,S	5	1
HBSW2010	0212429915	Sept. 1984	.34	P	5	1
			Holbrooks Road landfill			
HRSW1	0212404995	Apr. 1983	1.85	P,R	13	3
HRSW2	0212404990	Apr. 1983	1.52	P,R	13	3
			Statesville Road landfill			
SRSW2	0214620810	Aug. 1979	.03	P	20	3
SRSW3	0214620750	Oct. 1979	3.41	P	16	5
SRSW11	02146211	Oct. 1979	5.97	C,P,S	23	2
SRSW12	0214623000	Apr. 1980	11.8	P	3	0
SRSW14	0214628700	Apr. 1980	24.9	P	2	0
			York Road landfill			
YRSW8	0214632330	Aug. 1979	.37	P,R	14	0
YRSW9	0214632340	Apr. 1980	1.02	P,R	20	2
YRSW9A	0214632335	Oct. 1981	.87	P,R	17	3
YRSW21	02146300	Aug. 1969	30.7	C,P	2	1
YRSW21A	0214632322	Aug. 1982	38	P,R	17	3
YRSW41	0214632815	Mar. 1981	41.2	P,R	21	3

[1]U.S. Geological Survey downstream order identification number.

SELECTED WATER-QUALITY INDICATORS

Water-quality indicators were selected to evaluate the potential effects of leachate on surface- and ground-water quality at the four landfills. These indicators include dissolved solids, specific conductance, three inorganic constituents, total organic carbon (TOC), and other specific organic compounds. This section reviews the formation of leachate, describes the use of the indicators in the evaluation process, and draws general comparisons of water quality indicators between landfills.

As water percolates through the solid waste within a landfill, it extracts dissolved or suspended materials produced from the decay of waste. This liquid, called leachate, represents an extremely complex mixture containing both soluble and insoluble, organic and inorganic, ionic and nonionic constituents. The effects of the leachate on receiving surface and ground waters might include the depletion of dissolved oxygen caused by oxidation of soluble organics; addition of objectionable taste and odors; limitations of water uses as a result of high dissolved solids; and the introduction of health hazards related to potentially toxic materials and microbial contamination. The average infiltration of 7.6 in. of rainfall per year in Mecklenburg County is indicative of the amount of water which could potentially infiltrate a refuse site and become leachate.

If refuse has been buried in the saturated zone, as may be the condition in some older dumps, the constant contact of water with the refuse can generate greater volumes of leachate and higher concentrations of dissolved constituents in the leachate than if the refuse were buried in the unsaturated zone. In the unsaturated zone, leachate flow is vertically downward, as precipitation, contaminants, and solutions of contaminants move under the force of gravity to the water table. Some chemicals in the leachate may be trapped in the unsaturated zone by adsorption onto soil particles and organic material and silt or clay particles where they can be altered by oxidation and microbial activity.

Flow within the saturated zone is laminar with little mixing, and leachate reaching the saturated zone usually moves through the ground-water system in distinct leachate plumes. The shape and size of a plume depends on a number of factors, including the local geologic framework, length of the ground-water flow path, and type and concentration of contaminants. The density of contaminated fluids is another important factor in the formation and movement of a plume. Insoluble contaminants with a high specific gravity will sink, whereas those with a low specific gravity will float and stay near the water table and sometimes be within the capillary zone. These chemicals may move in different directions and at different rates from contaminants dissolved in the percolating ground water.

Water-analysis diagrams were used to compare concentrations of dissolved solids and major dissolved inorganic constituents in water samples. Diagrams of this type have been successfully used to examine (1) differences in background water composition caused by variations in bedrock or saprolite minerology, (2) mixing of one water source with another, (3) existence of a common source for two waters, and (4) influence of other factors, such as landfill leachate on the composition of ground or surface water at a site.

Specific conductance, chloride, hardness, and manganese were selected as indicators because (1) they have a history of successful use in detecting the existence and movement of leachate plumes in similar water-quality studies (U.S. Environmental Protection Agency, 1977); (2) they have been measured for the duration of the study; (3) they may have values that can be distinguishable from background levels; and (4) they are not significantly affected by well casing material or sampling procedures. Box plots are used to summarize the distribution of indicator values or concentrations for ground-water samples. Each box, shown later in this report, gives the median value (half of all values above, half below), the 75- and 25-percent quartiles, and the range of values. Also shown for comparison are mean values of indicator constituents at surface-water sites during base flow. Box plots were not computed for base-flow samples because of the small number of these samples.

Total organic carbon concentrations were examined in water samples as an indicator of possible leachate contamination. TOC is a measure of all suspended, dissolved, and precipitated organic compounds. The measurement of TOC is analogous to specific conductance in that TOC is also a gross measurement that does not distinguish between individual compounds.

Water samples were analyzed for a large number of specific organic compounds of environmental concern (Eddins and Cardinell, 1987). The presence of these compounds at or above detectable limits was evaluated as an indication of a possible landfill source of contamination.

Inorganic Indicators

Dissolved Solids

Water-analysis diagrams, modified after those proposed by Piper (1944), were drawn to show the relative dissolved solids concentration of major ions in surface and ground water for each landfill (fig. 12). The center of each circle is the location of the relative percentage of calcium plus magnesium, sodium plus potassium, sulfate plus chloride, and bicarbonate alkalinity for each analysis. The size of the circles in the diagrams is proportional to the dissolved-solids concentration of the sample.

The data in these diagrams represent samples taken in late 1985 and 1986 at a small number of sites. Some general observations can be made from an examination of these water-analysis diagrams:

1. Dissolved-solids concentrations at the Harrisburg Road site are substantially lower than those at the other landfill sites;

2. Substantial differences between the composition of ground-water samples from upgradient, background wells (HBW1, HBW10, HBW1504, HRW4, HRW6, SRW20, YRW2, and YRW3) indicate either the influence of off-site sources or local differences in mineralogy.

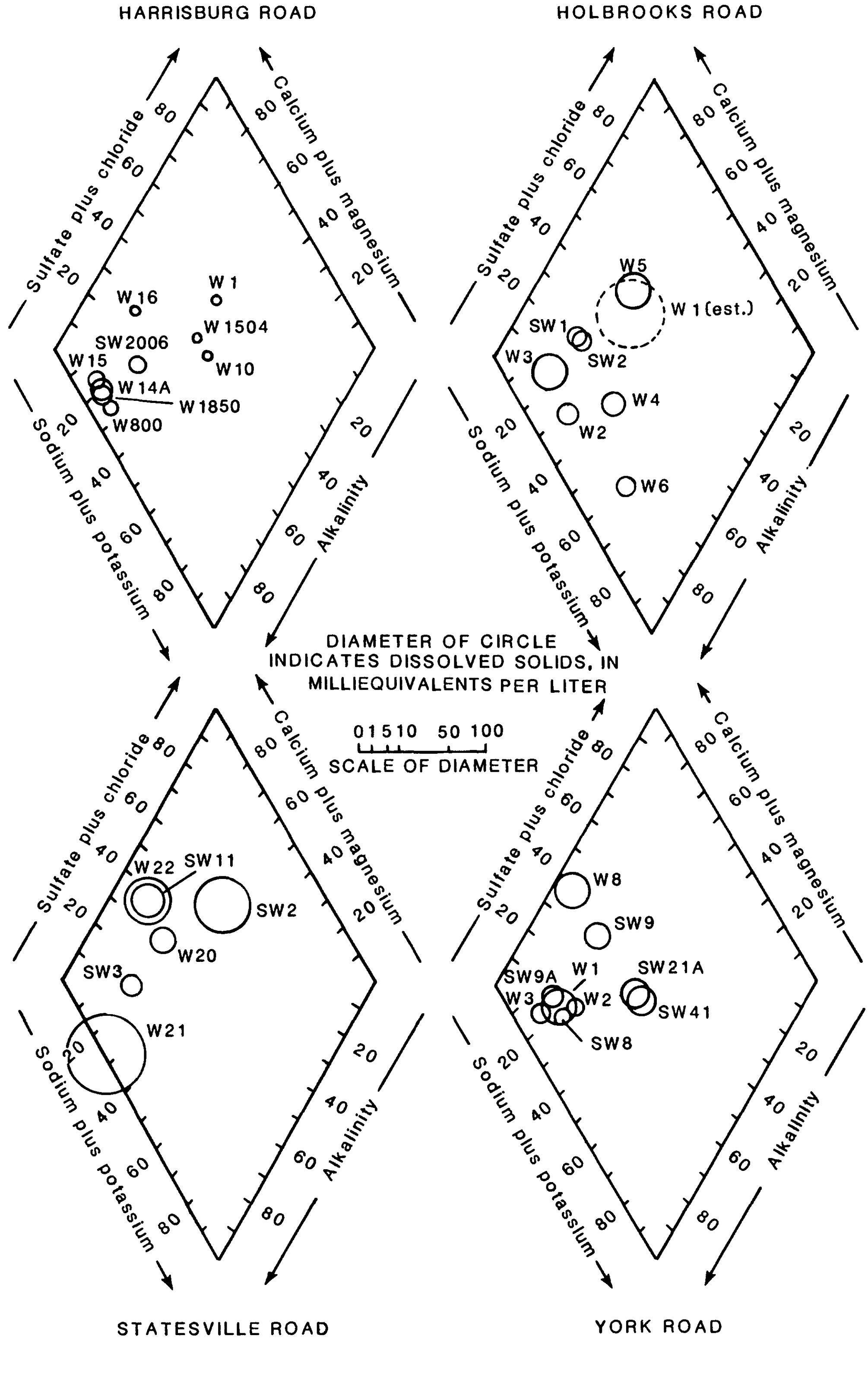

Figure 12.--Water-analysis diagrams for ground water and surface water at Harrisburg Road, Holbrooks Road, Statesville Road, and York Road landfills.

3. At all landfills, dissolved-solids concentrations in ground water increase as water moves downgradient. This is accompanied by an increase in the relative concentration of calcium, magnesium, and chloride, except at Harrisburg Road landfill, where alkalinity, not chloride, increased.

4. Increases in dissolved solids and the relative concentrations of calcium, magnesium, and chloride in surface waters as they flow through a landfill were noted for two streams. These increases occurred at the Statesville Road landfill between sites SRSW3 and SRSW11 on Irwin Creek and at the York Road landfill between sites YRSW9A and YRSW9 on the unnamed tributary to Sugar Creek.

5. There was no substantial change in the water quality of the main receiving streams adjacent to the Holbrooks Road landfill (between sites HRSW2 and HRSW1 on South Prong Clark Creek) or adjacent to the York Road landfill (between sites YRSW21A and YRSW41 on Sugar Creek).

Specific Conductance

Specific conductance is a measure of the ability of water to conduct an electrical current. Because that ability is dependent on the concentration and speciation of dissolved ionic constituents, specific conductance has been empirically related to inorganic dissolved-solids concentrations, where dissolved solids (in milligrams per liter, mg/L) can be approximated by specific conductance (in microsiemens per centimeter at 25 °C, μS/cm) multiplied by a factor generally ranging from 0.55 to 0.75 (Hem, 1985). Specific conductance has been successfully used for determining fluctuations and trends in ionic impurities in ground water and, more specifically, for monitoring landfill leachate. Specific conductance of fresh landfill leachate has been reported to range typically from 6,000 to 9,000 μS/cm (U.S. Environmental Protection Agency, 1977), corresponding to a dissolved-solids concentration of approximately 3,300 to 6,800 mg/L. Perhaps the greatest advantage of specific conductance measurements is the high degree of accuracy combined with the ease and relatively low cost of data collection.

Box plots, showing the distribution of specific conductance measurements for individual well sites or groups of similar wells, are presented for each landfill in figure 13. Also indicated in the figure are mean low-flow values of specific conductance for surface-water sampling locations.

Many of the general observations noted from the water-analysis diagrams previously presented are also apparent from an examination of the specific conductance box plots. The difference between specific conductance at wells upgradient of each landfill ranges from a low median value of 46 µS/cm at Harrisburg Road (a composite value of 19 individual wells) to a high median value of 270 µS/cm at well SRW20 upgradient of Statesville Road. The high background specific conductance value at well SRW20 is higher than the specific conductance at most downgradient wells at Harrisburg Road or York Road landfills. In all instances, except well HRW2 at Holbrooks Road, specific conductance increased downgradient.

The specific conductance at certain wells, such as HRW1 or SRW21, located within landfill cells indicates that water quality is highly affected. Specific conductance values ranging from 1,500 to 3,500 µS/cm were measured in ground-water samples collected from these wells within the buried refuse at Holbrooks Road and Statesville Road landfills. These values are higher than those of ground water collected from other wells during this study. The magnitude of specific conductance (and other indicators) within the refuse may vary substantially over short distances so that factors, such as well placement and screening depth, greatly influence the specific conductance value used to characterize the landfill leachate at a given site.

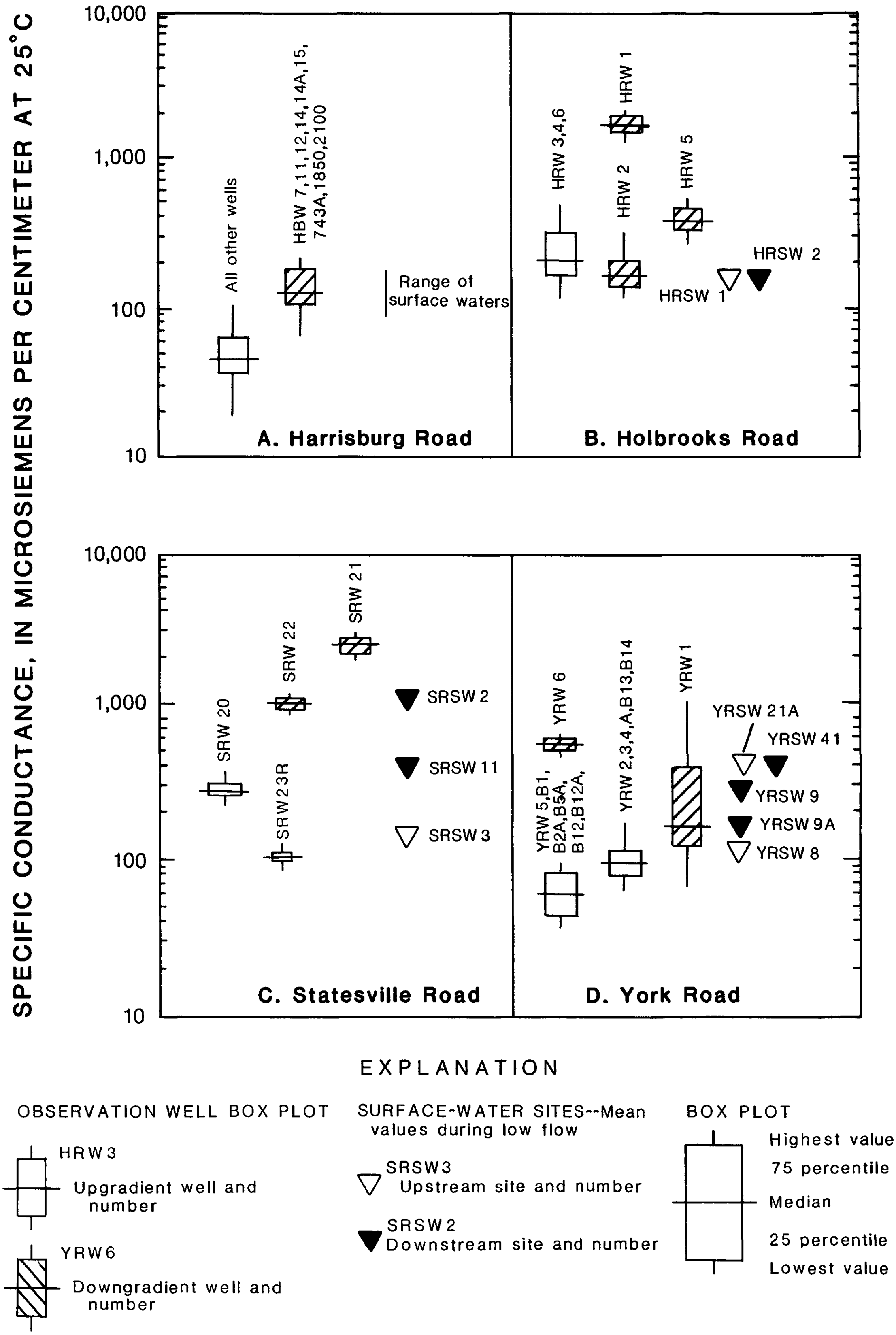

Figure 13.--Summary of specific conductance data at Harrisburg Road, Holbrooks Road, Statesville Road, and York Road landfills.

Surface-water specific conductance increased in the streams passing through Statesville Road (Irwin Creek, SRSW3 and SRSW11) and York Road (YRSW9 and YRSW9A) landfills. However, no substantial differences in specific conductance values were detected for upstream-downstream station pairs for South Prong Clark Creek (HRSW1 and HRSW2) adjacent to Holbrooks Road landfill or Sugar Creek (YRSW21A and YRSW41) adjacent to York Road landfill.

Although there are no water-quality criteria or standards for specific conductance, a level of acceptable values can be estimated from the empirical relation with dissolved solids. Water with a specific conductance greater than 770 μS/cm has a potential dissolved-solids concentration of 500 mg/L or greater and, thus, is potentially objectionable as a water supply (U.S. Environmental Protection Agency, 1986). Several wells consistently exceeded (SRW21, SRW22, and HRW1) or approached (HRW5, YRW1, and YRW6) this limit of 770 μS/cm. Surface-water sites SRSW2, SRSW11, and YRSW21A occasionally exceeded or approached 770 μS/cm.

Chloride

Chloride is a highly mobile constituent in water and does not enter into significant oxidation or reduction reactions nor form complexes with other ions unless concentrations are extremely high. The ready solubility of metallic, alkali, or alkaline chloride compounds makes chloride a particularly useful indicator of landfill leachate because it is not susceptible to attenuation. For this reason, chloride can also be used effectively to evaluate the attenuation of nonconservative compounds within landfill leachate plumes. Chloride concentrations in landfill leachate have been reported as high as 3,000 mg/L, with typical concentrations of approximately 500 mg/L (U.S. Environmental Protection Agency, 1977).

Natural chloride concentrations in the surface waters of undeveloped basins in the North Carolina Piedmont are low, about 5 mg/L (Simmons and Heath, 1979). In a survey of wells in Mecklenburg County in 1952, chloride concentrations generally ranged from 4 to 20 mg/L (LeGrand and Mundorff, 1952). The source of chloride is restricted to chloride-bearing minerals most often found in gabbro and diorite, such as is reported to underlie the studied landfills.

Chloride concentrations in wells upgradient of each landfill generally fell within the range noted by LeGrand and Mundorff (1952). Chloride in downgradient wells exhibited a much wider range of concentrations (fig. 14). At Harrisburg Road landfill, for example, chloride concentrations in downgradient wells increased 20 percent over upgradient levels; whereas, at York Road landfill chloride concentrations in water from well YRW6 were 20 times greater than those from upgradient wells. The greatest increases in ground-water chloride concentration over upgradient levels were at Holbrooks Road (wells HRW1 and HRW5) and Statesville Road landfills (well SRW22).

The general pattern of chloride concentration at surface-water sampling sites is consistent with the pattern observed for specific conductance--little change in mean chloride concentrations was seen between upstream and downstream sampling sites at either South Prong Clark Creek (HRSW1 and HRSW2) or Sugar Creek (YRSW21A and YRSW41) during low flows, although chloride concentrations increased at stations downstream of landfills at both Irwin Creek (from 5.5 mg/L at SRSW3 to 60 mg/L at SRSW11) and the unnamed stream at York Road landfill (from 6.5 mg/L at YRSW9A to 35 mg/L at YRSW9). The high chloride concentration in Sugar Creek, both upstream and downstream, appears to be caused by other sources upstream of the York Road landfill.

The highest median chloride concentrations during low flow were observed at downstream site SRSW2 at the Statesville Road landfill. This value is consistent with the high downgradient ground-water chloride values at this landfill (fig. 14).

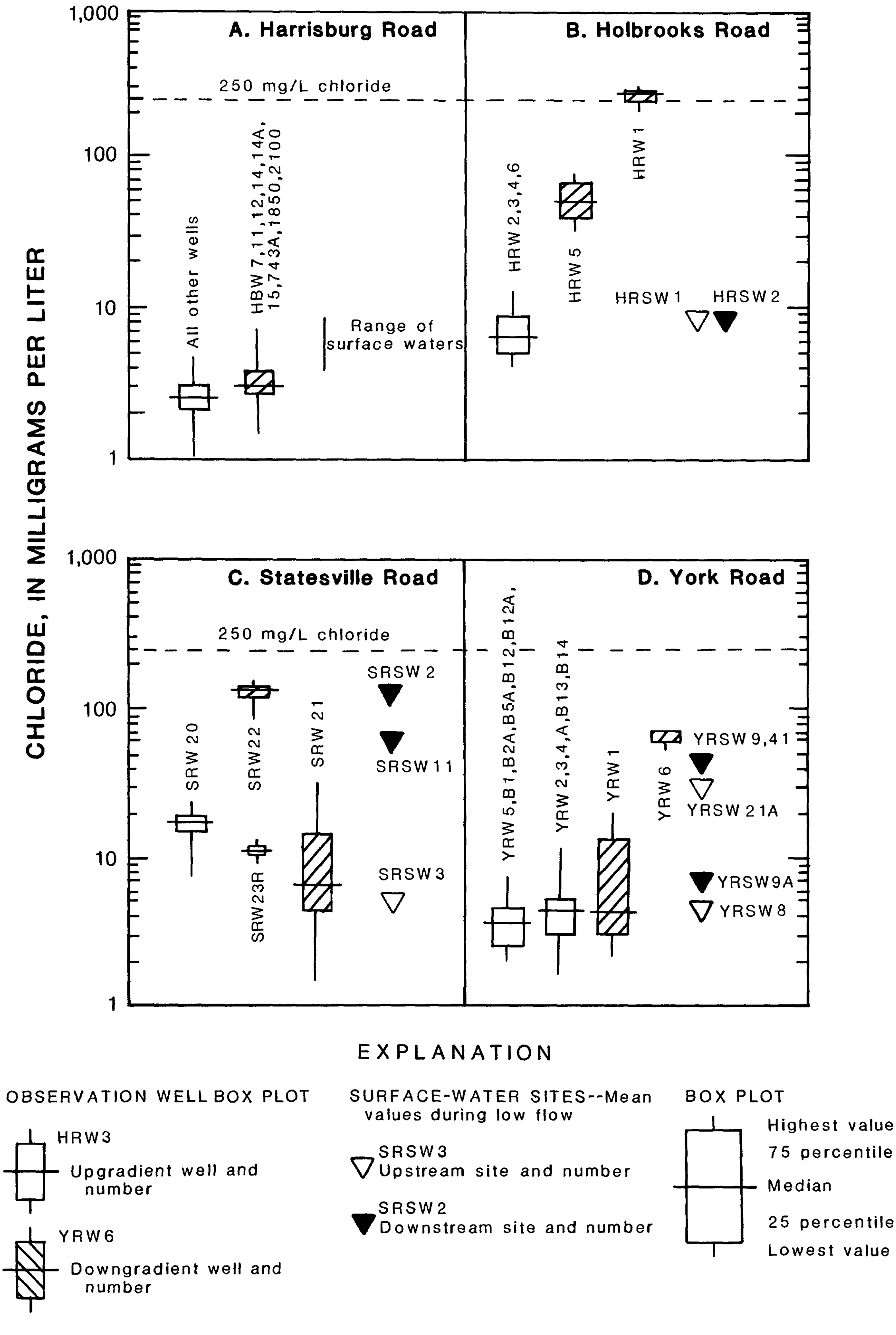

Figure 14.--Summary of chloride-concentration data at Harrisburg Road, Holbrooks Road, Statesville Road, and York Road landfills.

Hardness

Hardness is the property of water attributable to the presence of alkaline earths, such as calcium, magnesium, strontium, and other divalent metallic cations. No water-quality criteria or standards have been set for hardness because there is no proven health- or environmental-related effects. Tolerance limits on hardness for specific industrial uses are generally accepted, however. Several classification schemes for hardness values have been proposed, such as that suggested by Durfor and Becker (1964) in which four classes of water hardness were defined: 0 to 60 mg/L classified as soft; 61 to 120 mg/L as moderately hard; 121 to 180 mg/L as hard; and more than 180 mg/L classified as very hard water.

Increases in hardness of water in landfill environments are attributed to mobilization of divalent metallic cations from cation exchange in native soils, especially clays, by the advancing leachate plume (U.S. Environmental Protection Agency, 1977). Some studies have shown this caused an increase in dissolved calcium and magnesium in the plume relative to conservative indicators, such as chloride. Representative hardness concentrations as calcium carbonate ($CaCO_3$) in landfill waters are usually between 300 and 5,000 mg/L, although values of more than 22,000 mg/L have been reported (U.S. Environmental Protection Agency, 1977).

As with the previous indicators, hardness concentrations in ground water were lowest at the Harrisburg Road landfill, slightly higher at York Road, higher at Holbrooks Road, and highest at Statesville Road landfill (fig. 15). This is also evident when comparing hardness values between upgradient or downgradient wells at these landfills. This pattern may possibly reflect the greater availability of exchangeable calcium and magnesium in the geologic material at Holbrooks Road and Statesville Road landfills under both natural and leachate-enhanced weathering conditions.

Based on hardness concentrations in samples from each landfill, ground water from upgradient wells generally can be classified as soft, although water from the one upgradient well at Statesville Road landfill was

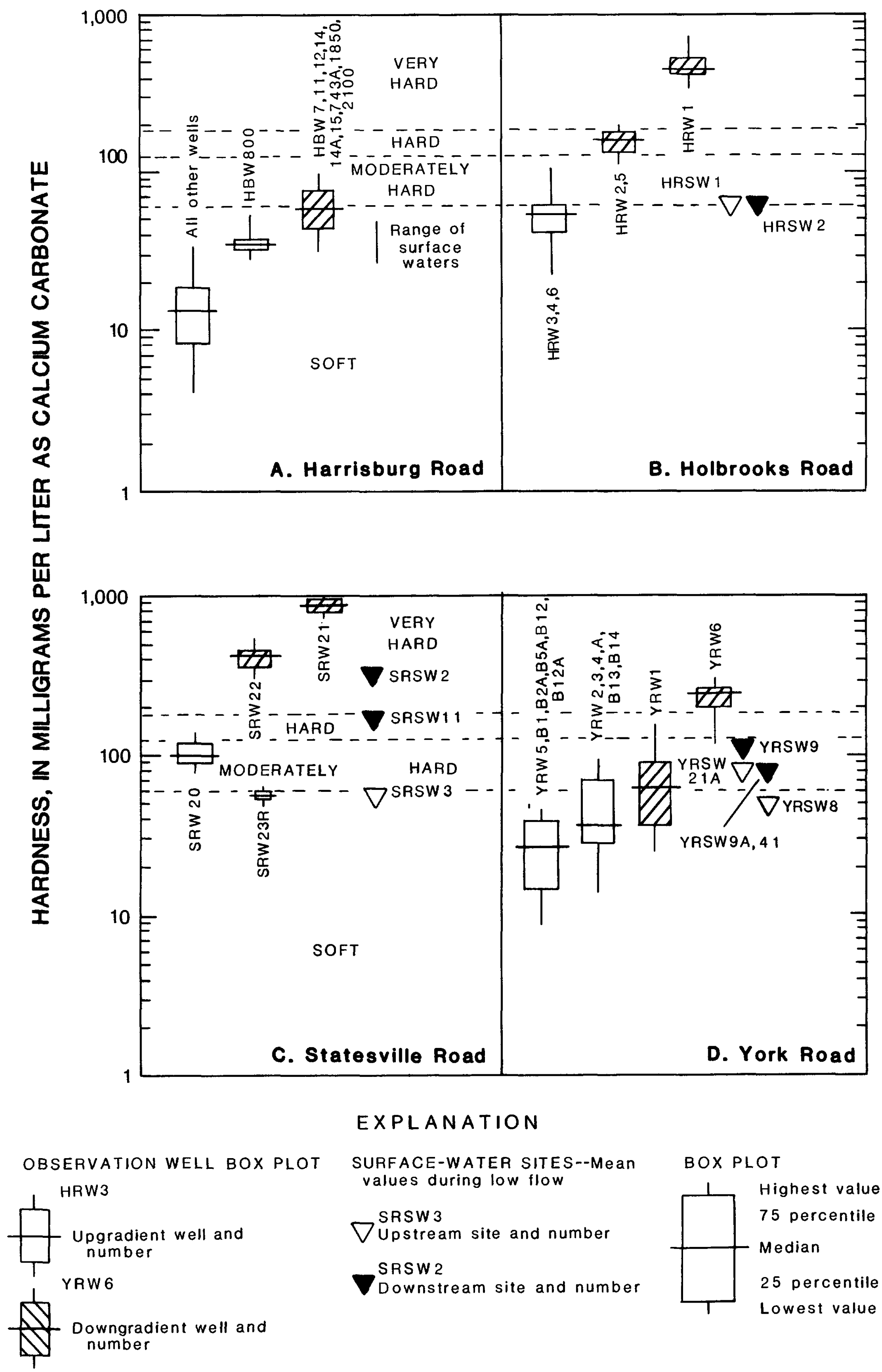

Figure 15.--Summary of hardness data at Harrisburg Road, Holbrooks Road, Statesville Road, and York Road landfills.

moderately hard. Hardness concentrations from well HBW800 are shown separately, because based on 12 samples, the distribution did not correspond with hardness concentrations of the upgradient group with which it should belong, possibly indicating a specific local anomaly. Hardness concentrations in water from all downgradient wells ranged from soft to very hard but were mostly hard to very hard. Hardness of ground water from well YRW1 varied widely and increased with time.

All surface-water samples taken at the Harrisburg Road and Holbrooks Road landfills, the upstream sample on Irwin Creek at the Statesville Road landfill, and the sample taken from the unnamed tributary along the northwest side of the York Road landfill were classified as soft water. Water from Sugar Creek and the other unnamed southeast tributary at the York Road landfill was moderately hard. Hard to very hard water was observed in downstream samples at the Statesville Road landfill.

Manganese

Manganese resembles iron in its chemical characteristics and occurrence in waters, although it is generally less abundant. Manganese is naturally occurring within the minerals of igneous and metamorphic bedrock; as weathering of these minerals progresses, manganese oxide coatings form on the residual soils and clay. These natural oxide coatings and manganese from disposed materials are the principal sources for mobile manganese under chemically reducing conditions at landfills. The reducing conditions are caused by consumption of all available free oxygen by the biological and chemical decay of organic materials. When the supply of free oxygen has been depleted, oxygen from metal oxides, such as manganous or ferrous oxides, is utilized, releasing the metal ions into solution. For these reasons, high concentrations of manganese are excellent indicators of intensive biological activity and are of particular importance in delineating anaerobic zones.

The main concerns with manganese in water are aesthetic in nature; manganese causes undesirable taste and discoloration of the water. It is that consideration, rather than any toxic concern, which has led to a 50 µg/L (micrograms per liter) standard for domestic water supplies (U.S. Environmental Protection Agency, 1986). Concentrations in landfill leachate have been reported as high as 100,000 µg/L (U.S. Environmental Protection Agency, 1977).

The relative manganese concentrations from water samples collected at upgradient wells at each of the four landfills differ in several ways from the general patterns observed for other indicator constituents. For example, low concentrations of manganese (more than half the samples were below the detection limit of 20 µg/L) were observed in water from one group of upgradient wells at the Harrisburg Road landfill (fig. 16). This could be anticipated because of relatively low background concentrations of the other indicator constituents. However, by contrast, water from a group of upgradient wells at the Holbrooks Road landfill, which contained very low median concentrations of manganese, also contained substantially higher levels of the other indicator constituents.

A second pattern of upgradient manganese distribution is seen in water samples from a second group of wells at the Harrisburg Road landfill. These wells are located in upgradient fringe areas around the landfill and yield water containing higher concentrations of manganese than the first group of wells described above.

Another difference seen in water-quality data for upgradient wells was that median concentrations of manganese were highest at the York Road landfill, whereas the concentrations of the other indicator constituents were relatively low. This is the reverse of the above situation where manganese concentrations were low and the other indicator constituents were higher.

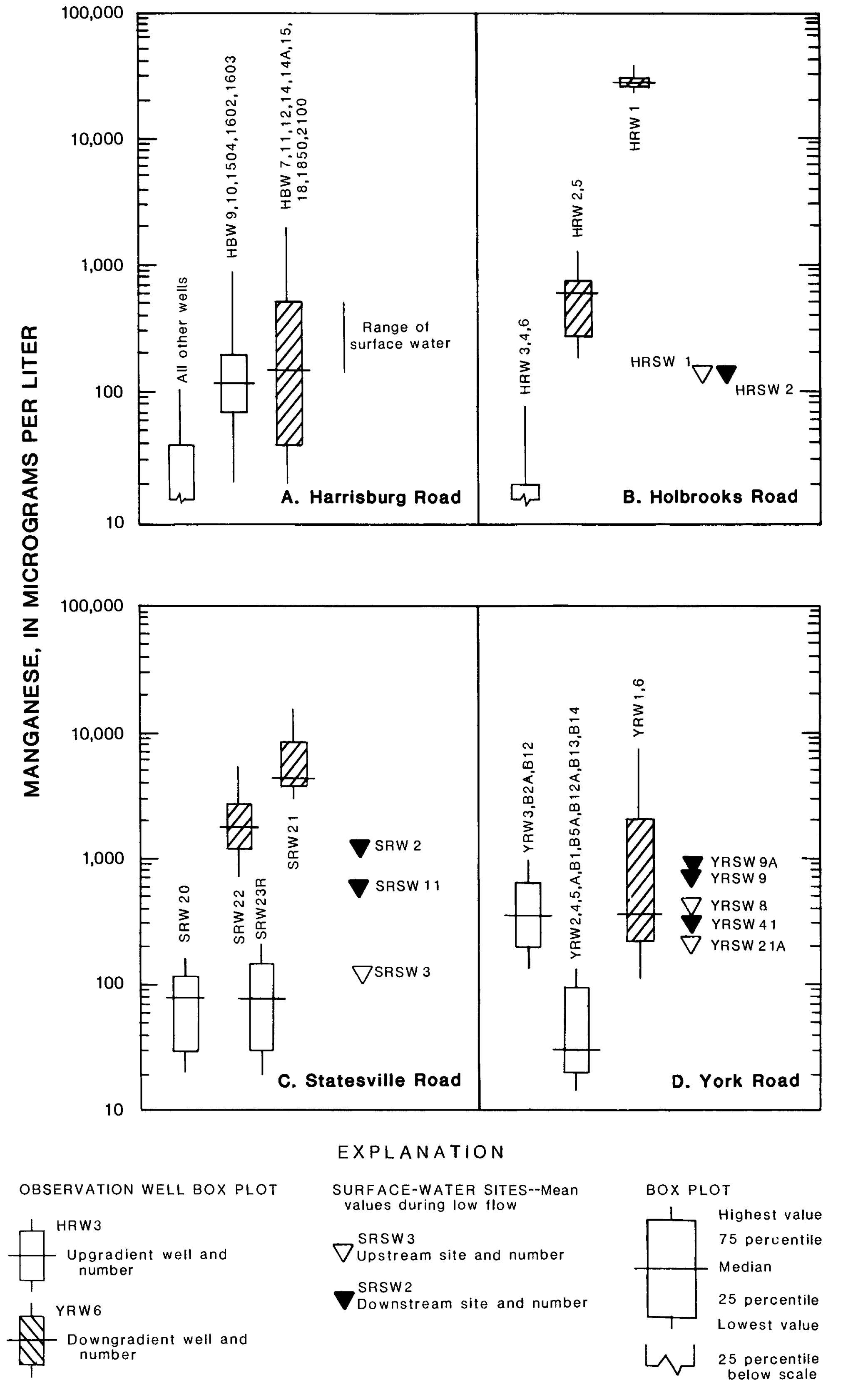

Figure 16.--Summary of manganese data at Harrisburg Road, Holbrooks Road, Statesville Road, and York Road landfills.

The relative concentrations of manganese in samples from downgradient wells are generally consistent with the patterns observed among the landfills for other constituents. There is, however, a greater relative increase at each landfill between manganese concentrations from background and downgradient wells.

Dissolved manganese concentrations in surface water indicate that it was one of the few constituents which consistently exceeded its water-quality criteria for domestic supply near all four landfills (U.S. Environmental Protection Agency, 1986). The variability among the surface-water sites at Harrisburg Road landfill was greater for manganese than most other constituents. The usefulness of using manganese as an indicator of the effects of landfills on surface-water quality is demonstrated by noting that manganese is the only constituent with consistently higher concentrations in the streams draining the York Road landfill than in Sugar Creek, the receiving stream. Sugar Creek along this landfill was affected by numerous upstream point and nonpoint sources but was relatively unaffected by the landfill leachate.

Organic Indicators

Total Organic Carbon

A total of 49 ground-water and 20 surface-water samples were analyzed for TOC. Variability of TOC concentrations, whether noted as differences among the landfills or as the difference between upgradient and downgradient (or upstream-downstream pairs for surface-water sites) sampling locations, were generally less than that noted for most inorganic water-quality constituents. The highest ground-water TOC concentrations were at downgradient wells at each of the landfills. These wells also had elevated concentrations of inorganic indicator constituents.

At Harrisburg Road landfill, the highest TOC value was 6.9 mg/L in water from downgradient well HBW1850, but a value of 5.5 mg/L was observed in water from well HBW10 upgradient from the landfill. This well site is lower topographically and downgradient from a nearby wood-processing plant, so the observed TOC value may be due, in part, to the influence of this plant. Samples of ground water from all other wells, both upgradient and downgradient of the landfill, had TOC concentrations less than 4 mg/L.

None of the observed values for TOC in surface water were less than the detection limit. These values ranged from 1.9 mg/L in Reedy Creek at the Harrisburg Road landfill to 8.2 mg/L in Irwin Creek at the Statesville Road landfill.

Specific Organic Compounds

Although TOC data provide useful information for assessing the effect of landfill leachate with regard to undesirable color, odor, taste, and oxygen deficit, the TOC determination cannot provide information on the presence of trace levels of potentially harmful organic compounds. Movement of these specific organic compounds in the ground-water system is highly dependent on the physical and chemical characteristics of the individual compound as well as the earth material through which a compound must move. Sorption is the main process controlling the migration of organic compounds in the subsurface. Retardation or attenuation is related to the carbon content of the solid phase and the octanol-water partition coefficient of the organic compound. In a refuse disposal area, abundant quantities of cellulose from paper products may retard the movement of many organic compounds by absorption. In addition, numerous aerobic and anaerobic biological processes can degrade organic compounds at rates varying from days to decades.

Identification and quantification of these trace organic compounds requires specific laboratory techniques to fractionate and segregate the individual compounds based on physiochemical properties. Four general groups of organic compounds were analyzed: (1) acid and base/neutral extractables, (2) purgable (volatile) compounds, (3) organochloride insecticide (polychlorinated biphenyls and polychlorinated naphthalenes), and (4) chlorophenoxy acid herbicides.

A total of 40 wells were sampled for compounds belonging to one or more of these organic groups. The analyses for chlorinated insecticides and chlorophenoxy acid herbicides were performed most frequently (74 and 67 ground-water samples, respectively). Acid and base/neutral extractables analyses were performed on 31 samples from 21 of these wells. Four volatile organic compound analyses were performed, all on samples from well HRW3. Twenty-four surface-water samples were analyzed for organic compounds, mostly for chlorinated insecticides and chlorophenoxy acid herbicides.

Results for most organic compounds were reported as being below detection limits. The most frequently identified compounds were the chlorophenoxy acid herbicides and two volatile chlorofluoromethanes.

Two chlorophenoxy acid herbicides were detected in more than one-half of the ground-water samples analyzed: 2,4 dichlorophenoxy acetic acid (2,4-D) and 2,4,5 trichlorophenoxy acetic acid (2,4,5-T). At three wells, the propionic acid species (2,4-DP and 2,4,5-TP or Silvex) of these compounds were detected. Although each of these herbicides is widely used and fairly hydrophilic (solubility ranging from 200 to 1,000 mg/L), and, therefore, mobile in a ground-water system, the frequency of its detection and persistence is unexpected as decomposition in the soil is generally estimated to take only several months (Connell and Miller, 1984). No apparent difference in the frequency of occurrence of these herbicides among landfills could be detected, and the differences in frequency of occurrence between upgradient and downgradient wells were not statistically significant.

These herbicides also were detected in 10 of 22 surface-water samples. All concentrations of these herbicides in either ground or surface water were below standards for domestic water supply, 100 μg/L for 2,4-D and 10 μg/L for 2,4,5-TP (U.S. Environmental Protection Agency, 1984).

The two chlorofluoromethanes were detected in three of the four ground-water samples analyzed for volatile organic compounds. The most probable source of chlorofluoromethane is aerosol spray cans within the landfill. Although initially on the EPA list of priority pollutants, these compounds were removed in 1981. Currently, the principal environmental concern regarding these compounds is not water-related, but atmospheric ozone depletion.

Various phthalate esters used in the manufacture of many plastics were detected in six ground-water samples. Other than 1,3 dichlorobenzene (detected twice), no other organic compounds were detected more than once in ground-water samples. Lindane and dieldrin were each detected once in surface-water samples.

WATER-QUALITY CHARACTERISTICS AT LANDFILLS

Previous sections reported individually on the hydrologic environment at each landfill, operational histories, water-quality parameters best suited as indicators of leachate, and general comparative observations of indicators between landfills. This section focuses on the water quality at each landfill by bringing together some of this earlier information plus the areal distribution of water-quality indicators, background levels, leachate observations, environmental factors, factors outside the landfills that may influence water quality, and the need for additional data.

Harrisburg Road Landfill

The large number of wells at the Harrisburg Road landfill (33 for water levels, 28 for ground-water quality) provided data to determine direction of ground-water flow and background values for indicator constituents. However, the placement of additional wells could be improved to provide better vertical and areal coverage immediately downgradient of landfill cells. Some wells in the northeastern corner were discontinued or destroyed as development of the landfill continued. Wells in the western part of the site as yet are unaffected by past or current landfill development.

Water quality was monitored at five surface-water sites on the three small, northward-flowing streams that drain the landfill. Two of the three drainage ponds located within the landfill were monitored. Unlike the other three landfills, there are no streams upstream of the landfill that were monitored to determine background surface-water quality.

Ground Water

With the exception of manganese, concentrations of inorganic indicators in ground-water samples from Harrisburg Road landfill were generally low in comparison to other landfill sites. However, data indicate that there is a group of wells with slightly higher concentrations of most of these constituents located in the northwestern parts of the landfill (fig. 17). The group consists of wells HBW7, HBW11, HBW12, HBW14, HBW14A, HBW15, HBW1850, and HBW2100, all downgradient of disposal areas (fig. 5). Although the concentrations of inorganic indicators at these wells are higher than background at this site, they are comparable to background values at other landfills, and the evidence for leachate migration is inconclusive.

One explanation for the differences in manganese concentration is differences in composition of soils and saprolite of the regolith. Another factor may be effects of nonlandfill-related activities, such as a wood-processing plant located near the southwestern part of the landfill. Although the other inorganic indicators from ground water in wells HBW8, HBW9, and HBW10, located closest to the plant, do not indicate such an effect, an elevated TOC concentration in HBW10 may reflect an influence of nonlandfill activity. A more detailed analysis was not possible with existing data.

Surface Water

Concentrations of inorganic indicators in surface water draining the Harrisburg Road landfill are also low in comparison to other sites. Although chemical differences among surface-water sites at the landfill are

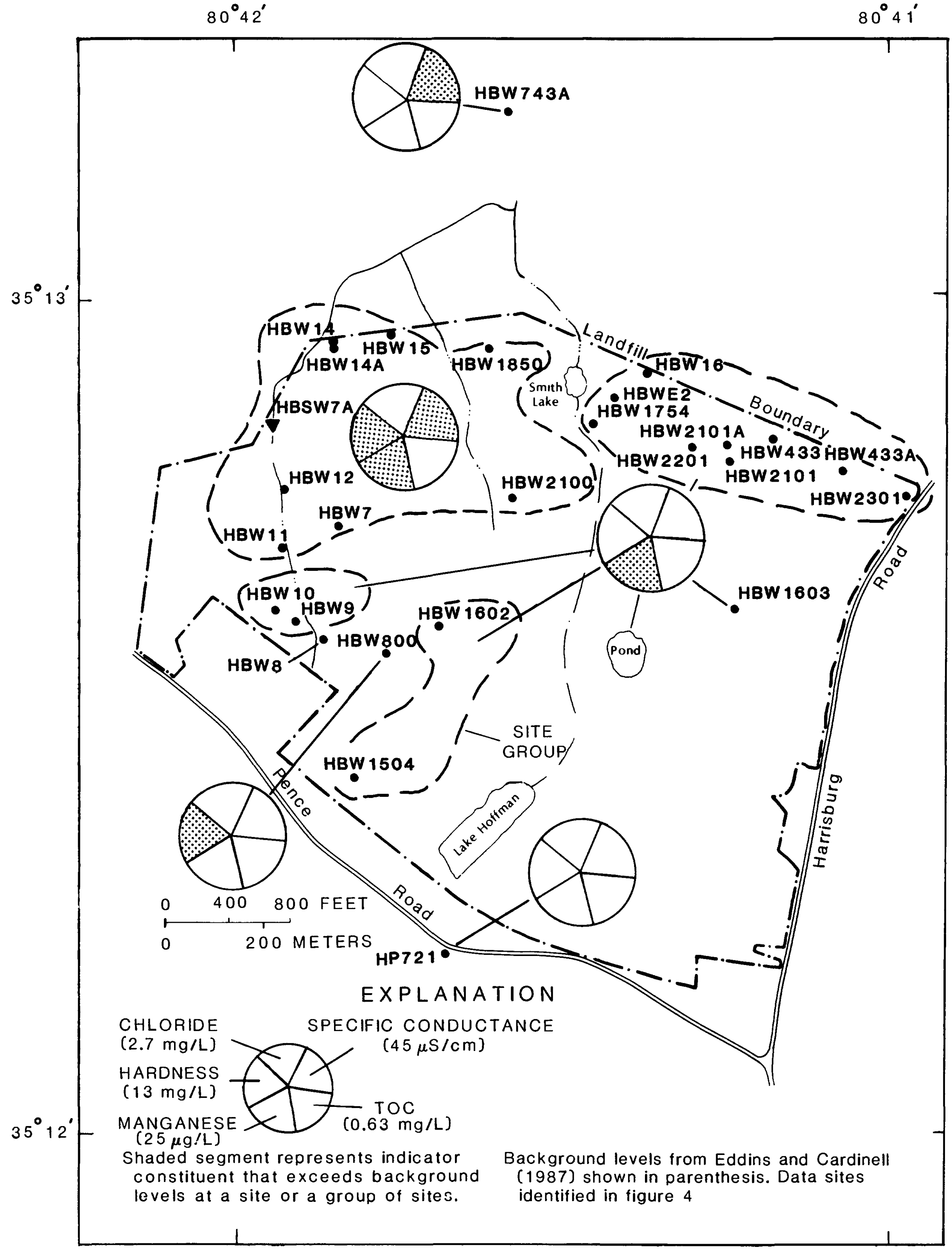

Figure 17.--Distribution of sites where water-quality indicators exceed background levels at Harrisburg Road landfill.

minor, the data indicate that the western-most tributary has the lowest concentrations of most constituents--the opposite of what was observed for ground water in this area of the landfill. The water-analysis diagram for HBSW2006 shows that the chemical composition of surface water draining the Harrisburg Road landfill during base flow appears to be a mixture of background (HBW1, HBW10, HBW1504) and downgradient (HBW14A, HBW15, and HBW1850) ground waters (fig. 12). No background surface-water site was present at this landfill.

Holbrooks Road Landfill

There are three wells upgradient and three wells downgradient of the landfill cells at the Holbrooks Road landfill. Well HRW1 is located at the toe of the older (western) cell and best situated to detect migration of landfill leachate. Well HRW5 is located approximately 300 ft further downgradient. Well HRW2 is the only well located downgradient of the newer landfill cell. All three of these wells are relatively shallow, the deepest being well HRW5--screened between 7.5 and 12.5 ft deep. Well HRW2 is very shallow--screened between 1.1 and 6.1 ft deep.

A short valley or draw tributary to South Prong Clark Creek divides the eastern and western halves of the landfill. This draw seldom carries water and was not sampled. Surface-water samples were collected from South Prong Clark Creek at one upstream and one downstream site. The landfill represents one-third of the intervening area between these sites and about 6 percent of the total basin area at the downstream station.

Ground Water

Placement of well HRW1 at the toe of the western landfill cell allows the observation of leachate directly from that older cell (fig. 6). Specific conductance and hardness values in ground water here were an order of magnitude higher than background, as schematically depicted in figures 13 and 15.

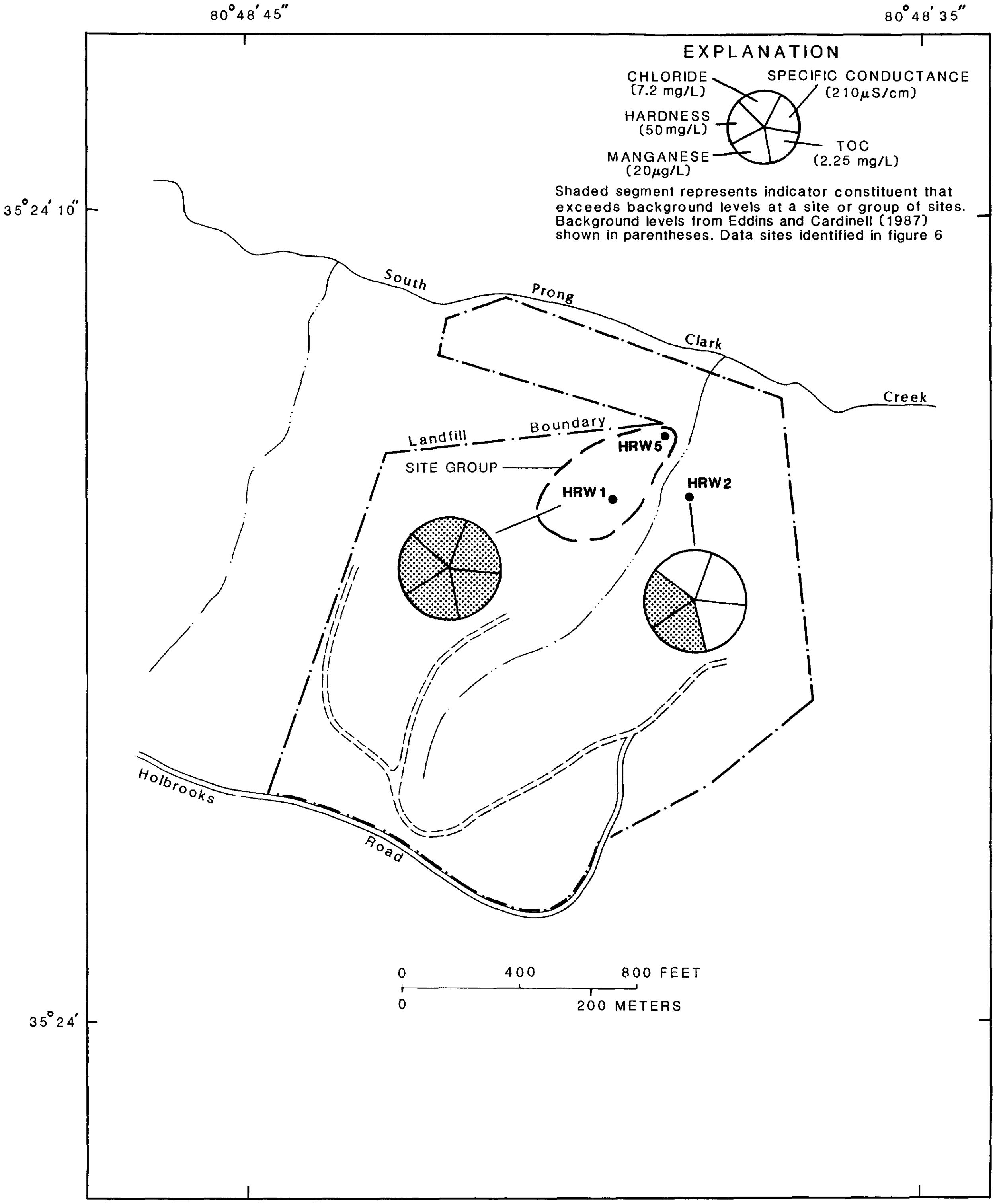

Figure 18.--Distribution of sites where water-quality indicators exceed background levels at Holbrooks Road landfill.

The increase in both chloride and manganese was even larger, approximately 40-fold for chloride (fig. 14) and 1,000-fold for manganese concentrations (fig. 16), and the organic indicator, TOC, was more than 10 times background values in upgradient wells.

Leachate has been observed in seeps at the toe of the western cell and north of well HRW5. HRW5 was so located to monitor the characteristics of the leachate plume further downgradient. Water from this well also showed an increase in indicator constituents above background values (fig. 18). For indicators other than manganese, values are generally more than 10-fold greater than background values; manganese concentrations at HRW5 were 20 times higher.

Ground water from well HRW2 at the toe of the eastern cell did not show the influence of leachate in any indicators other than hardness and manganese. Two reasons for this lack of effect of the landfill on other indicator constituents at well HRW2 are that (1) not enough time has elapsed for leachate to develop and migrate from the younger disposal area to the well, and (2) the well is screened to a depth of 6.1 ft, which may not be deep enough to sample leachate beneath the well.

Surface Water

There is no apparent effect of the landfill on the water quality of South Prong Clark Creek. Data for specific conductance and chloride concentrations (fig. 19) are nearly identical at the upstream (HRSW2) and downstream (HRSW1) sampling locations. However, the observed water quality at wells HRW1 and HRW5 suggests that leachate may eventually affect the water quality of the unsampled tributary.

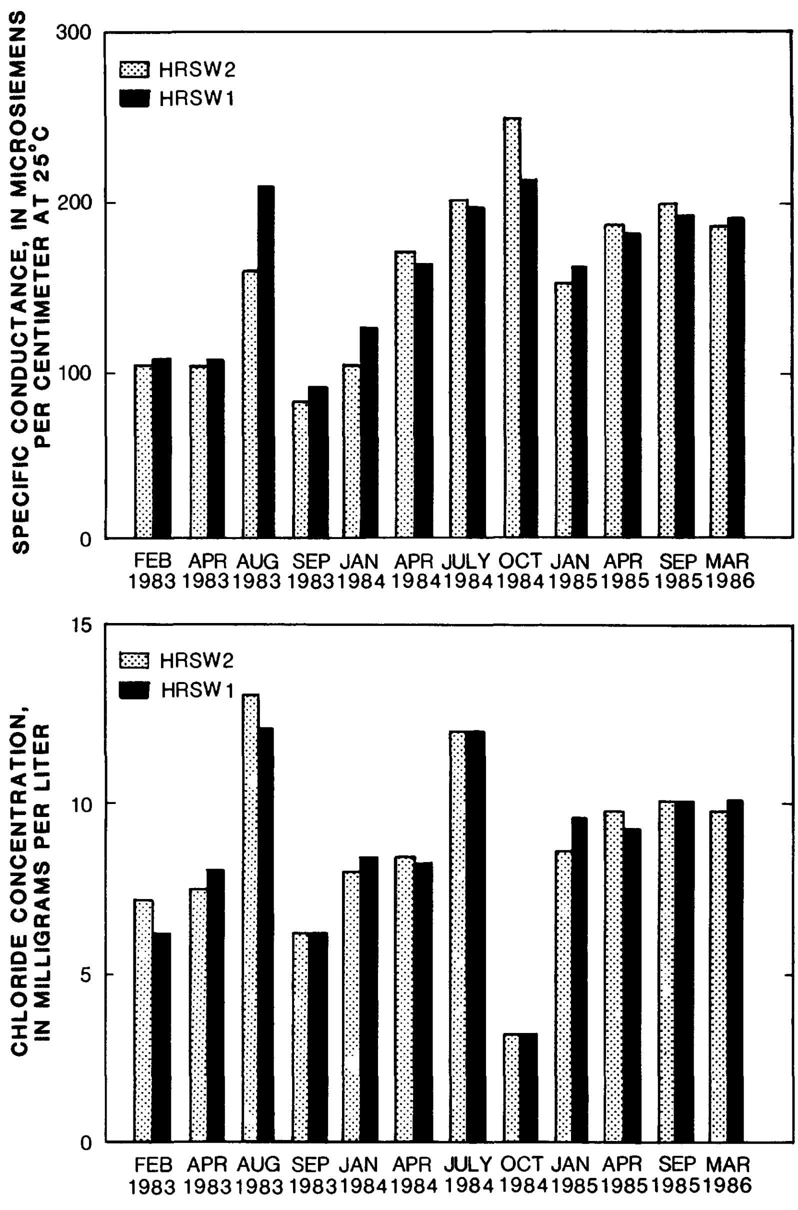

Figure 19.--Specific conductance values and chloride concentrations at surface-water quality monitoring sites HRSW1 and HRSW2 at Holbrooks Road landfill.

Statesville Road Landfill

Four wells in or adjacent to the Statesville Road landfill were sampled. Well SRW21 is near the eastern side of the west landfill cell (fig. 7) and is situated for determining ground-water quality directly beneath the landfill. Well SRW22 is outside of the southwestern corner of the west landfill cell and may or may not be positioned to detect effects of the landfill on ground-water quality. Two wells are located upgradient of the landfill to provide background data.

Irwin Creek flows to the southwest through the Statesville landfill. Surface-water samples were collected upstream of the landfill (SRSW3), immediately downstream of the landfill (SRSW11), and at a small tributary to Irwin Creek that drains the western landfill cell (SRSW2). The landfill area is approximately 10 percent of the intervening drainage area between sites SRSW3 and SRSW11. Samples were also collected further downstream at three other sites on Irwin or on Sugar Creek.

Ground Water

Concentrations of indicator constituents for ground-water samples taken from wells SRW20 and SRW23R, which should reflect background ground-water quality, were generally higher than those values obtained at background wells located near the other landfills (figs. 13 and 16). For all indicator constituents except manganese, the concentrations obtained at SRW20 were twice those from SRW23R (fig. 20). There are no apparent differences in the geology or geochemistry in the areas of these wells. These two wells are in an established neighborhood that is several decades old, and both are near commercial establishments, such as a service station. The background ground-water quality at these wells may be affected by the commercial and residential development.

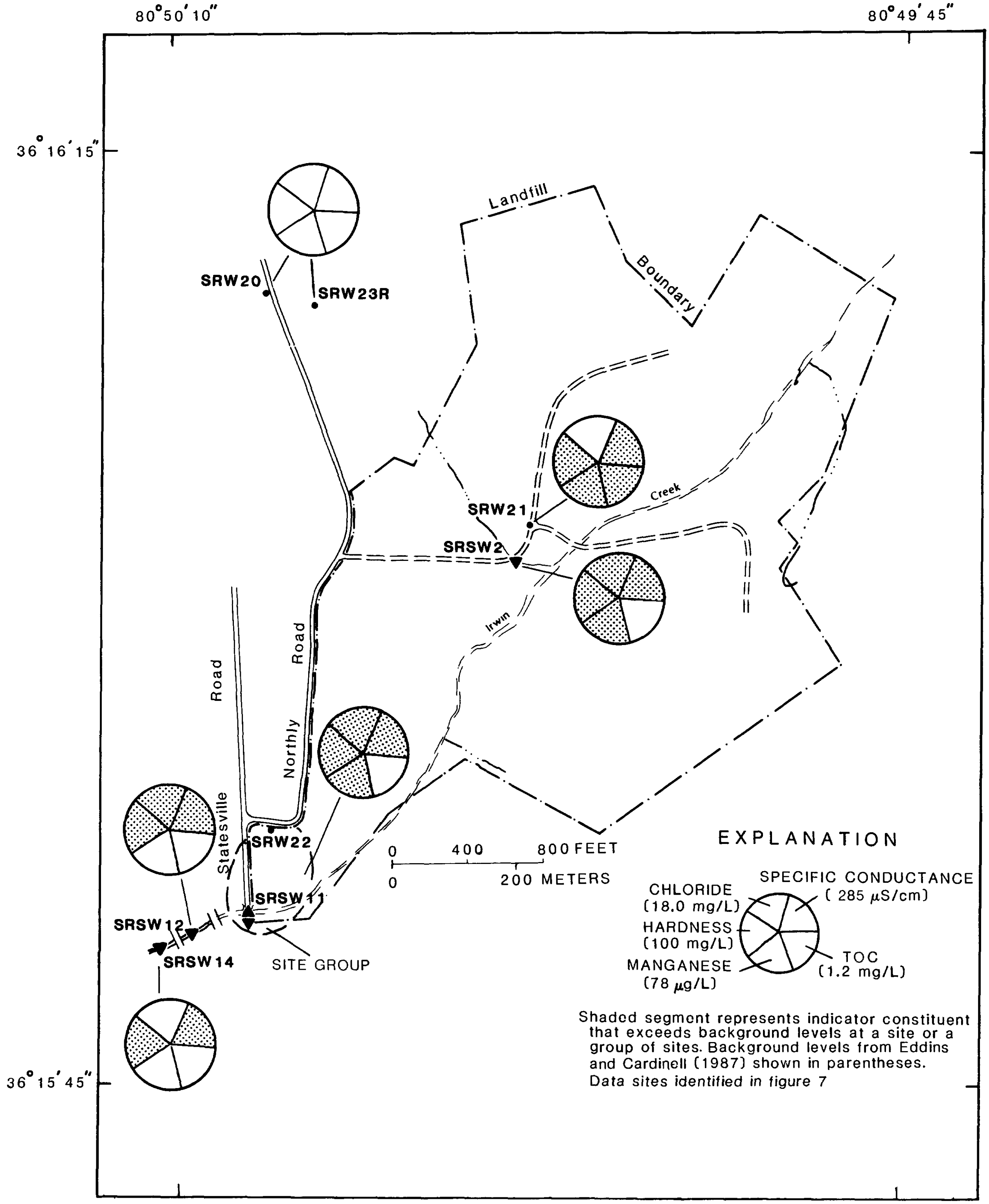

Figure 20.--Distribution of sites where water-quality indicators exceed background levels at Statesville Road landfill.

The highest values for all indicator constituents, except chloride, were from water samples collected from beneath the landfill at well SRW21. The unexpectedly low chloride concentrations (median 6.4 mg/L) at SRW21 are near background levels and were decreasing up to the time of the last sample. It is possible that chloride, which is very mobile and readily dissolved, has been nearly leached, or that the fill in that immediate area did not contain much chloride. In either case, however, this anomaly is areally limited, as base flow in the nearby tributary stream (SRSW2) contained chloride concentrations above 100 mg/L during the period.

The lack of additional ground-water level data near well SRW22 made it difficult to determine the direction of ground-water flow at this location and, thus, to assess whether the well would intercept leachate. Water-quality data, however, indicated that ground water was affected by leachate at SRW22. Although values of indicator constituents were generally not as high as at SRW21, values were substantially above levels in water from wells SRW20 and SRW23R. Chloride concentrations were generally above 100 mg/L; hardness values were above 340 mg/L as $CaCO_3$; the median specific conductance value was nearly 1,000 µS/cm, and manganese concentrations were more than 700 µg/L. During the study period, there was little variability of indicator constituents in ground water at each well, and the data showed no evidence of temporal trends other than the decline in chloride at SRW21.

Surface Water

Values of indicator constituents in surface water, except TOC, were higher at site SRSW2, on the small tributary which flows through the landfill to Irwin Creek, than at any other surface-water monitoring site in this study. The contributions from this tributary significantly increased the concentrations of indicator constituents in Irwin Creek. Figure 21 presents specific conductance, chloride, and hardness data for surface-water samples collected from Irwin Creek at sites upstream (SRSW3) and downstream (SRSW11) from the landfill and from the unnamed tributary (SRSW2). The change in water quality between sites SRSW3 and SRSW11 on Irwin Creek is

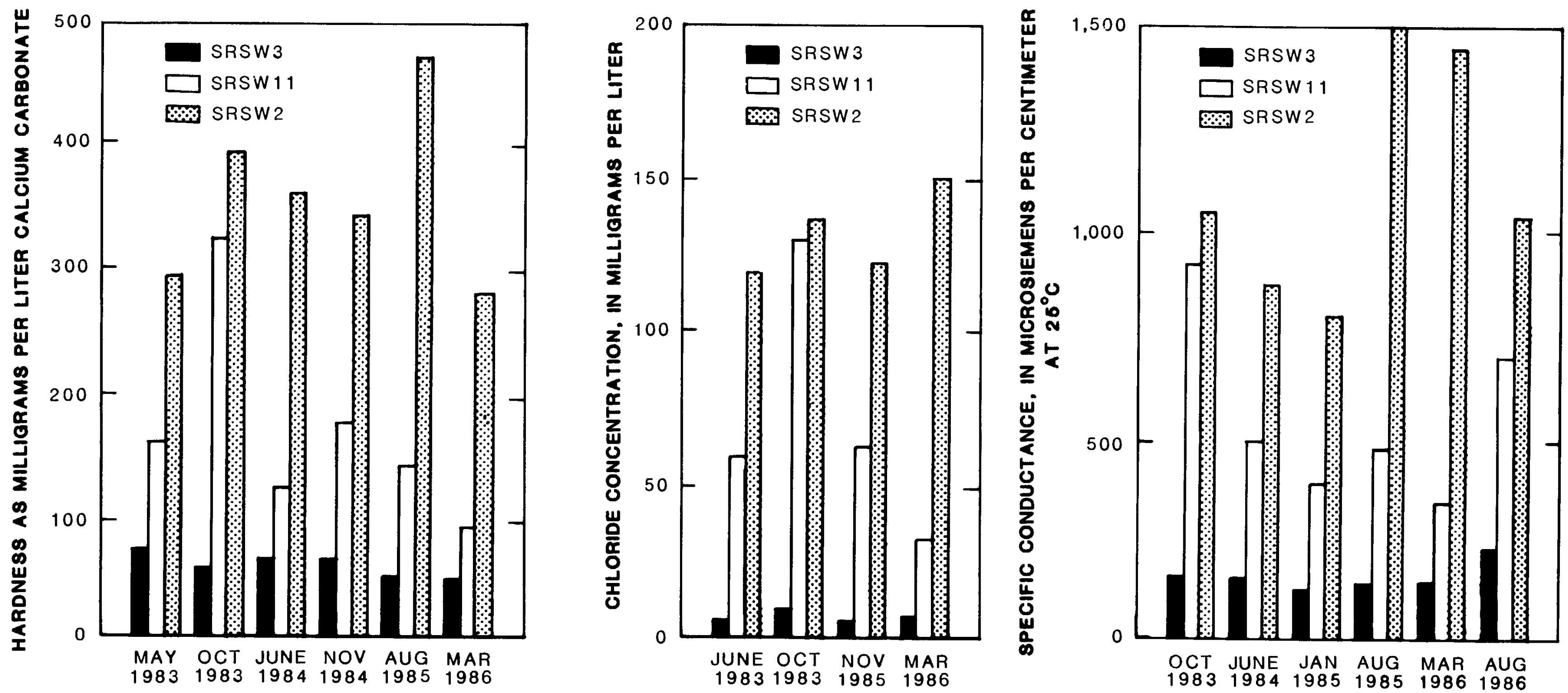

Figure 21.--Specific conductance values and chloride and hardness concentrations at surface-water quality monitoring sites SRSW2, SRSW3, and SRSW11 at Statesville Road landfill.

clearly apparent, especially the 10-fold increase in chloride concentration. Manganese concentrations also increased nearly 5-fold between SRSW3 and SRSW11. Such increases are not unexpected because much of the waste is buried in the saturated zone and leachate, no doubt, forms a considerable part of the base flow from this landfill area. Data collected at other sites further downstream indicate that high concentrations of all indicator constituents in Irwin Creek are diluted by other waters entering Irwin and Sugar Creeks.

York Road Landfill

Four wells (YRW1, YRW2, YRW3, and YRW4) are in the area of the 1981-83 landfill cell, with YRW1, at the toe of the cell, the best location to first detect leachate plume migration. One well, YRW6, is downgradient of the older parts of the landfill. Other monitoring wells provided background water-quality information; some were abandoned as new cells were established, and some were sampled only once.

Three surface-water sites were located on Sugar Creek and had fairly large drainage basins that exceeded 30 mi^2. Site YRSW41, was the only station downstream of the York Road landfill on Sugar Creek and had a 41.2 mi^2 basin drainage area. The landfill represents about 1 percent of this total drainage area. Two surface-water monitoring stations were established on the unnamed tributary which drains the eastern and southern areas of the landfill. Site YRSW9A is located downstream of the 1981-83 disposal area. Site YRSW9 was further downstream, and the intervening drainage area included most of the pre-1980 disposal cells. The remaining surface-water sampling site, YRSW8, was established on the unnamed tributary draining the northwestern part of the landfill. During the study, this stream was virtually unaffected by past or current landfill activity, and data at the monitoring site provided background information.

Ground Water

Samples from wells YRW1 and YRW6 show the largest effects of leachate from the York Road landfill moving into the ground-water system. Indicator constituents of specific conductance, hardness, chloride, and manganese in water from both wells showed an increase above background values (figs. 13-16). In addition, TOC values from well YRW1 were also above background (fig. 22). Both wells were downgradient from disposal cells (fig. 10), and elevated indicator constituents were not unexpected.

High concentrations of manganese were also observed in several background monitoring wells YRW3, YRWB2A, and YRWB12 (fig. 16). Although the other indicators reflected normal ground-water quality ranges at these sites, the median manganese concentration was 5 times higher than other background sites.

The variability of indicator constituents with time marks the progress of a leachate plume in the ground-water system. The temporal variability of these constituents, as measured in samples from well YRW6, did not show any notable pattern; leachate apparently arrived before sampling began and showed little change during the study. However, substantial temporal changes were seen in water-quality data from well YRW1. Beginning about 1985, or 2 years after closure of the cell, indicator constituents of specific conductance, chloride, manganese, and TOC increased markedly over background values measured during the previous 4 years (fig. 23). These data time the arrival of the leachate plume from this landfill cell.

Samples from background wells on the landfill property (YRW2, YRW3, YRW4, YRWA, YRWB13, and YRWB14) had values for indicator constituents ranging from 20 to 50 percent above background values from off-site wells. The number of samples was too limited and variability of measurements too large to assess the significance of these values.

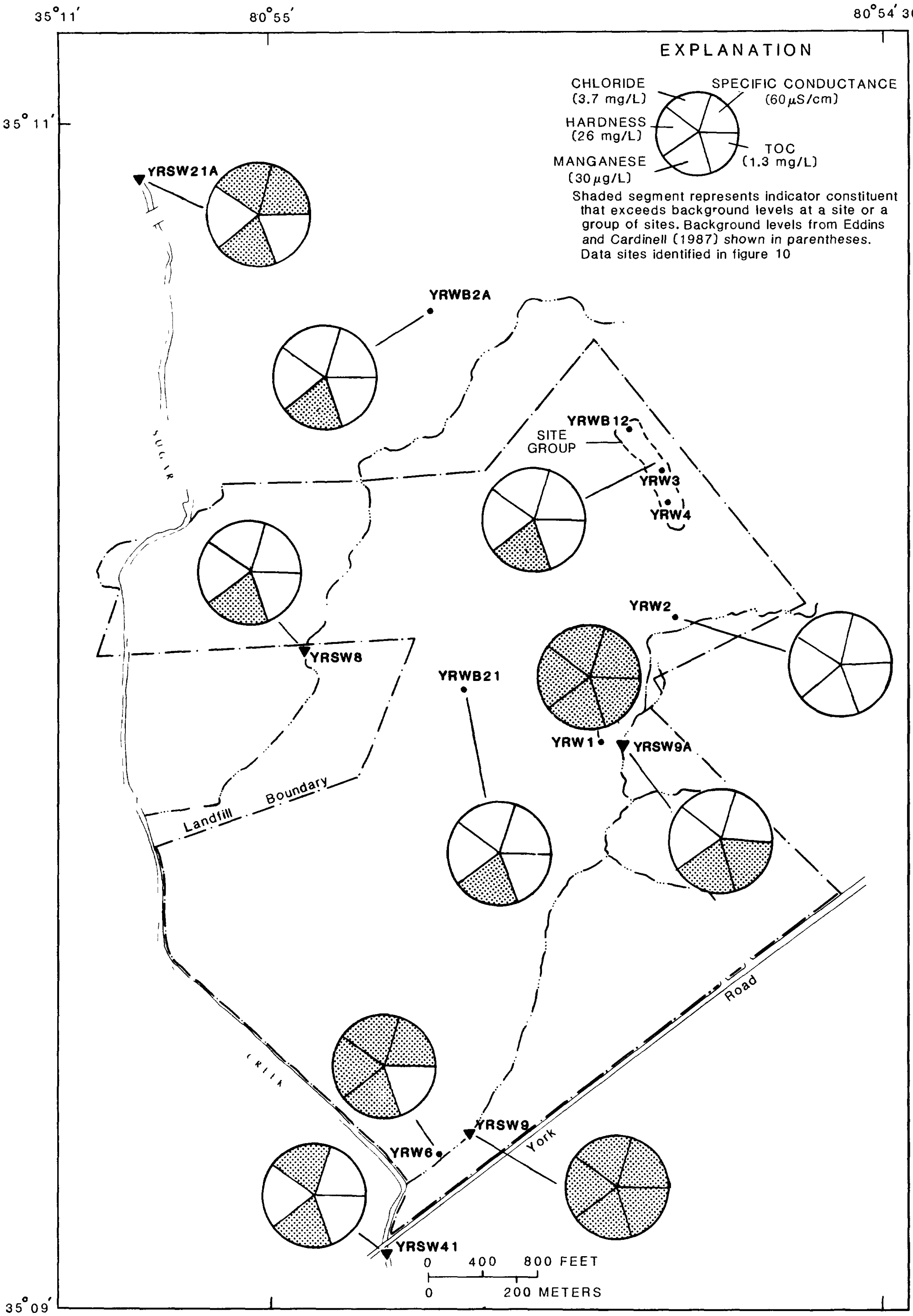

Figure 22.--Distribution of sites where water-quality indicators exceed background levels at York Road landfill.

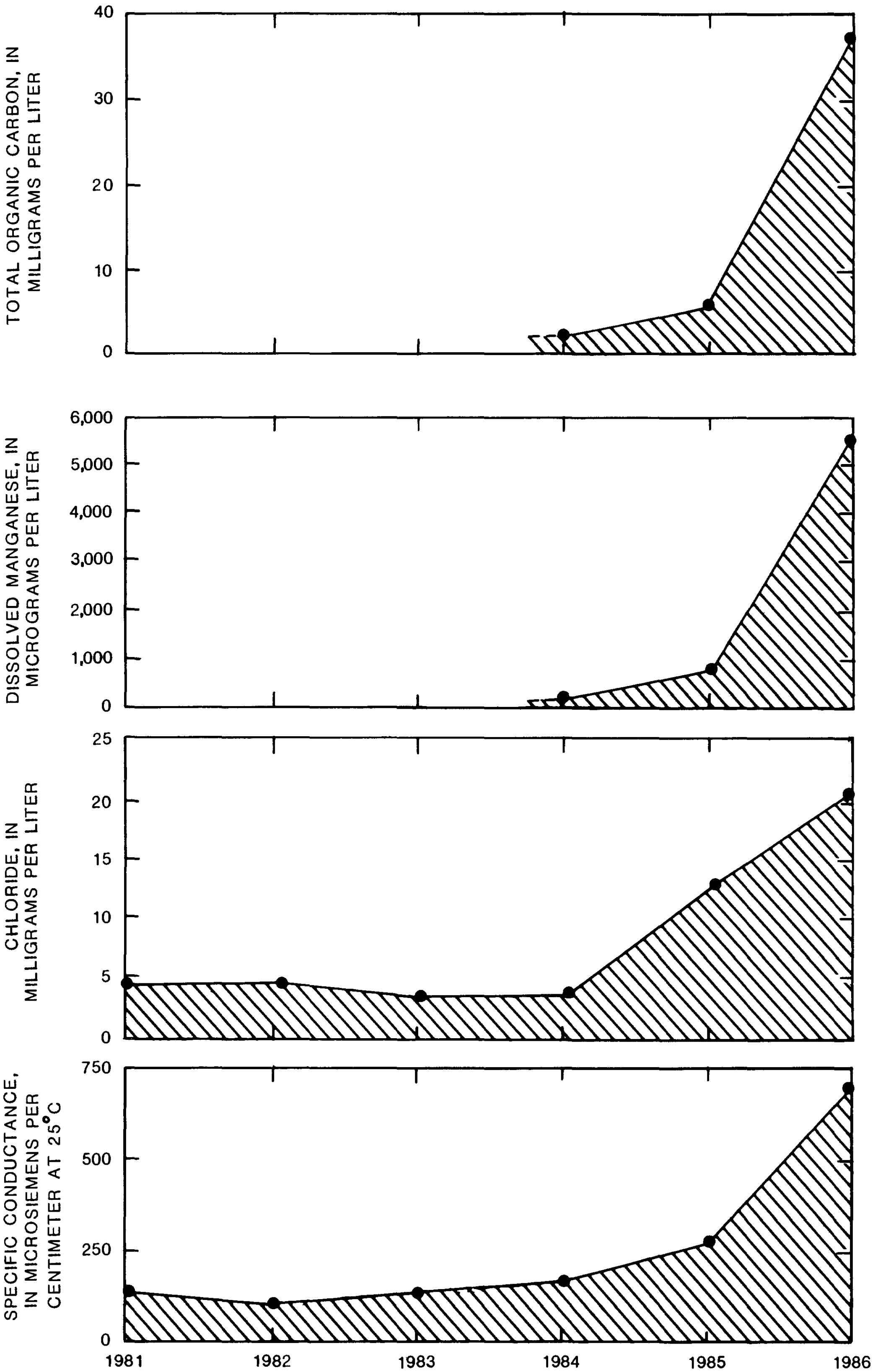

Figure 23.--Annual average specific conductance values and concentrations of dissolved chloride, dissolved manganese, and total organic carbon at well YRW1, 1981-86, at York Road landfill.

Surface Water

The unnamed tributary to Sugar Creek draining the eastern and southern parts of the York Road landfill is more affected by leachate than is the tributary draining the westernmost part of the landfill. For most constituents, concentrations increase downstream between sites YRSW9 and YRSW9A. Figure 24 presents specific conductance, chloride, and hardness values for a number of samples collected on the same day to illustrate the differences in water quality in these tributaries. The indicators for the unaffected tributary at site YRSW8 are lowest, whereas these constituents are in greater concentration and increase downstream in the southeast tributary.

Concentrations of inorganic indicator constituents at each site during base flow generally reflect the quality of the contributing ground water. At site YRSW8, the water quality corresponded to that in background wells (fig. 23); at site YRSW9A, stream base-flow quality corresponded to a mixture of background quality and the water quality in wells YRW1, YRW2, YRW3, and YRW4; and, at site YRSW9, the quality was the result of the combined input from upstream site YRSW9A and the leachate composition observed in well YRW6. Data at site YRSW9A did not indicate any temporal change in concentrations of indicator constituents as observed at well YRW1.

Results indicate that the York Road landfill had no appreciable effect on water quality in Sugar Creek. Comparing data collected on the same days at sites YRSW21A and YRSW41 showed no substantial difference for any of the indicator constituents. This may be due, in part, to the fact that the landfill represents only 1 percent of the basin area. However, concentrations of most constituents in Sugar Creek were higher than those at site YRSW9 because of the cumulative effects of numerous point discharges and four other landfills upstream. Manganese was the only indicator higher in the southeast tributary than in Sugar Creek.

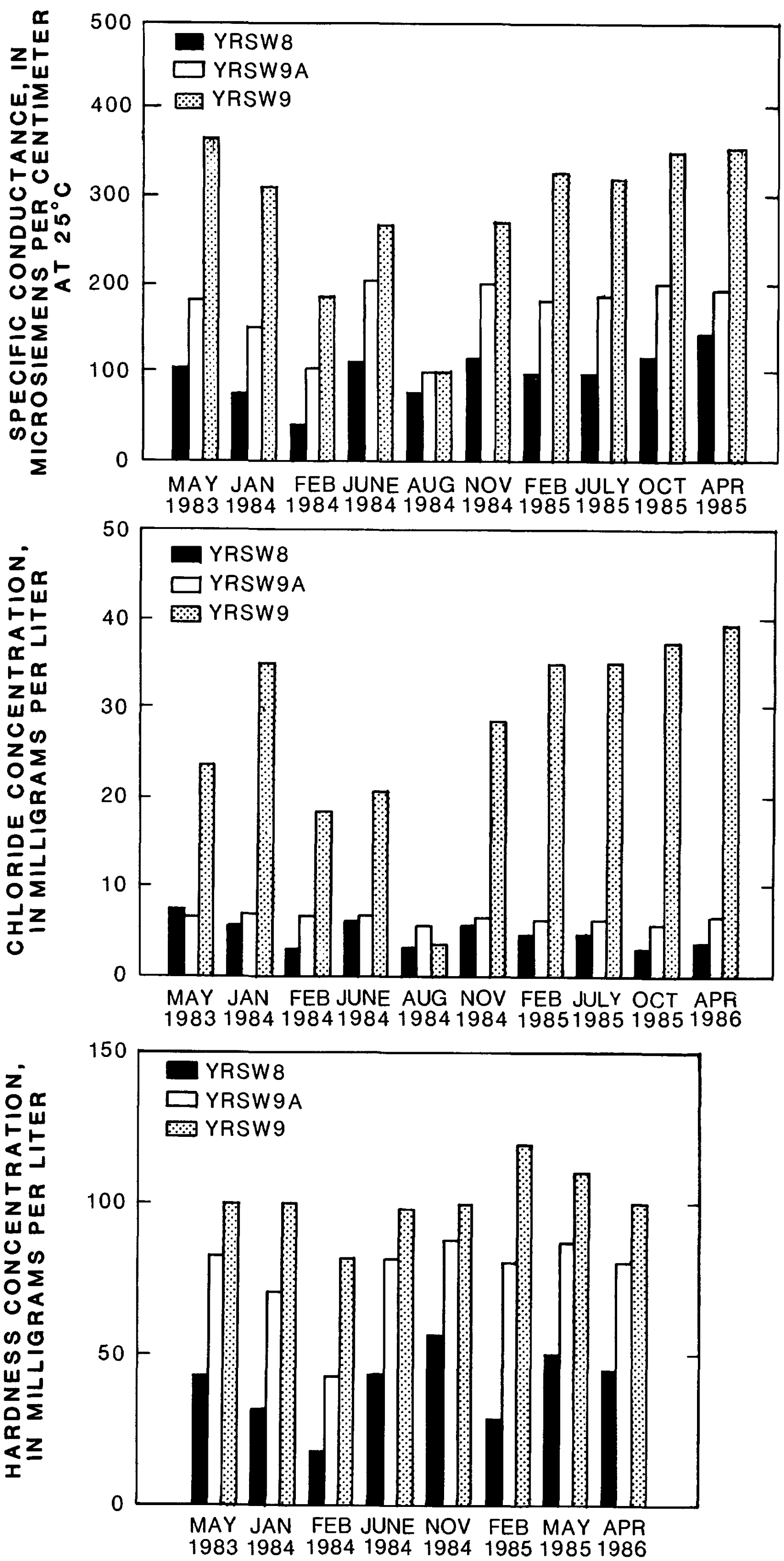

Figure 24.--Specific conductance values and chloride and hardness concentrations at surface-water quality monitoring sites YRSW8, YRSW9, and YRSW9A at York Road landfill.

SUMMARY

The hydrogeologic setting for landfills in Mecklenburg County, North Carolina, is typical of that for the North Carolina Piedmont; that is, it is a 3-stage system that consists of a regolith, a transition zone, and fractured crystalline rock. On the average, about 7 in. of rainfall enters the ground each year and percolates vertically through the unsaturated zone to the water table. From there, ground water moves laterally down the hydraulic gradient to discharge into streams. Beneath landfills, rainfall sometimes becomes mixed with a variety of chemical constituents forming a leachate that can contaminate the ground-water system and the streams receiving ground water.

The effect of landfill leachate on ground- and surface-water quality was investigated at four landfill sites in Mecklenburg County in the mid 1980's. These were the Harrisburg Road landfill, the Holbrooks Road landfill, the Statesville Road landfill, and the York Road landfill. A total of 53 wells and 20 surface-water sites in or near the landfills were monitored during the investigation.

Although the water samples were analyzed for more than 100 constituents, six properties or constituents were found to be the best indicators of leachate in the water chemistry. The indicators were specific conductance, chloride, hardness, manganese, total organic carbon, and dissolved-solids concentrations. Several organic pesticides and herbicides also were useful as indicators of leachate in some waters.

The interpretation of ground- and surface-water quality data at or near a landfill is complicated both by the complex chemical nature of landfill leachate and uncertainties in describing ground-water flow. Placement or depth of monitoring wells has an important bearing on which part of the ground-water system is measured and, consequently, on the interpretation of the data thus gathered. Where monitoring wells have been placed in or immediately adjacent to waste-disposal areas, the influence of landfill

leachate on ground-water quality can be readily apparent. At greater distances, this influence is not always as apparent, and knowledge of ground-water flow paths becomes increasingly important.

Similar problems occur in evaluating the effects of the landfill on surface-water quality. Whereas the effects were apparent at several of the smaller tributaries, the effects of leachate were often masked by dilution in larger streams. Therefore, surface-water concentrations alone were not necessarily an indication of which landfill sites were contributing greater loads of contaminants to the stream but were merely indicative of the greater assimilative capacity of the larger streams.

Within these limitations, ground-water and surface-water quality at the four Mecklenburg County landfills can be summarized as follows:

1. Differences in the composition of ground water at unaffected sites in the four landfills indicated differences in local bedrock and regolith minerology at each site.

2. Dissolved-solids concentrations and specific conductance in samples collected at downgradient wells were higher than those in upgradient wells at all four landfills. The increases were greatest in those wells closest to older disposal cells.

3. Chloride, manganese, and hardness concentrations in samples from downgradient wells increased more than did concentrations of the other indicators.

4. Water from several wells at Statesville Road, York Road, and Holbrooks Road landfills and surface-water sites at Statesville Road and York Road landfills had specific conductance values (taken as an indication of dissolved-solids concentrations) that might make them objectionable as water supplies.

5. Hardness was higher than background concentrations in most wells downgradient from landfills. Waters from six of these monitoring wells were classified as either hard or very hard. Upgradient wells generally contained soft water. Statesville Road landfill was the only site with hard or very hard surface waters.

6. Manganese concentrations showed the largest relative differences between upgradient and downgradient ground water. The downgradient increase in downgradient manganese was as large as 1,000-fold at Holbrooks Road landfill. Manganese concentrations at some upgradient and nearly all downgradient wells at each landfill exceeded 50 μg/L.

7. Differences in organic concentrations between upgradient and downgradient wells were not as well defined as for inorganic constituents. However, at three of the four landfills, the highest total organic carbon concentrations were at downgradient wells.

8. Two chlorophyenoxy acid herbicides, 2,4-D and 2,4,5-T, were detected in more than half the ground-water and nearly half of the surface-water samples. Chlorofluoromethane was detected in three of four ground-water samples analyzed for volatile organic compounds. Concentrations of other organic compounds were below detection limits.

9. Harrisburg Road landfill had the least effect on surface- and ground-water quality during the period of the study. Concentrations of most indicator constituents were low. This may be due to the fact that this is the youngest landfill, and waste disposal was progressing in a downgradient direction relative to ground-water flow.

10. Well HRW1, immediately downgradient of the western disposal area at Holbrooks Road, was substantially affected by leachate. Well HRW2, downgradient of the eastern disposal area, did not appear

affected, perhaps because of the younger age of this disposal area or the shallow depth of the well. There was no apparent effect of Holbrooks Road landfill on the South Prong of Clark Creek.

11. Statesville Road landfill was the oldest studied and appeared to influence water quality more than the other three landfills. The largest concentrations of most constituents were at well SRW21 and surface-water site SRSW3. These larger concentrations may result, in part, from the burial of refuse within the saturated zone in more than half the landfill. The water quality of Irwin Creek, as a result of the landfill, was substantially affected.

12. Older disposal areas in the southern half of York Road landfill were observed to affect adjacent surface- and ground-water quality. Temporal trends at well YRW1 indicated that leachate from the more recently used disposal areas were beginning to affect ground water. Influence of the landfill on the water quality of Sugar Creek was not evident.

The oldest landfill (Statesville Road) and the older sections of the Holbrooks Road and York Road landfills have had the greatest effect on the ground water and surface water at these sites. There was little evidence of ground- or surface-water quality changes at the Harrisburg Road landfill. These results illustrate influence of time on the movement of pollutants in ground water.

REFERENCES

Brunner, P.R., and Keller, D.J., 1972, Sanitary landfill design and operation: U.S. Environmental Protection Agency, EPA-SW-65.

Connell, D.W., and Miller, G.J., 1984, Chemistry and ecotoxicology of pollution: New York, New York, John Wiley & Sons, Inc., 274 p.

Daniels, R.B., Kleiss, H.J., Boul, S.W., Byrd, H.J., and Phillips, J.A., 1984, Soil systems in North Carolina: North Carolina Agricultural Research Service, North Carolina State University, Bulletin 467, 77 p.

Durfor, C.N., and Becker, Edith, 1964, Public water supplies of the 100 largest cities in the United States, 1962, U.S. Geological Survey Water-Supply Paper 1812, 364 p.

Eddins, W.H., and Cardinell, A.P., 1987, Surface- and ground-water quality data at selected landfill sites in Mecklenburg County, North Carolina, 1980-86: U.S. Geological Survey Open-File Report 87-564, 394 p.

Eddins, W.H., and Crawford, J.K., 1984, Reconnaissance of water-quality characteristics of streams in the city of Charlotte and Mecklenburg County: U.S. Geological Survey Water-Resources Investigations Report 84-4308, 105 p.

Farrar, S.S., 1985, Tectonic evolution of the eastern most Piedmont, North Carolina: Geological Society of America Bulletin, v. 96, p. 362-380.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, New Jersey: Prentice-Hall, 604 p.

Gilbert, N.J., Brown, H.S., and Schaeffer, M.F., 1982, Structure and geologic history of a part of the Charlotte Belt, South Carolina Piedmont, Southeastern Geology, v. 23, no. 3, p. 129-145.

Goldsmith, R., Milton, D.J., and Horton, J.W., Jr., 1982, Preliminary geologic map of the Charlotte 1° x 2° quadrangle, North Carolina and South Carolina: U.S. Geological Survey Open-File Report 81-56, 1 p.

Hack, J.T., 1982, Physiographic dimensions and differential uplift in the Piedmont and Blue Ridge: U.S. Geological Survey Professional Paper 1265, 49 p.

Heath, R.C., 1980, Basin elements of ground-water hydrology with reference to conditions in North Carolina: U.S. Geological Survey Water-Resources Investigations Open-File Report 80-44, 86 p.

Hem, J.O., 1985, Study and interpretation of the chemical characteristics of natural water (3rd ed.): U.S. Geological Survey Water-Supply Paper 2254, 263 p.

Law Engineering and Testing Company, 1980, Report of subsurface exploration and engineering evaluation Statesville Avenue landfill, Statesville Avenue at Northerly Road, Charlotte, North Carolina: Law Engineering and Testing Company, job no. CH 4442, 50 p.

_____1982, Report of geotechnical exploration and geohydrological evaluation York Road landfill expansion, Charlotte, North Carolina: Law Engineering and Testing Company, job no. CH 4762, 108 p.

LeGrand, H.E., 1967, Ground water of the Piedmont and Blue Ridge provinces in the southeastern states: U.S. Geological Survey Circular 538, 11 p.

LeGrand, H.E., and Mundorff, M.J., 1952, Geology and ground water in the Charlotte area, North Carolina: North Carolina Department of Conservation and Development Bulletin 63, 88 p.

North Carolina Department of Natural Resources and Community Development, 1985, Geologic map of North Carolina: North Carolina Department of Natural Resources and Community Development, 1 sheet, scale 1:500,000.

Nutter, L.J., and Otton, E.G., 1969, Ground-water occurrences in the Maryland Piedmont: Maryland Geological Survey Report of Investigations, no. 10, 56 p.

Pavish, M.J., 1985, Appalachian Piedmont Morphogenesis--in Tectonic Geomorphology, edited by M. Morisawa and J. T. Hacki: Boston, Mass., Allen and Unwin, 299 p.

Piper, A.M., 1944, A graphic procedure in the geochemical interpretation of water analyses: American Geophysical Union Transactions, v. 25, p. 914-923.

Ragland, P.C., Hatcher, R.D., Jr., and Whittington, D., 1983, Juxtaposed Mesozoic diabase dike sets from the Carolinas: A preliminary assessment: Geology, v. 11, p. 394-399.

Russell, G.S., Russell C.W., and Farrar, S.S., 1985, Alleghanian deformation and metamorphism in the eastern North Carolina Piedmont: Geological Society of America Bulletin, v. 96, p. 381-387.

Simmons, C.E., and Heath, R.C., 1979, Water-quality characteristics of forested and rural basins in North Carolina: in U.S. Geological Survey Water-Supply Paper 2185, Chapter 13, 1982.

Stewart, J.W., 1962, Water-yielding potential of weathered crystalline rocks at the Georgia Nuclear Laboratory: U.S. Geological Survey Professional Paper 450-b, 2 p.

U.S. Environmental Protection Agency, 1976, Quality criteria for water: Washington, D.C., U.S. Government Printing Office, 256 p.

_____1977, Procedures manual for ground water monitoring at solid waste disposal facilities: Office of Solid Waste, U.S. Environmental Protection Agency Manual SW-611, 269 p.

_____1984, Ground-water protection strategy: Office of Ground-Water Protection, U.S. Environmental Protection Agency Paper, August 1984, 54 p.

_____1986, Quality criteria for water: Office of Water Regulations and Standards, U.S. Environmental Protection Agency 440/5-86-001, 310 p.

U.S. Geological Survey, 1980-86 (annual), Water-resources data report--North Carolina: U.S. Geological Survey Water-Data Reports.

Wehr, Frederick, and Grove, Lynn, III, 1985, Stratigraphy and tectonics of the Virginia-North Carolina Blue Ridge: Evolution of a late Proterozoic-early Paleozoic hinge zone, Geological Society of America Bulletin, v. 96, p. 285-295.

☆U.S. GOVERNMENT PRINTING OFFICE 1989—650-613/88095