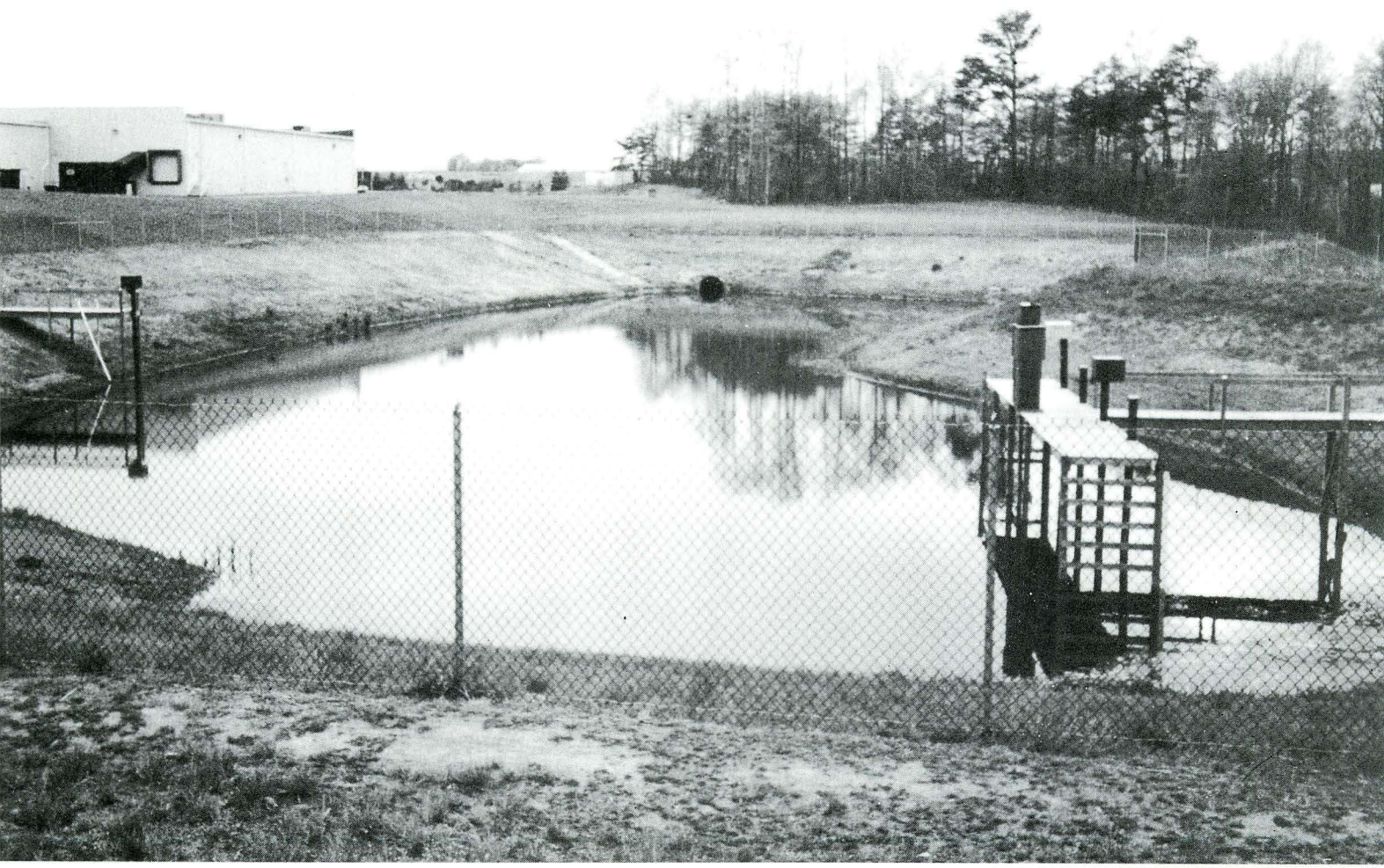
REPORT OF INVESTIGATIONS NO. 59

GEOCHEMISTRY AND FACTORS AFFECTING GROUND-WATER QUALITY AT THREE STORM-WATER-MANAGEMENT SITES IN MARYLAND

by
Franceska D. Wilde



Prepared in cooperation with the
United States Department of the Interior
Geological Survey,
The Maryland Department of the Environment,
and
The Governor's Commission on Chesapeake Bay Initiatives

Department of Natural Resources
Maryland Geological Survey
Emery T. Cleaves, Director
1994

CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To obtain metric unit
	Length	
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
foot per mile (ft/mi)	0.1894	meter per kilometer
	Area	
acre	0.4047	hectare
square mile (mi^2)	2.590	square kilometer
	Concentration	
parts per million (ppm)	1	milligram per liter
parts per million (ppm)	1	micrograms per gram
parts per million (ppm)	1	milligram per kilogram
parts per billion (ppb)	1	micrograms per liter
parts per billion (ppb)	1	microgram per kilogram
	Flow	
cubic foot per day (ft^3/d)	0.02832	cubic meter per day
gallon per minute (gal/min)	3.785	liter
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day
	Transmissivity	
foot squared per day (ft^2/d)	0.09290	meter squared per day
	Mass	
pound	0.4536	kilogram

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

Abbreviated water-quality units used in report: The concentration unit of milliequivalents per liter (meq/L) takes into account the ionic charge and combining weight of an ion. In an analysis expressed in meq/L, unit concentrations of all ions are chemically equivalent. (See Hem, 1985, p. 56 for a further explanation and comprehensive listing of conversion factors.) Specific electrical conductance of water is expressed in microsiemens per centimeter at 25 degrees Celsius (µS/cm). This unit is equivalent to micromhos per centimeter at 25 degrees Celsius. Pressure is expressed in pounds per square inch (lb/in^2).

Water temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) using the following equation:

$$°F = 1.8\,(°C) + 32$$

Chemical concentrations and water temperature are given in metric units. Chemical concentration is given in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter is a unit expressing the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water. One thousand micrograms per liter is equivalent to 1 milligram per liter, and 1,000 milligrams per liter is equal to 1 gram per liter (g/L). For concentrations less than 7,000 mg/L, the numerical value is the same as for concentrations in parts per million.

Department of Natural Resources
MARYLAND GEOLOGICAL SURVEY
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ABSTRACT

The effects of infiltration of storm runoff on ground-water chemistry and quality were examined at three suburban storm-water-management impoundments at sites in Annapolis, Greenmount, and Prince Frederick, Maryland. Geochemical and hydrologic data were collected from December 1985 through June 1989. The Annapolis and Prince Frederick sites are in the Coastal Plain physiographic province, and the Greenmount site is in the Piedmont physiographic province. This study was a cooperative effort of the U.S. Geological Survey, the Maryland Geological Survey, the Maryland Department of the Environment, and the Governor's Council on Chesapeake Bay Initiatives.

The objectives of the study were to determine whether the chemical composition of ground water beneath the impoundments changed as a result of storm-water infiltration, whether ground-water quality was adversely affected, and whether contaminants being sequestered in impoundments could potentially be mobilized to ground water.

Native geologic materials collected from drill cores at each site and bottom materials collected each September from the Annapolis and Greenmount ponds were analyzed for particle size, selected chemical constituents, and the predominant mineralogy. Aqueous solutions were analyzed for major ions, a large suite of trace elements, and volatile and polyaromatic organic compounds; pH, dissolved oxygen, alkalinity, chloride, and specific conductance were measured in the field. Samples of runoff, impoundment water, unsaturated-zone water, and ground water were collected triannually for extensive chemical analyses and at least monthly for field measurements. The results were compared for two sites with storm-water ponds (Annapolis and Greenmount) and one porous-pavement site with a subsurface impoundment (Prince Frederick).

Either primary or secondary maximum contaminant levels established by the U.S. Environmental Protection Agency (USEPA) for aluminum, cadmium, chloride, chromium, and lead in drinking water were exceeded from time to time in ground-water samples collected beneath and downgradient from the impoundments. In addition, uncharacteristically high concentrations of barium, copper, molybdenum, nickel, strontium, vanadium, and zinc occasionally were reported in ground water beneath impoundments, and median concentrations of barium, cadmium, chloride, copper, nickel, and zinc were elevated in some ground-water samples beneath the study sites. Chromium and lead were rarely detected in ground water. Low concentrations of arsenic were detected sporadically in storm water and ground water. Concentrations of volatile organic compounds were usually below or near detection in storm-water and ground-water samples; small concentrations of polyaromatic organic compounds were detected only in pond-bottom materials.

Pond-bottom materials generally were effective scavengers of trace metals introduced to storm-water impoundments in the runoff. Between 1986 through 1988, concentrations of lead increased from below detection level to 28 parts per million (ppm), and zinc concentrations increased from 54 to 344 ppm in bottom materials collected from the Annapolis impoundment. In addition, copper concentrations increased 3.5 to 40 ppm and nickel concentrations increased from 6 to 16 ppm in bottom materials at the Annapolis site. For the same time period at the Greenmount impoundment, concentrations of lead increased from 20 to 90 ppm; zinc concentrations increased from 59 to 469 ppm; and nickel concentrations increased from 35 to 48 ppm (there was a net decrease in the copper concentration). Despite this accumulation of metals in bottom materials, concentrations of these and other metals were considerably elevated in ground water beneath and downgradient from the impoundments. Cadmium concentrations did not increase in bottom materials, although cadmium was a common constituent in storm water and sorbed readily to the bottom materials in laboratory tests. Ground-water samples collected from the control wells at each site had concentrations of cadmium that were below or near detection, whereas concentrations were as high as 27, 26, and 8.4 μg/L (micrograms per liter) beneath the impoundments at Annapolis, Greenmount, and Prince Frederick, respectively.

Storm water was the primary source of most contaminants that were found at elevated concentrations in ground-water samples collected beneath the impoundments. Contaminants entered ground water as a result of several variables, including direct storm-water

infiltration; impoundment-related modifications of pH and redox that periodically favored metal mobilization from pond-bottom or aquifer materials; and formation of anionic or neutral complexes.

Metal mobility in the impoundments was mitigated by ion exchange, sorption, and mineral precipitation; storm water was aerobic and usually had neutral or higher pH that generally did not favor the presence of soluble species of most metals. Nevertheless, cadmium sorption in the impoundments may have been excluded by competing cations. Moreover, conditions for complexing of cadmium with organic compounds and chloride was favorable in impoundments and could have enhanced cadmium transport to ground water.

Algal photosynthesis modified the pond-water chemistry at Annapolis and Greenmount, increasing pH to 9.0 or greater, whereas algal respiration and rainwater dilution decreased pH to 6.5. Algal mediation of the pond-water pH at Greenmount resulted in a median pH of 9.2. Because aluminum solubility increases exponentially at about pH 9.0, aluminum concentrations in pond water at this site exceeded the U.S. Environmental Protection Agency's drinking-water regulation of 50 μg/L in most samples and may have contributed to elevated aluminum concentrations measured in ground water beneath the impoundment. Algal activity was less intense in the Annapolis impoundment, where the median pond-water pH was 7.7 and the median aluminum concentration was 30 μg/L; occasional measurements of aluminum concentrations greater than 50 μg/L in pond water corresponded with pH near or greater than 9.0. In ground water beneath the Annapolis pond, aluminum concentrations were below 50 μg/L in the samples collected, with only one exception.

The solubility of most trace metals increases with pH decrease below neutrality. Therefore, the decreases of pond pH below neutral possibly mobilized iron, copper, nickel, and zinc periodically from bottom materials; alternatively, metals dissolved in storm water could have been transported to ground water because kinetics were unfavorable for sorption to bottom materials.

The pH of ground water tended to keep the metals in solution at each site. Ground-water pH beneath the impoundments was reduced to below background pH: from 5.13 to between 4.18 and 4.94 at Annapolis, from 5.38 to between 4.9 and 5.29 at Greenmount, and from 6.71 to between 4.39 and 4.8 at Prince Frederick. Periodic mobilization of iron from the impoundment to ground water (and the consequent precipitation of iron hydroxides in the aquifer) has been suggested as a cause of reduced pH in beneath-pond ground water at the Annapolis and Greenmount sites. Lithologic composition is the primary control on order-of-magnitude changes in ground-water pH at Prince Frederick.

With the exception of chloride, ground-water contamination was least at the Prince Frederick site, possibly because of low contaminant concentrations in storm water entering the Prince Frederick impoundment, or because contaminant mobility was restricted by the well-buffered and stable chemical environment in the impoundment. Dissolution of the rock aggregate in the Prince Frederick impoundment buffered impounded water to a pH of about 8.4, but dissolution also released high concentrations of magnesium and low concentrations of nickel and possibly chromium that affected ground-water chemistry.

Chloride contamination was ubiquitous in ground water receiving storm-runoff infiltrate. The ground water beneath the impoundments was modified to a chloride-dominated solution at each site throughout the period of study (native ground waters were mixed cation-mixed anion, magnesium-nitrate/chloride, and calcium-bicarbonate types at respective study sites). The only major source of chloride to ground water was storm-water infiltration during periods of road salting (road salting occurred no more than five times a year during the study period).

Chloride concentrations were measured at least biweekly and before, during, and after selected storms. The effect of seasonal and storm-specific recharge on concentrations of chloride in ground water beneath the impoundments monitored was a temporary dilution—usually lasting no longer than several days. Chloride concentrations in ground water beneath impoundments increased whenever rainfall was low and evapotranspiration rates were high, resulting in highest concentrations during the summer and early autumn at each site. The magnitude and persistence of the chloride contamination indicated that chloride, although a very soluble constituent, was not being flushed readily from the ground-water systems studied. Chloride concentration in ground water beneath impoundments increased whenever rainfall was low and evapotranspiration rates were high.

Probable factors contributing to the persistent chloride domination of the major-ion chemistry of ground water at each study site were (1) low ground-water flow rates relative to storm-water infiltration rates; (2) limited dilution potential because sites were within a maximum of 300 feet from the inferred ground-water divide; and (3) capillary forces.

The unsaturated-zone chloride data suggest that capillary processes cause retardation of chloride transport and can allow chloride buildup, especially in the zone of tension saturation. This could serve as a model for explaining inhibition of transport of other contaminants. With the exception of chloride concentrations, however, the periods of data collection and (or) sampling frequency generally were insufficient to determine temporal trends in concentrations for trace metals and other constituents.

INTRODUCTION

Storm-water management is an integral part of State and Federal efforts in the Mid-Atlantic region to ameliorate nonpoint contamination of streams in general and of the Chesapeake Bay in particular. Runoff from densely populated, heavily trafficked urban and suburban areas was shown by the Nationwide Urban Runoff Program of the U.S. Geological Survey to carry significant contaminant loads to nearby streams and coastal areas, contributing to the degradation of water quality (U.S. Environmental Protection Agency, 1983). In 1982, the State of Maryland legislated management of storm runoff, mandating management implementation by 1984 for all new development (Maryland Department of Natural Resources, 1985). In 1987, the Federal Clean Water Act was amended to mandate storm-water management. The amended legislation requires all cities with a population of more than 100,000 to implement management of storm-water discharge by 1992, and provides that the potential for ground-water contamination from nonpoint sources be determined.

Ground water is a heavily used source of potable water in many parts of Maryland and the sole source of potable water for many domestic users and for some public-supply systems. Many inorganic contaminants (for example, heavy metals) and anthropogenic organic compounds tend to sorb to solid substances commonly found in soils and geologic materials. This characteristic forms the basis for the hypothesis that detention and infiltration of storm water in management structures will sequester contaminants and thus protect ground water from nonpoint contamination. Testing of this hypothesis at several sites was required because the efficacy of a structure to protect ground-water quality is likely to depend upon certain site-specific characteristics, such as the chemistry of runoff, composition of geologic materials, location of management structure in relation to the hydrologic system, and site construction and maintenance practices. Such factors have direct relevance to managers and regulators in developing specifications and storm-water-management strategies. Moreover, the extent of ground-water contamination from compounds that can be expected to remain in the aqueous solution infiltrating to ground water needed evaluation.

By 1985, literally thousands of storm-water-management structures were in place, under construction, or planned in the State of Maryland (Earl Shaver, Maryland Department of the Environment, oral commun., 1986). Thus, the potential for ground-water quality to be adversely affected by direct storm-water infiltration or indirect contaminant mobilization through management structures was recognized as an urgent issue requiring assessment.

The U.S. Geological Survey (USGS), in cooperation with the Maryland Geological Survey, the Sediment and Stormwater Division of Maryland Department of the Environment, and the Governor's Council on Chesapeake Bay Initiatives, began a 5-year study in 1985 to determine the existing and potential effects of storm runoff on ground-water quality at three storm-water management sites in Maryland.

PREVIOUS INVESTIGATIONS

Much has been learned by investigators, and research continues regarding the physical and chemical characteristics of storm-water runoff, storm-water management, and the effects of runoff on surface-water resources. Relatively little research has addressed the consequences to ground-water quality of runoff percolation through storm-water management structures, however.

The earliest work in the field explored the hydrologic effects of artificial recharge on aquifer systems (Meinzer, 1946). In Long Island, N.Y., where the sole sources of drinking water are aquifers underlying heavily populated areas that are vulnerable to seawater intrusion and anthropogenic contamination, the topic of artificial recharge was pursued vigorously (Brashears, 1941, 1946, and 1953; Johnson, 1948; Brice and others, 1959; Parker and others, 1967; Cohen and others, 1967; Seaburn, 1970 a,b; Aronson and Seaburn, 1974; Seaburn and Aronson, 1974; Aronson and Prill, 1977; Aronson, 1978; Prill and Aronson, 1978; Aronson and others, 1979; Schneider and Oaksford, 1984; Schneider and others, 1987; Ku and Simmons, 1986).

The concern for degradation of ground-water quality from artificial recharge of storm water and treated sewage effluent began to be addressed in the late 1960's with feasibility studies on Long Island by Cohen and others (1967). The work on Long Island continued with studies that monitored the migration of storm-water-borne heavy metal and organic contaminants (Schneider and Oaksford, 1984; Schneider and others, 1987; Ku and Simmons, 1986). Concern for the vulnerability of ground-water resources from storm-water infiltration was addressed by investigations in Arizona (Wilson and others, 1984), Sweden (Malmquist and Hard, 1981), California (Nightingale, 1987 a,b,c; Nightingale and others, 1985), Massachusetts (Pollock, 1984; LeBlanc, 1984), South Carolina (Dennehy and McMahon, 1989), and Florida (Schiffer, 1989).

Few of the studies cited above addressed the long-term effect of storm-water percolation to ground water. Within the timeframe of these investigations (1½ years or less), there was general agreement that concentrations of some contaminants in ground water were elevated above ambient concentrations as a result of infiltration but that the concentrations still were below health-concern levels and did not necessarily persist through time. Studies of contaminant accumulations in soils of storm-water management basins found elevated concentrations of cadmium, copper, lead, and zinc (Wigington and others, 1983 and 1986; Nightingale, 1985) and pesticides, phenols, and polychlorinated biphenyls (Nightingale, H.I., written commun., 1989).

The site-specific nature of the subsurface systems was emphasized by each investigator, indicating that conclusions for the respective studies have limited transfer value for predictions of the magnitude of contaminant mobilization from storm-water catchments to ground water.

PURPOSE AND SCOPE

This is the final report of a 5-year project to study the geochemistry and assess the effects on ground-water quality of storm-water infiltration at three storm-water-management sites in Maryland. The purpose of this report is to provide a comprehensive description of the investigation, the study sites, the data collected, and to evaluate the data in the context of two major objectives pertaining to ground-water quality:

1. Determine what changes occur in the chemical composition of ground water being recharged by storm-water infiltrate.
2. Assess the potential for mobilization of trace-element and organic contaminants sequestered in the storm-water impoundment.

Description of the geochemistry and of factors affecting ground-water quality that result from storm-water-infiltration practices is confined to the three study sites monitored and to the 3 years and 7 months of data collection from December 1985 through June 1989. Hydrologic data collected during the study period pertain to rainfall, storm runoff, impounded storm water, and ground water. Chemical data collected pertain to native geologic materials (materials in the unsaturated and saturated zones), materials accumulating in the impoundments (pond-bottom materials), and to rainwater, storm water (runoff and impounded water), water in the unsaturated zone, and ground water. Solid materials and aqueous solutions associated with storm-water-management sites were analyzed for inorganic and organic contaminants, as well as for major ions and physicochemical characteristics. Major-ion and trace-element ratios and concentrations are interpreted with respect to probable sources and sinks and to ambient hydrologic characteristics.

The relation between the hydrologic and geochemical systems and the quality of ground water are described and compared for the study sites. Similarities between the three sites of the aqueous and solid-phase chemistry are examined with respect to transferability to other storm-water-management sites. Factors are identified that are pertinent to the siting of storm-water management structures with the aim of protecting ground-water quality.

HYDROGEOLOGIC SETTING

Maryland encompasses an area of diverse geology that is divided into five physiographic provinces[1] (regions of distinctive geomorphology) (fig. 1A) (Edwards, 1981). The Piedmont province is bounded to the west by the Blue Ridge province and to the east by the Atlantic Coastal Plain province. The zone of contact between the Piedmont and the Coastal Plain provinces is characterized by numerous waterfalls, and thus is commonly known as the Fall Line (figs. 1A, 1B) (Otton, 1955). The Coastal Plain province in Maryland is widely dissected by the Chesapeake Bay. Water quality in the Chesapeake Bay is affected by contaminant loadings carried by streams that traverse the Atlantic Coastal Plain and Piedmont provinces.

Bedrock in the eastern part of the Piedmont province consists of metasedimentary and highly metamorphosed igneous rocks, including phyllite, schist, gneiss, gabbro, and marble (Hopson, 1964; Maryland Geological Survey, 1967; and Edwards, 1981). Bedrock in the study area is overlain by saprolite that can exceed 100 ft in thickness.

The Coastal Plain province consists of a wedge-shaped sequence of stratified sediments that dip gently to the southeast and range in thickness from zero at the Fall Line to nearly 8,000 ft at Ocean City, Md., and 2,627 ft at Lexington Park, Md. (Hansen and Wilson, 1984) (fig. 1B). This body of mostly unconsolidated gravel, sand, silt, and clay comprises a sequence of stratigraphic units that includes Quaternary deposits at the top of the geologic section, underlain by deposits of Tertiary and Cretaceous age, respectively. The bottommost Coastal Plain strata lie unconformably on an older Precambrian to Jurassic (?) complex of basement rocks (table 1 and fig. 1B).

SELECTION AND DESCRIPTION OF STUDY SITES

The study sites were selected to allow comparison of water-quality effects at (1) similar types of impoundments constructed in different geologic and hydrogeochemical terranes, and (2) different types of impoundments receiving runoff from parking lots.

More than 300 storm-water-management sites were inspected before final site selection. As infiltration is the priority method of storm-water management, an attempt was made to select sites at which infiltration occurs. Relatively few sites designed for infiltration had been constructed by the summer of 1985. Moreover, many of the sites designed for infiltration were clearly not functioning properly according to State of Maryland storm-water management specifications (Pensyl and Clement, 1987). Only a small number of these sites met the following selection criteria for the study:

1. Runoff to the impoundment should be typical of storm water discharging from heavily trafficked areas.
2. The impoundment should receive runoff through one major inlet.
3. Construction of observation wells upgradient of and through the impoundment should be feasible.
4. Evidence of at least partial infiltration of storm water to ground water should exist.
5. One site should be a porous-pavement facility.
6. At least one site should be in the Piedmont province and one should be in the Coastal Plain province.

Geographic Setting

The storm-water-management sites selected for this study are located in Maryland—in Annapolis (Anne Arundel County), Greenmount (Carroll County), and Prince Frederick (Calvert County)—and are referred to throughout this report by

[1]Hereafter, physiographic provinces are referred to as "provinces."

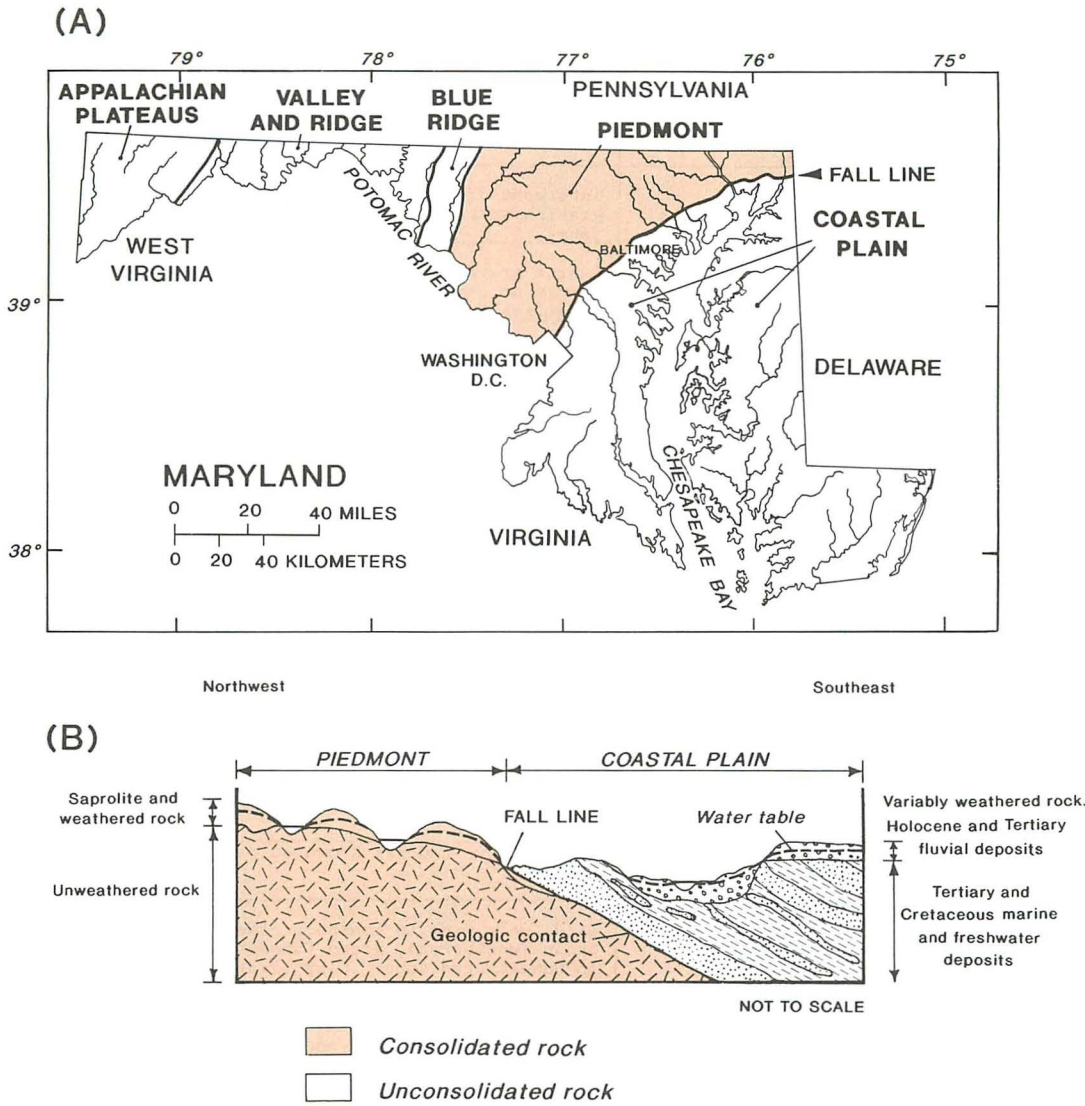

Figure 1.—(A) The physiographic provinces of Maryland and major streams draining to the Chesapeake Bay, and (B) generalized section showing geologic relation between Piedmont rocks and Coastal Plain deposits.

the name of the city in which each is located (fig. 2). The Annapolis and Prince Frederick study sites are in the Coastal Plain province and the Greenmount site is in the Piedmont province. Geologic materials that comprise the unsaturated zone and water-table aquifer are from the Aquia Formation at the Annapolis site, from the Prettyboy Schist saprolite at the Greenmount site, and from Upland deposits at the Prince Frederick site (Hansen, 1972a and 1972b; Meyer and Beall, 1958; Drummond, 1984).

Climate for the general area is temperate and is moderated further by proximity to the Atlantic Ocean. Temperatures tend to be coolest at Greenmount and warmest at Prince Frederick. Average precipitation is slightly higher at Greenmount than at the other sites. Although 1988 was considered a drought year in Maryland and precipitation was below normal for the winter and spring, unusually high rainfall occurred during July and August, and total rainfall for the year was close to average at each site.

Annapolis is a port city at the confluence of the Chesapeake Bay and the Severn River. The study site is at the northeastern boundary of the city of Annapolis, approximately 5 mi from the mouth of the Severn River, and lies within the Severn River watershed at the headwaters of Weems Creek. Annapolis has a population of 35,000 and is about 27 mi from Baltimore and Washington D.C., which have a combined population of 6 million. Thirty-year averages of temperature and rainfall for the period 1951–80 are reported for each county and for major municipalities by the State climatologist. For Annapolis, the 30-year average temperature is 55.6°F, with a winter average of 35.5°F and a summer average of 85.2°F. The 30-year average rainfall is 39.03 in.

Table 1.—Composite stratigraphic chart describing geologic units underlying the study sites

[Table modified from Wheeler and Wilde, 1989, table 1]

System	Series	Stratigraphic unit		Description of lithology
Quaternary	Pleistocene, and Pliocene (?)	Lowland deposits and Upland deposits (Glaser, 1971)		Interbedded quartz gravel, medium to coarse sand, and silt-clay; grayish-white to dark greenish-gray; peat, and sparse molluscan fauna.
?	?			Quartz gravel and medium to coarse sand overlain by massive silt; orange to reddish-brown where oxidized, otherwise pale-gray. Underlies Prince Frederick site.
Tertiary	Miocene	Chesapeake Gp	Eastover Formation (Ward and Blackwelder, 1980)	Sand, interbedded gray to whitish gray, fine to coarse-grained, and dark gray to blue-gray clays and silts.
			St. Marys Formation	Clay, gray, clayey silt and very fine sand; fossiliferous.
			Choptank Formation	Silty sand to sand, medium to coarse-grained, with some gravel and locally abundant shells; interbedded with gray to bluish-gray sandy silts and clays.
	?		Calvert Formation	
	Oligocene		Old Church Formation (?) (Ward, 1985)	Sand, grayish-green to grayish-white, medium to coarse-grained, glauconitic with calcite-cemented layers and shell debris. Coarsens upward from basal silts.
	?			
	Eocene	Pamunkey Group	Piney Point Formation	
			Nanjemoy Formation	
	Paleocene		Marlboro Clay	Clay, silty, reddish brown to pink or gray, micaceous.
			Aquia Formation	Sand, very fine to coarse-grained, poorly to well sorted rusty brown (weathered), green (unweathered); glauconitic with shells in unweathered zone. Clay layers are greenish gray to black with glauconite. Crops out at Annapolis site.
			Brightseat Formation	Sand, fine-grained, silty and clayey, with coarser grains near base; medium dark gray and dark greenish gray, quartzose, with mica and glauconite.
Cretaceous	Upper Cretaceous	Severn Formation [1] (Minard, 1980)		Sand, fine to coarse-grained, silty or clayey, reddish brown, glauconitic. Localized occurrence of poorly sorted, coarse-grained sand.
		Matawan Formation		Sand, fine-grained, silty or clayey, dark gray, micaceous, glauconitic.
		Magothy Formation		Sand, loose, fine to coarse-grained, white, associated with lignite and dark laminated silt-clay sands and gravels, coarser near base.
	?	Potomac Group	Patapsco Formation	Sand, fine to medium grained, interbedded with variegated silt to clay. Abrupt lateral and vertical changes in lithology.
	Lower Cretaceous		Arundel Formation	Clays, thick, variegated, dense with increasing interbedded sand lenses downdip of outcrop.
			Patuxent Formation	Sands or pebbly sands and gravels, medium to coarse-grained, with abrupt lateral and vertical changes to variegated silt and clay.
Jurassic to Upper Paleozoic				Not present at sites.
Lower Paleozoic (?) to Precambrian (?)		Gillis Formation [2] (Edwards, 1986)		Dark to light silvery gray, tan, and greenish-gray quartz-chlorite-muscovite phyllite. Underlies Greenmount site.

[1] Also known as the Monmouth Formation in Maryland.
[2] Formerly Wissahickon Schist of Meyer and Beall, 1958, and Prettyboy Schist of Crowley, 1976.

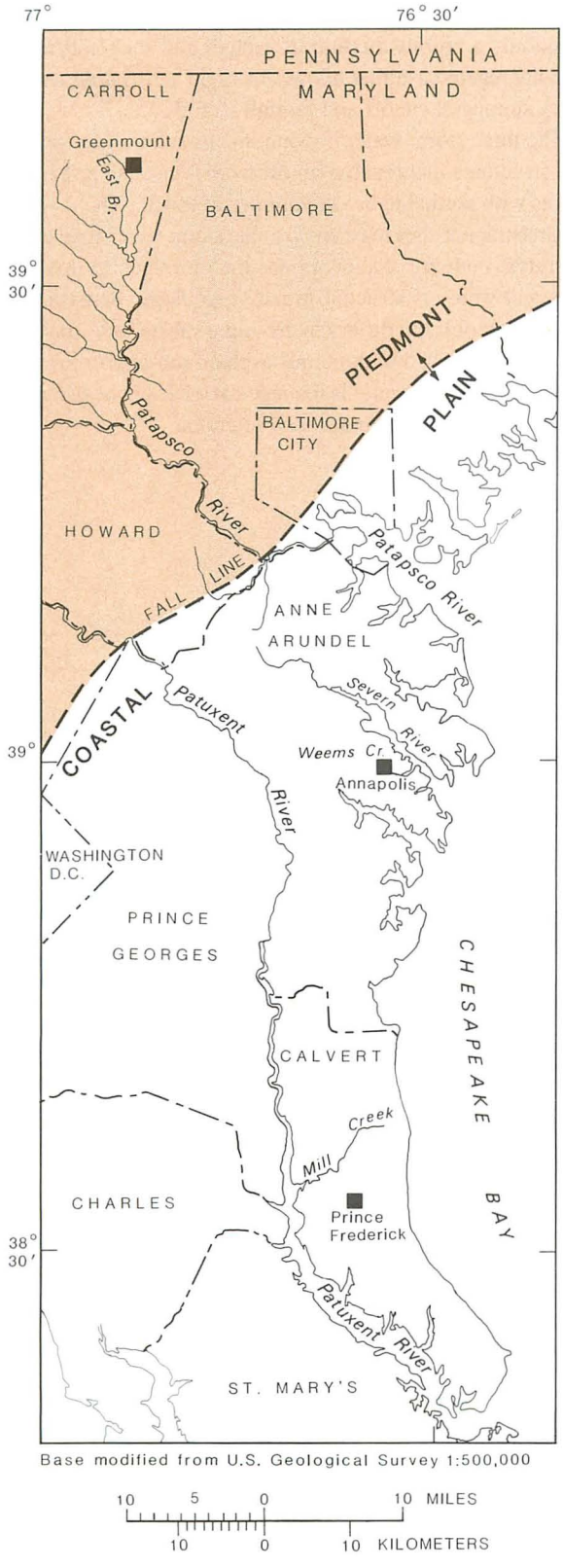

Figure 2.—Location of study sites.

The rural town of Greenmount is in northeastern Carroll County, 6 mi south of the Pennsylvania State line, approximately 30 mi northwest of Baltimore and 56 mi north of Washington D.C. The largest nearby incorporated town is Hampstead, which is 2.5 mi south of the study site and has a population of 1,293. The study site lies within the Patapsco River watershed near headwaters of the East Branch Patapsco River. Average winter and summer temperatures are 32.1°F and 72.3°F, respectively. The 30-year average rainfall is 43.00 in.

Prince Frederick, the county seat of Calvert County, has a population of about 1,000 and is approximately 25 mi southeast of Washington, D.C. and 50 mi south of Baltimore. The study site is less than 6 mi west of the Chesapeake Bay and about 10 mi east of the Patuxent River. It is situated within the Mill Creek watershed, which drains to the Patuxent River. The 30-year average temperature is 76.8°F in the summer and 38.1°F in the winter. Annual precipitation averaged 42.44 in. over the 30-year period.

Storm-Water Management

The term "storm water" is used in this report as a general term that includes the water entering and leaving storm-water-management structures (impoundments or ponds) and the impounded water. Where it was relevant to distinguish between inflowing, outflowing, and impounded storm water, the following terms apply: "runoff," "urban runoff," and "storm-water inflow" can be used interchangeably, and refer to storm water that enters an impoundment; "pond water" and "impoundment water" are used interchangeably for storm runoff that has been held or ponded by the management system; "storm-water discharge," "runout," and "storm-water outflow" have been used synonymously for storm water leaving an impoundment. The choice of terms within this report primarily depends upon context and differences in site construction. The terms "runoff," "pond" or "impoundment water," and "storm-water discharge" or "outflow" are used for the Annapolis and Greenmount sites, which have management structures at land surface; whereas the terms "storm-water inflow," "impoundment water," and "storm-water discharge" and "runout" are used for the Prince Frederick site, at which there is a subsurface management structure. The Prince Frederick study site was the only site at which storm-water outflow (runout) from the storm-water impoundment was monitored.

Three basic types of impoundments are used for storm-water management in Maryland: detention, retention, and infiltration structures. Numerous hybrids and varieties of these structures exist, all with the purpose of preventing direct discharge of turbid, contaminant-laden runoff to surface-water resources. Impounding storm water allows the particulate-associated fraction of the contaminant load to settle out. Detention ponds impede the rate of discharge, whereas retention ponds do not permit direct discharge of storm water.

Infiltration, the priority storm-water-management strategy in Maryland, involves the impoundment of storm runoff in

structures that subsequently allow the storm water to infiltrate and percolate through native and (or) artificial unsaturated-zone materials (Maryland Department of Natural Resources, 1985). Infiltration structures commonly used for urban runoff include basins or ponds (fig. 3A), trenches (fig. 3B), and porous pavement (fig. 3C) (Maryland Department of Natural Resources, 1985). 1990 State specifications limit water storage in infiltration structures to 72 hours; however, only 50 percent of the basins infiltrate according to specifications and water may be impounded for weeks, months, or longer in the other 50 percent of basins (Pensyl and Clement, 1987). (Geometry and dimensions of impoundments have important implications for infiltration and the effects of the reservoir on the ambient hydrogeologic system, although an assessment of the influence of these properties at the study sites is beyond the scope of this report.)

An infiltration pond is made by constructing an embankment or by excavating to relatively permeable materials (fig. 3A). Runoff enters the pond by overland flow and(or) through storm drains. Porous pavement is a pervious paving material (commonly a porous mixture of asphalt and rock course) on a stone-aggregate base that allows for rapid infiltration and temporary storage of runoff and rainfall (fig. 3C).

The three storm-water impoundments selected for study are local structures that receive runoff from typical suburban parking lots with normal to heavy volumes of traffic. The Annapolis and Greenmount sites have comparable storm-water-management structures: both are shallow ponds that are open to the atmosphere and were constructed in native geologic materials. The Prince Frederick site differs by having a subsurface, rock-filled impoundment paved with porous asphalt-and-aggregate surfacing material. Storm water is managed at each site by a combination of infiltration, detention, and retention.

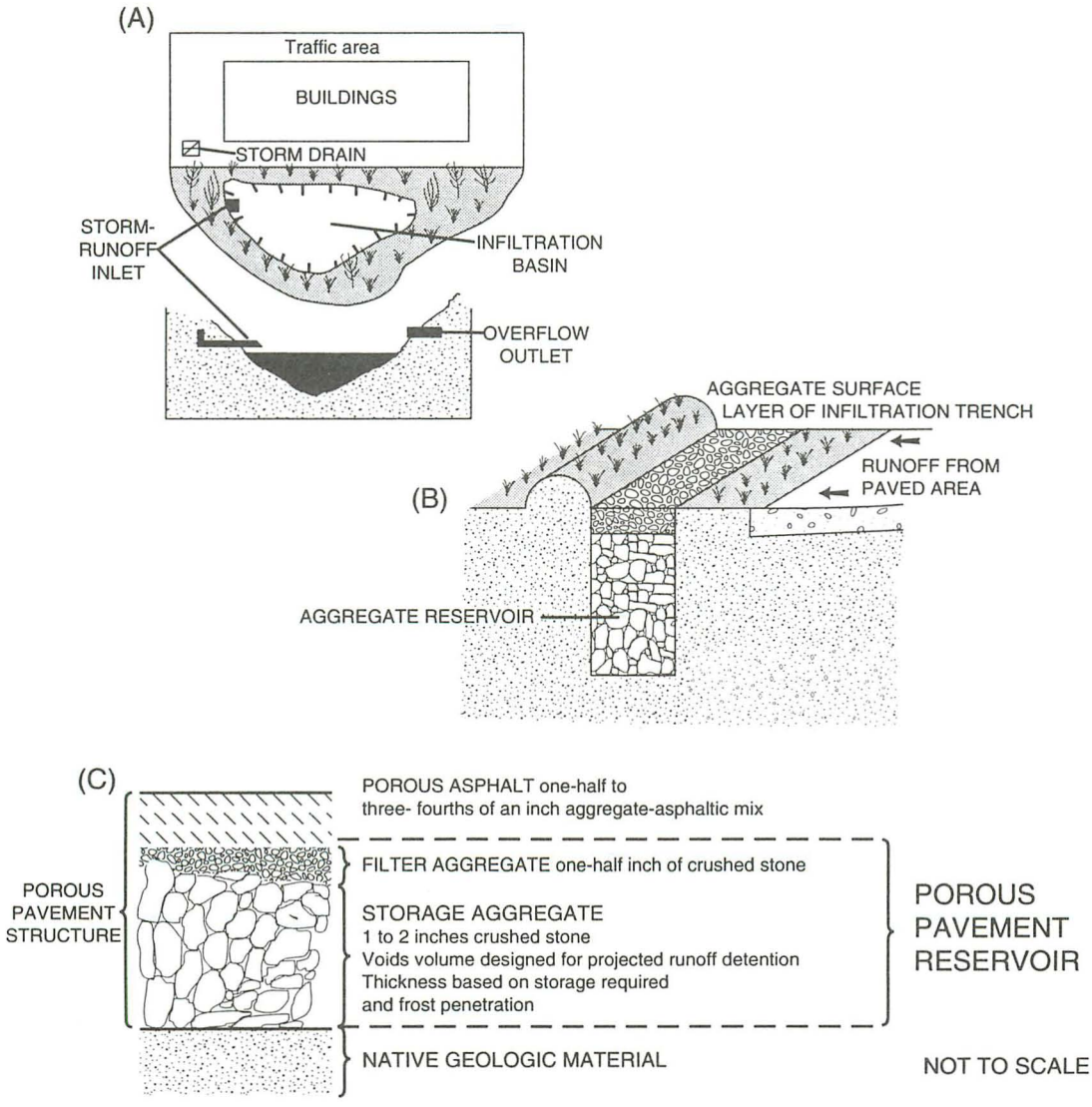

Figure 3.—Storm-water infiltration structures: (A) infiltration basin, (B) infiltration trench, and (C) porous pavement.

APPROACH AND METHODS

This investigation was designed to test the hypothesis that contaminants are sequestered or "filtered out" from aqueous transport by impoundment and unsaturated-zone materials. The approach taken was to conceptualize a model of potential geochemical sources of and potential hydrologic pathways to ground water beneath the impoundments, to systematically collect and evaluate chemical and hydrologic data representative of sources and sinks, and to determine the factors governing changes in ground-water quality beneath and downgradient from the storm-water impoundment. The project objectives would be met by proving or disproving the hypothesis. Disproof of the hypothesis required establishing that elevated contaminant concentrations in beneath-impoundment ground water occurred because of direct infiltration of impounded storm water or mobilization of contaminants from impoundment or unsaturated-zone materials. The sites were analyzed separately and subsequently compared.

Data requirements were based on a need to (1) compare hydrologic and chemical data associated with the impoundments with background data, (2) define the hydrologic system at each site to understand the relation between hydrologic pathways and constituent concentrations, and (3) identify constituent sources and sinks from the aqueous and lithologic geochemistry.

Data were collected from sampling stations upgradient or offgradient[1] from the storm-water impoundment (control stations), within the impoundment, and downgradient from the impoundment over a 3-year period. The terms "native" and "background" are used to refer to samples collected at control stations at the study site. Data or samples collected from wells screened in the water-table aquifer directly beneath the impoundment frequently are referred to as from "beneath-impoundment" or "beneath-pond" ground water. The term "downgradient" refers to the location of wells, data, or samples with respect to the direction of shallow ground-water flow beneath the storm-water impoundment. The data were collected synoptically from all stations at a given site whenever possible. Synoptic data collection provided a consistent point of reference for interpretation of changes in the geochemistry of ground water affected by storm-water infiltration from the impoundments.

The hydrologic systems were defined by determining storm-water infiltration rates, rates of water-table rise, direction and rate of ground-water flow, and the seasonal and storm-induced configuration of the water table. Water levels of rainfall, storm-water discharge, pond stage, and ground water were continuously recorded. The relations among rainfall, and water quality in the impounded storm water, and the water table were examined to help define pathways for contaminant transport. Configurations of the water table were plotted and hydraulic gradients were calculated from water-level measurements to help determine patterns of storm-related and seasonal ground-water recharge, the magnitude and rate of water-table rise, and the direction of ground-water flow. Characteristics of ground-water flow and recharge were important in evaluating differences in geochemistry between samples collected at different times from the same stations or wells. Ground-water-flow velocities were estimated from bromide tracer tests and from tables of estimated hydraulic properties (Heath, 1984, p. 13). Knowledge of flow velocities can be used to interpret and project residence times of contaminants in the aquifer systems.

Changes in the chemical composition of ground water resulting from storm water infiltrating through the impoundments were determined by comparing the chemical composition of native ground water with that beneath the impoundments and downgradient from the impoundments and by comparing the geochemistry of storm water with ground water. The computer program WATEQF was used to evaluate thermodynamic constraints and calculate mineral saturation indexes for most of the water samples collected (Ball and others, 1981). Calculations from the computer model WATEQF, activity-activity diagrams, and constituent plots on Eh-pH diagrams were used to determine mineral solubilities and the probable speciation states of inorganic contaminants. The aqueous geochemistry also was analyzed with the use of WATEQF, Stiff, and trilinear diagrams (Hem, 1985), time-series and boxplots, and plots of chemical activity and solubility for selected metals. Contaminant concentrations that were reported as being below the analytical detection limit or reporting level (referred to as "less-than" values) were used in calculating median values. "Less-than" values give information about the frequency of contaminant detection at a target level and, therefore, constitute an important and valuable body of knowledge. Boxplots show the reporting level concentration for each constituent; each analytical result that was below the reporting level was assigned an artificial value below the reporting level that was uniform for that constituent. For several cases in which constituents were analyzed by different methods that yielded different reporting levels, the reporting level shown is the one used most frequently. Other data were not used in constructing these boxplots. Boxplots do have two reporting levels indicated for selected cases in which the data have relevance to U.S. Environmental Protection Agency health standards.

It was critical to collect aqueous samples at temporal and spatial intervals that would bracket the range of constituent concentrations entering the system. Analyses were performed at least three times a year for the major-element and trace-element chemistry of impounded storm water and storm runoff, unsaturated-zone water, and ground water; storm-water and ground-water samples were analyzed for organic contaminants two to five times at each site. Monthly measurements were made of pH, dissolved-oxygen concentration, specific conductance, alkalinity, and chloride concentration. Each spring and fall, ground-water samples were collected before a storm, during storm-related recharge (rising limb of the hydrograph), and after recharge (near stable hydrograph).

The potential for contaminants to be sequestered by or mobilized from impoundment materials was assessed by comparing impoundment materials with native geologic materials, by com-

[1]Stations not located upgradient, but that are not affected by infiltration from impoundments (located along lines perpendicular to ground water flowpaths.)

paring annual constituent concentrations in pond-bottom materials, by performing simple laboratory experiments on pond-bottom materials for selected trace metals, and by plotting the composition of impoundment waters on solubility diagrams. Solid-phase materials from the unsaturated zone, the saturated zone, and the bottom of the storm-water ponds were analyzed for particle size, mineralogy, and chemistry.

Native and Pond-Bottom Materials

Solid-phase materials from the unsaturated zone, the saturated zone, and the bottom of the two storm-water ponds were collected and analyzed according to USGS protocols or as outlined below (U.S. Geological Survey, 1977). Samples were split and sent to the USGS laboratory in Harrisburg, Pa., for particle-size analyses, and to the Geology Department of Colgate University in Hamilton, N.Y., for mineralogical and inorganic chemical analyses. Mineralogical analyses were performed by X-ray diffraction on air-dried sediments. Chemical composition of the sediments was determined by X-ray fluorescence (XRF) or direct coupled plasma (DCP). Subsamples of the sediments were air dried, weighed, combusted at 180°C, and reweighed, and the loss on ignition (LOI) was determined. The LOI represents carbon compounds and mineral-bound water. Pond-bottom samples collected in 1988 were analyzed for organic compounds and total carbon and nitrogen by the Chesapeake Biological Laboratory at the University of Maryland in Solomons, Md. Total carbon concentrations were determined in the samples collected in 1988 by conversion of all the carbon in the sample to carbon dioxide and by use of a thermal-conductivity detector to quantify the results.

Split-spoon samples of native geologic materials were collected approximately every 5 ft during well drilling and were subsampled for laboratory analysis of the mineralogy, chemistry, grain-size distribution, cation-exchange capacity, and organic-matter content.

Samples of pond-bottom materials were collected from the Annapolis and Greenmount storm-water ponds in 1986, 1987, and 1988. Laboratory analyses of bottom materials included determination of grain-size distribution, inorganic and organic chemistry, total carbon and nitrogen content, and cation-exchange capacity. Bottom materials were collected with stainless-steel collectors. Composite samples for inorganic analyses were collected in a plastic bucket, homogenized by stirring with a plastic spatula, and filtered through a 2-millimeter plastic sieve. Composite samples for organic analyses were collected in a metal bucket, homogenized by hand with a stainless-steel spatula, and filtered through a 2-millimeter brass sieve. The samples sent to the laboratories were a composite of 15 samples collected at five evenly spaced points along three transects drawn across the Annapolis and Greenmount impoundments. These pond-bottom samples were split and stored in sterilized glass jars, frozen, and then sent to respective laboratories in Pennsylvania, New York, and Maryland.

Infiltration rates through the impoundment structures were estimated by use of a double-ringed infiltrometer according to the methods of Constantz (1983) (J.E. Constantz, U.S. Geological Survey, oral commun., 1985) and by calculation of the net drop in pond stage after accounting for evaporation. Evaporation rates were determined from data collected at the nearest weather stations reporting to the National Oceanic and Atmospheric Administration. Determination of infiltration rates was not a major goal of this study. The purpose for estimating infiltration rates was to show that infiltration of storm water could be expected to occur at measurable rates.

Aqueous Solutions

Chemical constituents were analyzed in the USGS National Water Quality Laboratory in Arvada, Co. Collection, preservation, and analysis of water samples followed the protocols of the U.S. Geological Survey (1977). Analyses for all samples collected are reported in the appendixes with the exception of the second sample collected from the Prince Frederick well CA Db 67; analytical values for this sample, including field measurements, bore no resemblance to the first or subsequent samples from that well and were deleted from the record at the study's end.

Replicate (sequential) samples or sample splits were obtained for approximately 5 percent of the samples of each aqueous solution analyzed for filtered and unfiltered inorganic constituents and organic carbon. Equipment blanks processed in the field were collected for rainwater once at the Annapolis site. All samples for analysis of volatile organic compounds were collected in triplicate. A principal quality-assurance criterion was internal consistency of the chemical data over time at stations upgradient, downgradient, and within and beneath the storm-water management structures.

Percentage differences in ion balances were computed by dividing the difference between total major cation and total major anion milliequivalents by the sum of the total milliequivalents for major cations and anions and multiplying by 100. Major-ion imbalances that were considered acceptable were 20 percent or less for rainwater, 10 percent or less for storm water, and 5 percent or less for unsaturated-zone water and ground water.

Temperature, pH, dissolved oxygen, specific conductance, alkalinity, and chloride were measured at the time of sample collection. All filtration and sample preservation and treatment was performed at the time of sample collection, and samples were chilled at 4°C until they were analyzed.

Analysis of a filtered sample yields constituent concentrations that are operationally defined as being dissolved and does not mean that constituents are completely dissolved in solution. The definition of the dissolved phase used in this study is that which was passed through 0.1- or 0.45-μm (micrometer) filters. Before December 1987, samples to be analyzed for iron, manganese, and aluminum were filtered through 0.1-μm filters (Kennedy and others, 1974), and samples to be analyzed for the re-

maining dissolved constituents were filtered through 0.45-μm filters. As of December 1987, all samples collected for analysis of inorganic dissolved constituents were filtered through 0.1-μm filters; however, 0.45-μm filters were used for dissolved nutrients (nitrogen and phosphorous species). Discussions in the report that compare constituent concentrations measured in filtered and unfiltered aqueous samples are intended to distinguish between constituents present as dissolved phase in contrast with suspended phases.

Atmospheric deposition

Each site was instrumented with a battery-operated rain gage, which provided a continuous record of the amount and magnitude of rainfall. Bulk samples of the deposition were collected through plastic funnels into 2-liter polyethylene containers in which wet and dry deposition were combined. Snowfall data were not collected.

The samples of atmospheric deposition collected were a composite of wet and dry deposition. Each sample was passed through a 0.1-μm filter into glass bottles that had been sterilized and oven dried; samples for metals analyses were collected in acid-rinsed bottles. The sample collected, therefore, represents rainwater plus the fraction of airborne particulates that were dissolved therein. For the sake of simplicity, the sample collected for chemical analysis is referred to as "rainwater."

Rainwater samples were collected at least weekly and measured in the field for pH, specific conductance, and sometimes for chloride concentration. Occasionally, the sample collected was a composite of more than one storm. Several samples from individual storms were analyzed for major and trace chemical components.

Storm water

Flow characteristics of storm runoff were determined with either an automatic-pressure-transducer flowmeter (Annapolis site) or with an automatic digital recorder (ADR) set up to record stage fluctuations behind a weir plate (Greenmount and Prince Frederick sites). Samples were collected that represented the "first flush," because previous studies at commercial or urbanized sites have indicated that high contaminant concentrations are common in the initial runoff from storms (Colston, 1974; Helsel and others, 1979).

An automatic sampler collected 2 to 3.2 gal of runoff in 24 350-mL (milliliter) glass bottles for most storms at the Annapolis and Greenmount sites. No runoff could be collected at the Prince Frederick site because rainfall and runoff percolate directly through the porous pavement to the subsurface impoundment: some of this percolate infiltrates underlying native sediments, and the rest discharges to a riprap channel. This discharge was similarly collected with an automatic sampler. The initial sample was collected approximately 4 minutes after runoff began, or when the stage reached the level set to activate the sampler. The remaining samples were withdrawn at 2-minute intervals, so that samples were collected during the first 50 minutes of each storm. The 24 samples were composited in a churn splitter and then prepared for analysis of inorganic constituents.

Runoff samples were collected on a weekly schedule; field measurements of pH, specific conductance, alkalinity, and chloride concentration were made at each site visit. The samples were usually of discrete storms; occasionally samples from more than one storm were composited. All the samples sent for laboratory analysis of chemical constituents were of discrete storms. Runoff samples that were sent to the laboratory for determination of the major- and trace-element chemical composition and methylene blue active substances[1] were collected at least twice each year—once for a spring storm and once for a summer or early fall storm. During 1988, storm-water samples were sent for laboratory analysis more frequently than in previous years.

Analyses for the determination of the presence and concentration of toxic organic compounds and dissolved and total organic carbon were performed from two to three times per site; these samples were collected in sterilized, oven-dried glass bottles. Loadings of constituents in storm water were occasionally calculated, but frequent failure of flow-monitoring equipment prevented sufficient load calculations for statistically significant evaluation or comparisons.

Pond-water levels (pond stage) were continuously recorded by ADR's at the Annapolis and Greenmount sites. Monthly field measurements of pH, specific conductance, alkalinity, and chloride were made on a grab sample of pond water collected from the platforms at the downstream end of each pond. Samples of pond water from Annapolis and Greenmount that were analyzed for major and selected trace elements were collected along three transects drawn across the impoundments. Five depth-integrated bailer volumes from evenly spaced intervals along each transect were composited in a churn splitter; samples that were analyzed for organic constituents were depth-integrated in a Teflon[2] (polytetrafluoroethylene or PTFE) bailer and collected from pond water near the well-access platforms. Storm water impounded in the subsurface rock reservoir at Prince Frederick was measured every other week for pH, specific conductance, chloride, and alkalinity. This sample was withdrawn from a permanent Teflon container placed beneath a well screened in the rock reservoir beneath the porous pavement.

Water in the unsaturated zone

Water in the unsaturated zone was collected with tube-type vacuum lysimeters installed within 1 to 2 ft of the bottom of each impoundment. Lysimeters were rinsed with a dilute solution of hydrochloric acid and at least 10 gal of distilled water before installation. The lysimeters are constructed of an upper polyvinylchloride (PVC) section of casing that screws onto a lower Teflon porous filtering sleeve and collection chamber. The lysi-

[1]Methylene blue active substances (MBAS). A method of determining detergent-like compounds using colorimetry to detect their reaction product with methylene blue.

[2]The use of trade or product names in this report is for identification purposes only and does not constitute endorsement.

meters have a 2.375-inch-outside diameter and 8-inch-long collection chamber; the porous Teflon sleeve has an average pore size of 50 μm. The sample was evacuated through a Teflon tube. The tubes used for sample and air evacuation were protected by a capped section of PVC piezometer casing.

Lysimeters were installed in augured holes of approximately 3.5-inch diameter during August 1987. They were packed in a slurry of native material and distilled water. After installation, a vacuum of about 20 lb/in^2 (pounds per square inch) was applied and water extracted repeatedly, until no more water could be extracted. At the Annapolis and Greenmount sites, lysimeters were installed at the edge of the pond, at an angle of 45° beneath the pond; water from the unsaturated zone was extracted from depths beneath pond bottom of 2.3 ft and 1.8 ft at Annapolis and Greenmount, respectively. A second lysimeter at the Annapolis site was installed vertically into the berm, 3 ft higher than mean pond-water level, with the midpoint of the porous section 0.6 ft beneath land surface. The lysimeter at the Prince Frederick site also was installed vertically; the top of the lysimeter was positioned at the base of the rock reservoir and water was extracted from 1.25 ft beneath the top of native unsaturated-zone sediments.

Lysimeter samples were extracted weekly or biweekly. Sample volumes of 450 to 500 mL were removed from the Greenmount and Prince Frederick lysimeters during the first 15 months. After that, the volume of sample declined to about 275 mL or less per collection. If sample volume was sufficient, field measurements of pH, specific conductance, chloride, and alkalinity were recorded. Samples of water from the unsaturated zone were analyzed for major and trace elements approximately three times each year during 1987–88 and 1988–89. Concentrations of organic compounds were not determined for unsaturated-zone water.

Ground water

Wells were installed at each site for water-chemistry sampling and for determining the hydraulic gradient of the water table and, thus, the direction of ground-water flow. The drill rig, drilling augers, and PVC casing were steam-cleaned before installation. Threaded, 3-inch PVC casing was used for the observation wells, and a 3- to 5-ft-long section of capped casing served as a footer at the bottom of each well. Each well screen was surrounded by a 3-in. packing of quartzose pea gravel that extended for at least 3 ft above the top of the screen, and the annular space around the casing above was sealed with bentonite slurry to land surface. Six-inch steel casing was set in 3 ft of concrete and used to protect the PVC casing exposed at land surface. Piezometers were installed similarly, but without steel casing. Piezometer casing was 1¾ in. in diameter. Wells were developed and purged either by means of compressed air followed by mechanical surging (Johnson Division, 1975) and subsequent pumping or by surging and pumping alone.

Wells were installed along the axis of ground-water flow if possible, and positioned upgradient from, downgradient from, and penetrating the storm-water-impoundment structures. Most of the wells and piezometers have a 10-ft-long screen, positioned to bracket the interval of historic water-table fluctuation.

Selected wells were equipped with automatic data recorders (ADR's) to record water levels continuously and were not sampled for water quality. Water-level-observation wells that penetrated the Annapolis and Greenmount impoundments were equipped with analog water-level recorders to allow storm-related fluctuations in water-table levels to be easily recognized in the field and to facilitate storm-related sampling of ground water. Water levels were measured monthly in all other wells and piezometers.

Ground-water samples were collected from wells for analysis of major and trace constituents in the winter, spring, and late summer to early fall of each year. During 1988, ground water was measured monthly for pH, specific conductance, alkalinity, temperature, and concentrations of dissolved oxygen and chloride. The upgradient or control wells were used to establish the background or native chemistry of ground water.

Before sampling, wells were either pumped dry (Prince Frederick site) or purged until the pH fluctuated less than a tenth of a pH unit, specific conductance fluctuated by 5 percent or less, and temperature was constant; water levels were then allowed to recover to prepumped levels. Ground-water samples were collected with Teflon point-source bailers, which were fitted with top and bottom check valves so that a sample could be withdrawn within a desired depth interval. The bailer was rinsed between use in different wells with 3 to 5 volumes of distilled water.

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GEOCHEMISTRY

Geochemistry and the quality of ground water at each study site were related to the composition of native geologic materials, impoundment materials, and storm water. The purpose of this section is to examine the relation between solid-phase and aqueous geochemistry and to summarize the changes in ground-water quality at the individual sites. A comparison between the Annapolis, Greenmount, and Prince Frederick sites with respect to the hydrologic and geochemical factors controlling ground-water quality is presented in the section on "Factors Affecting Ground-Water Quality at the Study Sites."

For each site, background information is given that provides a context in which to evaluate the geochemical data. Background information includes land use, construction of storm-water-management structures, site instrumentation, and site hydrology. Special emphasis is given to a description of hydrologic systems: atmospheric deposition, evapotranspiration, and storm-water infiltration interact with characteristics of the water-table aquifer and can exert a major influence on ground-water chemistry.

Native geologic and pond-bottom or impoundment materials are composed of mineral phases that can serve as sources and sinks for major and trace elements and can interact with storm water to release or retain these constituents. Therefore, the efficacy with which storm-water-management structures exclude contaminant movement to ground water is dependent upon physical, mineralogical, and chemical characteristics of geologic and impoundment material as well as on the hydrologic properties and biochemical and geochemical processes within the impoundment, unsaturated zone, and aquifer.

In addition, differences in impoundment design and construction affect contaminant movement. The Annapolis and Greenmount impoundments were similarly constructed in native geologic materials as wet ponds with berm infiltration that are open to the atmosphere and that readily accumulate storm-water-borne material. The discussions on the geochemistry of impoundment material for these two sites are parallel and focus upon changes in the chemistry of the accumulating sediments. In contrast, contact with the atmosphere and accumulation of sediments were restricted at the Prince Frederick site, where the impoundment is a subsurface structure. There was no opportunity to assess the chemistry of storm-water-borne materials that were able to enter the Prince Frederick impoundment; however, the Prince Frederick impoundment was filled with imported rock aggregate, and this use of imported material had a marked effect on the ambient geochemistry.

Native and pond-bottom materials had a large potential to scavenge the water column for many trace metals and anthropogenic organic compounds because of cation-exchange and sorption capacities. (Cation exchange, sorption, and complexation are explained in the section on "Factors Affecting Ground-Water Quality at the Study Sites"). Cation-exchange capacities of pond-bottom material increased with the influx of fine-grained sediments and affected the abundance of major elements in solution. Metals and organic compounds have a high affinity for sorption onto organic matter and manganese and iron oxyhydroxides; they also tend to form complexes with organic matter. Clays, because of their large surface area and slightly negative surface charge, are effective collectors of positively-charged metals and metal complexes (Horowitz, 1985). Clay particles commonly are coated with organic oozes and amorphous oxyhydroxide precipitates, which greatly enhance sorption potential. Trace elements can also be captured in the solids by coprecipitation with mineral phases or incorporation into precipitate lattices. The life cycle of the pond biota contributed a continuous supply of organic matter to the system that was augmented by organic compounds entering with runoff.

Aqueous solutions for which chemical data were collected include rainwater, storm water, water in the unsaturated zone, and ground water. Certain patterns of data were consistent between the study sites. Rainwater at each site was acidic, and rainwater pH is reported as a median value of the total number of samples collected. The volume-weighted mean pH takes an average of hydrogen-ion activities that have been normalized with respect to rainfall volume, and may be a more representative value than the median for pH (K.C. Rice, U.S. Geological Survey, oral commun., 1988). At each site, the volume-weighted mean was lower than the median pH. Because rainwater is a very dilute, acidic, and poorly buffered solution, contact with buildings, roads, and other surfaces resulted in rapid dissolution of ambient—commonly carbonate—materials. This caused storm water at each site to have a pH that was near neutral or higher than that of rainwater and to have greater specific conductance than that of rainwater. Algal photosynthesis and respiration resulted in large fluctuations of pH and concentrations of dissolved-oxygen and carbon dioxide in impoundment water (D.D. Lynch, U.S. Geological Survey, written commun., 1989).

The master variables of pH and redox potential, along with dissolved carbon and sulfur concentrations, affect the solubility of mineral phases and the mobility of chemical constituents. Redox and pH largely control the chemistry of aqueous solutions along vertical (pond to ground water) and horizontal (upgradient to downgradient ground water) flow paths, and can govern the concentration as well as the mobility of many trace metals. The

nature of these controls on water quality is mentioned in the text that follows, but is examined most rigorously in the section on "Factors Affecting Ground-Water Quality at the Study Sites."

Possible constituent solubility and the saturation state of mineral phases are commonly calculated for aqueous solutions by use of some version of the computer program WATEQF (Ball and others, 1981). The fundamental assumption underlying these calculations is chemical equilibrium. The equilibrium assumption applies only to closed aqueous systems, not to impoundment- or ground-water systems open to exchange with the atmosphere or subject to biological activity. Nevertheless, favorable reaction kinetics and the concepts of partial equilibrium and steady state (Stumm and Morgan, 1981) can justify a qualitative application of equilibrium calculations to such aqueous systems.

Saturation indexes were calculated by use of WATEQF for every ground-water and impoundment-water sample. Consistent results concerning supersaturation and undersaturation were used in conjunction with field and laboratory analyses to determine predominant phase transformations.

Water quality, as distinguished from aqueous geochemistry, is defined by government regulations regarding chemical constituents that specifically relate to human and environmental health. The regulations are intended to provide guidelines with which to measure contamination, and they reflect the best scientific knowledge regarding concentration levels at which selected inorganic and organic constituents threaten physical well being. Primary and secondary drinking-water regulations established by the U.S. Environmental Protection Agency (USEPA) have been generally adopted as State of Maryland human-health criteria for drinking water (Maryland Department of the Environment, 1989). Maryland toxic substances criteria for ambient surface waters (Maryland Department of the Environment, 1989) and USEPA drinking-water regulations (U.S. Environmental Protection Agency, 1991a) are listed in table 2. Drinking-water regulations are used in this report to evaluate the quality of ground water, unsaturated-zone water, and storm water; however, reference to regulations on freshwater aquatic life also may be appropriate to assess the chemical quality of runoff and impoundment water.

ANNAPOLIS SITE

J.R. Annapolis Plaza is a shopping plaza that was newly constructed in 1985 within a commercial area in Annapolis, Anne Arundel County. The storm-water impoundment was designed as an infiltration basin (pond) that would detain runoff from a 100-year storm. The site was hit by a hurricane in the fall of 1985 that delivered 7 in. of intense rainfall, flushing silts and clays into the structure before the sides of the pond could be properly stabilized; this may have contributed to the pond's subsequent inability to infiltrate storm water through its bottom according to State specifications. From that time, at least 10 in. of rain and runoff have remained ponded.

The Annapolis study site is bounded along its northern side by the north-branch headwaters of Weems Creek (fig. 4A). The area immediately surrounding the rest of the study site is a nonresidential, high-density commercial zone. The site consists of a 17.1-acre shopping plaza, including the 2-acre storm-water-management pond. The drainage area consists of 11.63 acres of impervious surfaces and 5.5 acres of vegetated area. The shopping plaza is graded so that all the runoff from the commercial area enters the storm-water pond by a subsurface storm-drainage system. The major inlet to the pond for most of the runoff is a 6-ft-diameter culvert located at the pond's southern corner, but a minor amount of runoff is delivered by a 0.5-ft-diameter pipe buried near the eastern corner (fig. 4B). A small amount of off-site runoff from an adjacent shopping mall also is channeled through the primary culvert.

The impoundment is an elongated structure, which retained a perched layer of storm water throughout the year. The height of the impoundment is approximately 16 ft. Maximum ponding depth is approximately 11 ft and is controlled by a small riser at the northwestern edge of the impoundment and by two 5-ft-diameter culverts set into the northern end of the impoundment. Overflow from the impoundment empties into Weems Creek through these structures.

Site Instrumentation and Hydrologic System

Instrumentation

The site map (fig. 4) shows the location of the impoundment and data-collection installations. Pond stage was continuously recorded by use of an ADR. A storm-water monitoring station was installed over a manhole upstream of the major inlet and 5 ft downstream from a Y-joint, where the runoff through two storm culverts was combined. A flowmeter recorded storm-water discharge in cubic feet per second; an automatic sampler was housed with the flowmeter.

Ground-water levels were monitored from all piezometers and wells, but data for ground-water chemistry were collected only from selected wells (fig. 4, table 3). Nine piezometers (1.25-in. diameter) were installed at locations upgradient from and surrounding the impoundment (fig. 4C). The control wells, AA De 140 and AA De 144, were about 980 ft south of the pond near an entrance to the study site. Three well clusters were installed; the wells of each cluster were spaced approximately 5 to 10 ft apart and were screened at variable depth intervals (fig. 4C, table 3). Well screens for wells AA De 140, 142, 143, 156, and 157 were positioned to ensure that the screen would intersect the water-table surface during low and high water-level fluctuations. Wells AA De 141, 144, 154, and 159 were equipped with ADR's during most of the data-collection period; AA De 158 was equipped with an analog water-level recorder.

Construction of five wells in the pond lasted 5 weeks, through July of 1986. The drill rig was supported on a floating platform. Steel casings, 6 in. in diameter and 10 ft long, were driven 6 ft into the formation beneath the pond, and the wells were constructed through the steel casings to prevent contamination of ground water with the surface water in the pond during well installation. Wells AA De 155, 156, 157, and 158 were

Table 2.—Regulations for concentration levels of selected contaminants from the Maryland Department of the Environment (1989) toxic substances criteria for freshwater aquatic life and from the U.S. Environmental Protection Agency regulations for drinking water (1991)

[Concentrations are shown in micrograms per liter (μg/L), unless otherwise indicated; --, no criterion or concentration level established; *, unenforceable or health advisory proposed level; USEPA, U.S. Environmental Protection Agency; mg/L, milligrams per liter; h, health advisories are indicated for 70-kg adults]

Chemical constituent	Freshwater aquatic life		Drinking water	
	Acute [1]	Chronic [2]	MCL [3]	SMCL [4]
Aluminum	--	--	--	50*
Arsenic	--	--	50	--
Arsenic, -tri	360	190	--	--
Barium	--	--	2,000	200h
Boron	--	--	--	300h
Cadmium	3.9	1.1	5	--
Chloride (mg/L)	--	--	--	250
Chromium (total)[5]	--	--	100 (50)	200-800h
Chromium, -hex	16	11	--	--
Chromium, -tri	1,700	210	--	--
Cobalt	--	--	--	--
Copper	18	12	1,300*	1,000
Iron	--	--	--	300
Lead[5]	82	3.2	50	--
Manganese	--	--	--	50
Mercury	2.4	.12	2	2h
Molybdenum	--	--	--	20*
Nickel	1,400	160	100*	600h
Nitrate or NO_2 + NO_3 (as N; mg/L)	--	--	10	--
Sodium (mg/L)	--	--	--	20h
Sulfate (mg/L)	--	--	400/500	250
Zinc	120	110	--	5,000
Benzene	--	--	5	--
Toluene	--	--	1,000	--
Tetrachloroethylene	--	--	5	--
1,1,1,-Trichloroethane	--	--	200	--
Total Dissolved Solids (mg/L)	--	--	--	500

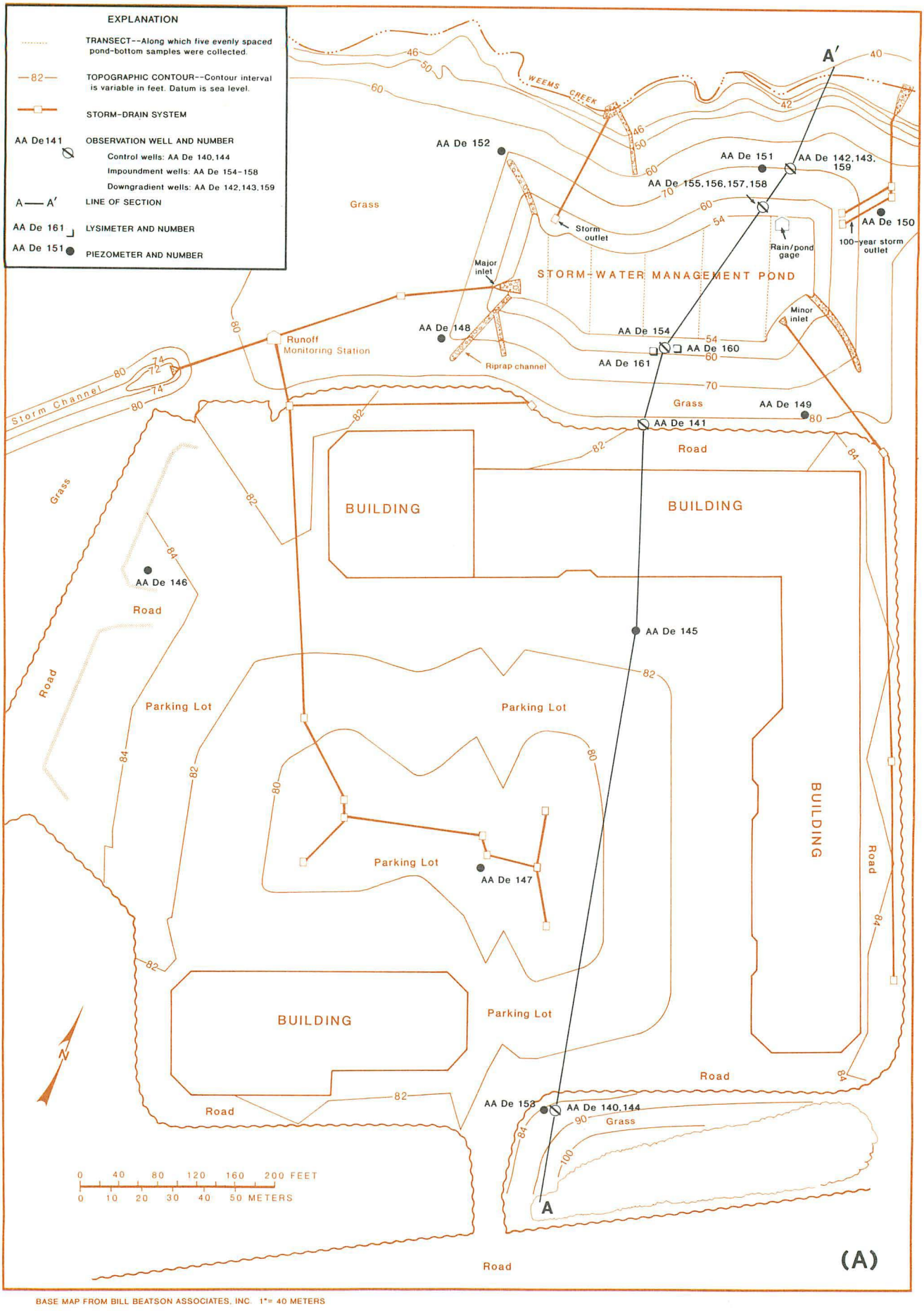
[1] Acute toxicity ("the capacity or potential of a substance to cause the onset of adverse effects in a living organism over a short term exposure") criteria determined by Maryland Department of the Environment.

[2] Chronic toxicity ("the capacity or potential of a substance to cause adverse effects in a living organism over a "long term exposure") criteria determined by Maryland Department of the Environment.

[3] MCL refers to maximum contaminant level, a USEPA primary drinking-water regulation. MCL is an enforceable regulation. Values marked with asterisks are health advisories or proposed maximum contaminant levels which are not enforceable.

[4] SMCL refers to secondary maximum contaminant level, a USEPA secondary drinking-water regulation intended as a guideline for the State. Values marked with asterisks are proposed secondary maximum contaminant levels and are not enforceable.

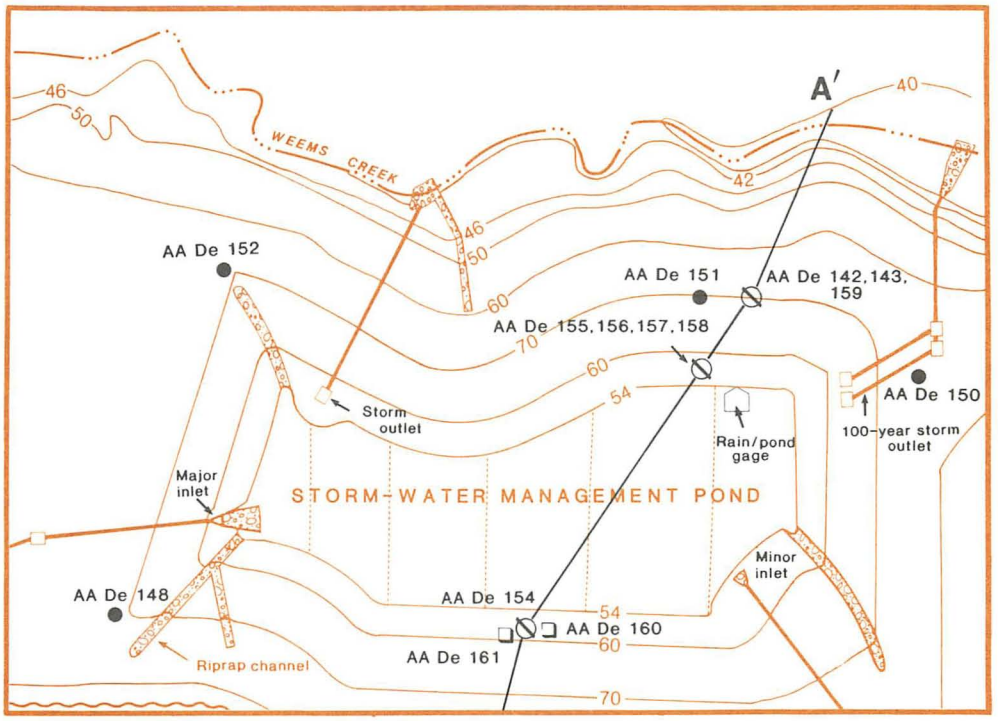
[5] Chromium and lead 1989 MCL's were 50 μg/L for drinking water. The 1991 MCL for chromium was 100 μg/L and for lead was proposed at 5 μg/L.



BASE MAP FROM BILL BEATSON ASSOCIATES, INC. 1"= 40 METERS

Figure 4.—(A) Location of wells, data-collection points, and line of section A-A′, and (B) detail of storm-water impoundment; (C) hydrologic section A-A′; and (D) photograph showing the storm-water impoundment at the Annapolis study site.

Detail (B)



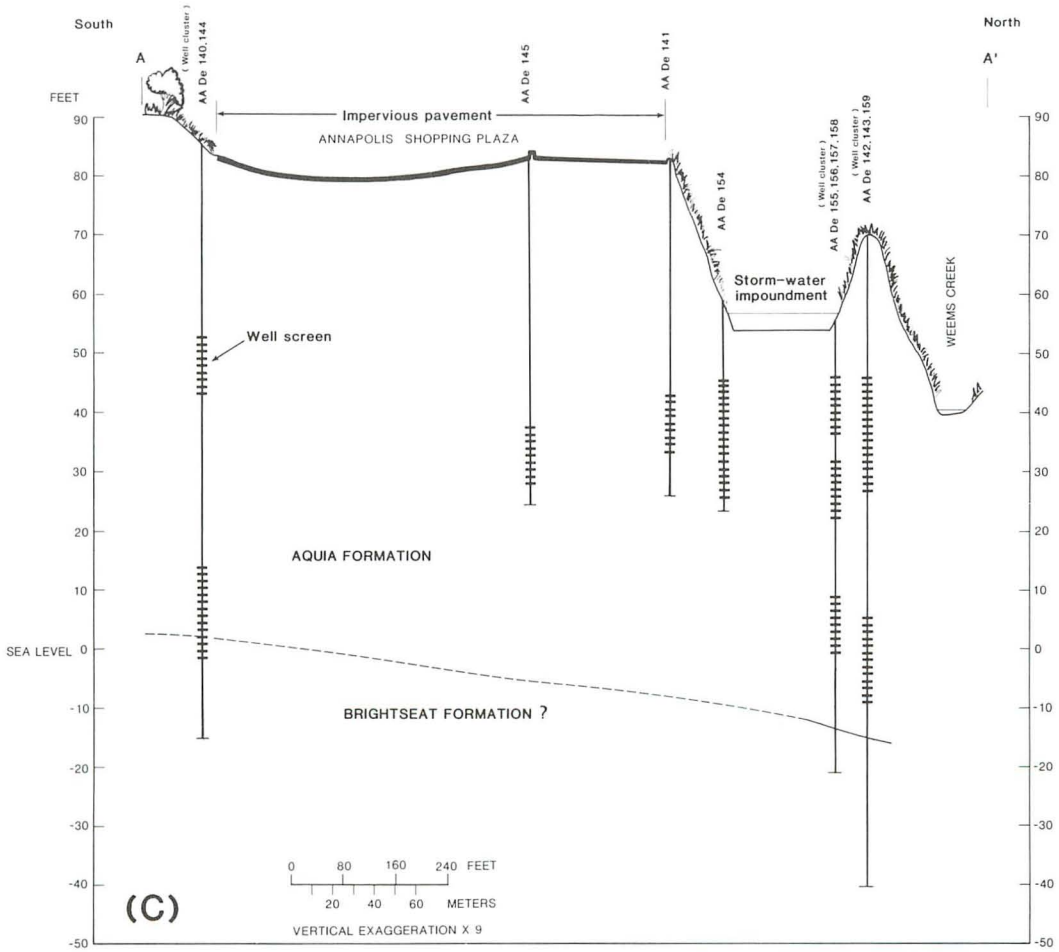


Figure 4.—Continued.

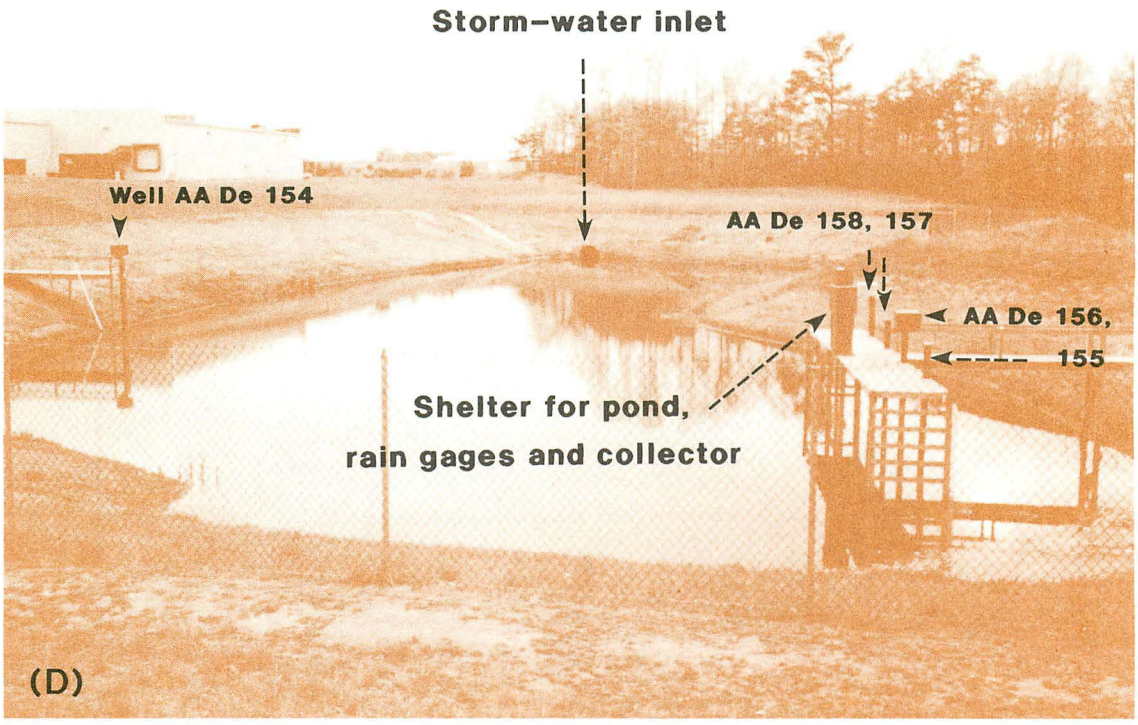


Figure 4.—Continued.

at the downgradient end of the impoundment with respect to the direction of ground-water flow. Well AA De 154 penetrated the impoundment at the southern side, and the two lysimeters—AA De 160 and AA De 161—were installed nearby. Two platforms were constructed to facilitate access to the wells and instruments. The rain gage, rainwater collector, and pond gage were installed on the north platform (fig. 4B).

A minimonitor that was instrumented to record pH, specific conductance, temperature, and dissolved oxygen at 15-minute intervals was installed in well AA De 156 from July 1987 to October 1988. The purpose of these continuous measurements was to determine whether a pattern of fluctuations in the measured characteristics correlated with filtration of water from storms and storm-related rises of the water table. Reliable records of these values were obtained only for specific conductance and temperature; the instruments to measure pH and dissolved oxygen did not operate reliably in the well.

Hydrologic system

The amount of rainfall recorded at the study site was slightly higher than the average for the Annapolis area. Rainfall at the study site for the period of data collection, from October 1986 through March 1989, totaled 113.26 in. for 185 storms (table 4). The total rainfall recorded during the 1987 and 1988 calendar years was 41.25 and 43.99 in., respectively. In 1989, an unusually wet year, a total of 56.1 in. of rainfall was measured at a nearby weather station in Annapolis. The wettest period of the year normally occurred from November through May, which corresponded to the major period of recharge to the water-table aquifer.

Evapotranspiration was not measured on site, but estimates of evaporation published by the National Oceanic and Atmospheric Administration (1986, 1987, 1988) indicate that evaporation mostly exceeded rainfall during April through October for the years shown (table 4). It was assumed that evaporation from November through March was negligible and that rainfall exceeded evaporation.

The impoundment at Annapolis retained a perched layer of water throughout the year. Fluctuations of pond stage reflected the magnitude and intensity of storms and rates of pipe discharge, evapotranspiration, and infiltration (fig. 5). Stage was ordinarily maintained to within 3.21 ft of pond bottom by an invert pipe extending from the riser to Weems Creek.

Comparison of pond losses with the estimated rates of evaporation when pond stage was below 3.2 ft indicated that more water was leaving the pond than could be accounted for by evapotranspiration. This discrepancy indicates leakage through the pond bottom. During December through February, when effects from evapotranspiration can be expected to be negligible, pond losses averaged 0.04 ft/d. Evaporation rates were highest during June and July; the rate in July 1987 was the highest rate for the period 1986–89—0.02 ft/d (8.28 in. for the month); however, the average rate of evaporation for April through November is less than 0.013 ft/d. Thus, evapotranspiration could only account for less than half of the pond losses, and the aver-

Table 3.—Records of wells at the Annapolis site

[ft, feet; in., inches; ft asl, feet above mean sea level; bls, below land surface; --, not applicable; *, lysimeter; Q, chemical data collected; L, water-level data collected]

Well number	Latitude and longitude [1]	State permit number	Date well constructed	Altitude (ft asl)	Depth drilled (ft bls)	Well depth (ft bls)	Diameter of casing (in.)	Length of screen (ft)	Top of open interval (ft bls)	Hydro-geologic unit	Static water level (ft bls)	First date water level measured	Data type	First year of data collection
AA De 140	3859190763221	AA-81-6267	5-12-86	85.03	51.5	45	3	10	32	Aquia	37.80	09-02-86	QL	1986
AA De 141	3859250763222	AA-81-6268	5-09-86	82.99	57	53	3	10	40	Aquia	35.40	08-12-86	L	1986
AA De 142	3859280763221	AA-81-6269	5-07-86	69.98	37	37	3	10	24	Aquia	26.64	09-02-86	QL	1986
AA De 143	3859280763221	AA-81-6270	5-08-86	69.91	50.5	46	3	10	33	Aquia	26.78	09-02-86	QL	1986
AA De 144	3859190763221	AA-81-6267	5-16-86	85.24	100.5	89	3	15	71	Aquia	37.62	10-02-86	L	1986
AA De 145	3859240763221	AA-81-6271	5-05-86	83.77	60	56	1.25	10	46	Aquia	36.85	05-09-86	L	1986
AA De 146	3859220763227	AA-81-6272	4-29-86	84.81	60	59	1.25	10	49	Aquia	34.40	05-06-86	L	1986
AA De 147	3859210763223	AA-81-6267	5-06-86	79.18	56	56	1.25	10	46	Aquia	30.70	05-09-86	L	1986
AA De 148	3859260763224	AA-81-6268	5-01-86	70.24	35	35	1.25	10	25	Aquia	19.99	05-09-86	L	1986
AA De 149	3859260763220	AA-81-6268	4-28-86	78.29	48	48	1.25	10	38	Aquia	33.79	05-09-86	L	1986
AA De 150	3859280763220	AA-81-6270	4-28-86	70.43	49	49	1.25	10	39	Aquia	28.25	05-09-86	L	1986
AA De 151	3859280763222	AA-81-6269	5-01-86	69.62	39	39	1.25	10	29	Aquia	26.82	05-09-86	L	1986
AA De 152	3859280763224	AA-81-6269	5-06-86	70.05	49	49	1.25	10	39	Aquia	22.59	05-09-86	L	1986
AA De 153	3859190763221	AA-81-6267	5-05-86	84.24	59	59	1.25	10	49	Aquia	35.60	05-09-86	L	1986
AA De 154	3859260763222	AA-81-6439	7-08-86	58.48	35	35	3	15	17	Aquia	11.00	07-08-86	L	1986
AA De 155	3859280763221	AA-81-6440	7-02-86	56.28	77.5	60	3	10	47	Aquia	10.60	07-02-86	QL	1986
AA De 156	3859280763221	AA-81-6440	6-24-86	55.92	39	39	3	10	24	Aquia	10.60	06-24-86	QL	1986
AA De 157	3859280763221	AA-81-6440	6-18-86	55.73	24	24	3	10	9.5	Aquia	10.80	06-18-86	QL	1986
AA De 158	3859280763221	AA-81-6440	6-13-86	55.94	43.5	43.5	3	10	23.5	Aquia	10.30	06-13-86	L	1986
AA De 159	3859280763221	AA-81-6270	6-12-86	69.68	110	109	3	15	64	Aquia	28.81	08-11-86	QL	1986
*AA De 160	3859260763222	--	8-19-87	57.71	3.65	3.42	2.38	.25	2.30	Aquia	--	--	Q	1987
*AA De 161	3858260763322	--	8-19-87	59.90	1.60	1.45	2.38	.25	.6	Aquia	--	--	Q	1987

[1] Symbols designating degrees (o), minutes (′), and seconds (")have been omitted from latitude and longitude. Latitude precedes longitude and each longitude begins with 076 degrees. For example: latitude, 38°59′19"; longitude, 076°32′21".

Table 4.—Monthly rainfall measured at the Annapolis study site and monthly evaporation measured at the Upper Marlboro weather station, October 1986 through March 1989

[--, no data available; in., inches]

Year	Month	Precipitation		Evaporation [1]	Comments
		Number of storms	Number of inches	Number of inches	
1986	October	4	2.23	3.26	
	November	8	7.29	1.74	
	December	5	7.25	--	
1987	January	8	3.73	--	Amount of rainfall
	February	3	2.63	--	during 1987 calendar
	March	4	1.09	--	year totaled 41.25 in.
	April	5	3.60	3.49	
	May	6	6.37	5.68	
	June	7	3.80	7.13	Amount of rainfall
	July	6	2.09	7.97	during 1987 water year
	August	5	2.35	5.33	totaled 47.95 in.
	September	10	5.53	3.86	
	October	4	1.82	2.98	
	November	4	4.76	2.01	
	December	9	3.48	--	
1988	January	12	3.27	--	Amount of rainfall
	February	6	4.67	--	during 1988 calendar
	March	4	3.06	--	year totaled 43.99 in.
	April	4	2.34	4.37	
	May	10	5.80	5.68	
	June	2	1.12	6.74	Amount of rainfall
	July	8	5.04	6.87	during 1988 water year
	August	6	6.21	6.30	totaled 43.93 in.
	September	4	2.36	4.02	
	October	5	2.61	3.08	
	November	8	5.95	2.09	
	December	5	1.56	--	
1989	January	7	2.92	--	
	February	8	3.68	--	
	March	8	4.17	--	
Total		185	113.26		

[1] Evaporation data compiled from climatological data summaries published by the U.S. National Oceanic and Atmospheric Administration (1986-88). Data were not adjusted for pan effects. Estimated annual pan coefficient for Class A pan coefficient is 0.75 (Fetter, 1988).

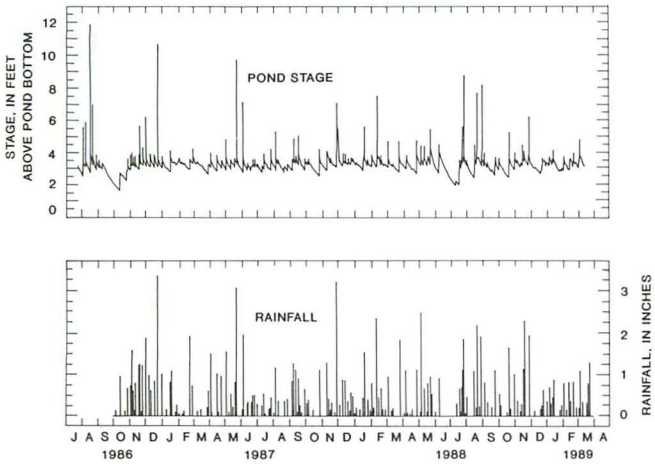


Figure 5.—Daily mean stage in storm-water pond and total daily rainfall at the Annapolis site, July 1986–March 1989.

age rate of storm-water infiltration through the bottom during dry weather (with pond stage less than 3.2 ft and no contribution from bank storage) was conservatively estimated at 0.04 ft/d.

Attempts to determine an initial infiltration rate through the sides of the impoundment by use of a double-ringed infiltrometer yielded extremely variable rates of 2.88 to 63.4 ft/d; however, the rate of infiltration to the water table (determined from the start of pond-stage rise to the start of water-table rise) ranged from 7.2 to 38.4 ft/d after the onset of a storm. Factors contributing to the rate variability include initial pond stage, intensity and magnitude of rainfall, and antecedent moisture content in the unsaturated zone.

The Aquia Formation, which forms the water-table aquifer at the study site, is a heavily used aquifer here and in other parts of the Maryland Coastal Plain (Bennion and Brookhart, 1949; Otton, 1955). The Aquia Formation has been extensively studied geologically and hydrologically (Chapelle and Drummond, 1983; Chapelle and Knobel, 1983; Glaser, 1971; Hansen, 1972a, 1972b, 1974, 1977; Kapple and Hansen, 1976; Otton, 1955; Weigle and Webb, 1970; Wolfe, 1967; Wright and Huffman, 1979).

The primary direction of ground-water flow is to the northeast; shallow ground water discharges to Weems Creek (fig. 6). The water-table gradient across the study site steepens in the downgradient direction, toward Weems Creek. Horizontal hydraulic conductivity of the water-table aquifer was estimated to be 10 to 50 ft/d—a range commonly cited for medium to coarse-grained silty sands (Heath, 1984).

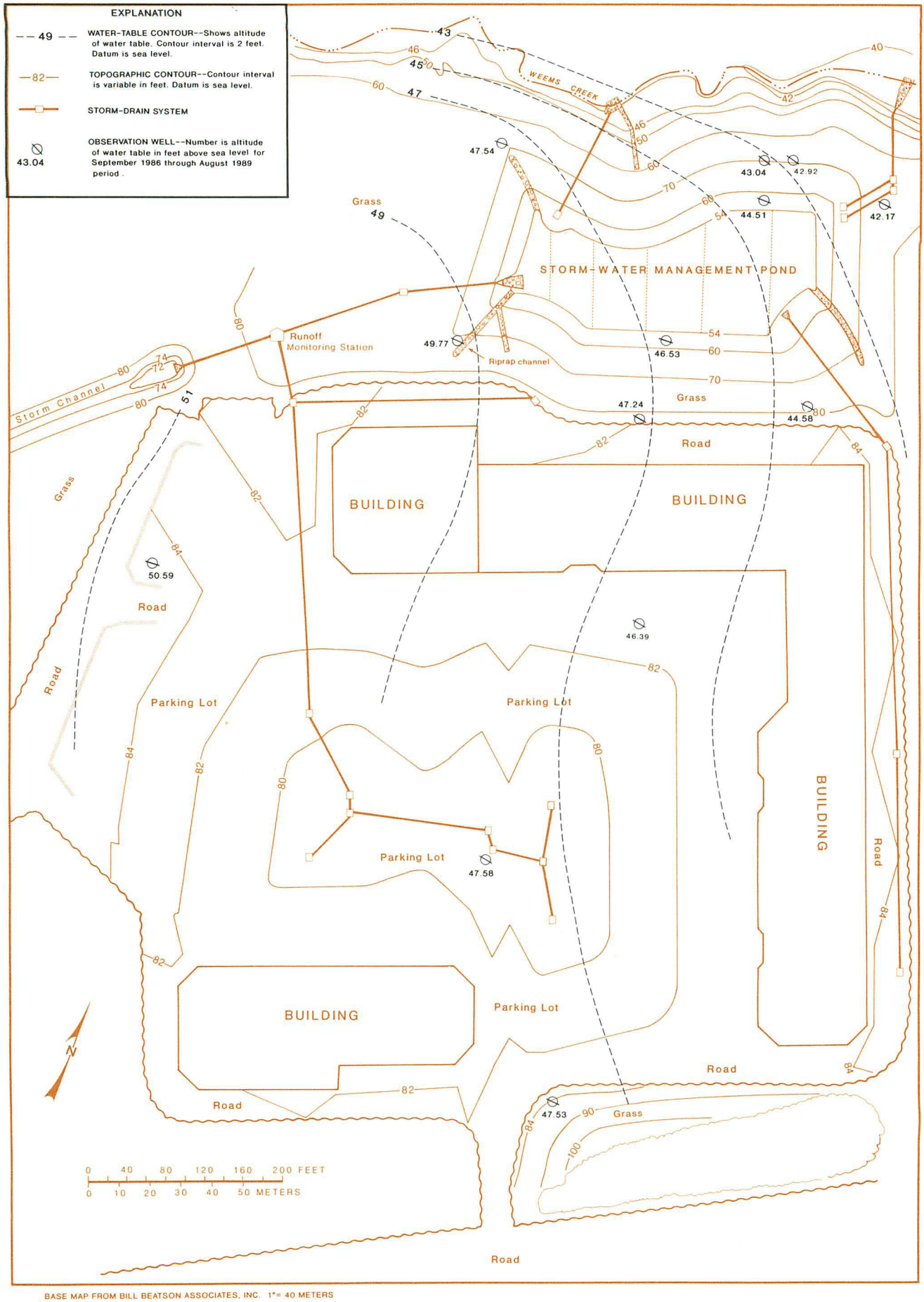
Ground-water-flow velocity was estimated by use of a bromide tracer. A 3-L solution of bromide (756 g/L [grams per liter]) and ground water from well AA De 157 was injected at the water table through piezometer AA De 148 on November 15, 1988. Samples were collected in duplicate several times a week from wells AA De 148, 152, and 156 and were returned to the office. A solid state ion-selective electrode and a reference electrode and temperature compensator were used for office measurements of bromide concentrations. Selected duplicate samples were sent to the laboratory and analyzed for bromide concentration by ion chromatograph (IC); the remainder were archived. Agreement between bromide electrode and IC analytical data was relatively good when concentrations exceeded 2 mg/L bromide; below that concentration, however, agreement was poor, and the electrode data were judged to be unreliable.

Results of the tracer test at the impoundment (table 5) indicated that the flow velocity through the Aquia aquifer at the water table was between 16 and 26 ft/d. The primary breakthrough of tracer at well AA De 152 was on November 28, but an initial pulse of bromide appears to have arrived 5 days earlier, on November 23. The elevated bromide concentration at AA De 152 was attenuated within 3 days, after which concentrations approached background levels. One factor that was not rigorously explored was the effect on bromide concentrations of the 4.28 in. of rain that fell on the site between November 15 and November 28. This period of heavy rain could help explain an early bromide pulse through preferential flow channels and rapid attenuation. The first indication that bromide tracer might have reached AA De 156 was on December 9, which was the date of the last sample collected and analyzed by the laboratory.

Although the variability of field measurements is within the concentration range shown for December 7 and 9 and precludes interpretation of these field data, the concentration increases of the laboratory data for these days indicates that bromide breakthrough occurred around that time. (Concentration values in this range measured on November 15 are attributed to unrefined sample-collection methods; the method was subsequently modified.) The ground-water-flow velocity calculated from a December 7th bromide breakthrough at AA De 156 is in agreement with the rate calculated between the injection well (AA De 148) and AA De 152.

The water table was from 8 to 13 ft beneath the storm-water impoundment during the study period. The storm-water impoundment serves as a recharge basin. It is adjacent to Weems Creek, which is a drain for the shallow ground-water-flow system. Ground-water flow is downward at the control wells: the head differences between water levels measured at the well screened at the water-table surface (AA De 140) were consistently higher than those measured at a well screened about 30 ft deeper (AA De 144) (fig. 7). Near the area of ground-water discharge toward the creek there is an upward component of flow: flow lines converge in the downgradient direction, and water levels measured at the deeper screened well (AA De 159) tend to be higher than or equal to those measured at AA De 143, screened at the water-table interface (fig. 7).

The effects of pond-water infiltration on water-table levels beneath and downgradient of the pond were superposed on the seasonal pattern of regional recharge (fig. 8). Throughout the year, the water table beneath and peripheral to the pond fluctuated in response to changes in stage caused by runoff to the impoundment (fig. 9). The rise of the water table often masked the effect of seasonal recharge (figs. 8 and 9). The impoundment wells were within 5 ft of the banks; therefore, the sharp response



BASE MAP FROM BILL BEATSON ASSOCIATES, INC. 1"= 40 METERS

Figure 6.—Mean water-table configuration at the Annapolis site.

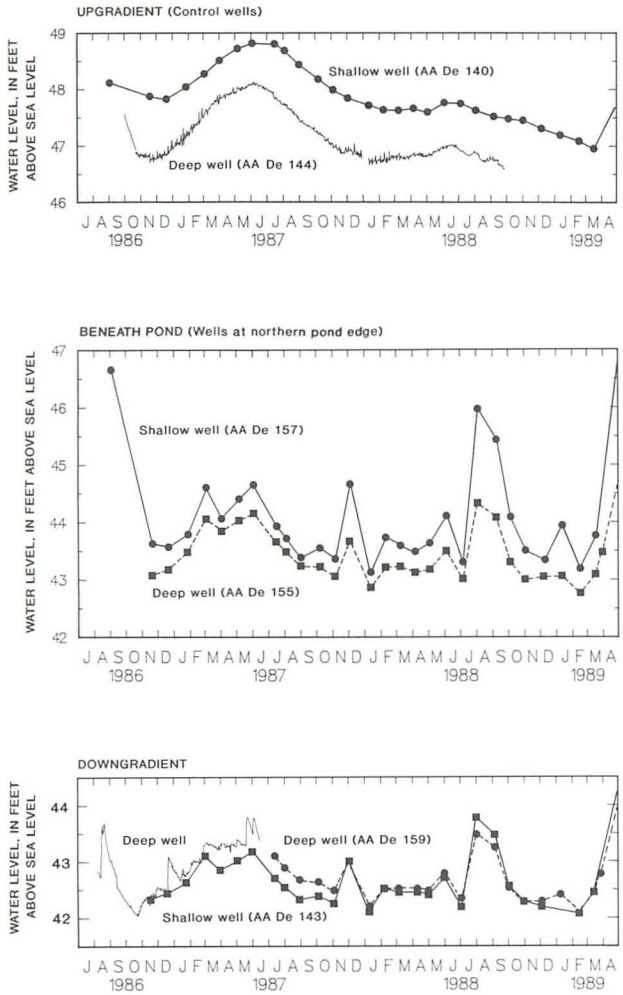


Figure 7.—Altitude of water levels between deep and shallow wells at the upgradient (control) station, northern pond edge, and downgradient station at the Annapolis site, July 1986–April 1989.

of ground-water levels to rainfall in wells adjacent to the ponds probably reflects the higher permeability of the vegetated pond berm compared to pond bottom (fig. 9).

Fluctuations of the upgradient hydraulic gradient were small throughout the period of study, and fluctuations in annual water-table levels were rarely greater than 1.25 ft at the control wells. The hydraulic gradient across the water table beneath the pond was steep, however, and head differences occasionally exceeded 5 ft between wells AA De 154 and AA De 143 (fig. 8). Throughout the period of data collection, the head at well AA De 154 fluctuated the most—greater than 3 ft in 1988. Analogous fluctuations in head were observed at wells on the opposite side of the impoundment and at the downgradient wells. The mean hydraulic gradient of the water table beneath the pond for the period of study was 11 percent, compared with 0.8 percent beneath the upgradient area.

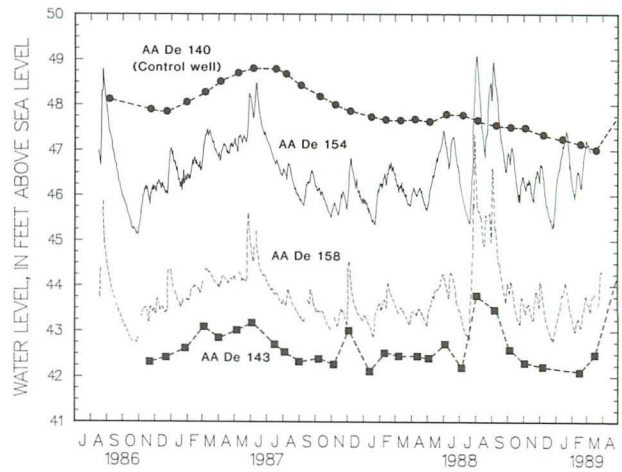


Figure 8.—Water table at the upgradient (control) well (AA De 140), well AA De 154 on the southern edge of the pond, well AA De 158 on the northern edge of the pond, and at the downgradient well (AA De 143) at the Annapolis site, July 1986–April 1989.

These fluctuations in hydraulic gradient beneath and near the impoundment were related to water-table mounding. A sectional view of the monthly water-table surface indicates a mound beneath the southern berm of the pond (fig. 10). Seasonal changes in water-table levels from regional recharge were superposed on the effects from mounding. In general, the degree of water-table fluctuations was greater beneath the pond, than in adjacent areas. The height of the mound beneath the Annapolis

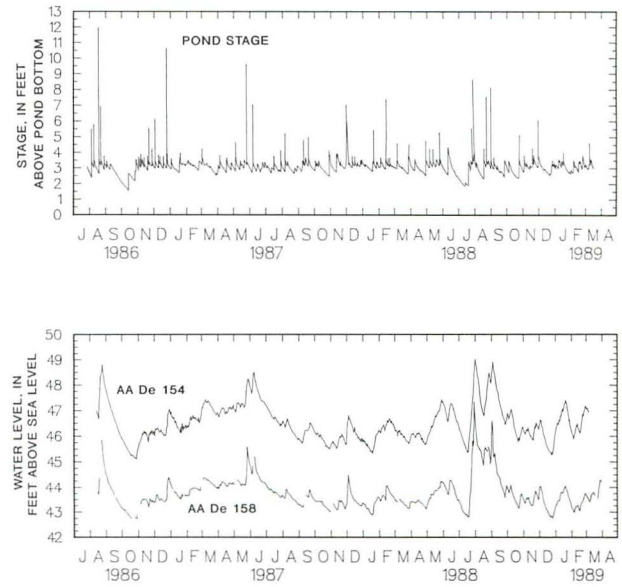


Figure 9.—Fluctuations of pond stage and the water table beneath the pond at the Annapolis site, July 1986—April 1989.

Table 5.—Results of bromide tracer test at the Annapolis site

[mg/L, milligrams per liter; --, no data; <, less than]

Date (1988)	Rainfall[1] (inches)	Injection well (AA De 148) (mg/L)		Downgradient piezometer (AA De 152) (mg/L)		Beneath-impoundment well (AA De 156) (mg/L)	
		Field	Lab	Field	Lab	Field	Lab
11-15	--	<1	--	<1	0.56	--	0.42
11-22	2.33	--	--	<1	.11	--	--
11-23	2.33	6,400	6,400	3.4	4.5	<1	--
11-25	2.33	3,500	--	1	.79	1.29	.11
11-28	4.28	3,700	--	66	55.0	1.1	--
11-29	4.28	3,200	--	3.5	4.9	1.4	--
11-30	4.28	2,900	--	4.1	4.5	1.2	--
12-01	4.28	2,050	--	<1	.25	<1	.12
12-02	4.28	1,400	1,400	<1	--	<1	--
12-06	4.28	180	190	<1	--	<1	--
12-07	4.28	155	--	<1	--	1.15	.45
12-09	4.34	240	--	<1	--	1.48	.53

[1] Cumulative inches of rainfall recorded at site starting 11-15-88.

pond depended upon the amount of rain: In calendar year 1987, the highest mounding occurred during May—the wettest month; in calendar year 1988, the highest mounding occurred during July and August—the wettest 2-month period. The lowest mound generally occurred in the late autumn/early winter months—the season when water-table altitudes were lowest.

The occurrence of mounding affects the direction and rate of ground-water flow and thus has implications for ground-water quality. Because no wells were constructed in the center of the pond, the water-table configuration beneath the impoundment center only can be inferred. The steep gradients between the southern and northern berms, however, indicate a northward-sloping water table and little or no mounding at the northern end.

Native Geologic Materials

The Annapolis site is within the Coastal Plain province, near the outcrop area of Paleocene deposits of the Aquia Formation (Hansen, 1974). The Aquia Formation is approximately 85 ft thick at the study site and is underlain by the Brightseat(?) Formation. The stratigraphy was based on mineralogical and palynological evidence from split-spoon samples. Palynological analyses of these underlying sediments were performed at the State University of New York at New Paltz. Based on the presence of diagnostic dinoflagellates *Danea californica, Deflandrea pulchra,* and *Fibrocysta bipolare,* the sediments were dated as Paleocene, and probably are from the Brightseat Formation (G.J. Brenner, State University of New York at New Paltz, written commun., 1987). These sediments differed from the overlying Aquia sediments by being better sorted, much finer grained, and higher in glauconite content, and by containing discrete shell material.

Aquia sediments tend to become better sorted and finer grained with depth. Sediments sampled from cores collected at the water-table interface were 83 percent sand, 6 percent silt, and 11 percent clay (well AA De 155, 10–12 ft) (table 6). The Aquia Formation is composed mostly of quartzose sands that are highly weathered to a depth of approximately 35 ft; iron-oxide ledges were found during drilling at 25 to 30 ft below land surface.

Sand-sized glauconite and goethite pellets are common; the goethite pellets were determined by Hansen (1974) not to be altered glauconite. Both types of pellets showed a high degree of weathering in the samples collected to 35 ft. The most commonly observed heavy minerals were ilmenite and magnetite, but these comprised less than 1 percent of the samples collected at the study site. Andalusite, epidote, garnet, hornblende, sillimanite, tourmaline, and zircon also have been identified in Aquia sediments of southern Maryland (Chapelle and Drummond, 1983). Shell material that might have originally been present was completely leached from the sediments to 43 ft below land surface. Sparse calcitic residues were found from 45 ft below land surface to the base of the Aquia. The major- and trace-element composition, determined from chemical analysis of the Aquia aquifer samples collected, closely resembles compositions reported in the literature (tables 7, 8) (Glaser, 1971; Hansen, 1974; Chapelle and Drummond, 1983).

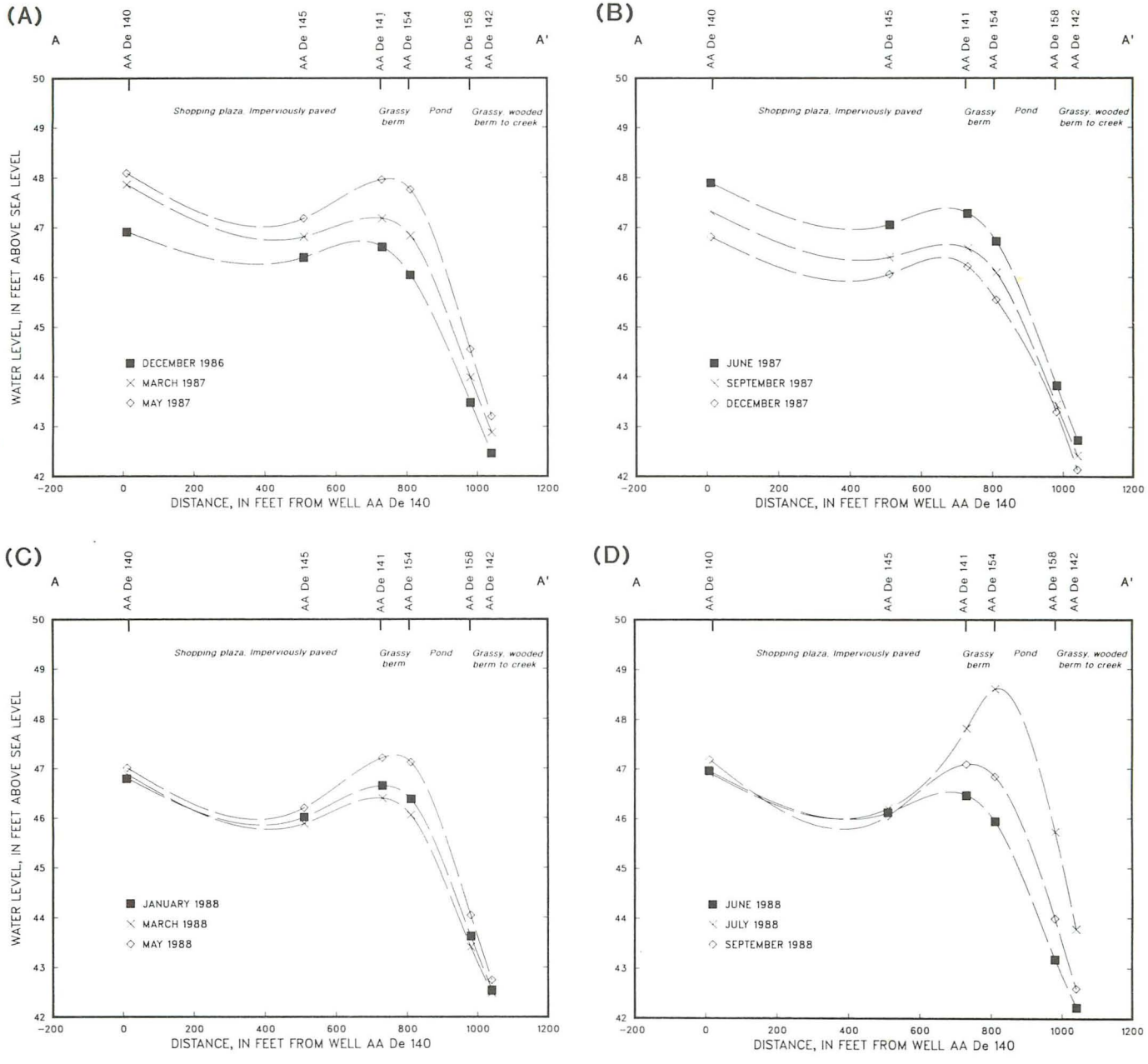


Figure 10.—Altitude of water-table at the Annapolis site: (A) December 1986, March and May 1987; (B) June, September, and December 1987; (C) January, March, and May 1988; (D) June, July, and September 1988. (Trace of section is shown in Fig. 4.)

Table 6.—Exchangeable base cations, cation-exchange capacities, and particle size of native geologic materials at the Annapolis site

[Ca^{2+}, calcium; Mg^{2+}, magnesium; K^{+}, potassium; Na^{+}, sodium; CEC, cation-exchange capacity (units are in milliequivalents per 100 grams of dry soil); --, no data; sand, > 0.062 millimeters; clay, ≤ 0.004 millimeters]

	Depth interval (feet below land surface)	Exchangeable base cations					Particle size (percent)		
		Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	CEC	Sand	Silt	Clay
Control well (AA De 144)	29 - 30.5	2.36	1.96	0.31	0.07	4.70	82	8	10
	49 - 50.5	.98	1.21	.16	.17	2.52	87	6	7
	79 - 80.5	2.31	1.19	.22	.16	3.88	83	7	10
	99 -100.5	1.88	1.15	.21	.13	3.37	87	4	9
Impoundment well (AA De 155)	2 - 4	--	--	--	--	--	80	6	14
	4 - 6	3.04	1.75	.19	.21	5.19	82	8	10
	10 - 12	2.63	1.53	.21	.16	4.53	83	6	11
	24 - 26	1.21	1.32	.14	.15	2.82	81	7	12
	45 - 51.5	--	--	--	--	--	87	8	5
	65 - 72	3.24	.55	.27	.13	4.19	87	9	4
Downgradient well (AA De 159)	18.5- 20	.04	.58	.16	.12	.90	75	15	10
	28.5- 30	.94	1.19	.16	.17	2.46	81	7	12
	38.5- 40	1.36	1.22	.17	.16	2.91	81	8	11
	73.5- 75	2.08	1.30	.17	.13	3.68	91	3	6
	83.5- 85	2.74	1.13	.23	.11	4.21	87	6	7
	103.5-110	3.33	.12	.13	.15	3.73	94	4	2

Pond-Bottom Materials

The storm-water impoundment was excavated in the Aquia Formation. Runoff discharging to the impoundment delivered material that mixed with and accumulated on Aquia sediments. Samples of bottom material were collected along transects shown in figure 4 and composited. (See "Approach" section). Each sample was 4 to 5.5 in. (10 to 14 centimeters) in length and about 3 in. (6.25 centimeters) in diameter. Thus, the samples comprised an increasing component of storm-water-borne material relative to native sediments each year. Pond-bottom samples were collected in fall 1986, 1987, and 1988. When the first pond-bottom sample was collected, the impoundment had been in operation for 1 year, and from 0 to 2 in. of sediment had accumulated. The net increase of bottom material between September 1986 and September 1988 was about 6 in.; channels scoured by the incoming runoff tended to have little or no accumulation, but accumulation was substantial at channel margins and in local depressions.

Accumulated sediments were not anaerobic, although pockets with the greatest accumulated thicknesses commonly emitted an organic odor when disturbed. As the bottom accumulation increases, the oxidation of organic matter ultimately may produce anaerobic conditions in the pond-bottom sediments; this can affect future sediment chemistry and the chemistry of associated aqueous phases.

Large differences were noted between the physical, mineralogical, and chemical properties of bottom material collected in 1986 and those of material collected in subsequent years (table 9). The 1986 sample can be considered as having a composition close to that of the Aquia sediments that initially comprised pond-bottom materials, because accumulation of storm-water-borne sediment was 2 in. or less at that time. The composition of core samples collected from 4 to 12 ft from pond bottom while drilling well AA De 155 in general bracketed the composition of the 1986 pond-bottom sample (tables 6, 7, 8, 9). Sand-sized particles decreased by nearly 30 percent during 1986–88, whereas silt and clay components increased by factors of 4.8 and 7.5,

Table 7.—Major-element chemistry of native geologic materials at the Annapolis site

[Reported in weight-percent oxide, normalized to 100 percent; ft bls, feet below land surface; LOI, loss on ignition; analytical method for elements was X-ray fluorescence; geologic material are from the Aquia Formation for all depth intervals except the bracketed intervals which comprise the lower Aquia and Brighseat(?) Formations]

Well number	Depth of sample (ft bls)	Calcium (CaO)	Magnesium (MgO)	Sodium (Na_2O)	Potassium (K_2O)	Phosphorus (P_2O_5)	Silica (SiO_2)	Aluminum (Al_2O_3)	Iron (Fe_2O_3)	Manganese (MnO)	Titanium (TiO_2)	Percent LOI	Final percentage
AA De 144[1]	29 - 30.5	0.08	0.14	0.16	2.19	0.15	73.97	4.80	16.65	0.13	0.64	1.12	100.03
	49 - 50.5	.07	.21	.16	1.45	.30	76.07	3.93	14.70	.03	.41	2.67	100.00
	[79 - 80.5]	.13	.15	.22	1.40	.15	85.90	3.23	6.62	.04	.37	1.80	100.01
	[99 -100.5]	.10	.31	.18	1.54	.18	83.66	2.86	8.74	.03	.46	1.94	100.00
AA De 155[2]	4 - 6	.10	.20	.23	2.27	.27	76.02	4.64	12.87	.03	.45	2.92	100.00
	10 - 12	.07	.61	.10	1.86	.24	70.03	3.79	19.37	.06	.33	3.54	100.00
	24 - 26	.06	.05	.05	1.00	.23	83.76	2.86	9.59	.04	.18	2.18	100.00
	45 - 51.5	.07	.32	.26	1.61	.07	85.41	4.00	5.96	.02	.62	1.66	100.00
	[65 - 72]	1.07	.38	.13	1.66	.36	84.65	2.48	6.72	.03	.42	2.11	100.01
AA De 159[3]	18.5- 20	.07	.32	.29	1.35	.17	78.74	3.44	11.87	.04	1.20	2.52	100.01
	28.5- 30	.07	.01	.18	1.86	.32	68.45	4.09	20.96	.03	.38	3.66	100.01
	38.5- 40	.05	.01	.11	1.30	.32	67.32	3.54	23.14	.02	.30	3.89	100.00
	73.5- 75	.08	.22	.08	1.88	.12	86.19	2.30	7.26	.01	.31	1.55	100.00
	83.5- 85	.13	.21	.13	1.82	.16	86.42	2.69	6.84	.02	.44	1.15	100.01
	[103.5-110]	.82	.24	.23	.97	.22	89.20	2.73	3.15	.04	1.26	1.13	99.99

[1] Upgradient (control) well.
[2] Impoundment well.
[3] Downgradient well.

Table 8.—Trace-element chemistry of native geologic materials at the Annapolis site

[Reported in parts per million; ft bls, feet below land surface; <, below detection with analytical method used]

Well number	Depth of sample (ft bls)	Cadmium (Cd)	Chromium (Cr)	Cobalt (Co)	Copper (Cu)	Lead (Pb)	Molybdenum (Mo)	Nickel (Ni)	Vanadium (V)	Zinc (Zn)
AA De 144 [1]	29 - 30.5	<1	220	89	4.0	14	2	19	310	110
	49 - 50.5	3	190	74	3.0	14	2	28	220	160
	79 - 80.5	1	140	240	7.0	14	6	13	120	65
	99 -100.5	<1	160	160	3.0	14	4	14	94	55
AA De 155 [2]	4 - 6	1	230	82	3.5	8	3	18	140	110
	10 - 12	1	350	43	2.0	12	<1	16	260	140
	24 - 26	2	140	120	3.5	14	3	25	300	150
	45 - 51.5	2	170	150	4.0	10	5	14	98	80
	65 - 72	2	150	160	4.5	8	5	16	78	100
AA De 159 [3]	18.5- 20	<1	190	130	6.0	8	10	9	140	51
	28.5- 30	<1	250	72	4.0	14	1	16	270	120
	38.5- 40	2	210	71	2.5	12	<1	20	270	170
	73.5- 75	<1	160	87	2.5	4	3	11	110	50
	83.5- 85	<1	150	87	3.0	12	3	12	98	60
	103.5-110	1	120	250	6.0	10	8	12	62	47

[1] Upgradient (control) well.

[2] Impoundment well.

[3] Downgradient well.

respectively. The largest change occurred between 1986 and 1987, when the percentage of silt increased 200 percent and the percentage of clay increased 550 percent. Between 1987 and 1988, increases in silt and clay were 58 and 15 percent, respectively.

Cation-exchange capacity (CEC) was calculated as the sum of total exchangeable cations. The CEC of background sediments was less than 5.2 meq/100 g (milliequivalents per 100 grams) (table 6). The increase in the total CEC of bottom material collected in 1988 compared with 1986 was threefold: the larger CEC can be explained by the increase in the clay fraction (table 9). The CEC for 1987 and 1988 exceeded 10 meq/100 g, which commonly is cited as the limit for the CEC of kaolinite (Drever, 1988). These data indicate that the clay-mineral composition was also changing to include illites, mixed-layer clays, or montmorillonites, which typically have CEC's in the range of 10 to 40 meq/100 g (illite) and 80 to 150 meq/100 g (montmorillonite).

A plot of pond-water compositions on clay-stability diagrams indicates that pond water is in equilibrium with gibbsite, kaolinite, and illite—illite being compositionally intermediate between muscovite and montmorillonite (Krauskopf, 1967) (fig. 11). Calculations of the ion-activity product indicated saturation of pond water with respect to aluminum, iron, and manganese hydroxides, which, in turn, indicated precipitation of oxyhydroxides of these metals.

Major elements

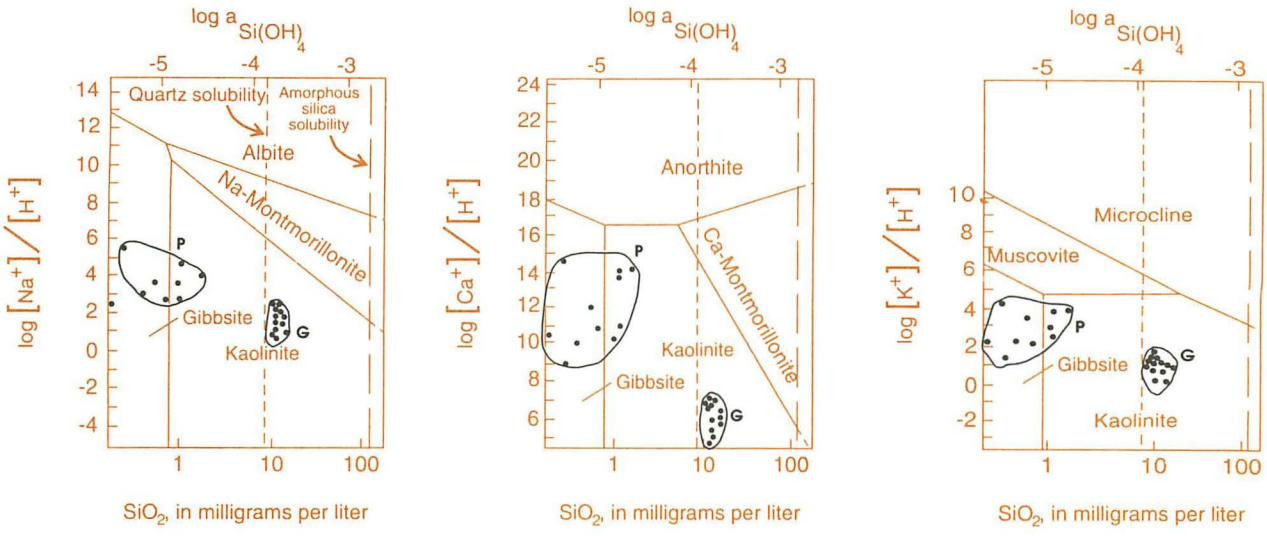
Ten constituents comprised the major bottom-sediment chemistry at the Annapolis impoundment (table 9). The greatest increases measured were in the proportions of calcium, magnesium, and loss on ignition (LOI). The LOI increased by a factor of 2 between 1987 and 1988. This increase does not correlate with the period of greatest increase in silt and clay. Therefore, the LOI increase is attributed primarily to an increased organic carbon component of bottom material; weight loss resulting from water being driven from silts and clays is probably minor. The percentages of aluminum, phosphorous, potassium, and titanium in bottom material also increased. Net decreases were noted in percentages of iron, silica, and sodium, and the percentage of manganese did not change.

The shift in the relative abundances of the major elements was related to changes in particle-size distributions and reflected changes in the bulk mineralogical composition of bottom material between 1986 and 1989. The proportion of quartz and glauconite decreased as the proportion of the incoming clay

Table 9.—Composition of pond-bottom materials at the Annapolis site, 1986–1988

[Units for exchangeable base cations are in milliequivalents per 100 grams dry sample; CEC, cation-exchange capacity; major-element analysis by X-ray fluorescence, reported in weight-percent oxide and normalized to 100 percent; trace-element analysis by X-ray fluorescence (XRF) or direct-coupled plasma (DCP), reported in parts per million (ppm)]

Component	1986	1987	1988
Particle size (percent)			
Sand	94	75	66
Silt	4	12	19
Clay	2	13	15
Exchangeable base cations and cation-exchange capacities			
Calcium (Ca^{2+})	3.04	8.13	13.13
Magnesium (Mg^{2+})	1.75	1.21	2.51
Potassium (K^{+})	.19	.41	.40
Sodium (Na^{+})	.21	.37	.22
CEC (sum base cations)	5.19	10.12	16.26
Major elements (percent)			
Aluminum (Al_2O_3)	4.14	4.63	5.53
Calcium (CaO)	.14	.19	.57
Iron (Fe_2O_3)	11.89	11.86	11.56
Magnesium (MgO)	.63	.66	1.09
Manganese (MnO)	.01	.01	.01
Phosphorus (P_2O_5)	.11	.14	.16
Potassium (K_2O)	1.72	1.96	2.13
Silica (SiO_2)	77.04	76.67	70.93
Sodium (Na_2O)	.24	.14	.09
Titanium (TiO_2)	.56	.54	.61
Loss on ignition (LOI)	3.52	3.22	7.31
Sum	100.00	100.02	99.99
Trace elements (ppm)			
Arsenic (As)	<3	<3	<3
Barium (Ba)	185	324	218
Boron (B)	160	150	120
Cadmium (Cd)	<1	<1	<1
Chromium (Cr)	130	130	140
Cobalt (Co)	82	87	113
Copper (Cu)	3.5	29	40
Gallium (Ga)	20	26	9
Lead (Pb)	<2	24	28
Molybdenum (Mo)	4	8	6
Nickel (Ni)	6	8	16
Rubidium (Rb)	75	69	69
Strontium (Sr)	14	4	24
Vanadium (V)	210	170	150
Yttrium (Y)	42	40	47
Zinc (Zn)	54	60	344
Zirconium (Zr)	242	250	261



EXPLANATION

P Pond water G Ground water

Figure 11.—Stability relations for clay minerals and aqueous solutions with respect to clay minerals at the Annapolis site. [log a $Si(OH)_4$ is log activity of silicic acid.]

minerals increased. In addition, interactions between water and sediment affected the chemical composition of the clay minerals and precipitate phases. Clay minerals identified in 1986 bottom material by X-ray diffraction included kaolinite, montmorillonite ("smectite"), illite, and a mixed-layer phase. The clay-stability diagrams (fig. 11) show that sodium and calcium montmorillonite would not be stable in the pond environment given conditions of chemical equilibrium.

The most abundant element in bottom material was silica. The ratio of silica to other elements generally is greater in the Aquia Formation (because of its predominantly quartzose mineralogy) than in the accumulating bottom material. Because clay minerals are aluminosilicates, the sediment accumulating in the pond can be expected to be enriched in aluminum relative to the background sediments and relative to silica. The decrease of silica in bottom material between 1986 and 1988 was 8 percent. Aluminum increased by 34 percent. Silica to aluminum (Si:Al) ratios were about 19:1, 17:1, and 13:1 for 1986, 1987, and 1988, respectively.

Iron was the second most abundant element, comprising from 9 to 23 percent of shallow Aquia sediments (table 7) and almost 12 percent of bottom material. Iron in bottom sediments decreased by 2.8 percent during the 3-year period; iron to aluminum (Fe:Al) ratios were 2.9:1, 2.6:1, and 2.1:1 for respective years.

The primary source of iron in native sediments is glauconite, a potassium-rich and iron-rich silicate that is present as sand-sized particles in the Aquia Formation (Wolfe, 1967). Goethite is a minor source of iron in the Aquia, except where iron-hydroxide precipitation forms secondary cements and indurated ledges. Dilution of quartz and glauconite by sediments accumulating in the pond accounted, in part, for the decrease in silica and iron.

The decrease was substantially smaller for iron than silica, indicating a continuing source of iron to the impoundment. Sources potentially include iron-rich clays and colloids, iron coatings on sediments, and precipitation of iron oxides. The montmorillonite group of clay minerals commonly incorporate iron [+3] as well as magnesium and additional aluminum in the octahedral layer; nontronite, for example, incorporates iron [+3] in its structure, in considerable excess compared with combined aluminum and magnesium. An influx of nontronitic montmorillonite into the impoundment could help account for the increase in aluminum and magnesium and could also provide a source of iron. Nontronite was not stable in the pond environment. Saturation-index calculations (log IAP/KT) for the pond water indicate that dissolution of nontronite but precipitation of hydrous iron oxides could be expected. In addition, iron entering the pond as oxide coatings would be stable and would contribute iron to the bottom materials.

Calcium abundance changed the most dramatically in the bottom sediments, increasing by more than 300 percent for exchangeable calcium as well as for percentage of calcium in the bulk sample. There was virtually no source of calcium in native material at a depth interval of 15 ft above sea level, yet calcium was by far the most abundant element in runoff and pond water. Pond water generally was undersaturated with respect to calcite and other carbonates (log IAP/KT = -0.07 to -2.6); saturation indexes also indicated that pond water was undersaturated with respect to calcium montmorillonite. This undersaturation indicates that calcium was not accumulating in bottom sediments as a result of authigenic clay formation but could have been incorporated into clay lattices through ion-exchange processes. Calcium is preferentially exchanged onto clay lattices compared with the other major cations, and this preferential exchange would be enhanced in the presence of a large concentration gra-

dient between the aqueous solution (pond water) and bottom sediments.

Magnesium increased by 73 percent in pond-bottom sediments between 1986 and 1988, and there was also a net increase in exchangeable magnesium. The source of exchangeable magnesium in bottom sediments may have been incoming clay and other detrital minerals; however, magnesium-bearing silicate and aluminosilicate minerals generally were unstable in pond water. Because the concentrations of magnesium dissolved in pond water were equivalent with those in runoff, aqueous solutions did not appear to provide a source of exchangeable magnesium. The source of magnesium in Aquia sediments was primarily glauconite (Wolfe, 1967). Upward diffusion of magnesium that was released by glauconite dissolution could have been a source of the magnesium to clays in the bottom sediments, and this magnesium could have participated in ion-exchange reactions. The decrease in exchangeable magnesium in the 1987 sample was coincident with the increase in exchangeable sodium for that year. Although magnesium ions are smaller than sodium ions, the hydration effect is greater; this increases the effective radius of the magnesium ion and could have allowed for ionic substitution by sodium. The chemical data for storm water are consistent with this hypothesis; the number of samples are not numerous enough to show definitively that magnesium concentrations were higher in 1987, but concentrations are generally greater than those measured in subsequent years (Appendix A).

The primary source of potassium in native Aquia sediments is glauconite. Although the amount of potassium in bottom material increased by 24 percent during 1986–87 and 1987–88, exchangeable potassium increased only between 1986 and 1987 and remained constant the following year (table 9). The weathering of glauconite to goethite can result in the formation of authigenic clays (Wolfe, 1967), but the probable source of exchangeable potassium was incoming clay minerals, especially illite. This hypothesis is substantiated by the close correlation of exchangeable potassium with the clay fraction of bottom sediments and with relatively constant potassium-to-aluminum (K:Al) ratios. The fertilizer used in landscaping at the shopping plaza can account for the increase in nonexchangeable potassium. Phosphorus—also from fertilizers—increased as well. Potassium-to-phosphorus (K:P) ratios, however, decreased from 15.6:1 in 1986 to 13.3:1 in 1988, because of preferential element partitioning between solid and aqueous phases: phosphorus partitions preferentially to solid phases, whereas potassium commonly is present as a major constituent in aqueous solutions.

Sodium in the native sediments also was from glauconite, although it was a minor component (table 9). The percentage of sodium in bottom material decreased yearly resulting in a total decrease of 62.5 percent. This decrease of sodium percentage indicated either that accumulating sediments were impoverished with respect to sodium or, conversely, that sodium was not accumulating in bottom material. Assuming that all the sedimentary sodium was from native sediments, the decrease in percentage of sodium indicates a dilution factor of about 2.67 for a 24-month period. The increase in exchangeable sodium in the 1987 sample may have been a function of high sodium concentrations in pond water that drove ion-exchange reactions, as discussed previously with respect to a decrease in exchangeable magnesium for that year's sample. High concentrations of sodium in pond water were found during winter 1987 because deicing salts were stored near the impoundment that year.

Trace elements and organic compounds

Enrichment of pond-bottom material was substantial for copper, lead, nickel, and zinc; increases were ambiguous for barium, chromium, cobalt, molybdenum, and strontium (table 9). Relative to initial concentrations measured in the 1986 pond-bottom sample, zinc increased 6.4 times, lead increased from undetected to 28 ppm, and copper increased 11.4 times. Concentrations of nickel and cobalt respectively increased 2.7 times and 1.4 times; molybdenum, strontium, and barium concentrations showed net increases, but were lowest in the 1987 sample. The small increase in chromium concentration was within the margin of analytical error. Concentrations of arsenic and cadmium remained below detection. Boron, gallium, and vanadium concentrations were greater in the initial sediments than they were in the accumulated pond-bottom material. Gallium concentration decreased by a factor of about 2.2 in 24 months, similar to that of sodium (2.67). Boron and vanadium decreased by factors of 1.3 and 1.4, respectively.

Enrichment of bottom material could have resulted from settling of colloidal or particulate suspended matter, scavenging of trace elements in solution by suspended and bottom material, and mineral precipitation. There was no evidence that native geologic materials were a source of trace metals to sediments accumulating in the pond. Considerable areal and vertical variation in trace-element concentrations is characteristic of Aquia sediments native to the site (table 8), and the range of concentrations for a trace element in Aquia samples commonly exceeded that of pond-bottom materials, including the 1986 sample. Therefore, the trend toward enrichment or depletion of bottom materials with respect to trace elements must be measured relative to concentrations in the first (1986) composite pond-bottom sample collected. Nevertheless, concentrations of copper, lead, and zinc measured in the last (1988) pond-bottom sample collected were appreciably greater than the highest concentrations measured for Aquia sediments.

Trace-metal enrichment of bottom material was enhanced by (1) increased sorption potentials related to the increase in silt-clay fractions and organic matter and (2) the presence of iron oxyhydroxides. The shift in particle-size distribution from 6 percent to 34 percent silt and clay resulted in an enormous increase in available surface area and therefore in collection sites for metals. Pond biota, natural organic substances, and anthropogenic organic compounds from runoff provided an organic component to the sediments that was analyzed at about 3 percent in the 1988 pond-bottom sample. Amorphous manganese and iron hydroxides (postulated from saturation-index calculations as precipitating from pond water) and organic matter are efficient scavengers of heavy metals.

The predominant source of trace constituents in accumulating bottom material apparently was from nonpoint, anthropogenic waste that enters the storm-water pond in runoff from the shopping plaza and as atmospheric deposition. Each of the trace elements listed in table 9 was detected in storm water and was present periodically at substantial concentrations. (Aqueous samples were not analyzed for gallium, rubidium, yttrium, or zirconium.)

Simple sorption experiments with cadmium, chromium, copper, lead, and zinc were performed on Aquia sediments and bottom material collected from the Annapolis pond (table 10). Air-dried sediments were shaken in wash solutions with variable concentrations of one of the metals listed. Wash solutions were prepared with 10 mg/L pure calcium carbonate ($CaCO_3$), which buffered all but the zinc solution to a pH within the range of the impoundment waters. Annapolis pond-water pH ranged from 6.82 to 9.07, with a median value of 7.70. The experiment was designed to give insight to sorption patterns for selected metals on sediments from the study site and not as a rigorous or independent study. Although the results are tentative, it is instructive to examine some of the results of this experiment and compare them with the field data.

Comparison of the laboratory effluent concentrations between native and pond-bottom sediments shows that Aquia sediments sorbed nearly as much or more of the metals from the wash solution as the accumulated bottom material; however, the pH (and possibly the metal concentration) of the solutions were important sorption controls. It is interesting to note that calcium was desorbed in every case from accumulated pond-bottom sediments but was sorbed by the calcium-poor native sediments. The experimental data indicate competition for sorption, with calcium sorption increasing on native sediments as aqueous concentrations of cadmium, copper, and lead decreased. It is apparent that sorption-desorption in actual pond-bottom systems can involve a complex interactive process.

Some observations about the experimental data and correlations with bottom-sediment analyses were instructive:

1. Cadmium is expected to partition to bottom material (Horowitz, 1985; Elder, 1988), and this partitioning was corroborated by the experimental data: 100-percent sorption on native and bottom sediments occurred at pH 7.68 and 7.88, and 94-percent sorption occurred on bottom sediments at pH 6.85. Pond-water pH falls within this range, and cadmium concentration in pond water was about 0.01 mg/L. The fact that cadmium was not detected in the bottom-sediment samples collected annually is considered problematical and will be examined later in this report.
2. Chromium sorption was similarly modest for native and accumulating sediments in contact with solutions having a concentration of 0.5 mg/L or greater. Likewise, elemental analysis indicated that any increase of chromium concentration in bottom material, if it occurred, was minor. The data do not indicate that pH was a sorption control for chromium under the experimental conditions.
3. Copper desorbed from bottom sediments if pH of solutions was comparatively high; copper concentration was comparatively low. Copper concentrations increased substantially in bottom material collected in 1987 and 1988. This increase corresponds to experimental data showing that 70 percent of the copper in solution sorbed to native as well as to accumulating sediments.
4. Lead sorption from the experimental solutions was 100 percent at pH greater than neutral and 89 percent at pH of 4.65. This sorption pattern corresponds to bottom-sediment data showing a large increase in lead in the 1987 pond-bottom sample. It does not explain the lack of lead accumulation in the 1988 sample, unless there was no appreciable source of lead that year.
5. Zinc concentrations in bottom material increased modestly in 1987 but increased almost sixfold between 1987 and 1988; however, zinc desorbed from native and bottom material in contact with a 0.3-mg/L solution at pH 6.47. Additional experimental data for zinc were flawed because neutral or higher pH was not maintained; therefore, these results are not shown. Nevertheless, strong control of pH on zinc solubility can be inferred from the data at pH 6.47 and has been reported in the literature (Jenne, 1977; Hem, 1963).

The organic-carbon content of the 1988 pond-bottom sample was 2.4 percent, which is less than the amount of organic matter expected in contaminated sediments (J.E. Baker, University of Maryland Center for Environmental and Estuarine Studies, written commun., 1989). Carbon analyses were not performed on previous samples, but each year bottom-material samples were blacker and more putrid, indicating an increase in the organic-matter content. In the opinion of the analysts, the contribution by biological material to the hydrocarbons detected was not significant (J.E. Baker, University of Maryland Center for Environmental and Estuarine Studies, written commun., 1989).

Only trace amounts of low-molecular-weight hydrocarbons were present; this indicates that the input is dominated by petroleum-derived products, though short-chain hydrocarbons (gasoline components, for example) were absent. Aromatic hydrocarbons totaled 19.48 μg/g dry sediment. Constituents detected from the polycyclic aromatic hydrocarbon (PAH) fraction included phenanthrene, fluoranthene, pyrene, benzo[a]anthracene, chrysene, benzo[b&k]fluoranthene, and benzo[a]pyrene. The total aliphatic hydrocarbon concentration was 1,827.3 μg/g (dry weight). Elevated concentrations of aliphatic hydrocarbons were dominated by a large unresolved complex of long-chain and high-molecular-weight hydrocarbons: analysts suggested the presence of complex mixtures such as tars and asphalts.

Aqueous Solutions

pH, specific conductance, and dissolved oxygen

The median pH of rainwater at the Annapolis site was 4.44 for the 3-year period of data collection (table 11). Values of pH greater than 5.20 were rare; samples in which such values were recorded were visibly contaminated with insects or correlated with landscaping activities. The volume-weighted mean pH of

Table 10.—Results of laboratory experiment[1] of trace-metal sorption onto pond-bottom and native materials collected from the Annapolis site

[mg/L, milligrams per liter; initial concentration of calcium in wash solution was 10 mg/L; values shown under sorption are the difference between concentrations measured in the wash solution and concentration measured in the batch solution, in mg/L; a minus (-) before the concentration indicates the amount of metal released from solids and that no sorption occurred]

Metal	Concentration of metal in wash solution (mg/L)	Initial pH of wash solution	Sorption onto pond-bottom sediments		Sorption onto native sediments	
			Metal	Calcium	Metal	Calcium
Cadmium	1.00	6.85	.94	-4.6	.84	6.3
	.10	7.68	.10	-7.2	.10	7.2
	.01	7.88	.01	-8.0	.01	8.0
Chromium	5.00	7.28	.66	-6.2	1.19	8.3
	.50	7.78	.07	-8.2	.06	7.1
	.05	7.80	.05	-8.6	.05	6.9
Copper	5.00	6.96	3.50	-8.2	3.46	.1
	.50	7.58	- .07	-6.8	.15	1.7
	.05	7.78	- .47	-3.0	- .18	5.3
Lead	5.00	4.65	4.45	-13.0	4.50	2.4
	.50	7.22	.50	-7.8	.50	7.0
	.05	7.61	.05	-7.0	.05	7.5
Zinc	.30	6.47	- .32	-7.6	- .10	7.8

[1] Experiment performed by Robert Ylagon, under the direction of Dr. Richard April Colgate University, Hamilton, N.Y., written commun., 1989.

rainwater was 4.26. The median specific conductance of rainwater was 30 microsiemens per centimeter at 25°C (μS/cm), and the range was from 8 to 124 μS/cm. The relation between pH and specific conductance of rainwater was inverse (fig. 12A).

Storm runoff at the Annapolis site was collected directly from a subsurface steel culvert before the runoff entered the impoundment. The median pH of runoff at Annapolis was 7.01, and the range was from 5.98 to 7.64. The median specific conductance of runoff was 95 μS/cm, but the range was from 36 to 2,600 μS/cm (table 11). There was no correlation between pH and specific conductance for runoff or pond water because the initial increase in dissolved solids that buffers the solution to a near-neutral pH occurs immediately. Subsequent additions of dissolved solids that resulted in increased specific conductance did not involve reactions affecting pH.

Impounded storm water was distinguished from runoff because its chemical characteristics were modified by hydrologic, biological, and geochemical processes in the pond. Specific conductance was lower in pond water than in runoff. In part, these data may have been an artifact of sampling frequency because fewer data were collected of ponded water than of runoff; however, specific conductance was seasonally elevated when dissolution of deicing salts caused high chloride concentrations in pond water and in runoff. Specific conductance was less in pond water than in runoff because chloride moved out of the impoundment with the storm-water infiltrate and because of subsequent dilution.

Pond-water pH was always higher than runoff pH; the median pH of pond water was 7.70, but values as high as 9.07 were measured. Concentrations of dissolved oxygen measured in pond water ranged from 8.00 to 12.40 mg/L but varied with water depth, temperature, time of day, and proximity to algal blooms; because of this variation, a median concentration is not meaningful. The low dissolved-oxygen (DO) concentrations were those that were measured near the pond bottom. The large fluctuations of pH and dissolved oxygen in pond water are attributed to diurnal photosynthesis and respiration of algal populations. Values of pH measured in the early morning hours were lower than the pH measured in the afternoon of the same day. Moreover, the statistical relation between field-measured pH

Table 11.—Median, minimum, and maximum values for specific conductance, pH, dissolved oxygen, and concentrations of major ions in filtered aqueous solutions at the Annapolis site

[Concentrations in milligrams per liter unless otherwise noted; µS/cm, microsiemens per centimeter at 25 degrees Celsius; --, no data; <, below detection at value shown; *, sole measurement shown as maximum concentration; #, median concentration for dissolved oxygen in pond water is not meaningful; µm, micrometer]

Station description	Concentration	Specific conductance[1] (µS/cm)	pH[1]	Dissolved oxygen[1] (DO)	Dissolved organic carbon[2] (DOC)	Calcium[2] (Ca)	Magnesium[2] (Mg)	Sodium[2] (Na)	Potassium[2] (K)	Bicarbonate[1] (HCO_3)	Sulfate[2] (SO_4)	Chloride[1] (Cl)	Nitrate[2] (NO_3 as N)	Silica[2] (SiO_2)
Rainwater	Median	30	4.44	--	--	--	--	--	--	0	--	--	--	--
	Minimum	8	3.40	--	--	1.1	0.18	1.2	--	0	1.7	0.8	<0.01	0.16
	Maximum	124	6.37	--	--	2.2	.44	1.3	--	1.7	13.0	2.1	1.6	.25
Storm-water runoff	Median	95	7.01	--	*	18.0	.77	3.7	1.35	27.43	17.0	4.2	1.1	.84
	Minimum	36	5.98	--	*	6.8	.6	.8	.7	6.09	5.0	.3	.79	.29
	Maximum	2,600	7.64	--	64.0	44.0	2.4	7.3	2.8	97.04	61.0	550	4.1	1.5
Impounded storm water	Median	78	7.70	#	11.2	11.0	.87	1.8	1.3	22.86	12.0	3.2	< .10	.75
	Minimum	49	6.82	8.00	4.1	7.7	.75	.2	.8	19.75	7.8	1.0	< .10	.17
	Maximum	230	9.07	12.4	15.0	12.0	1.3	11.0	2.5	33.65	16.0	60.0	.47	2.7
AA De 140[3]	Median	33	5.13	8.99	1.0	1.25	.65	1.75	1.7	3.04	1.15	4.4	.95	14.0
	Minimum	24	4.81	6.73	.5	.93	.5	1.5	1.6	1.21	.3	3.8	.66	13.0
	Maximum	44	5.40	9.69	2.3	3.5	.9	2.1	4.8	4.51	6.3	10.0	1.20	14.0
AA De 142[4]	Median	58	5.29	6.21	1.2	3.6	2.4	3.8	2.1	3.96	.5	12.5	*	--
	Minimum	33	4.91	6.19	.6	3.4	1.8	3.1	1.9	3.16	.3	10.5	*	13.0
	Maximum	93	5.51	7.60	1.6	6.9	3.1	4.0	2.5	5.60	5.8	22.0	.31	14.0
AA De 143[4]	Median	75	5.35	6.32	1.2	3.3	2.2	4.8	3.4	4.45	1.2	17.0	.32	16.0
	Minimum	24	5.06	4.59	1.0	3.0	1.7	4.0	2.6	3.16	.7	4.0	.24	14.0
	Maximum	120	5.80	8.24	1.8	8.2	3.5	7.5	4.0	7.31	4.8	28.0	.38	17.0

Table 11.—Median, minimum, and maximum values for specific conductance, pH, dissolved oxygen, and concentrations of major ions in filtered aqueous solutions at the Annapolis site—Continued

Station description	Concentration	Specific conductance[1] (µS/cm)	pH[1]	Dissolved oxygen[1] (DO)	Dissolved organic carbon[2] (DOC)	Calcium[2] (Ca)	Magnesium[2] (Mg)	Sodium[2] (Na)	Potassium[2] (K)	Bicarbonate[1] (HCO_3)	Sulfate[2] (SO_4)	Chloride[1] (Cl)	Nitrate[2] (NO_3 as N)	Silica[2] (SiO_2)
AA De 156[5]	Median	208	4.94	2.85	1.0	9.3	5.6	11.0	5.7	3.91	1.4	47.0	.115	18.0
	Minimum	70	4.63	.47	.9	7.5	4.8	6.9	4.4	1.95	< .2	16.0	< .10	17.0
	Maximum	372	5.34	5.35	1.3	16.0	10.0	14.0	6.2	9.14	2.8	85.0	.31	19.0
AA De 157[6]	Median	225	5.01	2.72	1.3	9.85	3.8	21.0	3.65	5.48	.7	56.3	.445	15.0
	Minimum	69	4.18	2.44	1.1	3.3	1.2	10.0	2.2	2.43	.3	14.0	.32	12.0
	Maximum	975	5.50	4.41	1.6	69.0	25.0	49.0	12.0	10.97	3.8	270	.99	16.0

[1] Data shown for specific conductance, pH, dissolved oxygen, bicarbonate and chloride are for weekly or monthly samples that include samples sent to the laboratory (Appendix F).

[2] Data shown are laboratory analyses of dissolved organic carbon, calcium, magnesium, sodium, potassium, sulfate, nitrate, and silica concentrations (Appendix A); DOC samples filtered through 0.45-µm-silver filters; cation and anion samples filtered through 0.1-µm filters except for bicarbonate samples (unfiltered) and nutrient samples (0.45-µm filters).

[3] Control well.

[4] Downgradient well.

[5] Beneath-pond well screened approximately 10 feet below water-table surface.

[6] Beneath-pond well screened at water-table surface.

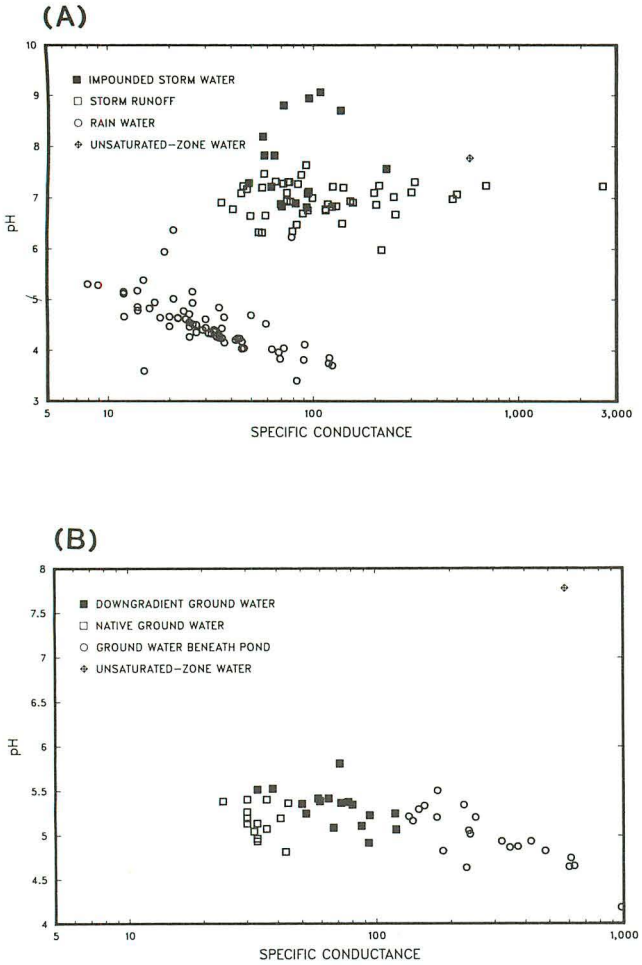


Figure 12.—Specific conductance and pH at the Annapolis site: (A) rain-water, storm water, unsaturated-zone water; and (B) ground water, unsaturated-zone water. (Specific conductance is expressed in microsiemens per centimeter at 25 degrees Celsius.)

and percent saturation of dissolved oxygen was strong (table 12). The data, which did not reveal a seasonal trend, indicate the year-round presence of algal populations (D.D. Lynch, U.S. Geological Survey, written commun., 1989).

The sole lysimeter sample collected for element analysis had a pH of 7.77 and a specific conductance of 580 μS/cm. These values are believed to be representative of water from the unsaturated zone at this depth because the values plot in a pH-specific conductance field relative to pond water and ground water that is consistent with plots of unsaturated-zone water at the other study sites. Sample volume was insufficient for measurement of redox potential with a platinum electrode.

Native ground-water chemistry was monitored at the control well, AA De 140. The control well is near the ground-water divide and, thus, in the zone of recharge to the unconfined aquifer. The chemical composition of ground water at AA De 140 is similar to that in nearby wells that are screened at a similar depth interval in the Aquia aquifer. Native ground water was acidic (median pH of 5.13) and very dilute, with a median specific conductance (33 μS/cm) close to that of rainwater (fig. 12B). Although the specific conductance of native ground water was constant, pH varied between 4.81 and 5.40 and always was lowest when recharge recently had occurred (table 11). The median concentration of dissolved oxygen in native ground water was 8.99 mg/L, and concentrations were typically between 8.00 and 9.50 mg/L. Fluctuations in dissolved-oxygen concentrations did not correlate well with recharge or pH.

The pH of ground-water samples collected at the water-table surface beneath the pond (5.01, median pH) was consistently lower than background (5.13, median pH at control well) and was more than two orders of magnitude lower than median pond-water pH (7.70); ground-water samples collected 10 ft deeper (well AA De 156) tended to have lower values (4.94, median pH). This pattern of pH indicates either that storm-water infiltrate is not mixing appreciably with underlying ground water, or that the pH of the infiltrate decreased dramatically through the unsaturated zone, and (or) that chemical processes in the aquifer are causing an increase in hydrogen-ion activity. The specific conductance of ground water beneath the pond was an order of magnitude greater than the specific conductance of native ground water and was a clear indication that infiltration of pond water was leaving a distinct chemical imprint on underlying ground water (fig. 12B). Changes in specific conductance and subsequent analysis of additional chemical data establishes that storm-water infiltration did modify ground-water chemistry beneath and downgradient of the pond. Therefore, the reduced ground-water pH was a function of geochemical or biochemical processes in the intervening unsaturated zone and aquifer. Possible processes that account for the change in pH are reviewed in the section on "Factors Affecting Ground-Water Quality at the Study Sites."

The pH of ground-water samples collected downgradient from the control well and the pond (5.35, median value at AA De 143) was higher than the pH of samples collected at the control well (5.13). The chemical data and the hydrologic analysis

Table 12.—Field pH and percent saturation of dissolved oxygen in pond water at the Annapolis site

[r, correlation coefficient; --, no data]

Date	Field pH	Dissolved oxygen (percent saturation)
05/ 1/87	8.71	119
09/ 1/87	8.95	152
--	7.29	104
06/ 3/88	7.83	104
08/17/88	6.84	98
10/11/88	7.83	99
12/ 6/88	7.29	88
01/19/89	7.09	91
	r= 0.85	

indicated that this was caused by simple mixing, probably from deeper, upward-moving ground water. Downgradient water samples collected near the base of the aquifer (AA De 159) had much higher pH (6.41) and alkalinity (40.5 mg/L as $CaCO_3$) because of residual carbonate shell material in aquifer sediments at this depth. (Chemical data for the sample collected from AA De 159 are listed in Appendix A.) Mixing was also from direct infiltration of precipitation: specific conductance of downgradient water (75 μS/cm, median value) was less than that of beneath-pond ground water (225 μS/cm; table 11) but also less than that of downgradient water measured at depth (110 μS/cm) and more than twice that of native ground water. Although the specific conductance of ground water beneath the pond increased on the average more than sixfold compared with background, specific conductance of shallow downgradient ground water was only about twice as high. Specific conductance of ground water beneath the pond and downgradient of the pond varied considerably, compared with the relatively constant specific conductance at the control well. This variation reflected the large fluctuations in specific conductance of pond water.

Unlike ground water sampled at the control well, there was no correlation between variations in pH or specific conductance and recharge from specific storms. Beneath-pond and shallow downgradient ground-water samples with low pH, however, tended to have high specific conductance (fig. 12B).

Dissolved-oxygen concentrations were reduced considerably in ground water beneath the pond (0.47 to 5.35 mg/L) compared to background (6.73 to 9.69 mg/L) or to pond water (8.00 to 12.40 mg/L). Analogous with the pattern for pH, dissolved-oxygen concentrations decreased further in samples collected 10 ft deeper, from well AA De 156. Ground water collected downgradient from the impoundment had dissolved-oxygen concentrations that were intermediate (4.59 to 8.24 mg/L) between those of upgradient and beneath-pond concentrations (fig. 13). Dissolved-oxygen concentrations fluctuated considerably in ground water collected from all the wells; this fluctuation was likely to have been caused by biological metabolism as well as by periodic mixing with oxygenated water from storm recharge.

Major elements

Rainwater and storm water.—Three rainfall samples from this site, in which pH was 3.70, 3.96, and 4.64, were analyzed for selected dissolved constituents (Appendix A). Calcium, sodium, and hydrogen ions were the dominant cations in these samples and sulfate was the dominant anion. The variability in sulfate and nitrate concentrations was considerable, but sodium concentrations were virtually equivalent in the three samples.

The relative abundances of major ions were similar in rainwater and storm water, except for a large increase in bicarbonate and correlative decrease in hydrogen ions in storm water. Storm water, compared with rainwater, had higher concentrations of all major ions, but the greatest year-round increases were in calcium and bicarbonate concentrations.

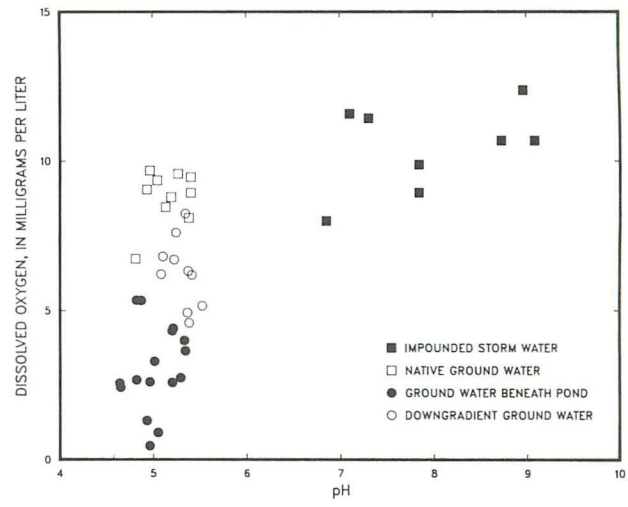


Figure 13.—Dissolved-oxygen concentrations and pH of pond water and ground water at the Annapolis site.

Calcium was the dominant cation and bicarbonate and sulfate the dominant anions in most storm-water samples collected throughout the year (fig. 14, table 11); however, a substantial population of storm-water samples had greatly elevated chloride concentrations (Appendix F), and this population was characterized as a sodium chloride type of solution. Elevated concentrations of chloride were accompanied by elevated concentrations of sodium and increases in specific conductance in storm water, which were caused by the dissolution of deicing salts during the winter and early spring. Runoff and pond-water samples that were analyzed for major ions usually were not collected during the peak times of deicing; thus, the trilinear diagram (fig. 14), on which relative percentages of the major ions are plotted, shows two samples of intermediate sodium and chloride enrichment. Increases in specific conductance correlated positively with the seasonal rise in sodium and chloride concentrations. Elevated concentrations of chloride in pond water were attenuated within days to a few weeks because of the conservative movement of chloride through the impoundment with the storm-water infiltrate and by dilution from subsequent storms. Pond water did not become increasingly saline over time.

Concentrations of calcium, sodium, and all major anions were substantially reduced in impounded storm water compared with runoff, whereas magnesium, potassium, and silica concentrations remained similar in each type of storm water (table 11). The elements depleted in pond water were expected to enrich either bottom sediment, or subsurface water, but substantial changes were not expected for concentrations of magnesium, potassium, or silica. Nevertheless, magnesium and potassium, as well as calcium, increased in bottom sediments and probably accumulated as storm-water-borne particulates. The aqueous concentrations of these elements were being controlled by mineral solubilities that possibly were mediated by biochemical reactions. Because bicarbonate and sulfate were abundant in the

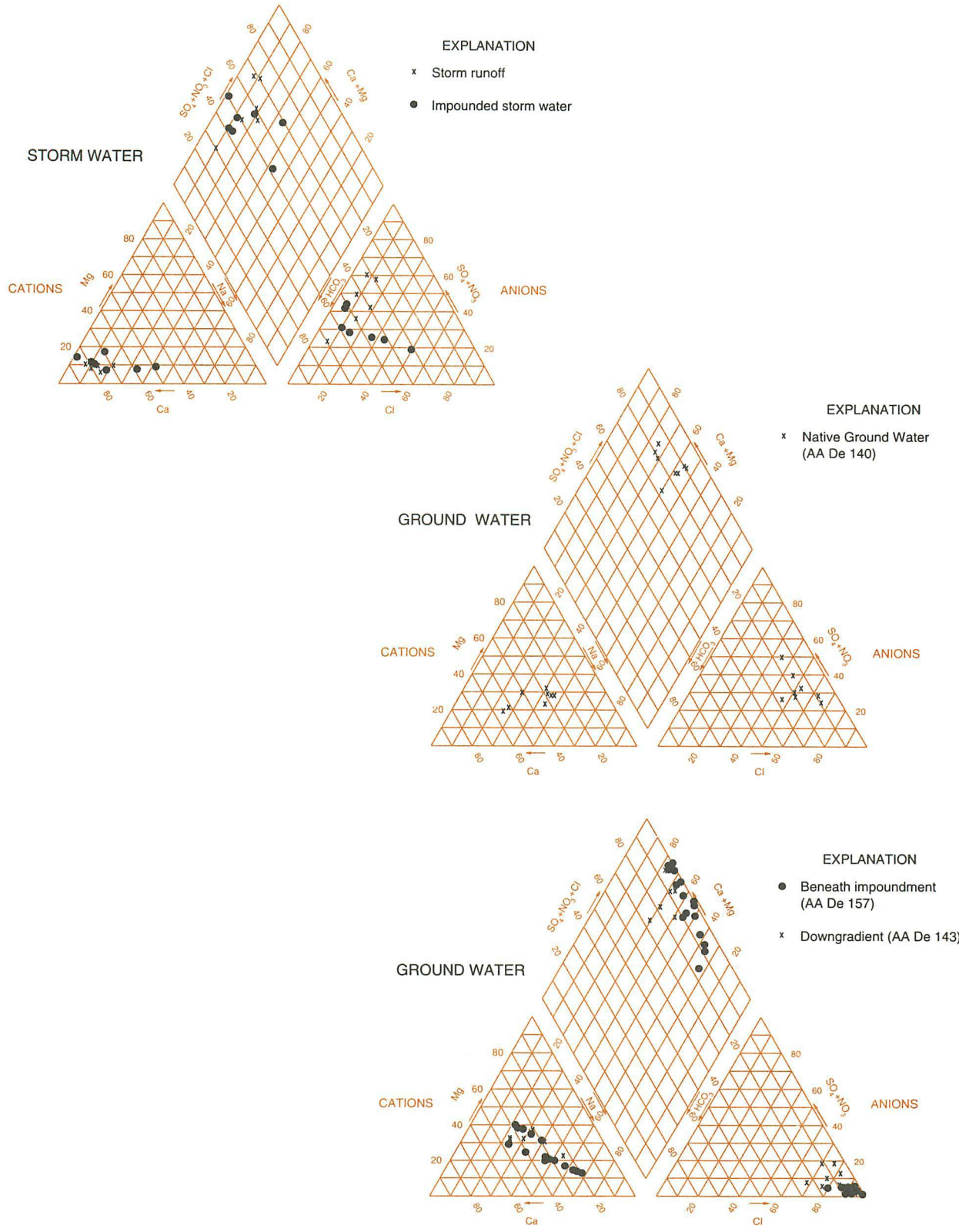


Figure 14.—Percentage of major ions in aqueous solutions at the Annapolis site. (Samples collected each spring, summer/fall, and winter of 1986–1987, 1987–88, 1988–89.)

runoff entering the pond, reactions causing mineral precipitation with available cations were considered.

WATEQF was used to test hypotheses regarding the probable or possible saturation state of selected minerals in pond water at the Annapolis Plaza. The full range of pH, temperature, total dissolved solids, dissolved oxygen (redox), and dissolved-carbon concentration possible for the impoundment water was explored, and saturation indexes calculated from WATEQF were compared to chemical and mineral data acquired for the sediments accumulating in the impoundment. The results of the modeling exercise indicated that although pond water was always undersaturated with respect to carbonates and sulfates (or sulfides), it generally was saturated with respect to aluminum oxide phases (boehmite), gibbsite, ferric and manganese hydroxides, kaolinite, and noncalcic montmorillonite. Therefore, clay-mineral chemistry seems to provide the major control on concentrations of these cations in pond water. Sodium, sulfate, chloride, and nitrate were expected to move conservatively with storm-water infiltrate percolating through the unsaturated zone.

Water in the unsaturated zone.—Collection of water samples from the unsaturated zone was largely unsuccessful at this site. Two lysimeters were installed and reinstalled on three occasions. Although the distilled water used to prepare a packing slurry of native material was extracted through the lysimeters after installation, sample evacuation thereafter yielded only one viable sample from AA De 160. The volume of this sample was small; thus, the sample was analyzed only for total concentrations of selected trace metals.

Ground water.—The major-ion chemistry of ground-water native to the site (well AA De 140) was similar to the composition of rainwater, with the exception of minor additions of bicarbonate and balancing cations that had been leached from overlying Aquia sediments. Surficial formation sediments are highly weathered and contain few leachable minerals, as evidenced by the low specific conductance of the ground water (table 11).

Native ground water collected from the control well was a chemically mixed type. After a sizeable rainfall, native ground water plotted as a calcium chloride to calcium sulfate/nitrate type water, but plotted as a sodium/calcium chloride type during periods of relatively low recharge (fig. 15). The source of sulfate appeared to be from rainwater (table 11). Nitrate in rainwater appeared to be highly variable, from less than 0.01 mg/L to a concentration (1.6 mg/L) that exceeded the highest concentration measured in the native ground water; the occasional high concentrations indicate that rainwater could be a sporadic source of nitrate to ground water. The primary source of nitrate was probably leaching of nitrogen compounds from fertilizers; the control well is in a landscaped margin at the southeastern edge of the Annapolis Plaza parking lot.

The chloride ion comprised an average of 51 percent of major anions in native ground water. Although chloride concentrations were slightly elevated during the winter and early spring, correlation between chloride concentrations and specific conductances was poor.

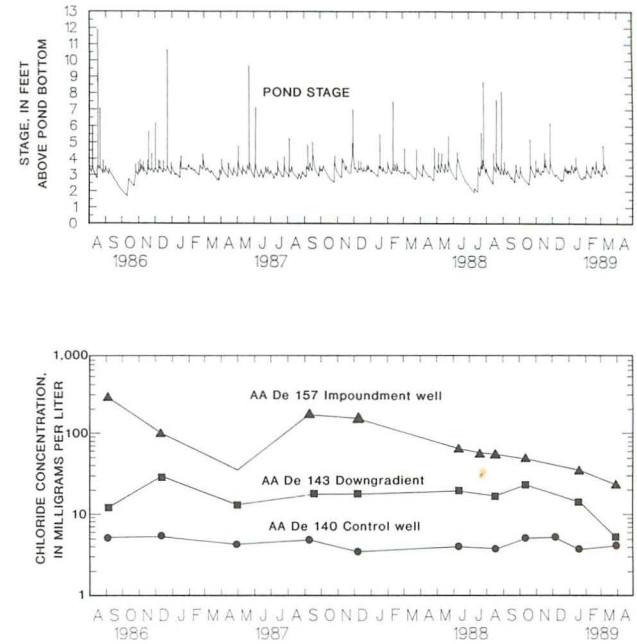


Figure 15.—Chloride concentrations in ground water and pond stage at the Annapolis site, April 1986–April 1989. (Chloride data from Appendix F.)

The chemistry of shallow ground water beneath the storm-water impoundment (well AA De 157) and downgradient from the impoundment (wells AA De 142 and AA De 143) plotted as a chloride water enriched in sodium (fig. 15). This water type represented an important shift in the major-ion chemistry of ground water at the study site. Chloride comprised an average 97 percent of the major anions in ground water beneath the impoundment, remaining substantially higher than background throughout the year (fig. 15). Dispersion and dilution by mixing with deeper ground water and rain caused a decrease in chloride concentrations in downgradient ground water, so that chloride comprised an average 77 percent of the major-anion concentrations.

Storm water was the only possible source of such high concentrations of sodium and chloride for ground water beneath the study site. These elevated chloride and sodium concentrations in ground water present unambiguous evidence of the influence that storm-water infiltration can have on the composition of underlying and downgradient ground water. The evolution of beneath-pond ground-water composition falls slightly off the mixing lines between native ground water and the two storm-water populations, and is probably a result of chemical processes affecting water percolating through pond-bottom materials and the unsaturated zone.

The mean ratios of calcium to magnesium (Ca:Mg) and calcium to potassium (Ca:K) in beneath-pond ground water collected from well AA De 157 were higher than those of native ground water, and ratios of calcium to sodium (Ca:Na) and calcium to chloride (Ca:Cl) were lower. No temporal trend was discerned for ion ratios in native ground water; however, ion ratios

for shallow, beneath-pond ground water indicated a temporal trend toward increasing potassium, sodium, and chloride and decreasing calcium and magnesium. Nevertheless, calcium and magnesium enrichment of ground water beneath the impoundment was substantial compared to ground water collected from the control well.

Calcium was depleted with respect to magnesium in downgradient samples compared to ground-water samples collected from the control well and from well AA De 157. With the exception of the Ca:Mg ratio, the chemical composition of groundwater samples collected from the downgradient wells was consistently intermediate between that of native and beneath-pond ground water (figs. 12–14). Ground water that was collected from well AA De 156 (10 ft deeper than AA De 157), however, had a lower Ca:Mg ratio than ground water from AA De 140 or AA De 157; moreover, the cation ratios of downgradient ground water were between those of AA De 157 and 156. These cation ratios are evidence that the major-ion composition of water collected from the downgradient wells reflects vertical mixing of shallow with deeper ground water.

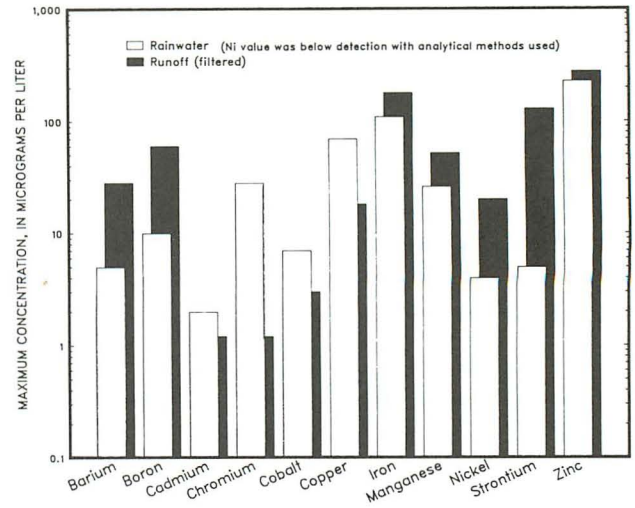


Figure 16.—Maximum concentrations of trace metals in rainwater and filtered runoff at the Annapolis site.

Trace elements and organic compounds

Rainwater and storm water.—The trace elements detected in rainwater included barium, boron, cadmium, chromium, cobalt, copper, iron, manganese, nickel, strontium, and zinc (table 13). Not detected in rainwater were beryllium, lead, lithium, molybdenum, and vanadium: the absence of these constituents cannot be considered representative, as only three samples were analyzed for selected constituents. Moreover, the analytical method used to determine concentrations in rainwater was not sufficiently sensitive for many constituents; more sensitive analytical methods that were used for some metals for storm-water samples recorded concentrations below the reporting level used for rainwater samples.

Comparison of trace-metal concentrations in filtered runoff with concentrations in rainwater indicated that rainwater may be a major source of the dissolved portion of cadmium, chromium, copper, iron, manganese, and zinc in storm runoff at the Annapolis site (fig. 16). A full suite of trace constituents was detected in filtered storm water at the Annapolis site; median values indicate that concentrations generally were low to moderately elevated. The unfiltered fraction of some storm-water samples, however, had extremely high concentrations of some metals (table 13).

The distinction between concentrations of trace elements found in the filtered fraction compared with the unfiltered fraction of storm water is relevant to an understanding of the mobility of the constituents in the storm-water-management system. A comparison of filtered with unfiltered concentrations of some constituents measured in samples of runoff collected at the Annapolis site is shown on figure 17A. Virtually all of the arsenic, boron, cadmium, copper, nickel, and zinc enter the impoundment as a dissolved phase; that is, concentrations of these constituents were approximately equivalent in the filtered and unfiltered samples. Chromium and lead primarily entered the Annapolis pond in suspended phases.

A comparison of filtered with unfiltered concentrations of the same constituents measured in pond-water samples (fig. 17B) indicates a much higher ratio of suspended phase (unfiltered fraction) to dissolved phase (filtered fraction) for constituent concentrations in pond water. Comparison of filtered and unfiltered concentrations for median and maximum values in pond water reveals that molybdenum and possibly arsenic and barium were the only constituents whose filtered concentrations approximated unfiltered concentrations; unfiltered concentrations were substantially greater than filtered for boron and copper, and were at least an order of magnitude greater for cadmium, chromium, lead, nickel, and zinc. This comparison indicates that dissolved boron, cadmium, copper, nickel, and zinc are scavenged by colloidal or other solids that remain suspended in pond water for some time but may eventually flocculate and become incorporated in bottom sediments. In fact, copper, nickel, and zinc did become substantially enriched in bottom materials, along with lead. (No solid-phase data are available for boron). Cadmium and chromium did not fit this model; cadmium had been expected to accumulate in the solid phase and to be found at measurably higher concentrations in bottom materials.

Concentrations of aluminum, antimony, iron, manganese, strontium, and vanadium were analyzed on filtered samples only. Concentrations of iron, manganese, strontium, and vanadium were higher in runoff than in pond water, indicating that these constituents were removed from surface water by mineral precipitation or by being scavenged by solid phases, and (or) that they remained dissolved in the aqueous phase and moved out of the pond with storm-water infiltrate. Within the neutral-to-basic range of pH in pond-water, and given saturated dissolved-oxygen concentrations, any residual iron and manganese should

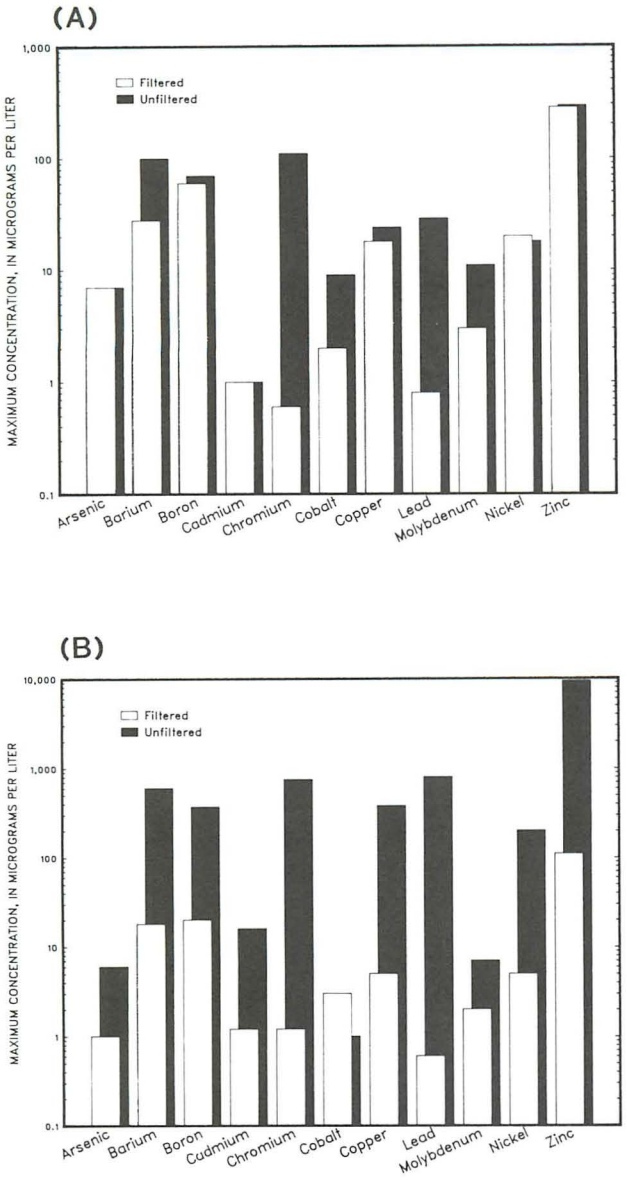


Figure 17.—Comparison of maximum concentrations of trace elements in filtered and unfiltered (A) runoff and (B) pond water at the Annapolis site.

be oxidized and precipitate out of solution. Vanadium concentrations decreased in bottom materials between 1986 and 1988, and an initial increase in strontium in bottom materials in 1987 was followed by a decrease in 1988. Aluminum concentrations in pond water increased whenever the pH approached or exceeded 9.00; because the high values for pH were the result of biological processes in the pond, a comparison with aluminum concentrations in runoff is not instructive.

Organic compounds were not detected in the storm-water samples, with the exception of methylene blue active substances. There was evidence that trace quantities of volatile organic compounds (VOC's) entered the pond, but the sampling procedures used were not designed to preserve VOC's. Concentrations of dissolved organic carbon as high as 64 mg/L were measured in pond water, indicating large influxes of organic carbons from time to time.

Water in the unsaturated zone.—Antimony, barium, boron, chromium, copper, molybdenum, nickel, and zinc were detected in the unfiltered sample of unsaturated-zone water (table 13). Of these, only barium, boron, and molybdenum were detected in concentrations that exceeded those measured in native ground water. The data are too sparse to justify any conclusions, but they provide some evidence of a storm-water source of barium, boron, and molybdenum in ground water.

Ground water.—Virtually all of the trace constituents that were detected in storm water were also detected in ground water (table 13). Antimony was detected in the particulate fraction of several storm-water samples, but was not detected in ground water (except for one sample at the detection limit); lithium was detected in some ground-water samples, but was not detected in storm-water samples. Trace-element concentrations in unfiltered storm water exceeded concentrations in ground water, as would be expected. Concentrations of trace elements in filtered storm-water samples were also generally higher than in ground-water samples collected from the control well. Exceptions to this concentration pattern were chromium, lead, lithium, and manganese.

For most of the trace metals detected in samples of beneath-pond ground water, however, filtered concentrations exceeded those measured in storm water. Specifically, concentrations of dissolved barium, cadmium, chromium, copper, lead, nickel, and zinc were substantially higher in beneath-pond ground water than in impounded storm water and, except for arsenic and zinc, in runoff as well. Dissolved boron, cobalt, and molybdenum concentrations were about the same in samples of beneath-pond ground-water and storm water.

Aluminum, iron, manganese, strontium, and vanadium were analyzed only for filtered samples. Of these, manganese and strontium concentrations were higher in beneath-pond ground-water samples, but aluminum, iron, and vanadium concentrations were less than or similar to concentrations in samples collected of runoff and ponded water.

Rainwater (and also trace quantities of heavy minerals in the Aquia Formation) was a possible source of trace elements to native ground water at Annapolis. Most of the trace elements dissolved in ground water beneath or downgradient from the impoundment were detected in native ground water as well (table 13). Only dissolved arsenic and vanadium were not detected in native ground water but were detected in some ground-water samples collected beneath the pond; however, dissolved concentrations of most trace elements were higher and more variable in beneath-pond and downgradient samples than in native ground-water samples (fig. 18). The highest trace-element concentrations (filtered and unfiltered) were found in beneath-pond ground-water samples, with the notable exception of iron (table 13). Iron concentrations were considerably depleted in beneath-pond ground water compared with concentrations in native ground water; iron concentrations in native and downgradient waters were similar. Median as well as maximum concentrations of barium, cadmium, copper, nickel, strontium, and zinc were

Table 13.—Summary concentrations of selected trace constituents in rainwater, storm water, water from the unsaturated zone, and ground water at the Annapolis site

[Values in micrograms per liter (µg/L), unless otherwise indicated; mg/L, milligrams per liter; f, filtered sample (samples passed through 0.1 micron filter); u, unfiltered sample[1]; <, below detection[2]; --, no data; MBAS, methylene blue active substances]

Chemical constituent[3]	Rainwater		Storm water[4]		Ground water						Unsaturated-zone water
					Upgradient		Beneath pond		Downgradient		
	Minimum	Maximum	Median	Maximum	Median	Maximum	Median	Maximum	Median	Maximum	(Unfiltered sample)[5]
Aluminum (f)	--	--	30	60	30	40	20	50	20	30	--
Antimony (u)	--	--	<1	4	<1	1	<1	<1	--	< 1	1
Arsenic (f)	--	--	1	7	<1	2	<1	4	<1	1	--
(u)	--	--	2.5	7	1.5	5	<1	2	2	3	--
Barium (f)	4	5	8	28	--	15	66	180	26	33	--
(u)	--	--	<100	600	--	[5]<100	--	200	--	--	100
Boron (f)	--	--	20	60	10	10	20	40	10	20	--
(u)	--	10	50	370	20	30	20	20	--	[5]20	40
Cadmium (f)	<1	2	.65	1.2	.3	1	9	27	3	9	--
(u)	<1	--	1	16	<1	2	7	13	1	12	<1
Chromium (f)	<5	28	.5	1.2	2	3	1.3	8	1.4	4	--
(u)	--	20	30	750	40	70	<10	130	30	60	3
Cobalt (f)	<3	<3	1	3	1.6	3	1.7	5	1	2.9	--
(u)	--	7	1	9	2	2	2.5	3	1.0	2	--
Copper (f)	<10	70	5	18	3	6	6	35	2	9	--
(u)	--	16	18.5	380	9	14	7	15	10.5	27	8
Iron (f)	50	110	39	180	20	77	6	13	11	90	--
Lead (f)	<10	<10	<.5	.8	<5	.7	<5	5	<.5	1.1	--
(u)		<5	11.5	800	<5	20	<5	7	6	10	<5

Table 13.—Summary concentrations of selected trace constituents in rainwater, storm water, water from the unsaturated zone, and ground water at the Annapolis site —Continued

Chemical constituent[3]		Rainwater		Storm water[4]		Ground Water						Unsaturated-zone water
						Upgradient		Beneath pond		Downgradient		
		Minimum	Maximum	Median	Maximum	Median	Maximum	Median	Maximum	Median	Maximum	(Unfiltered sample)[5]
Lithium	(f)	<4	<4	<4	<4	<4	6	<4	15	5	6	--
Manganese	(f)	9	26	9	52	39	57	23	80	32	78	--
Molybdenum	(f)	<10	<10	1	3	<1	1	<1	4	1	2	--
	(u)	<1	--	2	11	<1	3	<1	2	3	5	5
Nickel	(f)	<10	<10	2.5	20	3	8	27	62	10.5	69	--
	(u)	--	4	11	200	7	11	34.5	44	9	10	8
Strontium	(f)	3	5	26	130	5	12	38	210	18.5	32	--
Vanadium	(f)	<6	<6	3	19	<1	<1	<1	2	<1	<1	--
Zinc	(f)	160	230	47	280	40	97	80	200	27	83	--
	(u)	--	230	230	9,300	40	140	95	200	60	110	50
Organic compounds (μg/L)												
MBAS (mg/L)		--	--	0.28	2.6	0.01	0.04	0.03	0.08	0.03	0.05	--
Benzene		--	--	--	<.2	--	<.2	<.2	<.2	--	.2	--
Toluene		--	--	--	<.2	--	<.2	<.2	.3	--	.6	--
Trichlorofluoro--methane		--	--	--	<.2	--	<.2	.2	5.2	--	<.2	--
1,1,1--Trichloro--ethane		--	--	--	<.2	--	<.2	<.2	.2	--	<.2	--

[1] Concentrations of constituent for filtered samples may exceed those shown for unfiltered samples because filtered samples were collected more frequently than unfiltered samples.

[2] Value shown as below detection is the reporting limit set by the USGS National Water Quality Laboratory; detection/reporting limits depend upon the analytical method requested, which varied as appropriate according to initial screening of constituent concentrations in the water source.

[3] See Appendix A for a comprehensive table of laboratory analyses.

[4] Data shown are for runoff and impounded storm water.

[5] Value shown is sole concentration measured on unfiltered sample.

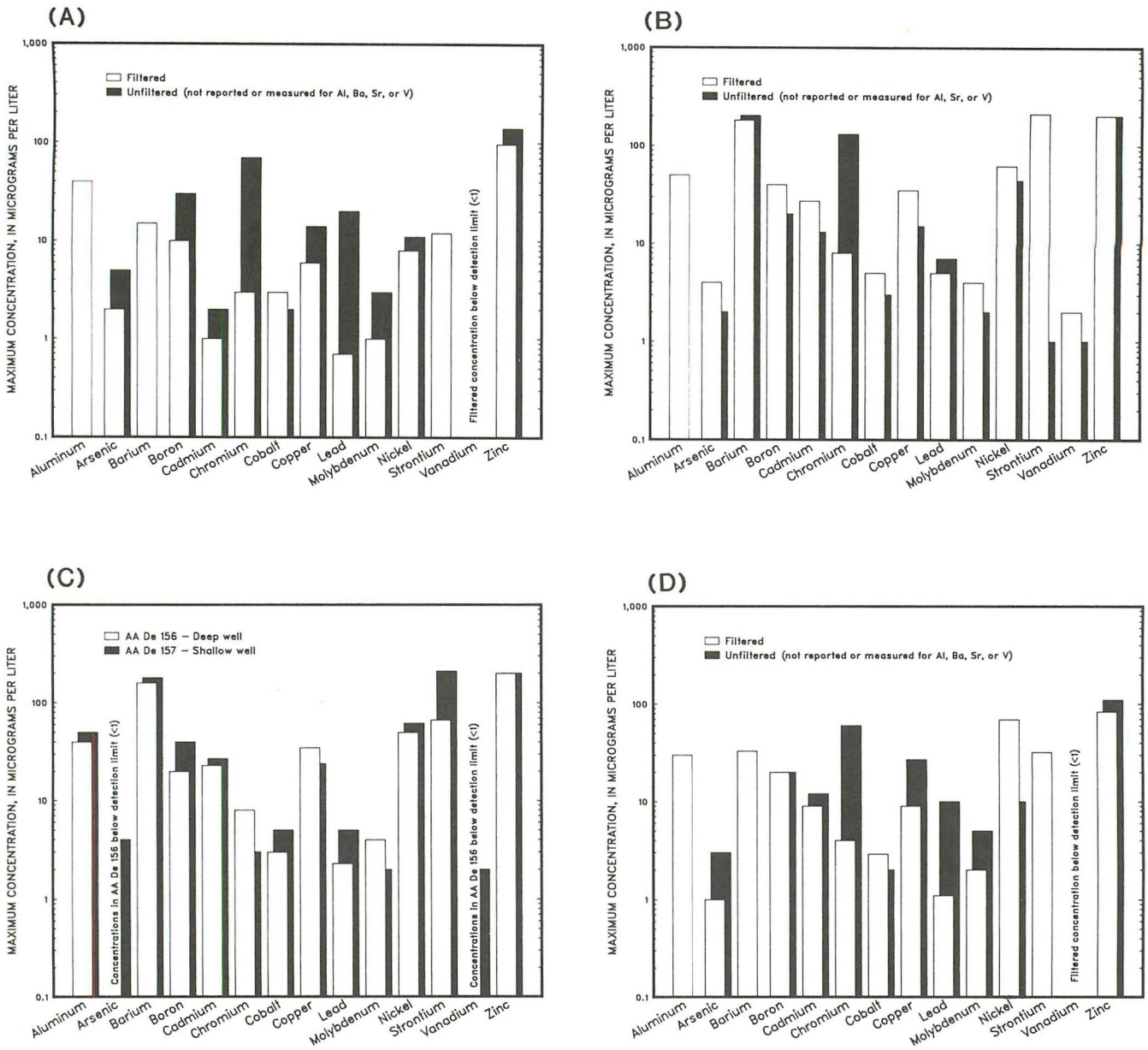


Figure 18.—Comparison of maximum concentrations of trace elements in filtered and (or) unfiltered ground water at the Annapolis site: (A) native (upgradient) ground water, (B) beneath-pond water, (C) filtered samples collected from shallow (AA De 157) and deeper (AA De 156) impoundment wells, and (D) downgradient ground water.

substantially elevated in beneath-pond samples compared with native ground water (table 13).

The median concentrations of boron, chromium, lead, lithium, and vanadium were similar in beneath-pond and native ground water, but maximum concentrations in some samples collected from wells AA De 156 or 157 were substantially elevated (fig. 18C). Comparison of trace-element concentrations for aqueous samples collected beneath the pond at the water-table surface and 10 ft deeper (wells AA De 157 and AA De 156, respectively) indicate that concentrations of chromium, copper, and molybdenum were occasionally greater in ground-water samples collected from a deeper interval, although most of the other constituents that were at elevated concentrations in the shallow well were at somewhat lower concentrations in the deeper well (fig. 18C). Chloride concentrations also were higher in some deeper samples, indicating that the downward hydraulic gradient in ground water beneath the impoundment may have transported constituents downward rapidly—within hours or a few days. Therefore, the highest concentrations near the water-table surface were probably missed in sampling, depending on the initial concentration and duration of the constituent, as well as when the constituents entered the system relative to the time of sample collection.

Trace-element concentrations in samples collected down-

gradient typically were somewhat lower than concentrations in beneath-pond ground water. The lower concentrations in downgradient samples are interpreted as a result of dilution from upward-moving ground water, dilution from downward percolating rainwater, and dispersion, diffusion, and other retardation mechanisms affecting solute transport.

A marked difference was noted in constituent partitioning between the suspended and dissolved phases in ground-water samples collected from beneath the pond compared with ground-water samples collected from the downgradient and control wells (figs. 18B and 18D). Trace-element concentrations determined in filtered and unfiltered samples were approximately equivalent for ground water collected beneath the pond; that is, barium, boron, cadmium, copper, lead, nickel, zinc, and possibly arsenic, cobalt, and molybdenum appeared to be present primarily in the dissolved phase. In upgradient and (or) downgradient ground water, however, a larger proportion of arsenic, copper, lead, and zinc were associated with suspended phases than with the beneath-pond water. Data were insufficient to define causal relations; nevertheless, similar concentration and enrichment patterns were observed at the other study sites, and the data are believed to be representative and relevant.

Samples of ground water collected beneath and downgradient from the impoundment had median concentrations of dissolved organic carbon that were equal to or insignificantly higher than those in native ground water; organic carbon concentrations were highest in unfiltered ground-water samples collected from the control wells (table 11). Methylene blue active substances concentrations were slightly elevated in beneath-pond and downgradient ground-water samples compared with native ground water. Anthropogenic trace organic compounds were not detected in samples of native ground water, but benzene, toluene, trichlorofluoromethane, and 1,1,1-trichloroethane were detected in some ground-water samples collected from beneath-pond or downgradient wells (table 13).

The wide variation in trace-element concentrations in beneath-pond ground water reflected concentration variations in pond water: elevated concentrations of major and trace constituents were not constant in runoff, but they occurred from time to time. As a result, occasional slugs of storm water with high contaminant loads entered the impoundment. Because the maximum normal pond stage was 3 ft, dilution was limited and effective only to varying degrees, depending largely upon incoming constituent concentration and amount of precipitation. Of the constituents that strongly partitioned to suspended materials, partitioning was 100 percent for lead only. Any influx of runoff with high contaminant concentrations provided a dissolved fraction of contaminant that could be transported to ground water. The mechanism for contaminant transport can be physical, by flushing through the unsaturated zone because of increased vertical hydraulic gradients (head), and (or) the transport mechanism can be by chemical diffusion, with contaminants being driven by concentration gradient. Therefore, contaminants periodically entered ground water in slugs of "enriched" storm-water percolate.

Hydraulic transport of contaminants to ground water was mitigated by geochemical and biochemical reactions, especially within the impoundment but also through the unsaturated zone. Biogeochemical processes within the unsaturated zone (beneath the pond) can be inferred as a probable cause of the lowered pH and reduced concentrations of dissolved oxygen in underlying ground water. The pH and reduced dissolved oxygen characteristic of beneath-pond ground water was conducive to mobility of many trace elements; however, the increase in pH and dissolved-oxygen concentrations in downgradient ground water was sufficient to cause oxidation and restrict metal mobility.

Recapitulation of Annapolis Site Characteristics and Water Quality

The Annapolis storm-water-management structure (fig. 4) was constructed in the unconsolidated sediments of the Aquia Formation. The depth to water table beneath the storm-water impoundment (pond) ranged from about 8 to 12 ft. The average hydraulic gradient from the piezometric surface upgradient from the impoundment was 0.8 percent; the gradient steepened to an average of 11 percent beneath the impoundment. The height of the water-table mound beneath the pond fluctuated according to the volume of rainfall, but the mound persisted as a permanent feature caused by storm-water impoundment. The rate of ground-water flow beneath the pond was estimated from bromide tracer tests at 16 ft/d.

Bottom materials collected from the impoundment in 1986, 1987, and 1988, contained increasing percentages of silt- and clay-sized particles (fig. 19A), increased in cation-exchange capacity from about 5.2 to 16.3 ppm, and increased substantially in calcium and magnesium concentrations while decreasing in silica and sodium concentrations (table 9, fig. 19B). Trace-metal concentrations in bottom materials increased appreciably for cobalt, copper, lead, nickel, strontium and zinc, whereas cadmium remained below detection, chromium concentrations were constant, and boron and vanadium decreased (table 9, fig. 20).

Certain effects of storm-water-infiltration practices on ground-water quality were persistent and showed no amelioration throughout the 3-year period of data collection: in ground water beneath and downgradient from the impoundment, concentrations of dissolved solids (estimated from specific-conductance measurements), chloride, and sodium were substantially elevated; in ground water beneath the impoundment, pH was consistently lower by about a tenth of a unit, and dissolved-oxygen concentrations decreased substantially. An upward component of ground-water flow was evident at the downgradient wells that mixed with water moving horizontally through the aquifer; to some extent, this upward gradient mitigated the effect of infiltrate mixing with ground water beneath the impoundment.

Chloride was the easiest storm-water contaminant to trace to underlying ground water; deicing salt was the sole source of chloride in runoff to the impoundment, and storm-water infiltration was the sole source of elevated chloride concentrations to ground water. Specific conductance correlated highly with chloride in ground water and storm water. Chloride concentrations

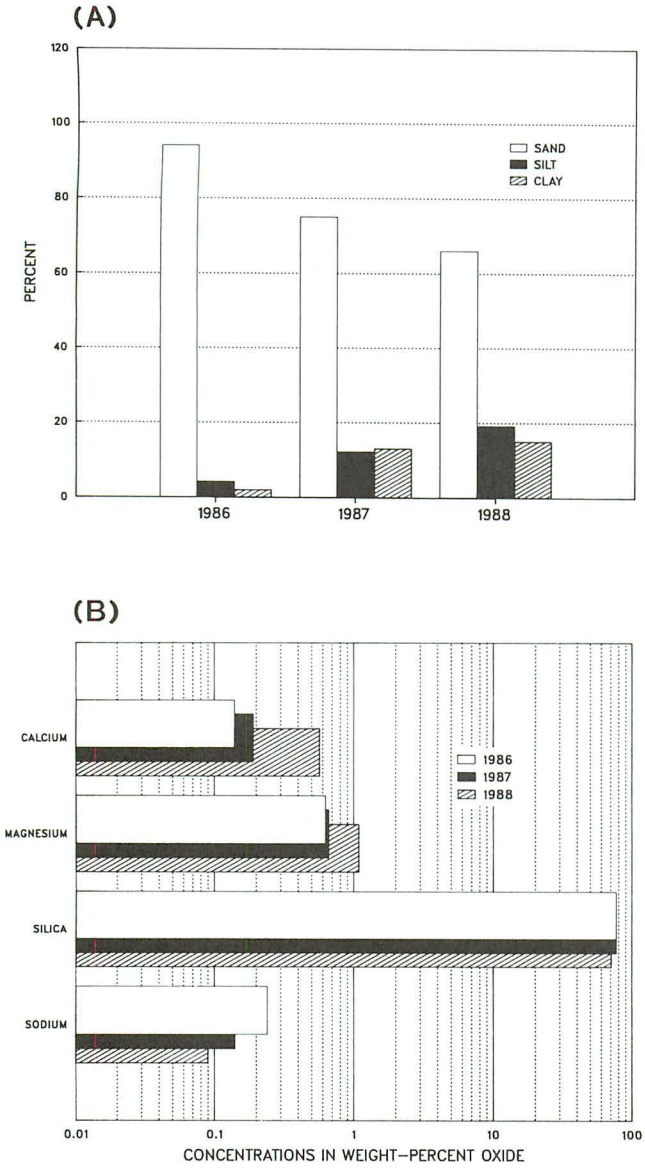


Figure 19.—Changes in pond-bottom materials at the Annapolis site for 1986–1988: (A) particle-size distribution, and (B) concentrations of calcium, magnesium, silica, and sodium.

were substantially elevated in ground water receiving stormwater infiltrate, with chloride constituting 97 percent of major anions compared with 51 percent in ambient ground water at the site (fig. 21).

U.S. Environmental Protection Agency (USEPA) secondary maximum contaminant level (SMCL) of 250 mg/L for chloride was exceeded in storm water whenever deicing salts were applied (U.S. Environmental Protection Agency, 1991a). The SMCL for chloride was exceeded occasionally in beneath-pond ground water; however, the highest chloride concentrations in ground water tended to occur in the late summer or early fall, during periods of high evapotranspiration. Elevated chloride concentrations from winter and early spring deicing was some-

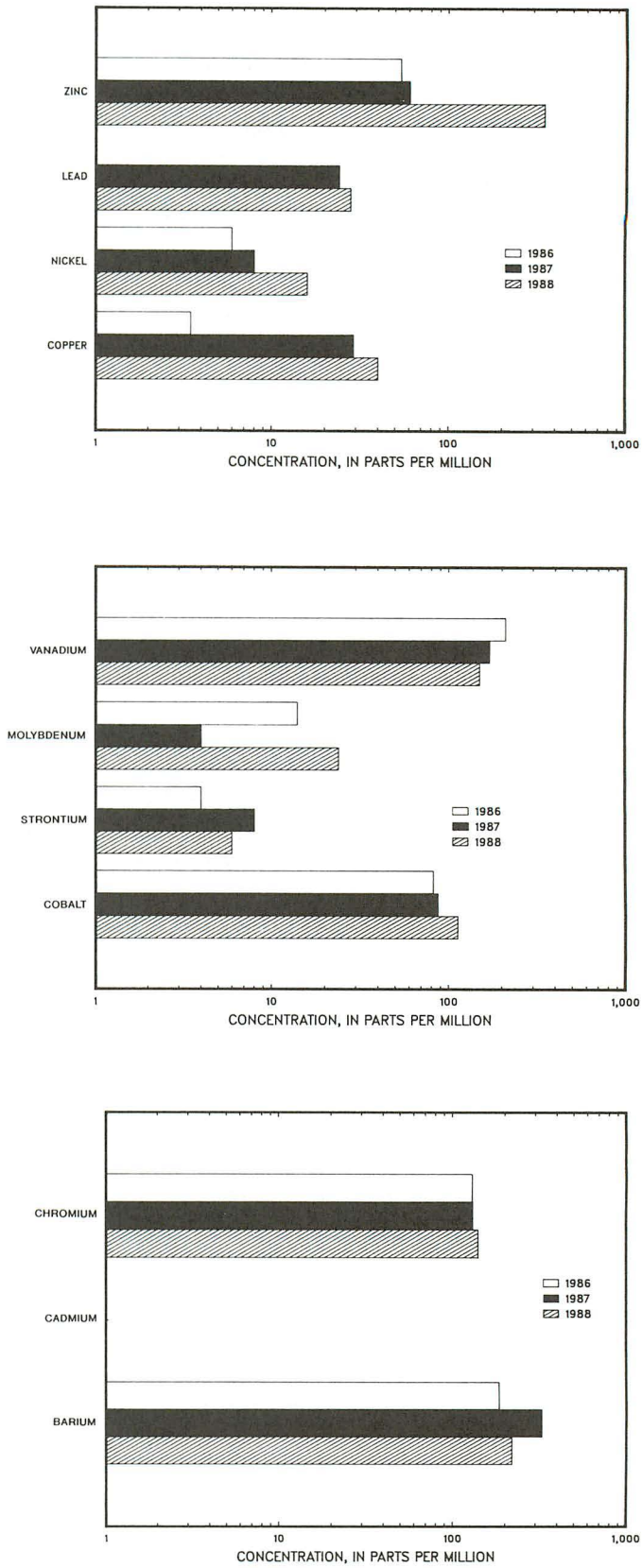


Figure 20.—Concentrations of heavy metals in Annapolis pond-bottom materials.

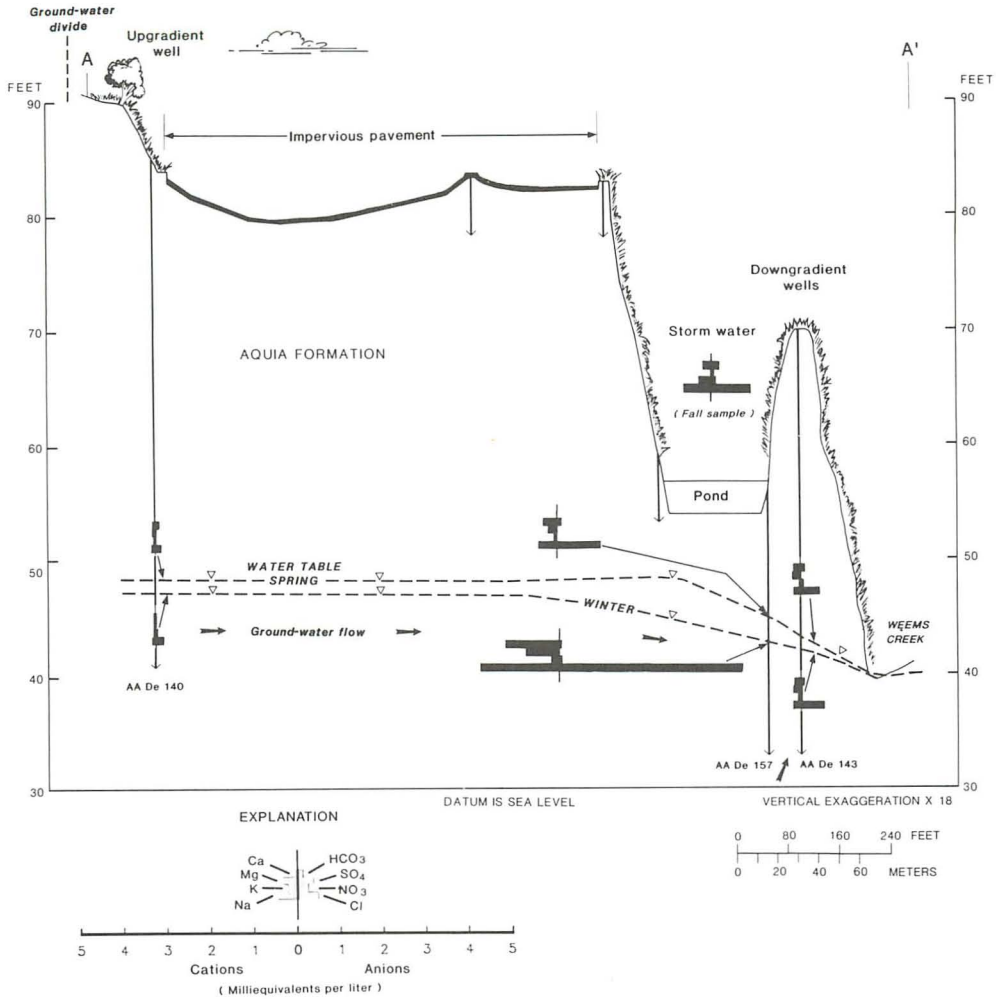


Figure 21.—Hydrogeologic section from upgradient (control) well to downgradient wells at the Annapolis site showing the major-ion chemistry of ground water with respect to seasonal high and low water table.

what muted by the volume of seasonal recharge. A temporal trend toward increasing chloride concentrations was evident in ground water as long as the seasonal application of deicing salts provided a chloride source.

Nitrate concentrations did not exceed the maximum contaminant level (MCL) of 10 mg/L as nitrogen in any aqueous solution analyzed at the Annapolis site (U.S. Environmental Protection Agency, 1991a) (table 11). Nitrate concentrations were greatest in upgradient ground water, primarily from use of landscaping fertilizers at the site; effects of beneath-pond ground water were apparently diluted by storm-water infiltration.

Concentrations of inorganic and organic contaminants that entered the hydrogeologic system in runoff at the Annapolis site fluctuated greatly and caused corresponding fluctuations in ground water. Concentrations of inorganic constituents in storm- and ground-water samples periodically exceeded the MCL's or SMCL's; MCL's for organic contaminants never were exceeded in the samples analyzed. Data were insufficient to determine whether, over time, contaminant concentrations would increase or would be detected with greater frequency.

In some unfiltered samples of storm water, concentrations of chromium, lead, and zinc exceeded MCL's or SMCL's. Concentrations of barium, copper, iron, and nickel in storm water did not exceed MCL's or SMCL's, but they were substantially elevated and, along with chromium, lead, and zinc, entered the storm-water pond with runoff. Moreover, indirect mechanisms accounted for mobilization of some ambient metals in storm water and subsequent transport of these metals to ground water. For example, aluminum concentrations in filtered pond water periodically exceeded the SMCL; these elevated concentrations were not related to input from runoff but to biochemical processes within the impoundment that increased pH sufficiently to cause aluminum mobilization.

Ground-water samples from the impoundment wells had elevated concentrations of barium, boron, cadmium, chromium, copper, nickel, and zinc, which were related to storm-water infiltration (table 13, fig. 22). Downgradient ground-water samples generally had lower contaminant concentrations than samples of beneath-pond ground water because of dilution from rainfall and upward-moving ground water.

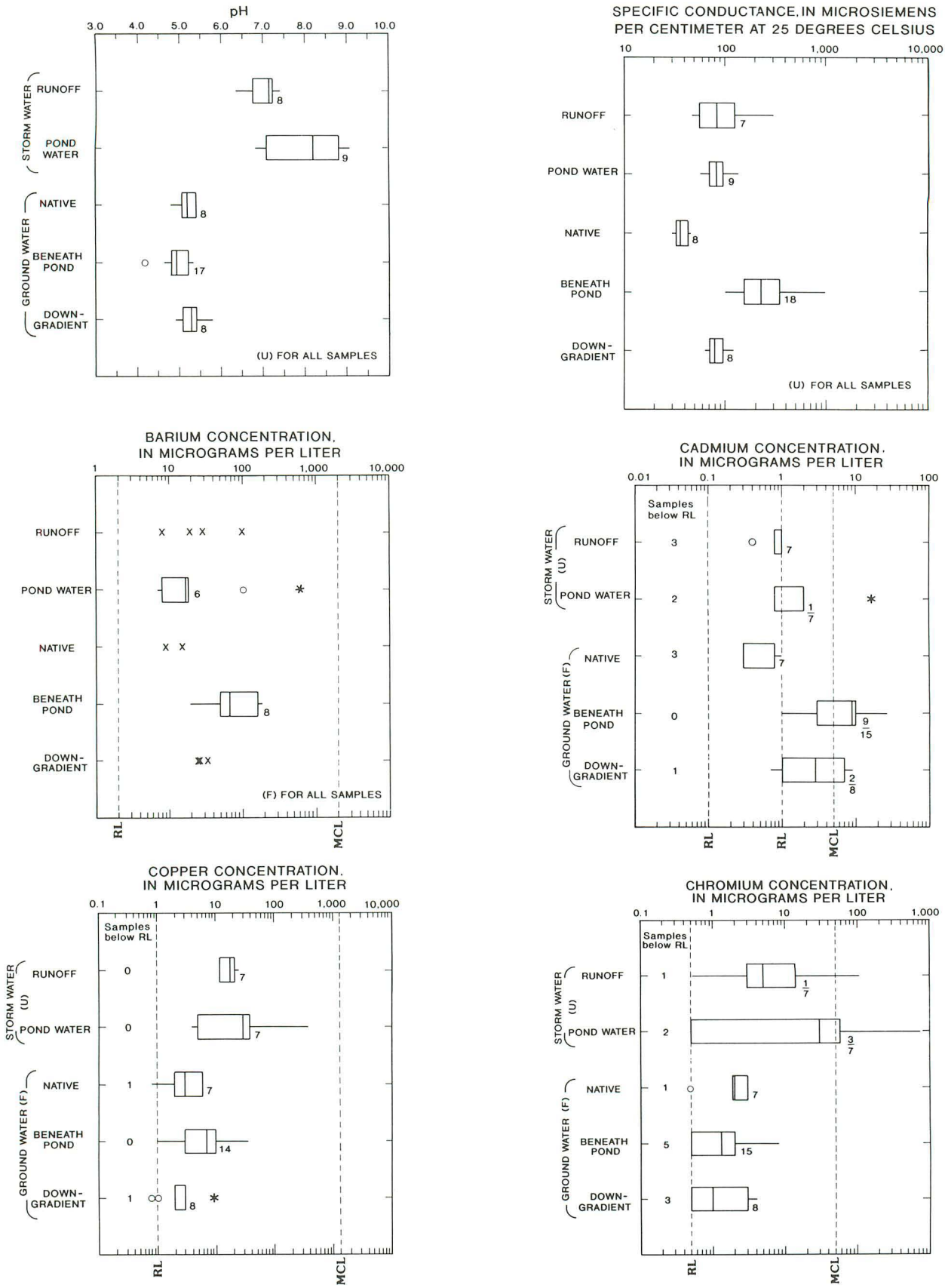
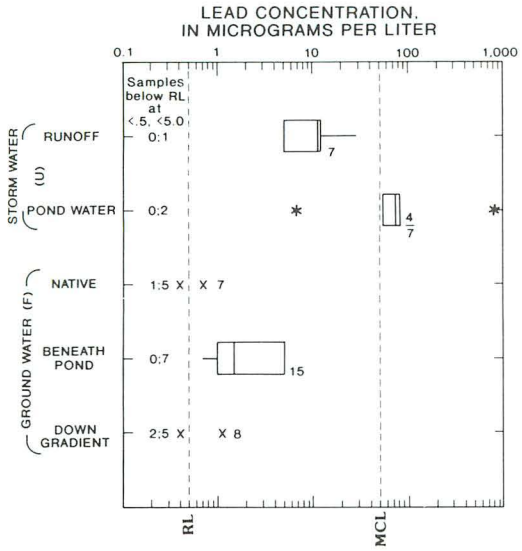
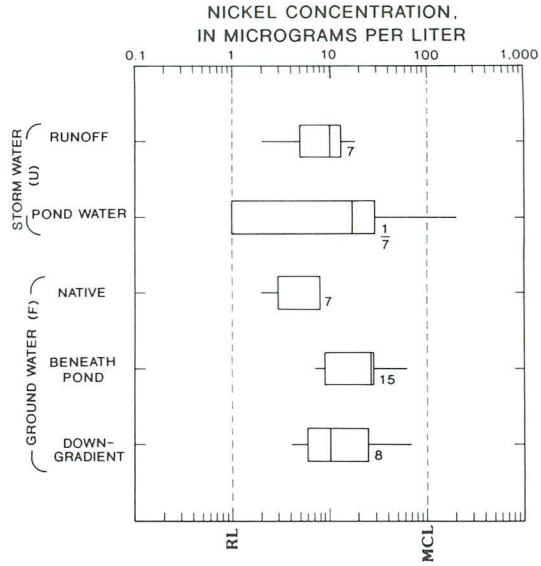
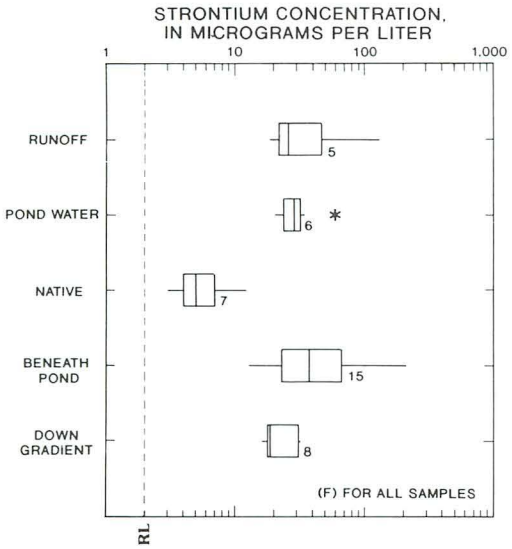
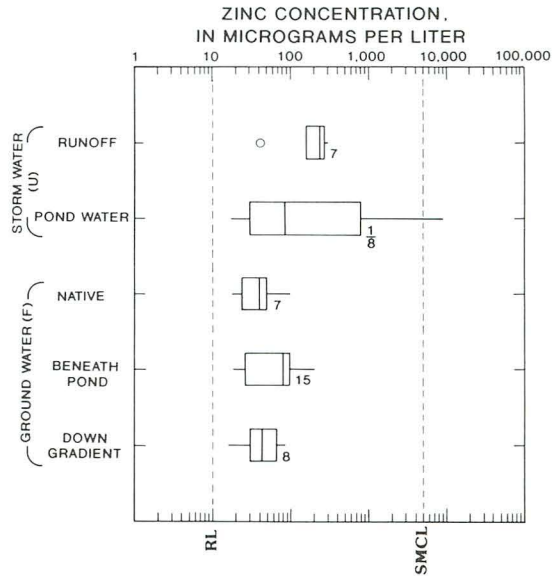


Figure 22.—Summary of pH, specific conductance, aqueous concentrations of selected trace metals at the Annapolis site.

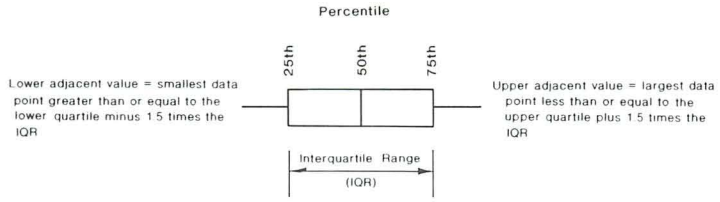








EXPLANATION



○ Outside values: plotted individually 1.5 to 3.0 times IQR beyond the box

* Outliers: plotted individually at points > 3.0 times IQR beyond the box

X Single value

(F) Samples analyzed from filtered water

(U) Samples analyzed from unfiltered water

1/7 Number of samples with concentrations exceeding **MCL**; Total number of samples *(If no concentrations exceed the* **MCL**, *only the total number of samples is shown.)*

MCL MAXIMUM CONTAMINANT LEVEL (U.S. Environmental Protection Agency, 1991)

SMCL SECONDARY MAXIMUM CONTAMINANT LEVEL (U.S. Environmental Protection Agency, 1991)

RL REPORTING LIMIT (Operational definition of detection limit with analytical method used; some constituents have been analyzed with more than one method, yielding different detection (reporting) limits. All reporting limits used are plotted or indicated in text, and number of samples below detection limits is noted on boxplots.)

Some ground-water samples collected from beneath-impoundment and downgradient wells had cadmium concentrations that exceeded the MCL of 5 μg/L (U.S. Environmental Protection Agency, 1991a) (fig. 22). High cadmium concentrations were not measured in any of the storm-water samples, but no other source of aqueous or mineral-bound cadmium to ground water is apparent. Cadmium either entered the site in high concentrations at times when storm water was not being sampled or continually entered the infiltration system in low concentrations, resulting in a buildup of high cadmium concentrations in ground water. (Mechanisms governing cadmium mobility are discussed in the section on "Factors Affecting Ground-Water Quality at the Study Sites".)

GREENMOUNT SITE

North Carroll Plaza in Greenmount, Carroll County, is a major shopping center for a rapidly growing area. The storm-water-management impoundment was constructed in 1970 as a dry pond or detention basin to control runoff to and from the North Carroll Shopping Plaza. In 1986, the pond was retrofitted with a conventional storm-water riser that provided extended detention capabilities, allowing for infiltration and as much as 4 ft of storm-water retention. The pond bottom was tilled and a crop of winter wheat was established in the impoundment before ponding to enhance infiltration; however, water remained in the pond throughout the period of study.

The study site lies within the drainage basin of the East Branch Patapsco River, which eventually drains into the Chesapeake Bay. A headwaters stream of the East Branch lies 700 ft southwest of the storm-water pond (fig. 23A). The site is bounded to the west by a marshy field which is dissected by a runoff-fed intermittent stream that discharges into East Branch. The stream is fed by seasonal springs, seeps, and overflow through the riser in the pond. Farmed fields border the pond on the north and south.

The Greenmount impoundment is roughly circular, although somewhat elongated along a northwest-southeast axis (fig. 23A). The 0.5-acre storm-water pond receives runoff from 15.8 acres, 8.7 of which are imperviously paved. Runoff from the shopping plaza and adjacent highway is channeled to the impoundment through a subsurface storm-drain system; overland runoff is from surrounding farmland. The distance from pond bottom to top is approximately 7 ft; a 4.5-ft maximum ponding depth is controlled by the riser. The impoundment was sized to contain runoff from a 20-year storm.

Site Instrumentation and Hydrologic System

Instrumentation

The locations of wells and data-collection installations are shown on the site map (fig. 23). The conduit delivering storm runoff from the shopping plaza to the pond was modified from an open, erosive channel to a buried 24-in.-diameter storm culvert. The storm culvert opens to a channel lined with locally quarried riprap. A double-notched weir plate was installed in the channel, approximately 5 ft from the culvert. An ADR was installed to monitor pond stage behind the weir. In addition, a Manning automatic sampler for collection of storm runoff, a Belfort rain gage, and a bulk collector for rainwater were housed in a shelter near the weir plate.

Test holes were drilled before construction of the wells and were backfilled after the direction of ground-water flow had been determined from temporary wells. Seven wells were installed during fall and winter 1985, and a lysimeter was installed during 1987 (fig. 23; table 14). The control well, CL Bf 198, is about 640 ft upgradient from the pond; land surface at the well is approximately 50 ft higher in elevation than the pond bottom. A platform was constructed to facilitate access to wells (CL Bf 194 and 195), to the lysimeter (CL Bf 201), and to the pond gage, which are located at the downgradient end of the impoundment in the area of deepest ponding.

Well screens were positioned within the interval of water-table fluctuation; however, two wells screened at deeper intervals were installed adjacent to wells screened at the water table for observation of vertical hydraulic gradients and changes in constituent concentrations with depth: CL Bf 194 was screened 40 ft deeper than CL Bf 195, and CL Bf 200 was screened 61 ft deeper than CL Bf 199 (fig. 23B). Samples of unsaturated-zone water were withdrawn through the porous Teflon lysimeter sleeve (CL Bf 201) at approximately 1.8 ft beneath the pond bottom.

Wells that were instrumented with ADR's during most of the period of data collection included CL Bf 196 and 197; an ADR was installed in CL Bf 200 for about 1 year, and CL Bf 194 was equipped with an analog water-level recorder. Well CL Bf 196 was especially difficult to access during the winter; thus, the water-level records are less complete for this well than for the others. Water-level records at the other wells consist of measurements made with a hand-held tape.

Hydrologic system

The amount of rain recorded at the Greenmount site was close to the 30-year average during 1987 but below average for the 1988 calendar year (table 15). Total rainfall was 43.94 in. in 1987 and 39.81 in. in 1988. Rainfall data were not collected at the study site after March 1989; however, the weather station near Westminster, Carroll County, recorded 43.14 in. of rain for 1989. Rainfall at the study site totaled 107.42 in. for 201 storms during the period of data collection, October 1986 through March 1989 (table 15). Rainfall tended to be highest during November through May, which corresponded to the major period of regional ground-water recharge. Nevertheless, the wettest 3 months of the study period were November 1986, September 1987, and July 1988.

Evaporation data were not collected at the study site, but evaporation-pan data recorded at the National Oceanic and Atmospheric Administration weather station in Beltsville, Md., were used to provide a basis for estimating evapotranspiration (table 15). Evaporation exceeded rainfall for June, July, and Au-

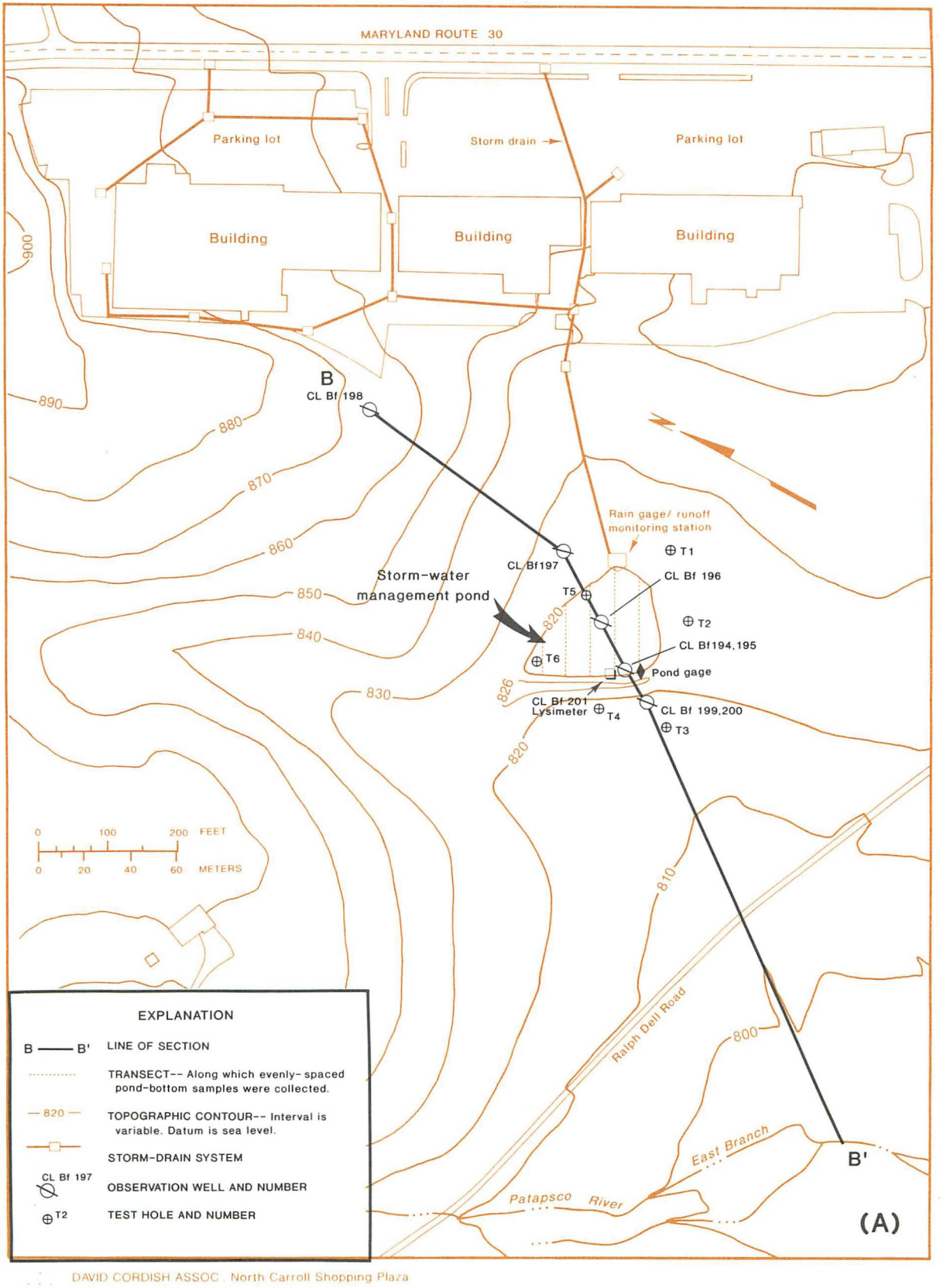


Figure 23.—(A) Location of wells, data-collection points, and line of section B-B′; (B) hydrologic section B-B′; and (C) photographs showing storm-water impoundment at the Greenmount study site.

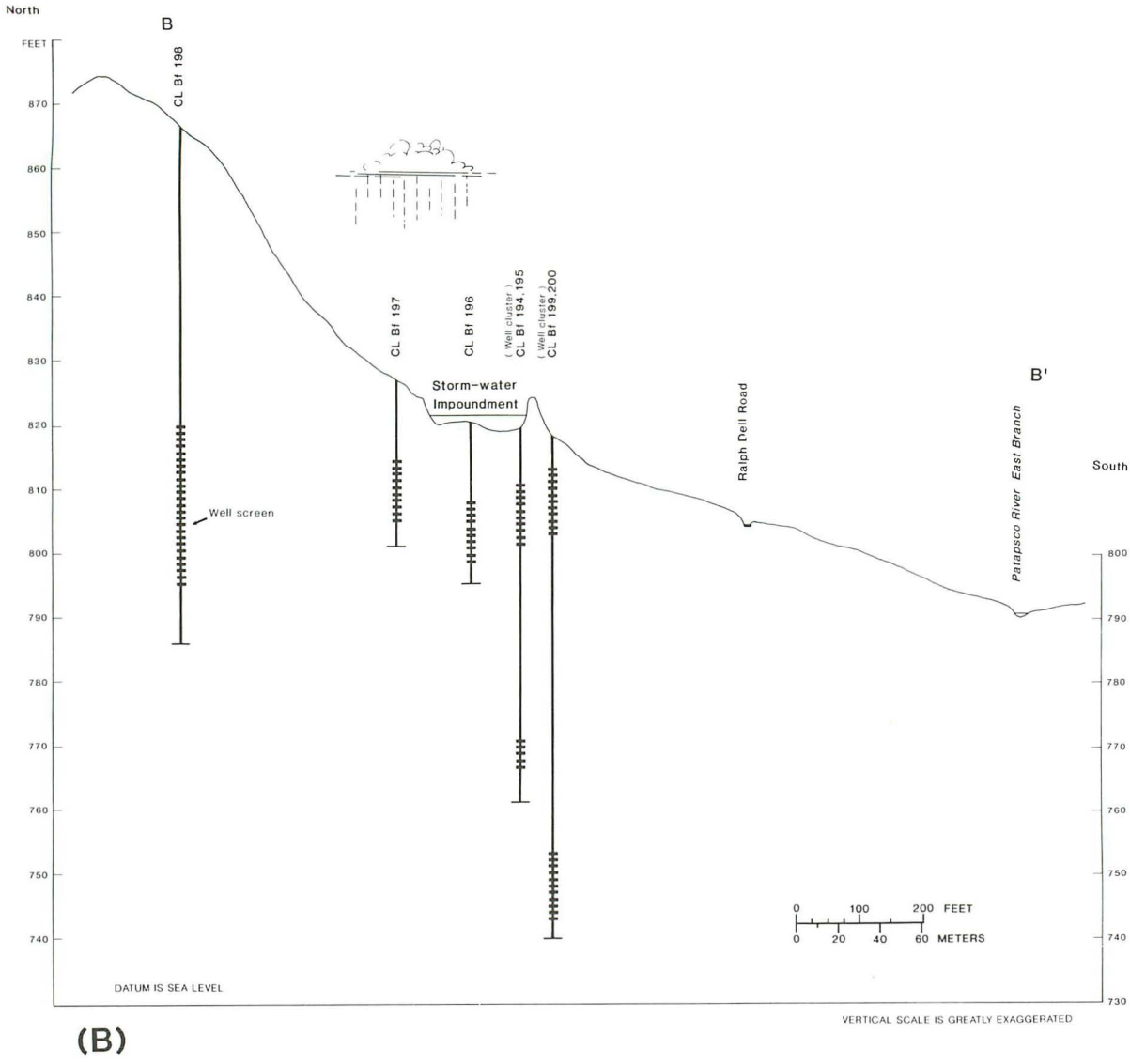
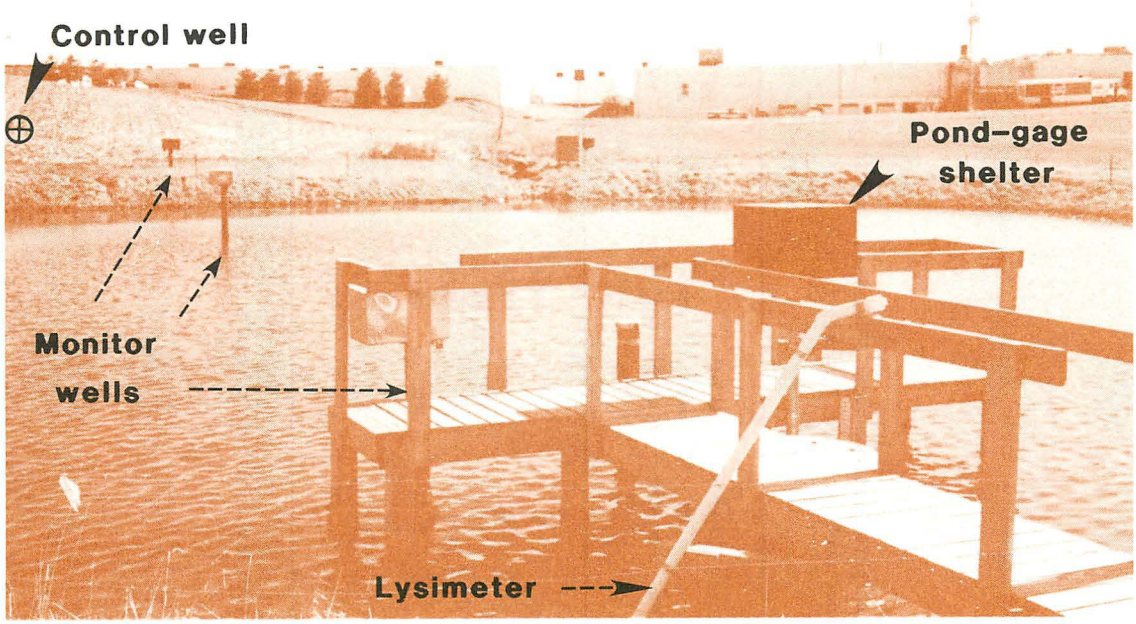


Figure 23.—Continued.

gust of 1987, 1988, and 1989. It was assumed that rainfall exceeded evaporation during November through March.

Storm water remained perched in the pond throughout the year, with at least 1.5 ft of water covering the deepest section of the impoundment after December 1986 (fig. 24). About one-quarter of the upstream side of the pond dried up during periods of low rainfall. The magnitude and intensity of rainfall and runoff to the pond were recorded as rises in pond stage (fig. 24). Subsequent pond-stage decline was caused by flow through the riser, infiltration through the pond sides or berm, leakage through the pond bottom, and evapotranspiration.

Comparison of pond losses with evaporation when pond stage was below the top of the riser, calculation of stage decline during periods of minimal evapotranspiration, and changes in water-table levels indicated that leakage occurred through the sides and bottom of the impoundment. Leakage, inferred as the rate of stage decline after losses from evaporation have been factored out, ranged from 0.02 to 0.05 ft/d, depending on pond stage. Attempts to determine initial infiltration rates through the bottom and sides of the pond by use of a double-ringed infiltrometer yielded rates from 0.864 to 1.008 ft/d. The infiltration rate to the water table (vertical movement through the unsaturated zone), as calculated from the start of pond-stage rise to the start of water-table rise after a storm, ranged from 31.2 to 130 ft/d. The rise and decline of the water table beneath and downgradient of the impoundment were a result of infiltration through the pond and can be seen on the hydrographs as relatively small fluctuations that closely follow the rise and fall of pond stage (fig. 25). Seasonal variations produced the most pronounced changes in ground-water levels. Depth to water table beneath the pond ranged between 2.5 and 10 ft, and was an important factor in the variability of infiltration rates (in addition to pond stage, antecedent moisture conditions, and intensity and magnitude of rainfall).



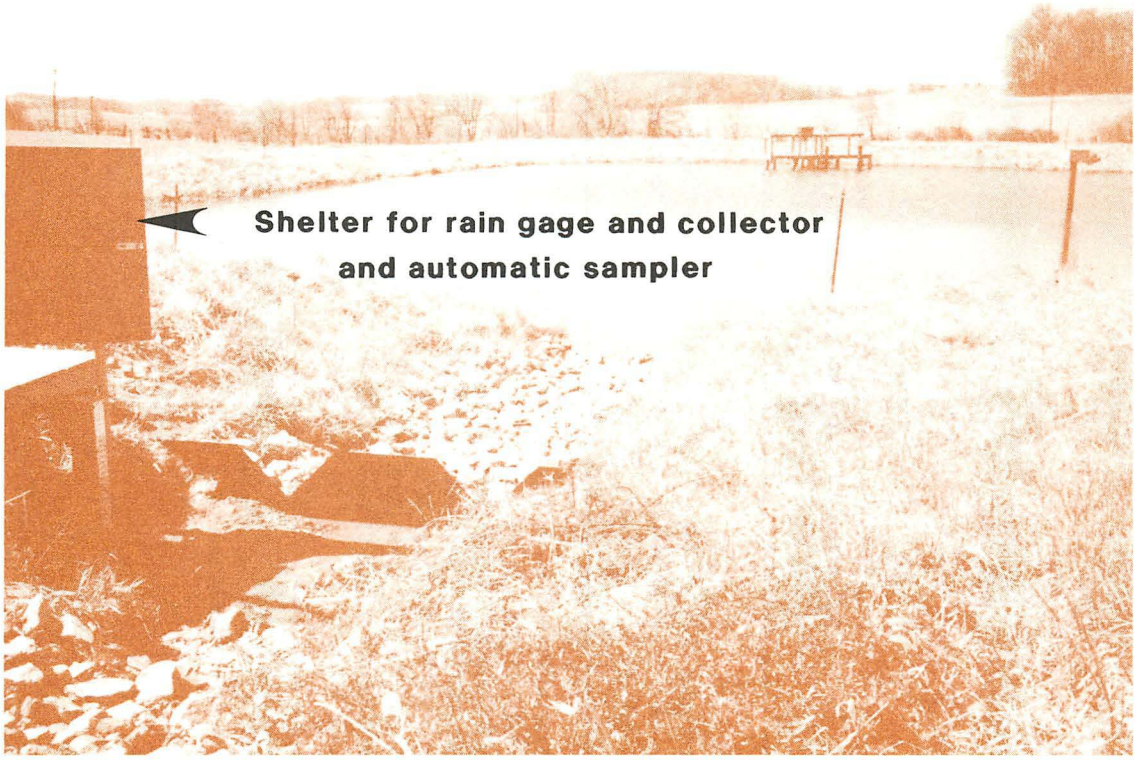


Figure 23.—Continued.

Table 14.—Records of wells at the Greenmount site

[ft, feet; in., inches; ft asl, feet above sea level; ft bls, feet below land surface; PRTB, Prettyboy Schist aquifer; Q, chemical data collected; L, water-level data collected; --, not applicable; *, lysimeter]

Well number	Latitude and longitude[1]	State permit number	Date well constructed	Altitude (ft asl)	Depth drilled (ft bls)	Well depth (ft bls)	Diameter of casing (in.)	Length of screen (ft)	Top of open interval (ft bls)	Hydro-geologic unit	Static water level (ft bls)	First date water level measured	Data type	First year of data collection
CL Bf 194	3938110765211	CL-81-2609	12-19-85	819.36	58.5	53	3	5	48	PRTB	7.16	01-07-86	QL	1986
CL Bf 195	3938110765211	CL-81-2610	12-10-85	819.34	18	18	3	10	8	PRTB	6.16	01-10-86	QL	1986
CL Bf 196	3938120765209	CL-81-2611	12-16-85	820.56	25	25	3	10	12	PRTB	7.38	01-07-86	L	1986
CL Bf 197	3938130765209	CL-81-2612	12-17-85	826.89	25.5	25	3	10	12	PRTB	13.61	01-07-86	L	1986
CL Bf 198	3938170765208	CL-81-2613	01-09-86	866.29	80	73	3	25	46	PRTB	55.1	01-14-86	QL	1986
CL Bf 199	3938100765210	CL-81-2608	12-20-85	818.48	21	18	3	10	5	PRTB	6.42	01-07-86	QL	1986
CL Bf 200	3938100765210	CL-81-2863	01-03-86	818.65	79	79	3	10	66	PRTB	6.66	01-03-86	QL	1986
*CL Bf 201	3938110765211	--	08-18-87	820.55	3.1	2.9	2.3	.25	1.8	PRTB	--	--	Q	1987

[1] Symbols designating degrees (o), minutes (′), and seconds(″) have been omitted from latitude and longitude on table. Latitude precedes longitude and each longitude begins with 076 degrees. For example: latitude 39°38′11″; longitude 76°52′11″.

Table 15.—Monthly rainfall measured at the Greenmount site and monthly evaporation measured at the Beltsville weather station, October 1986 through March 1989

[--, no data available; in, inches]

Year	Month	Precipitation: Number of storms	Precipitation: Number of inches	Evaporation[1]: Number of inches	Comments
1986	October	5	1.35	3.72	
	November	8	8.06	--	
	December	6	6.38	--	
1987	January	9	2.98	--	Amount of rainfall
	February	3	1.44	--	during 1987 calendar
	March	3	1.44	--	year totaled 43.94 in.
	April	5	4.58	3.71	
	May	7	5.83	5.16	
	June	9	5.14	7.09	Amount of rainfall
	July	4	1.44	8.28	during 1987 water year
	August	4	2.57	7.13	totaled 40.37 in.
	September	7	9.16	4.94	
	October	5	3.62	3.35	
	November	4	3.98	--	
	December	5	1.76	--	
1988	January	5	2.26	--	Amount of rainfall
	February	5	2.89	--	during 1988 calendar
	March	4	2.27	--	year totaled 39.81 in.
	April	7	2.97	4.79	
	May	1	6.09	6.04	Amount of rainfall
	June	3	.89	8.03	during 1988 water year
	July	10	7.05	8.12	totaled 40.27 in.
	August	7	3.56	6.62	
	September	4	2.93	4.31	
	October	4	2.70	3.53	
	November	6	4.77	--	
	December	4	1.43	--	
1989	January	3	1.15	--	
	February	7	3.06	--	
	March	7	3.67	--	
Total		201	107.42		

[1] Evaporation data compiled from climatological data summaries published by the U.S. National Oceanic and Atmospheric Administration (1986-88). Data were not adjusted for pan effects. Estimated annual pan coefficient for Class A pan is 0.75 (Fetter, 1988).

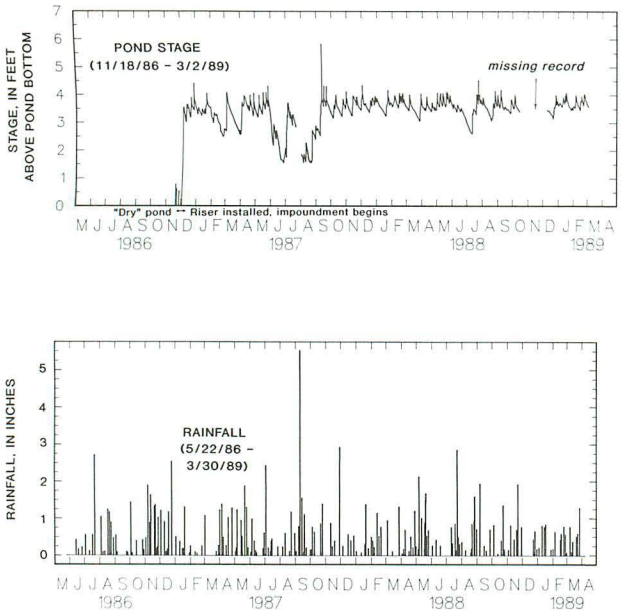


Figure 24.—Daily mean stage in storm-water pond and total daily rainfall at the Greenmount site, June 1986–March 1989.

The water-table aquifer at the Greenmount site is in a thick section of saprolite formed from weathering of the Prettyboy Schist (Meyer and Beall, 1958; Hilleary and Weigle, 1981). The Prettyboy Schist is tapped extensively for domestic, farm, industrial, and public water supplies. Potable water for the area generally comes from wells drilled deeper than 100 ft and are open to the upper fractured-rock part of the formation.

Based upon the available data, the direction of unconfined ground-water flow is generally southwestward across the study site; shallow ground water discharges either to the East Branch Patapsco River or as transient springs and seeps in the adjacent (downstream) field (fig. 26). Flow, in general, would be expected to be downgradient, although flow through the saprolite can preferentially follow macropores, fractures, or relict geologic structures and therefore may not be perpendicular to lines of equal water levels. Ground-water-flow velocity was not measured at this site. Hydraulic conductivity is highly variable in the Prettyboy Schist, but tests at several nearby wells indicated an aquifer transmissivity of about 650 ft^2/d (Meyer and Beall, 1958). The wells tested were screened in the upper part of the relatively unweathered fractured rock; the part of the aquifer composed of saprolitic overburden rarely is tapped for water use. Hydraulic conductivity is believed to be controlled by macropore flow, resulting in comparatively high flow velocities exceeding 50 ft/d (Meyer and Beall, 1958). Water entering the pond was the sole source of chloride to underlying and downgradient ground water: the rate at which slugs of water containing high chloride concentrations (from dissolution of deicing salts) moved from well CL Bf 195 to well CL Bf 199 was roughly calculated to be at 60 ft/d. Horizontal hydraulic conductivities have been reported to be as high as 100 ft/d for similar media (Heath, 1984).

The position of the water table fluctuated 5 to 7 ft each year between January 1987 and March 1989, after storm water was impounded by installing a riser in the management structure (fig. 27). Water-table levels averaged about 55 ft below land surface at the upgradient well, but only about 6 ft below land surface at the downgradient well. After December 1, 1986, the depth to water table beneath the pond was as shallow as 2.5 ft in the early spring and as deep as 10 ft in the early fall. The storm-water pond is in the area of natural discharge for the shallow ground-water-flow system. Comparison of the hydrographs for the downgradient wells, screened 60 ft apart (vertically), indicates that there may be a relatively small downward component of flow beneath the pond (fig. 28A) that decreases at the downgradient wells (fig. 28B).

Seasonal water-table fluctuations at the control well (CL Bf 198) were similar to those beneath the pond (fig. 27). Fluctuation patterns in hydrographs from nearby wells are similar, and major fluctuations in ground-water levels in the area seem to reflect changes caused by seasonal recharge patterns (James and others, 1988).

The hydraulic gradient between the upgradient well and the well on the eastern berm of the impoundment was less than 0.001, whereas the mean gradient on the water table across the impoundment was almost 0.02 (fig. 29). The mean gradient decreased to 0.005 between the pond and the downgradient wells, but it fluctuated widely. Low reverse gradients were measured for 3 months during 1987.

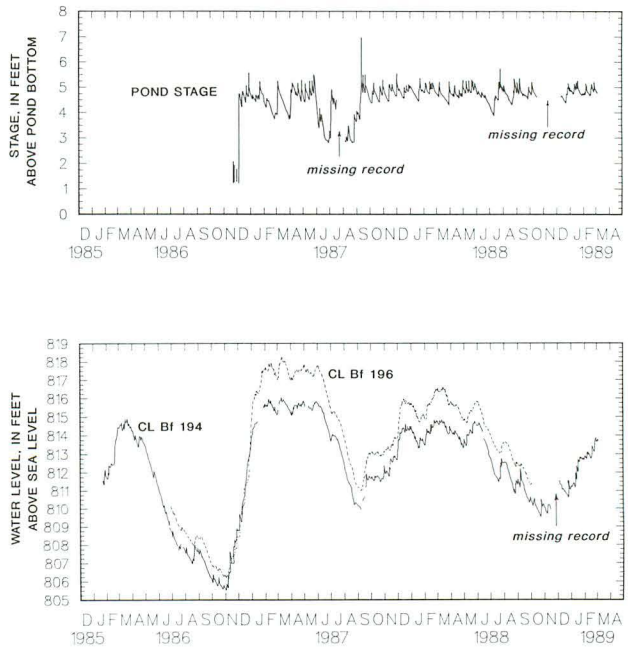


Figure 25.—Fluctuations of pond-water stage and the water table beneath the pond at the Greenmount site, January 1986–March 1989.

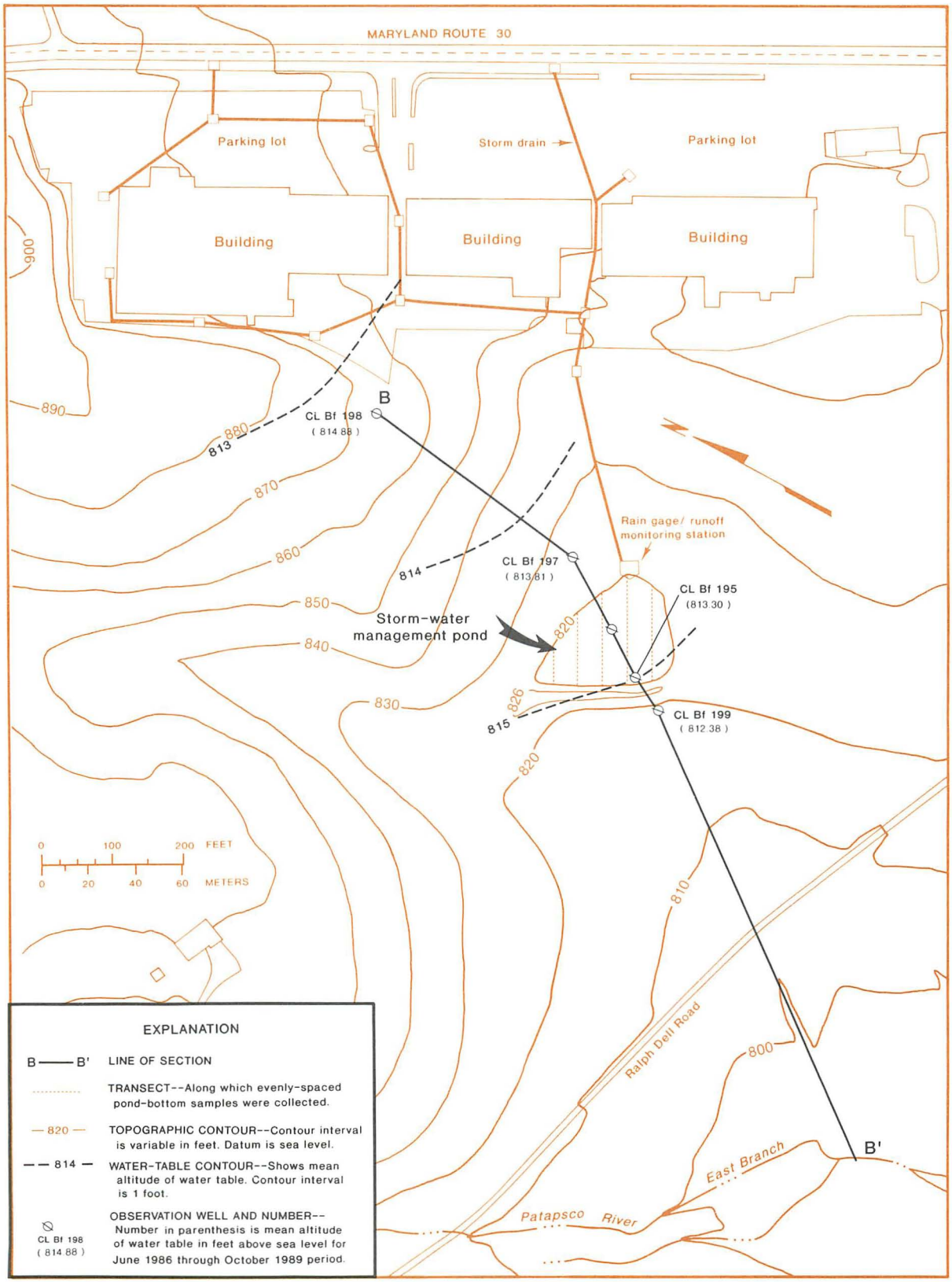


Figure 26.—Mean water-table configuration at the Greenmount site.

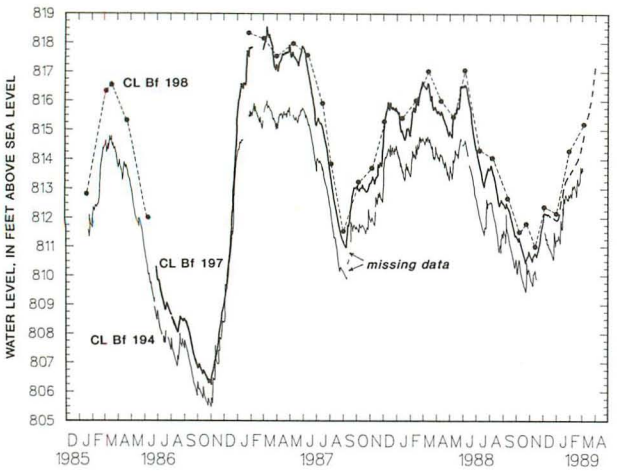


Figure 27.—Water table at the upgradient (control) well (CL Bf 198), at well CL Bf 197 on eastern berm of pond, and at well CL Bf 194 beneath pond near western berm at the Greenmount site, January 1986–March 1989.

The water-table gradients between wells CL Bf 196 and 197, and wells CL Bf 200 and 194, decreased during periods of unusually high rainfall; for example, September–October 1987 and July 1988 (figs. 29B and 29D). Changes in water-table gradient were related to water-table mounding and were superposed on the regional pattern of recharge. The mounding resulted from transient recharge through the impoundment, especially through the berms.

Native Geologic Materials

Greenmount is in the east-central Piedmont physiographic province of Maryland, which is composed of metamorphic rocks of Precambrian to Ordovician(?) age (table 1). Early geologic investigations determined that the basement rocks in the area belonged to the eastern sequence of the Wissahickon Formation, which is part of the Glen Arm Series of metasedimentary rocks (Hopson, 1964; Edwards, 1981; Edwards, 1986, unpublished abstract). Crowley (1976) designated the Wissahickon as a group and identified the rocks of this area as belonging to the Prettyboy Schist Formation. Recent geologic mapping near the Greenmount study site and a cursory examination of some core materials recovered from drilling at the site led Edwards to suggest that the materials are phyllites of the Gillis Formation (Jonathan Edwards, Maryland Geological Survey, oral commun., 1989; Edwards, 1981). Pending further geologic investigation however, the designation of Prettyboy Schist has been adhered to in this report to avoid confusion regarding hydrogeologic nomenclature.

Weathering of Prettyboy Schist basement rocks resulted in a thick mantle of unconsolidated, friable material referred to as "saprolite." The saprolite is approximately 80 ft thick at the Greenmount study site. The schistose structure of the parent rock was preserved in samples collected below 15 ft, and sampling with the split-spoon method became impossible below 30 ft because the rock was too hard. Field and laboratory analysis of split-spoon samples showed that the saprolite is poorly sorted and ranges in composition from 33 to 66 percent sand and 5 to 33 percent clay (table 16). In addition to particle-size distribution, saprolite cored at selected depth intervals was analyzed for major-element composition, cation-exchange capacities, and trace-element chemistry (tables 16, 17, 18).

The Prettyboy Schist is dominated by a quartz-mica-garnet-plagioclase mineralogy (Hopson, 1964; Crowley, 1976). Hand-lens and X-ray-diffraction analyses of saprolite collected from the split-spoon samples indicated a mineralogy dominated

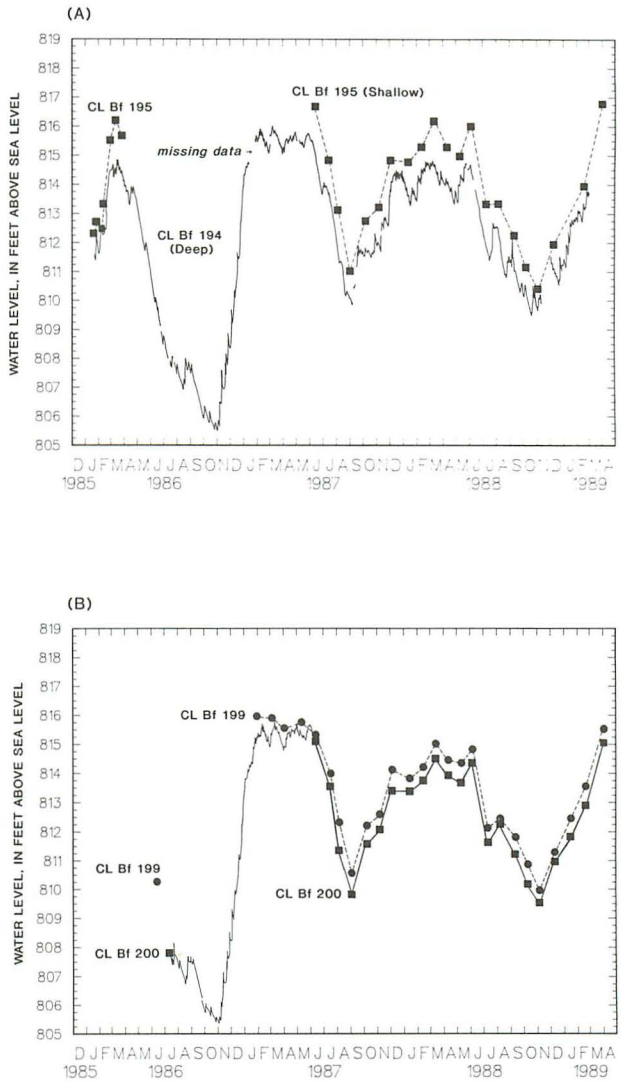


Figure 28.—Water levels in deep and shallow wells at the Greenmount site: (A) beneath the pond near western berm (CL Bf 194, CL Bf 195), and (B) downgradient wells (CL Bf 199, CL Bf 200), January 1986 –April 1989.

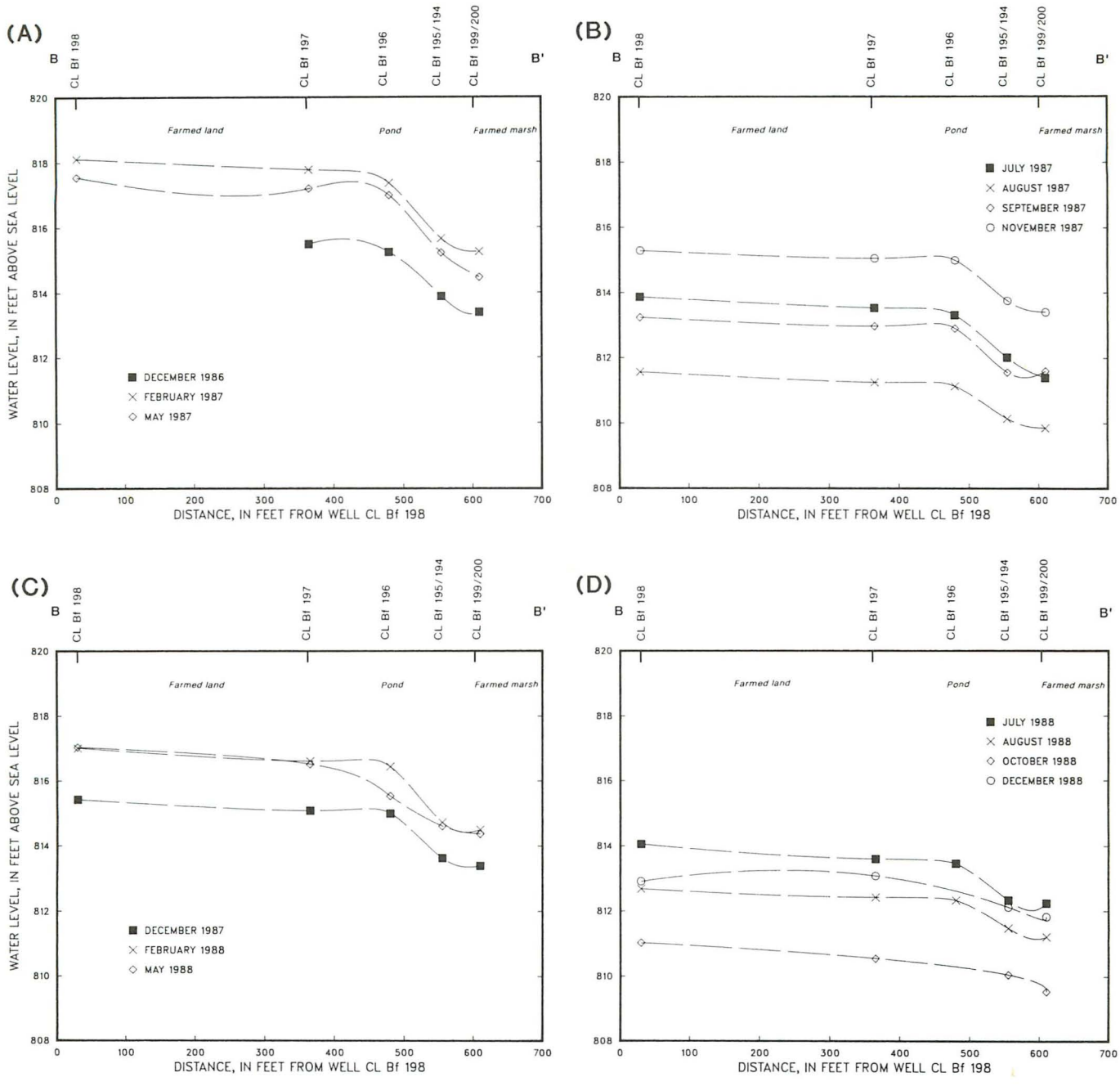


Figure 29.—Altitude of water table at the Greenmount site: (A) December 1986, February and May 1987; (B) July, August, September, November 1987; (C) December, February, May 1988; (D) July, August, October, December 1988. (Refer to Fig. 26 for map showing mean-water-table configuration.)

by quartz and muscovite and including plagioclase (albite-oligoclase), potassium feldspar, biotite, garnet, kaolinite, and hematite. The garnet was severely weathered, and the quartz was commonly stained yellow with iron-oxide (limonitic?) coatings. Other minerals reported by Hopson for this rock unit included chlorite, epidote, staurolite, kyanite, allanite, apatite, tourmaline, monazite, and zircon. The chemical composition for the pelitic schist given by Hopson corresponds reasonably well with that of materials collected at the study site. Concentrations of iron and titanium were much higher and calcium and magnesium much lower in samples collected at the study site, however, than that reported in the literature for Wissahickon rocks (tables 17 and 18) (Hopson, 1964; Crowley, 1976).

Table 16.—Exchangeable base cations, cation-exchange capacities, and particle size of native geologic materials at the Greenmount site

[Ca^{2+}, calcium; Mg^{2+}, magnesium; K^{+}, potassium; Na^{+}, sodium; CEC, cation-exchange capacity; units are in milliequivalents per 100 grams of dry soil; --, no data; sand, >0.062 millimeters; clay ≤0.004 millimeters]

Well number	Depth interval (feet below land surface)	Exchangeable base cations					Particle size (percent)		
		Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	CEC	Sand	Silt	Clay
Upgradient well									
CL Bf 198	14 -16	0.17	0.08	0.06	0.15	0.46	71	22	7
Impoundment wells									
CL Bf 194	4 - 6	2.03	.35	.07	.16	2.61	38	39	23
CL Bf 194	6 - 9.5	.26	.08	.04	.13	.51	65	30	5
CL Bf 194	19.5 -21.5	.24	.34	.07	.16	.81	42	25	33
CL Bf 195	0 - 1	--	--	--	--	--	66	25	9
CL Bf 195	1 - 2	--	--	--	--	--	52	29	19
CL Bf 195	2 - 3	--	--	--	--	--	50	33	17
CL Bf 195	3 - 4	--	--	--	--	--	43	36	21
CL Bf 195	4 - 5	--	--	--	--	--	33	46	21
CL Bf 195	5 - 6	--	--	--	--	--	57	31	12
CL Bf 195	6 - 8	--	--	--	--	--	57	36	7
CL Bf 196	0 - 1	--	--	--	--	--	52	27	21
CL Bf 196	1 - 2	--	--	--	--	--	37	39	24
Downgradient well									
CL Bf 199	2 - 4	2.92	.25	.05	.20	3.42	39	37	24
	4 - 6	1.99	.19	.12	.14	2.44	60	26	14
	6 -10	.61	1.01	.05	.16	1.83	47	43	10
	26 -27.5	.18	.30	.10	.16	.74	48	34	18

Pond-Bottom Materials

The storm-water impoundment was excavated in the saprolite of the Prettyboy Schist. Runoff discharging to the impoundment delivered materials that mixed with and accumulated on the saprolite. Bottom material was collected along transects (fig. 23A) and composited, filtered, and preserved according to the methods previously described. Pond-bottom samples were collected in fall 1986, 1987, and 1988. The initial sample was collected before impoundment of runoff and was similar in composition to that of the native materials. Net sediment accumulation was 10 in. for the period September 1986 through September 1988. The thickest accumulations of storm-water-borne material were in the topographically lowest part of the pond near the platform, in local depressions, and along channel margins. The three samples collected represented a respectively decreasing proportion of native materials relative to storm-water-borne materials.

Anaerobic conditions probably are developing in pond-bottom sediments. The water column above the sediment-water interface is well oxygenated, but dissolved sulfide was measured in pond water on two occasions. Presence of sulfide ions in pond water indicates disturbance of anaerobic bottom sediments during collection of pond-water samples (O.P. Bricker, U.S. Geological Survey, oral commun., 1990). Disturbance of bottom materials usually produced an odor associated with the decomposition of organic materials but not the smell of hydrogen sulfide.

Sediment data for 1986 represents native materials and contrasts the physical and chemical properties of this sample with those of accumulating bottom materials collected in 1987 and 1988 (table 19). A major redistribution in the proportion of particle sizes occurred between 1986 and 1988: sand-sized particles decreased by 73 percent, while silt and clay increased by factors of 4.5 and 5.8, respectively. The clay fraction increased by 400 percent between 1986 and 1987, but only by 15 percent between

Table 17.—Major-element chemistry of native geologic materials at the Greenmount site

[Reported in weight-percent oxide, normalized to 100 percent; ft bls, feet below land surface; LOI, loss on ignition; analytical method for elements was X-ray fluorescence]

Well number	Depth of sample (ft bls)	Calcium (CaO)	Magnesium (MgO)	Sodium (Na_2O)	Potassium (K_2O)	Phosphorus (P_2O_5)	Silica (SiO_2)	Aluminum (Al_2O_3)	Iron (Fe_2O_3)	Manganese (MnO)	Titanium (TiO_2)	Percent LOI	Final percentage
CL Bf 198 [1]	14 - 16	0.04	0.11	1.64	2.25	0.17	63.99	16.46	9.93	0.45	1.09	3.87	100.00
CL Bf 194 [2]	4 - 6	.08	.09	1.76	2.31	.10	66.21	15.49	8.80	.07	1.20	3.89	100.00
	6 - 9.5	.06	.18	.76	3.68	.09	62.27	20.50	6.10	.01	1.36	5.00	100.01
	19.5- 21.5	.07	.01	2.79	3.00	.11	55.58	20.67	11.66	.07	1.44	4.61	100.01
	58 - 59	.07	.92	3.02	3.19	.07	53.49	21.64	11.29	.23	1.58	4.50	100.00
CL Bf 199 [3]	2 - 4	.09	.20	1.25	2.64	.09	64.22	17.47	7.87	.08	1.23	4.86	100.00
	4 - 60	.09	.22	1.38	2.51	.09	65.44	16.44	7.99	.11	1.18	4.54	99.99
	66 - 10	.08	.16	1.46	2.70	.11	61.13	18.14	10.07	.19	1.29	4.68	100.01
	26 - 27.5	.06	.13	2.14	4.54	.07	49.12	24.58	12.38	.03	1.77	5.19	100.01

[1] Upgradient (control) well.
[2] Impoundment well.
[3] Downgradient well.

Table 18.—Trace-element chemistry of native geologic materials at the Greenmount site

[Reported in parts per million; ft bls, feet below land surface; <, below detection with analytical method used]

Well number	Depth of sample (ft bls)	Cadmium (Cd)	Chromium (Cr)	Cobalt (Co)	Copper (Cu)	Lead (Pb)	Molybdenum (Mo)	Nickel (Ni)	Vanadium (V)	Zinc (Zn)
CL Bf 198 [1]	14 - 16	<1	58	190	130	26	4	55	110	73
CL Bf 194 [2]	4 - 6	<1	72	99	53	20	5	35	120	59
	6 - 9.5	<1	90	59	76	26	13	15	150	52
	19.5- 21.5	<1	96	78	96	22	4	60	140	92
	58 - 59	<1	100	100	28	22	4	100	140	330
CL Bf 199 [3]	2 - 4	<1	82	93	50	24	5	40	140	61
	4 - 6	<1	72	110	56	26	6	46	110	61
	66 - 10	<1	80	120	73	26	5	54	140	84
	26 - 27.5	<1	110	47	43	34	3	35	190	88

[1] Upgradient (control) well.

[2] Impoundment well.

[3] Downgradient well.

1987 and 1988; the silt fraction increased by 183 percent between 1986 and 1987, but only by 59 percent between 1987 and 1988. The diminishing increase in the proportion of fine-grained sediments between 1987 and 1988 may indicate that size distributions of sediments accumulating in storm-water impoundments attain a steady state over time.

The cation exchange capacity (CEC) of 1986 bottom material compared with 1988 bottom material increased by a factor of 13.4 (table 19). This increase in the sum of total exchangeable cations is related to the increase and change in the clay mineralogy, the increase in organic matter content, and the formation of manganous, ferric, and aluminous precipitates. The difference between initial CEC (2.61 meq/100 g) and the CEC of 1988 (35.03 meq/100 g) not only reflects the increase in fine-grained materials but also indicates a difference in the exchange medium. A typical range of CEC for kaolinite, the most likely exchange medium in native material along with iron-oxide coatings on mineral grains, is from 1 to 10 meq/100 g. The CEC of 35 meq/100 g indicates an increase in illite, montmorillonite, or iron-oxide precipitates.

The presence of clay phases and hydroxide precipitates in the accumulating bottom material was determined by X-ray diffraction and by optical analysis of thin-section mounts, as well as by inference from clay-stability diagrams and from mineral-saturation indexes calculated with WATEQF (Truesdell and Jones, 1974). The optical analysis identified an iron-rich clay, possibly nontronite, and ferric hydroxides. A plot of pond water on clay-stability diagrams shows that pond water plots near the gibbsite-kaolinite-muscovite border (fig. 30); however, saturation calculations from WATEQF consistently indicated that water in the Greenmount impoundment could be saturated with respect to several montmorillonitic phases, including those that were calcic and those richer in sodium, potassium, magnesium, and iron.

Calculations from WATEQF also indicated supersaturation of pond water with respect to amorphous oxyhydroxide mineral phases that have high exchange potential. Equilibrium calculations for pond water showed the possibility of saturation with respect to iron, manganese, and aluminum hydroxides, indicating that amorphous oxyhydroxide phases of these elements might be precipitating and contributing to the increase in CEC.

Positive saturation indexes (log IAP/KT) imply that, given the presence of these mineral phases and a system governed by thermodynamic equilibria, these minerals would not dissolve. Biological processes affect pH and redox states and otherwise strongly mediate iron and manganese speciation making hypotheses based on chemical equilibria highly speculative at best. Nevertheless, considering the pond-water medians for pH (9.21) and dissolved-oxygen concentration (11.65 mg/L), the rapid reaction rate of hydroxide precipitation under conditions favoring microbial activity, and the consistently positive saturation indexes, it is reasonable to infer the presence of amorphous manganese and iron-hydroxy precipitates. The presence of iron oxyhydroxide phases was confirmed by optical analysis.

Table 19.—Composition of pond-bottom materials at the Greenmount site, 1986–1988

[Units for exchangeable base cations are in milliequivalents per 100 grams dry sample; CEC, cation-exchange capacity; major-element analysis by X-ray fluorescence, reported in weight-percent oxide and normalized to 100 percent; trace-element analysis by X-ray fluorescence (XRF) or direct-coupled plasma (DCP), reported in parts per million (ppm); --, no data]

Component	1986[1]	1987[2]	1988[2]
Particle size (percent)			
Sand	84	46	23
Silt	12	34	54
Clay	4	20	23
Exchangeable base cations and cation-exchange capacities			
Calcium (Ca^{2+})	2.03	15.34	33.72
Magnesium (Mg^{2+})	.35	.49	.60
Potassium (K^{+})	.07	.17	.21
Sodium (Na^{+})	.16	.27	.50
CEC (sum base cations)	2.61	16.27	35.03
Major elements (percent)			
Aluminum (Al_2O_3)	15.49	17.66	18.0
Calcium (CaO)	.08	.82	2.35
Iron (Fe_2O_3)	8.80	9.54	8.62
Magnesium (MgO)	.09	.52	.97
Manganese (MnO_2)	.07	.15	.08
Phosphorus (P_2O_5)	.11	.15	.20
Potassium (K_2O)	2.31	2.84	2.89
Silica (SiO_2)	66.21	59.16	52.3
Sodium (Na_2O)	1.76	.86	.99
Titanium (TiO_2)	1.2	1.30	1.24
Loss on ignition (LOI)	3.89	7.00	12.34
Sum	100.01	100.00	99.98
Trace elements (ppm)			
Arsenic (As)	--	<3	<3
Barium (Ba)	--	460	398
Boron (B)	--	110	110
Cadmium (Cd)	<1	1	1
Chromium (Cr)	72	68	76
Cobalt (Co)	99	99	110
Copper (Cu)	53	38	39
Gallium (Ga)	--	24	18
Lead (Pb)	20	30	90
Molybdenum (Mo)	5	5	5
Nickel (Ni)	35	37	48
Rubidium (Rb)	--	101	80
Strontium (Sr)	--	79	82
Vanadium (V)	120	150	160
Yttrium (Y)	--	53	54
Zinc (Zn)	59	119	469
Zirconium (Zr)	--	292	271

[1]Native materials.

[2]Pond-bottom materials after pond retrofit.

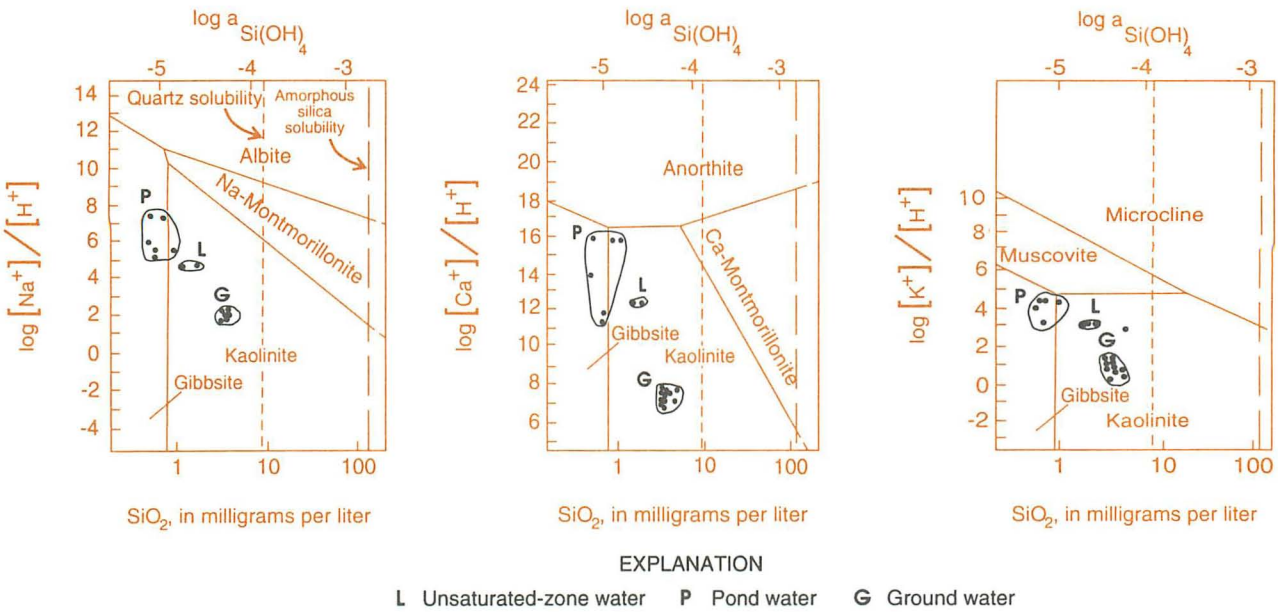


Figure 30.—Stability relations for clay minerals and aqueous solutions with respect to clay minerals at the Greenmount site. [log a $Si(OH)_4$ is log activity of silicic acid.]

Major elements

Ten constituents and LOI comprised the analyses of major-element chemistry of pond-bottom material at Greenmount (table 19). Between 1986 and 1987, the proportions of calcium, magnesium, and LOI increased by factors of 29.4, 11, and 3.2, respectively. The proportion of sand-sized particles decreased from 84 percent in 1986 to 23 percent in 1988. The factor by which the LOI increased in 1988 (1.76) was similar to that in 1987 (1.8), but the increase in the fine-particle-size fraction (silt plus clay) was much greater between 1986 and 1987 than between 1987 and 1988. This comparison indicates that the increase in LOI was related primarily to an increase in organic matter and to the combustion of organic matter. Also increasing were the relative abundances of aluminum, potassium, and phosphorus. Sodium decreased by 44 percent, silica decreased by 21 percent, and fluctuations in iron concentrations resulted in a net decrease of 2 percent. Net changes did not occur in the relative abundances of manganese and titanium.

The source of the major elements comprising native geologic materials at the Greenmount site were quartz, plagioclase, potassium feldspar, mica, garnet, hematite, and kaolinite minerals. The mineralogy of pond sediments changed considerably as storm-water-borne materials accumulated, however, resulting in different clay phases and increased proportion of clay minerals. The accumulating minerals (identified by X-ray diffraction) included kaolinite, montmorillonite, almandine garnet, quartz, muscovite, trace-element hydrated oxides, and metal sulfides. Optical scan of a thin-section mount of the bottom materials also identified ferric hydroxides, possibly nontronite, and a very fine carbonate matrix (Ruth Deike, U.S. Geological Survey, oral commun., 1988).

Silica was the most abundant element in bottom material from 1986 through 1988, followed by aluminum. Quartz was the greatest source of silica; primary and secondary aluminosilicate minerals are ubiquitous in Prettyboy saprolites as plagioclase, potassium feldspar, muscovite, kaolinite, and garnet. Decreases in the percentage of silica by 21 percent were accompanied by a 16-percent increase in aluminum, reflecting a decrease in quartzose sands and an increase in fine-grained aluminosilicate minerals that predominate in clay and silt. Silica to aluminum (Si:Al) ratios were approximately 4.3:1, 3.3:1, and 2.9:1 for 1986, 1987, and 1988, respectively. The increase in aluminum was greatest in the 1987 sample, and corresponded to the greatest increase in clay.

Iron followed silica and aluminum in abundance in native and pond-bottom materials. Garnet and hematite account for most of the iron in native materials. The net abundance of iron, manganese, and titanium in bottom materials from 1986 through 1988 remained fairly constant, although percentages were slightly higher in 1987 compared with the other 2 years. Pigment from a mixing spatula may have contaminated the 1987 sample, and it is possible that apparent increases of iron, manganese, and titanium for that year are attributable to sampling error. Analyses of other elements in the 1987 sample did not appear to be affected. The iron-to-aluminum (Fe:Al) ratios decreased in each year's sample (0.57:1, 0.54:1, and 0.48:1, respectively), indicating general dilution of the native iron-bearing minerals and a proportionately lower input of iron to bottom material. The iron-to-silica (Fe:Si) ratio increased slightly (from 0.13:1 to 0.17:1), however, indicating that incoming clay phases may have included an iron-rich montmorillonite (nontronite?) and (or) that incoming iron was precipitating as an oxyhydroxide phase. Ratios of titanium to aluminum and of titanium to silica followed

the pattern for iron, whereas analogous ratios with manganese were essentially constant in the 1986 and 1987 samples.

Potassium was the fourth most abundant element comprising Prettyboy Schist mineralogy, the sources being muscovite and feldspar. Potassium increased by 25 percent in bottom materials between 1986 and 1988, but most of the increase occurred between 1986 and 1987. The potassium-to-aluminum ratio (K:Al) remained relatively constant for the three samples (0.15:1 in 1986, and 0.16:1 in 1988), indicating that the increase of potassium in bottom materials was linked to the 1987 increase in clay—probably as illite. The amount of exchangeable potassium tripled for the entire period, and much of the increase can be seen in the 1987 sample. Fertilizer used on the adjacent fields was a source of potassium and phosphorus. Although the percentage of phosphorus in bottom materials increased steadily during the 3 years, the potassium-to-phosphorus ratios ($K:PO_4$) steadily decreased.

Sodium followed potassium in abundance of native geologic materials. The native source of sodium was albite (a sodic plagioclase) and possibly mica (paragonite). Sodium in bottom materials decreased by 44 percent (becoming seventh in elemental abundance); sodium-to-aluminum (Na:Al) ratios decreased from 0.11:1 to 0.05:1 between 1986 and 1987/1988, a decrease consistent with a change in clay mineralogy from sodic to potassic and with the large storm-water-borne input of potassic clays (illite) between 1986 and 1987. Interestingly, exchangeable sodium more than tripled. Periodically high inputs of sodium from dissolution of deicing salts is the likely source of the exchangeable sodium in bottom materials.

The abundance of calcium and magnesium in bottom materials increased the most of all major elements during the period of data collection. Calcium and magnesium are very minor components of the Prettyboy saprolite, comprising less than 0.1 percent. Calcium abundance increased more than 29 times, and calcium replaced sodium as the fifth most abundant element in 1988 bottom materials. Magnesium increased almost elevenfold, becoming about equal to sodium in abundance. Exchangeable calcium and magnesium increased by factors of 16.6 and 1.7, respectively. On-site farming practices and dissolution of carbonate materials by runoff were probably important sources of total and exchangeable calcium and magnesium to the Greenmount impoundment. It is improbable that clay minerals entering the impoundment were major sources of calcium or magnesium. The abundances of both elements increased substantially in 1987 and 1988; this pattern was dissimilar to that for the abundance of clay-sized particles and the clay-comprising elements of aluminum and potassium, which increased substantially only in the 1987 sample. Moreover, the ratios of calcium to aluminum (Ca:Al) and magnesium to aluminum (Mg:Al) increased substantially each year (from 0.005:1 to 0.13:1 for Ca:Al, and from 0.006:1 to 0.05:1 for Mg:Al). Ca:Mg ratios in bottom materials were 0.89:1, 1.6:1, and 2.4:1 for 1986, 1987, and 1988, respectively. The implication is that the increase in calcium and magnesium and decrease in the abundance of other cations is due to preferential replacement or exclusion of other cations by calcium and magnesium on clay-exchange sites in addition to the formation of carbonate precipitates that were identified optically in the matrix of pond-bottom sediments.

Trace elements and organic compounds

Increases in trace-element concentrations in pond-bottom materials were substantial for lead (4.5 times) and zinc (8 times), and moderate for cobalt, nickel, and vanadium (1.1 to 1.4 times) at Greenmount between 1986 and 1988 (table 19). Cadmium was not detected in native geologic materials at any depth but was present at the detection limit in 1987 and 1988 samples of bottom material. Concentrations of arsenic (below detection), boron, chromium, molybdenum, strontium, and yttrium remained virtually constant. There were net decreases in barium, copper, gallium, rubidium, and zirconium concentrations. Of the trace constituents analyzed in native Prettyboy Schist materials, only copper concentrations exceeded concentrations analyzed in subsequent pond-bottom samples. (Aqueous solutions were not analyzed for gallium, rubidium, yttrium, and zirconium.)

The trace elements and organic compounds accumulating in pond-bottom material were introduced primarily as dissolved or suspended phases of runoff; direct atmospheric deposition may have contributed substantial amounts of some constituents. Geologic materials of the Prettyboy Schist saprolite probably were not a source of trace elements to the accumulating sediments. Comparison of the trace-element concentrations reported for 1986 and 1987 shows minor changes in chromium and nickel but a decrease in copper of greater than 28 percent. This decrease indicates that the copper concentrations characteristic of the native geologic materials were being diluted with incoming sediments, despite substantial concentrations entering the impoundment in storm water. (Concentrations of elements in aqueous solutions are presented in the following section on "Aqueous Solutions.") Decreases of elemental concentrations in the bottom material could have been from dissolution or desorption as well as from simple dilution; therefore, barium and copper concentrations may be found elevated in aqueous solution. Elements such as arsenic, boron, cadmium, chromium, molybdenum, and strontium that were not detected or did not increase appreciably in bottom materials also may have remained in aqueous solution. Storm water was a potential source for each of the trace elements shown on table 19, including barium and copper.

Pond-bottom materials at the study site were expected to be enriched in metals and other trace elements. Metals have large affinity to sorb and form complexes with organic matter, to sorb to manganese and iron oxyhydroxides, and to collect on clays. The particle-size distribution shifted from 16 percent to 77 percent silt plus clay, resulting in an enormous increase in solid-phase surface area and consequently providing a large increase in sites for the collection of dissolved or suspended metals. Hydroxide precipitates, which commonly form gels that coat clays and other sediments, were identified in the pond-bottom materials. The CEC and sorption potential for amorphous hydroxides are greater than those of clays and much greater than those of

native mineral phases. Organic matter has even greater sorption potential. Analogous to the Annapolis site, the Greenmount pond supports a varied biota, including rooted aquatic plants, invertebrates, and algae, that contribute a continuous supply of organic matter to the pond; in addition, anthropogenic organic compounds enter the pond in runoff.

Batch experiments identical with the Annapolis experiments were performed on bottom material collected in 1988 from the Greenmount pond (table 20), and similar wash solutions were used. The pH of these wash solutions ranged from 6.47 to 7.88, with one exception for the 5 mg/L lead solution; the biologically-mediated pH of pond water at Greenmount had a median value of 9.21, within a range of 7.34 to 10.21. The experimental results were qualitatively similar for bottom materials collected at Annapolis and Greenmount (tables 10 and 20). Calcium was released rather than sorbed from the accumulated bottom material.

1. Cadmium sorption was complete for each concentration of wash solution within the pH range 6.85 to 7.88. Cadmium was not detected in native saprolite, but concentrations were at detection (1 ppm) in the bottom material collected in subsequent years. In light of this experiment, it is important to note that cadmium concentration did not increase in bottom material between 1987 and 1988 despite substantial cadmium concentrations in occasional storm-water samples.
2. Chromium sorption was complete from the 0.05-mg/L laboratory solution at pH 7.8, but very modest amounts sorbed at wash-solution concentrations of 0.5 and 5 mg/L at lower pH values. It is not inferred from these data that pH controlled chromium solubility, however. Chromium concentrations in the bottom material remained virtually constant. The apparent concentration fluctuations were within the analytical margin of error and could not be further interpreted.

Table 20.—Results of laboratory experiment[1] of trace-metal sorption onto pond-bottom materials collected in 1988 from the Greenmount site

[mg/L, milligrams per liter; initial concentration of calcium in wash solution was 10 mg/L; values shown under sorption are the difference between concentrations measured in the wash solution and concentration measured in the batch solution, in mg/L; a minus (-) before the concentration indicates the amount of metal released from solids and that no sorption occurred]

Metal	Concentration of metal in wash solution (mg/L)	Initial pH of wash solution	Sorption onto pond-bottom materials	
			Metal	Calcium
Cadmium	1.00	6.85	1.00	- 5.2
	.10	7.68	.10	- 8.4
	.01	7.88	.01	- 9.4
Chromium	5.00	7.28	.40	- 8.0
	.50	7.78	.19	- 9.8
	.05	7.80	.05	-10.8
Copper	5.00	6.96	3.34	-11.8
	.50	7.58	- .09	- 8.0
	.05	7.78	- .57	- 6.8
Lead	5.00	4.65	4.40	- 9.6
	.50	7.22	.50	- 4.8
	.05	7.61	.05	- .4
Zinc	.30	6.47	- .24	- 8.8

[1] Experiment performed by Robert Ylagon, under the direction of Dr. Richard April, Colgate University, Hamilton, N.Y., written commun., 1989.

3. Nearly 70 percent of the copper in the 5-mg/L solution was sorbed at a near-neutral pH, but desorption occurred at lower concentrations and pH greater than 7.5. Copper was an important trace component of the native saprolite; accumulation of storm-water-borne material seemed to have the effect of diluting the copper concentration by 27 percent. The data indicate the possibility of the release of native copper.
4. Lead sorption was 90 percent of the 5-mg/L solution, even at pH 4.65; 100-percent sorption occurred with lower concentration solutions at greater-than-neutral pH. These data correspond with the yearly analysis of pond-bottom samples by showing a substantial increase in lead concentrations.
5. Release of zinc, rather than sorption, occurred for the bottom material in contact with a 0.3-mg/L zinc solution at pH 6.47. Nevertheless, zinc concentrations increased substantially in the bottom materials. These data indicate that pH controls on zinc solubility are essential in the interpretation of zinc concentrations in bottom material and aqueous solutions.

Inspection of the yearly pond-bottom samples collected at Greenmount indicated a chronological increase in the organic-matter fraction: the samples were increasingly blacker and more putrid, similar to pond-bottom samples collected at the Annapolis impoundment. The presence of anthropogenic organic compounds was determined for the 1988 pond-bottom sample; total carbon content was about 3 percent, and these materials were minimally contaminated with anthropogenic compounds (J.E. Baker, University of Maryland Center for Environmental and Estuarine Studies, written commun., 1989).

Concentrations of constituents detected from the polycyclic aromatic hydrocarbons (PAH) fraction were near detection and included phenanthrene, fluoranthene, pyrene, benzo[a]anthracene, chrysene, benzo[b&k]fluoroanthene, benzo[a]pyrene, indeno[1,2,3-cl]pyrene, and benzo[ghi]perylene. Aromatic hydrocarbons totaled 15.1 μg/g (dry weight) in the sample. Elevated concentrations of aliphatic hydrocarbons were detected, but these were dominated by a large unresolved complex of long-chain and high-molecular-weight hydrocarbons. Aliphatic hydrocarbons totaled 611.5 μg/g (dry weight) in the sample. More volatile organic compounds—short-chain hydrocarbons (gasoline components) and low-molecular-weight PAH's—were not detected. Hydrocarbons of biologic origin comprised a minor proportion of the total organic-carbon fraction.

Aqueous Solutions

pH, specific conductance, and dissolved oxygen

Rainwater collected during a 3-year period at the Greenmount site had a median pH of 4.64 (table 21); the volume-weighted mean was 4.35. Figure 31A indicates that pH values for rainwater grouped in two fields: most samples were within pH values of 3.4 and 5.2, but a group of samples had a pH of 5.4 or higher. The Greenmount site is adjacent to cornfields and in an area in which aerial dusting of farmland is common. pH values that exceeded 5.4 were attributed to dissolution of airborne particulates from liming and other agricultural activities, and samples with the highest pH were visibly contaminated with insects and bird droppings. There was a negative correlation between the less-than-5.2 group of pH values and the specific conductance of rainwater. The median specific conductance of rainwater was 35 μS/cm, and the range was from 8 to 96 μS/cm.

Runoff entering the impoundment at Greenmount had pH values that ranged from 6.51 to 7.80; the median was 7.11. The specific conductance of runoff at Greenmount ranged from 88 to 6,750 μS/cm (fig. 31); the median was 280 μS/cm (table 21). The highly elevated specific conductances were measured in the winter or spring, whenever deicing salts were spread on the

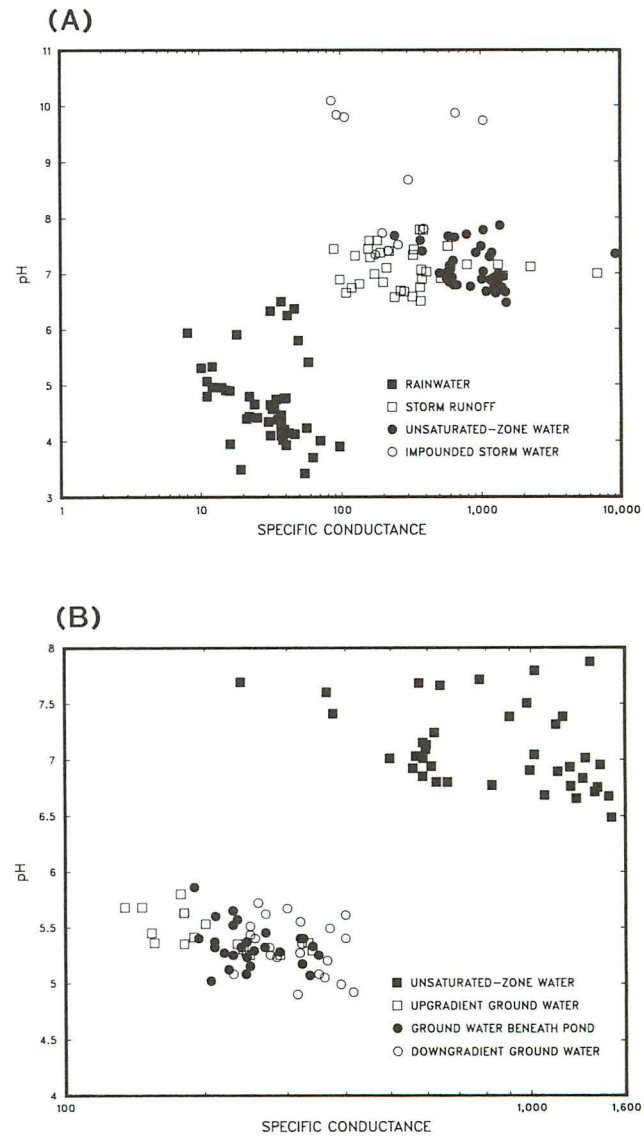


Figure 31.—Specific conductance and pH at the Greenmount site: (A) rain water, storm water, unsaturated-zone water; and (B) ground water, unsaturated-zone water. (Specific conductance is expressed in microsiemens per centimeter at 25 degrees Celsius.)

Table 21.—Median, minimum, and maximum values for specific conductance, pH, dissolved oxygen, and concentrations of major ions in filtered aqueous solutions at the Greenmount site

[Concentrations in milligrams per liter unless otherwise noted; µS/cm, microsiemens per centimeter at 25 degrees Celsius; --, no data; <, below detection at value shown; *, sole measurement shown as maximum concentration; #, median value for dissolved oxygen in pond water is not meaningful; µm, micrometer]

Station description	Concentration	Specific conductance[1] (µS/cm)	pH[1]	Dissolved oxygen[1] (DO)	Dissolved organic carbon[2] (DOC)	Calcium[2] (Ca)	Magnesium[2] (Mg)	Sodium[2] (Na)	Potassium[2] (K)	Bicarbonate[1] (HCO_3)	Sulfate[2] (SO_4)	Chloride[1] (Cl)	Nitrate[2] (NO_3 as N)	Silica[2] (SiO_2)
Rainwater	Median	35	4.64	--	--	*	*	*	--	0	--	1.9	--	*
	Minimum	8	3.43	--	--	*	*	*	--	0	--	.2	--	*
	Maximum	96	6.50	--	--	0.88	0.11	0.7	--	2.44	--	20.0	--	0.4
Storm-water runoff	Median	280	7.11	*	--	19.0	1.2	7.6	1.9	65.04	22.0	18.3	*	1.2
	Minimum	88	6.51	*	1.5	8.9	.7	2.7	.9	25.6	13.0	.2	*	.8
	Maximum	6,750	7.80	7.96	8.6	53.0	7.7	14.0	5.9	160	66.0	601	1.5	6.6
Impounded storm water	Median	216	9.21	#	7.0	20.0	1.02	20.5	1.7	62.48	10.2	17.9	< .10	.7
	Minimum	85	7.34	6.02	1.3	16.0	.55	1.5	.8	42.06	6.6	2.2	< .10	.6
	Maximum	1,030	10.24	15.53	9.3	36.0	1.4	180	2.5	121	1.0	300	.11	1.0
CL Bf 194[3]	Median	230	5.54	3.57	1.35	8.9	8.1	19.0	1.7	15.24	5.5	29.0	11.0	7.3
	Minimum	190	5.29	.64	1.2	8.4	7.2	11.0	1.5	12.19	3.5	18.0	9.3	6.8
	Maximum	269	5.86	5.70	2.1	11.0	9.5	22.0	1.8	24.99	7.5	35.0	12.0	7.8
CL Bf 195[4]	Median	258	5.29	.68	1.5	9.9	7.7	16.0	1.6	10.67	18.0	30.0	4.7	6.5
	Minimum	194	5.02	.18	1.2	7.8	1.1	11.0	.9	9.14	< .2	16.0	3.9	.97
	Maximum	350	5.45	3.80	7.4	20.0	19.0	24.0	4.2	13.41	24.0	74.6	27.0	7.3
CL Bf 198[5]	Median	186	5.38	6.40	1.0	7.3	8.5	9.1	1.75	9.94	1.35	18.8	13.0	6.0
	Minimum	135	5.25	6.00	.5	5.1	5.3	6.2	1.0	6.58	< .2	10.0	3.1	5.9
	Maximum	340	5.80	6.87	1.9	15.0	11.0	32.0	2.6	16.46	24.0	54.0	20.0	6.2

Table 21.—Median, minimum, and maximum values for specific conductance, pH, dissolved oxygen, and concentrations of major ions in filtered aqueous solutions at the Greenmount site—Continued

Station description	Concentration	Specific conductance[1] (µS/cm)	pH[1]	Dissolved oxygen[1] (DO)	Dissolved organic carbon[2] (DOC)	Calcium[2] (Ca)	Magnesium[2] (Mg)	Sodium[2] (Na)	Potassium[2] (K)	Bicarbonate[1] (HCO_3)	Sulfate[2] (SO_4)	Chloride[1] (Cl)	Nitrate[2] (NO_3 as N)	Silica[2] (SiO_2)
CL Bf 199[6]	Median	309	5.29	4.21	1.2	15.0	5.9	22.0	1.5	11.16	11.0	60.0	3.4	6.1
	Minimum	230	4.90	2.00	.7	8.0	4.5	9.3	.5	7.07	5.0	32.0	2.8	5.5
	Maximum	415	5.72	6.51	2.3	26.0	16.0	40.0	2.5	23.17	34.0	88.1	7.9	6.9
CL Bf 201[7]	Median	828	7.01	--	--	47.0	4.1	69.0	--	259	28.5	67.0	< .10	1.7
	Minimum	240	6.48	--	--	33.0	3.3	12.0	1.1	52.43	5.0	3.8	< .10	1.3
	Maximum	9,107	7.98	--	--	170	18.0	110	1.8	323	93.0	645	.13	3.5

[1] Data shown for specific conductance, pH, dissolved oxygen, bicarbonate, and chloride are for weekly or monthly samples that include samples sent to the laboratory (Appendix G).

[2] Data shown are laboratory analyses of dissolved organic carbon, calcium, magnesium, sodium, potassium, sulfate, nitrate, and silica concentrations (Appendix B); DOC samples passed through 0.45-µm-silver filters; cation and anion samples passed through 0.1-µm filters, except for bicarbonate samples (unfiltered) and nutrient samples (0.45 µm pore diameter).

[3] Beneath-pond well screened approximately 40 to 46 feet beneath water-table surface.

[4] Beneath-pond well screened at water-table surface.

[5] Control well.

[6] Downgradient well.

[7] Lysimeter.

Greenmount Plaza parking lot. There was no correlation between pH and specific conductance for runoff.

The specific conductance of impounded storm water was somewhat lower than that of runoff: minimum values were similar, but the median value for impounded water was 216, compared with 280 for runoff, and the maximum value for impounded water was 1,030 compared with 6,750 µS/cm runoff. Because many more runoff samples were collected than pond-water samples, it is possible that the lower specific conductance of the pond water compared with runoff was an artifact of sampling frequency—especially for the highest value measured. Nevertheless, specific conductance correlated positively with chloride concentrations at the 96-percent confidence level for runoff and at the 98-percent confidence level for pond water for specific conductance greater than 220 µS/cm. Therefore, the lower specific conductance and chloride concentrations in pond water are interpreted as having been depleted by dilution and storm-water infiltration. The pattern of specific conductance and chloride concentrations in runoff and impounded storm water is directly analogous with the Annapolis site.

Biological mediation caused considerable variation in pH and dissolved-oxygen concentrations. The median pH of storm water collected from the impoundment was 9.21—more than two orders of magnitude higher than the pH of the incoming runoff. Pond-water pH ranged from 7.34 to 10.24 (the 10.24 pH value is not shown on figure 32 because it had no corresponding dissolved-oxygen value); dissolved-oxygen concentrations ranged from 6.02 to 15.53 mg/L (fig. 32), and depended upon water depth, temperature, time of day, and proximity to algal blooms. Concentrations of dissolved oxygen measured near pond bottom were between 6 and 8 mg/L. Diurnal fluctuations of pH and dissolved oxygen were evident throughout the year, and some of the highest pH measurements were recorded during the winter. The data did not reveal a seasonal trend, indicating

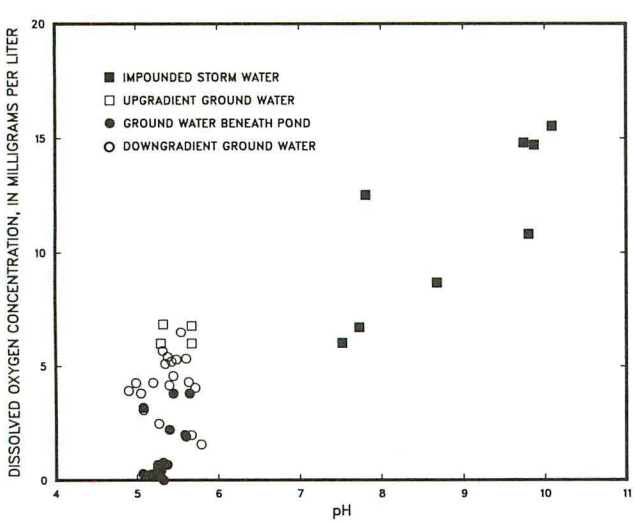


Figure 32.—Dissolved-oxygen concentrations and pH of pond water and ground water at the Greenmount site.

that algal communities were active throughout the year (D.D. Lynch, U.S. Geological Survey, written commun., 1989). The strong statistical relation between field-measured pH and the percent saturation of dissolved oxygen (standard deviation as r equaled 0.90) is further evidence of biological mediation (table 22).

The chemistry of shallow unsaturated-zone water collected beneath the impoundment (CL Bf 201) resembled that of storm water, with values of pH and specific conductance plotting within the storm-runoff field (fig. 31). The median pH (7.1) of water in the unsaturated zone was significantly lower than that of pond water because the effect of algal photosynthesis was removed. The median specific conductance was 828 µS/cm (table 21), which was substantially higher than that of pond water; specific conductances tended to cluster at the high end of the runoff range.

Dissolved-oxygen concentration or the redox potential of unsaturated-zone water was not successfully measured. Oxygenated conditions were generally assumed, with concentrations of dissolved oxygen between that of pond water and underlying ground water. There was evidence of sulfide in the interstitial water of pockets of bottom sediments, however, and actual redox gradients may be complex and nonuniform. Such redox gradients may account for the oxygen depletion observed in ground water beneath the impoundment.

The control well (CL Bf 198), at which native ground-water chemistry was monitored, was located upgradient in a vegetated area behind the shopping plaza. The median values for pH, specific conductance, and dissolved-oxygen concentration were 5.38, 186 µS/cm, and 6.40 mg/L, respectively (table 21). pH and dissolved-oxygen concentration were within a relatively narrow range. Specific conductance was highly variable, however, because ground water near the control well was vulnerable to nonpoint and point sources of contamination. Although ground water at this well was contaminated with organic compounds and some metals, the pH and concentrations of most major ions in samples collected from this well appeared to be representative of native ground-water chemistry. There was no correlation between pH and specific conductance or specific conductance and chloride in native ground water.

The storm-water impoundment lies 390 ft downgradient from the control well. Shallow ground water was collected beneath the impoundment from well CL Bf 195 and downgradient from the impoundment from well CL Bf 199. The pH of all downgradient ground water and most samples of beneath-pond ground water was slightly, but consistently, lower than background pH. The lowest ground-water pH was measured in shallow downgradient samples. Sample pH of downgradient ground water collected at a screened interval of 61 ft (CL Bf 200) below that of the shallow well was consistently higher than that of the shallow wells; these pH values (5.35 median) were similar to background values measured from the control well (5.38, median pH). There was no evidence of upward ground-water flow at the downgradient wells.

The specific conductance of ground water was substantially higher in samples collected at the water table from wells CL

Table 22.—Field pH and percent saturation of dissolved oxygen in pond water at the Greenmount site

[r, correlation coefficient]

Date	Field pH	Dissolved oxygen (percent saturation)
3/23/88	9.74	131
3/31/88	9.87	143
6/02/88	7.73	76
7/14/88	7.52	74
9/28/88	9.80	114
12/08/88	10.09	118
1/27/89	7.81	94
	r = 0.90	

Bf 195 and 199 than at the control well (CL Bf 198). Specific conductance was higher in downgradient ground water than in beneath-pond ground water: median specific conductance was 309 µS/cm at well CL Bf 199 and 258 µS/cm at well CL Bf 195 (table 21). Increases in specific conductance in ground water beneath and downgradient of the impoundment correlated positively with increases in chloride concentration.

Dissolved-oxygen concentrations were notably depleted in ground water beneath and downgradient from the pond: ground water beneath the impoundment and downgradient ground water had median concentrations of 0.68 (CL Bf 195) and 4.21 mg/L (CL Bf 199), respectively. There appeared to be a temporal trend toward decreasing dissolved-oxygen concentrations in beneath-pond ground water. Reduced oxygen in ground water is likely related to biological consumption of oxygen, evidenced by anaerobic pockets in pond-bottom materials. Shallow ground water downgradient from the impoundment had dissolved-oxygen concentrations that also were lower than background but they were considerably higher than those in beneath-pond ground water. The comparatively high concentrations and fluctuation in dissolved-oxygen concentrations at the downgradient well resulted from mixing with recharging rainwater.

Major elements

Rainwater and storm water.—The major- and trace-element composition of rainwater was partially analyzed in two rainwater samples collected at the Greenmount site (table 21 and Appendix B). The most complete of these analyses was for a rainwater sample with a pH of 5.31, which represents an order of magnitude increase in hydrogen-ion concentration over the median pH of rainwater monitored at the site. Therefore, ion concentrations in this sample are not considered representative, but they provide an indication of possible major-element and trace-element concentrations.

In the trilinear diagram (fig. 33), storm water plotted in two compositional fields. Throughout most of the year, runoff entering the impoundment plotted in a calcium bicarbonate/sulfate field, but associated pond water was depleted in sulfate and plotted as a calcium bicarbonate solution. When deicing salts were applied at the Greenmount Plaza parking lot and adjacent roads, dissolution of the salt resulted in storm and pond water with highly elevated concentrations of sodium and chloride. Sodium chloride domination of pond-water type was discontinuous through the winter and spring months and lasted from several days to as much as 3 weeks after salting.

Concentrations of sodium in runoff and pond water essentially balanced those of chloride. The highest concentration of chloride recorded in runoff at Greenmount was 601 mg/L in January 1987 (table 21). The mean chloride concentration for the period December through March was 99 mg/L, compared to 36.5 mg/L for April through November. Elevated chloride concentrations (115 to 440 mg/L) also occurred in some samples of runoff during the 1988 June-early July drought; however, this chloride input was attributed to effluent from meat-preparation activities, which normally amounted to a small fraction of runoff entering the pond. Chloride concentrations were not elevated in pond water during the drought period. Chloride concentrations in pond water followed the seasonal pattern for runoff, and no trend toward chloride enrichment in pond water was evident.

Concentrations and relative abundances of the major ions in pond water were similar to those in runoff, except for lower sulfate concentrations in pond water. The apparent difference in sodium concentrations is likely to be an artifact of when sampling occurred—the range of chloride concentrations corresponding to the sodium concentrations given is 4.2 to 27 mg/L, on samples collected in the late spring, summer, and early fall. Chloride data and data for specific conductance, pH, and alkalinity were collected almost weekly throughout the year (for more detail, refer to Appendixes B and G). Nevertheless, the percentage of calcium, magnesium, and potassium increased in pond-bottom sediments, indicating that the source of major cations accumulating in bottom materials was largely from the particulate fraction of storm water. Ratios of calcium to major cations or anions were higher for pond water than for storm water, except for bicarbonate which balanced calcium in runoff and pond water. Calcium was enriched with respect to Ca:Mg and Ca:K ratios in pond water and bottom materials. Concentrations of dissolved species of these major cations were controlled by mineral equilibria in bottom materials. The percentage of sodium decreased in bottom materials although sodium concentrations periodically were elevated in pond water: dissolved sodium moved conservatively with chloride out of the impoundment in storm-water infiltrate.

Equilibrium modeling with WATEQF was useful for evaluating possible saturation states of mineral phases and thereby shedding light on the partitioning of elements between the solid and aqueous phases in impoundment waters. The implication is that concentrations of major ions dissolved in pond water are controlled by the dissolution or precipitation of mineral phases. The results of the modeling exercise indicate that storm water was saturated with respect to iron, manganese, and aluminum hydroxides and oxyhydroxides, illite and montmorillonite, and

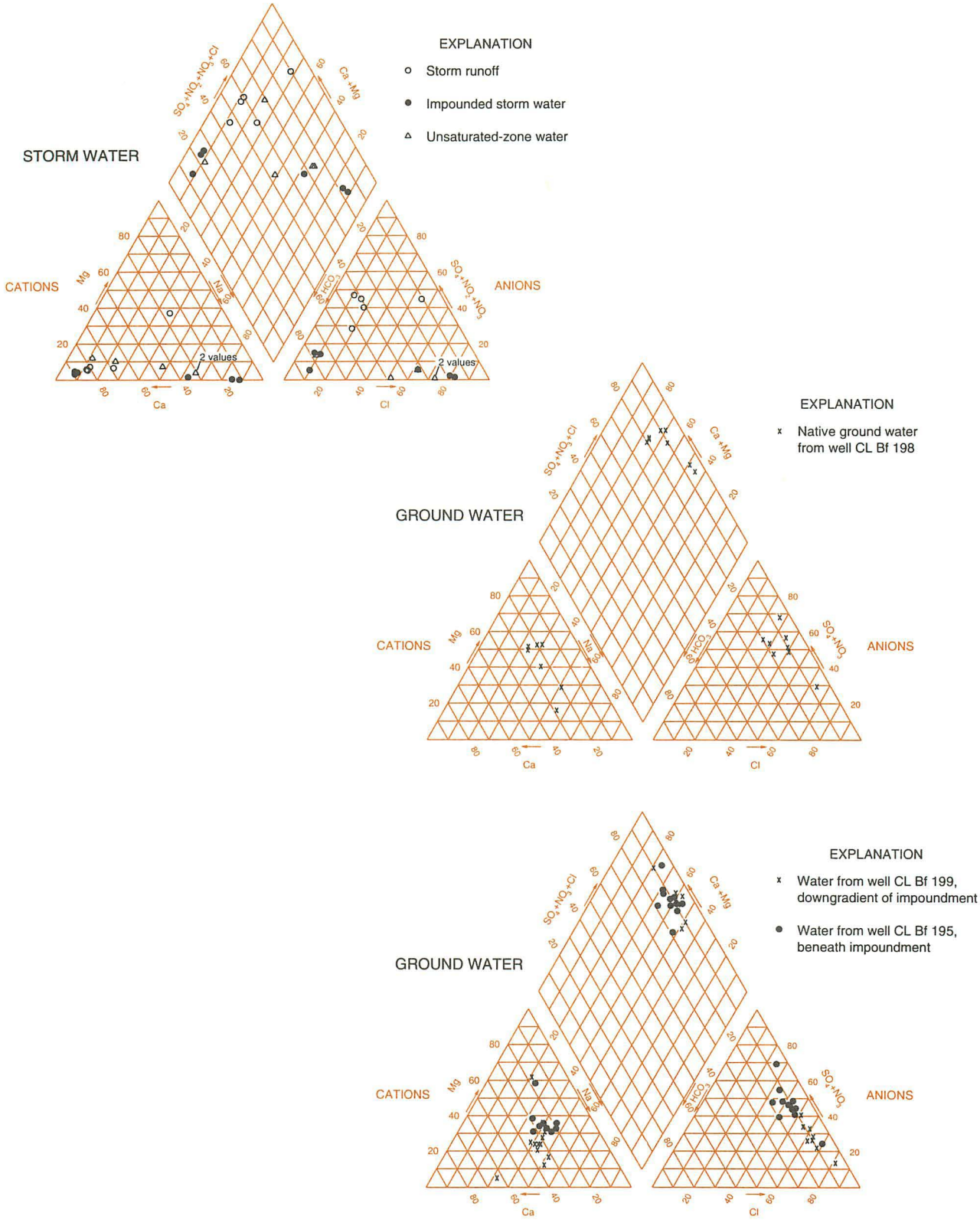


Figure 33.—Percentage of major ions in aqueous solutions at the Greenmount site. (Samples collected each spring, summer/fall, and winter of 1986–87, 1987–88, 1988–89.)

carbonate minerals. Optical analysis of bottom materials from Greenmount confirmed the presence of these mineral phases. Of special interest was the formation of a fine-grained carbonate matrix, indicating that calcium, possibly magnesium, and bicarbonate concentrations in solution were controlled by carbonate precipitation.

Water in the unsaturated zone.—The major-ion composition of water collected from the unsaturated zone beneath the impoundment was similar to the composition of impounded storm water; however, only the first sample, collected in December 1987, plotted as a calcium bicarbonate water type. Subsequent samples, collected in March and September 1988 and in March 1989, were predominantly calcium/sodium chloride solutions (fig. 33).

Unsaturated-zone water had substantially higher concentrations of calcium, sodium, bicarbonate, sulfate, and chloride than did storm water or ground water (table 21). Median concentrations of every major constituent except potassium and nitrate were substantially higher than those in runoff or pond water. Calcium carbonate precipitates at the water-sediment interface in the pond apparently dissociated after burial, causing elevated concentrations of calcium and bicarbonate in unsaturated-zone water.

Major-ion concentrations tended to be greatest in the fall, when the water table was usually more than 5 ft beneath pond bottom and evapotranspiration was high; however, the most elevated concentrations of sodium and chloride were coincidental with deicing activities (Appendixes B and G). The highest chloride concentration recorded in unsaturated-zone water collected from lysimeter CL Bf 201 was 645 mg/L, in April 1989 (Appendix G). Figure 34 indicates that chloride concentrations may be increasing in unsaturated-zone water over time and shows that chloride concentrations commonly exceeded those in storm water during the period of data collection.

Ground water.—Native ground water at the Greenmount site (collected from well CL Bf 198) was a chemically mixed type that plotted toward the magnesium nitrate field with contributions from sodium, calcium, and chloride ions (fig. 33). There was no natural source of nitrogen in formation waters, and the high nitrate concentrations indicated contamination from farming activities. Farming could have been a source of magnesium as well. Nevertheless, this solution composition was typical for ground water reported from nearby wells screened in the Prettyboy Schist aquifer at a similar depth interval and was representative of the background chemistry of ground water at the site. The chloride ion comprised an average 32 percent of major anions in ground-water samples collected at the control well. Background fluctuations of chloride concentration during the year were minor and did not correlate with specific conductance.

The major-anion composition of shallow ground water beneath and downgradient from the pond shifted from a nitrate field toward a chloride field, and downgradient ground water plotted as a chloride type (fig. 33). Ground-water samples collected from well CL Bf 199 plotted as chloride-dominated water: chloride increased from 32 percent (CL Bf 198) to 43 percent

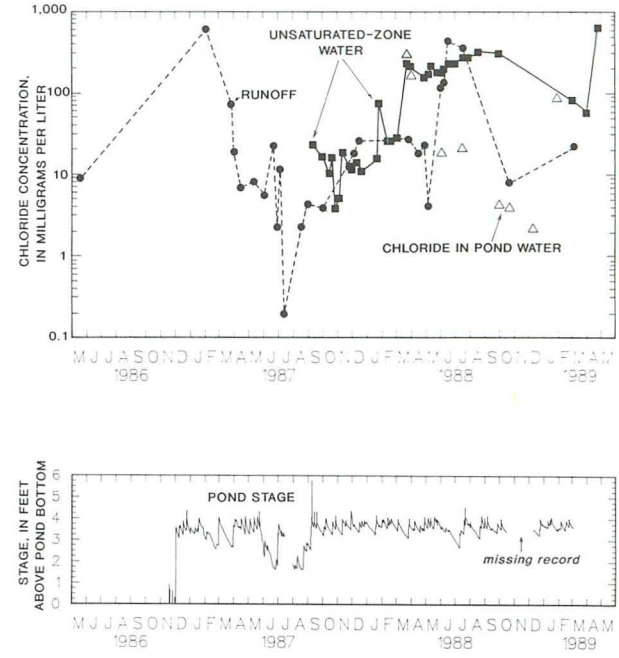


Figure 34.—Chloride concentrations in storm water and unsaturated-zone water, and pond stage at the Greenmount site, May 1986–May 1989. (Data from Appendix G.)

(CL Bf 195) and 57 percent (CL Bf 199) of the major anions (fig. 33). One of the notable characteristics of beneath-pond ground water was the persistence of elevated chloride concentrations throughout the period of study (fig. 35). Chloride concentrations in downgradient ground water were about 4.2 times greater than background during the summer and fall and 2.8 times greater during the winter and early spring.

Cations remained mixed, but ground-water composition shifted from being magnesium-dominated to being sodium-plus-calcium dominated (fig. 33). Na:Ca, Na:Mg, and Na:K ratios increased between upgradient and downgradient ground-water samples, reflecting the input from the dissolution of deicing salts. Calcium also may have been a component of road salt. Potassium concentrations were constant in ground-water samples collected at all wells and were equivalent with concentrations in storm water and unsaturated-zone water.

The Ca:K ratios in ground-water samples increased in the downgradient direction, whereas the Mg:K ratios decreased substantially between beneath-pond and downgradient ground-water samples. Calcium concentrations were considerably higher in storm water compared with background ground water, and even greater concentrations in unsaturated-zone water were probably caused by dissolution of carbonate minerals. Concentrations of magnesium were lower in storm water and in unsaturated-zone water than in ground-water samples collected at the control well. Decreases in downgradient magnesium concentrations might be explained by dilution in the absence of a significant storm-water or aquifer source of magnesium. Nitrate

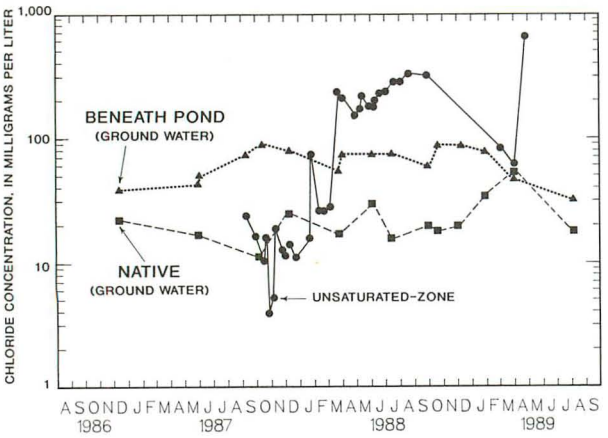


Figure 35.—Chloride concentrations in unsaturated-zone water and ground water at the Greenmount site, December 1986–August 1989. (Data from Appendix G.)

concentrations in ground water also decreased toward the downgradient well, but the $Mg:NO_3$ ratio increased. It is likely that the nitrate-concentration decrease was caused by dilution and that nitrate ions were conserved—that is, were not reactive—compared to magnesium ions; in addition, storm water and unsaturated-zone water provided a larger source of magnesium than of nitrate (table 21). The amount of nitrate contributed by runoff from adjacent farmland is unknown. Storm-water runoff was analyzed only once for nitrate, in mid-May 1986, and the concentration was found to be only 1.5 mg/L. Nevertheless, this nitrate concentration was much greater than any measured in pond water or unsaturated-zone water, and it indicates the rapid movement of storm-water-borne nitrate to ground water. Geographically, runoff to the pond would be expected to provide a significant input of nitrate to ground water. The data indicate that the major source of ground-water nitrate is upgradient from the impoundment.

The trilinear diagram (fig. 33) shows that the composition of ground water beneath and downgradient from the pond is between the composition of upgradient ground water and impounded storm water/unsaturated-zone water. This pattern indicates mixing of the two end members to produce the major-ion composition shown for the beneath-pond and downgradient ground water.

Kaolinite was probably the stable clay phase in the aquifer system: ground water plotted in the kaolinite stability field on clay-stability diagrams (fig. 30) and was saturated with respect to kaolinite (saturation indexes calculated by WATEQF). There was little evidence to demonstrate that ion exchange on clay minerals was an important control on major-cation concentrations in ground water at Greenmount.

Trace elements and organic compounds

Rainwater and storm water.—The trace elements detected in two rainwater samples collected at the Greenmount site were copper, iron, manganese, strontium, and zinc. Arsenic, barium, cadmium, chromium, cobalt, lead, lithium, molybdenum, nickel, and vanadium were not detected in these samples—aluminum and boron were not analyzed in rainwater (table 23). The detection, concentrations, or absence of trace elements in these samples cannot be considered representative of rainwater at the site. One of the samples had an anomalously high pH (5.68). The analytical method for determining concentrations of chromium, lead, molybdenum, and nickel in rainwater samples was less sensitive than methods used for storm water. Nevertheless, the concentrations of detected elements were instructive. A zinc concentration of 190 μg/L in rainwater (fig. 36) was substantially greater than the median of zinc concentrations in storm water (25 μg/L, table 23). Concentrations of copper and iron in rainwater were comparable to median concentrations of these constituents in ground water.

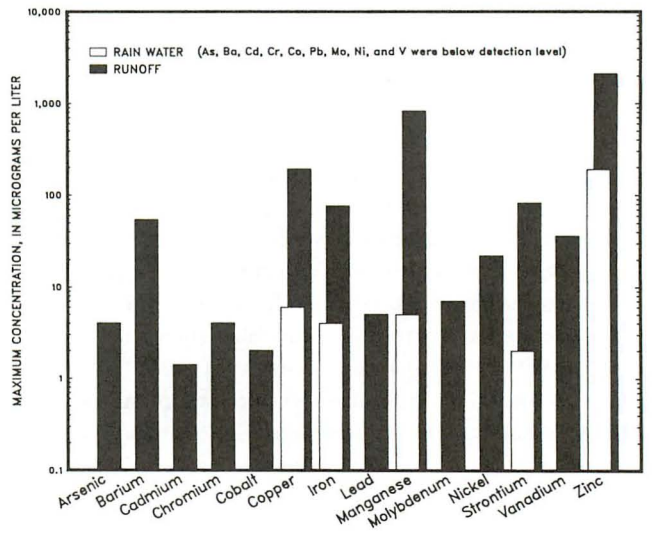


Figure 36.—Concentrations of selected trace elements in rainwater and filtered runoff at the Greenmount site.

Although the trace-element concentration ranges of runoff and impoundment water are easily combined when distinguished from ground water, some notable partitioning characteristics distinguish the components of storm water (fig. 37, Appendix B). The ratio of elements partitioned in the filtered compared with the unfiltered fraction was, in general, greater in runoff than in pond water. Filtered concentrations of arsenic, barium, boron, cadmium, copper, lead, nickel, and zinc were notably diminished in impounded water compared with runoff (boron and barium data are not shown on fig. 37—see Appendix B) (fig. 37). The pattern for the unfiltered fraction is mixed: concentrations of nickel, copper, and zinc decreased in impounded water, but concentrations of cadmium, lead, and chromium increased and arsenic concentration did not change. (No data are available for unfiltered boron, barium, or molybdenum concentrations). Occasional samples of runoff had highly elevated

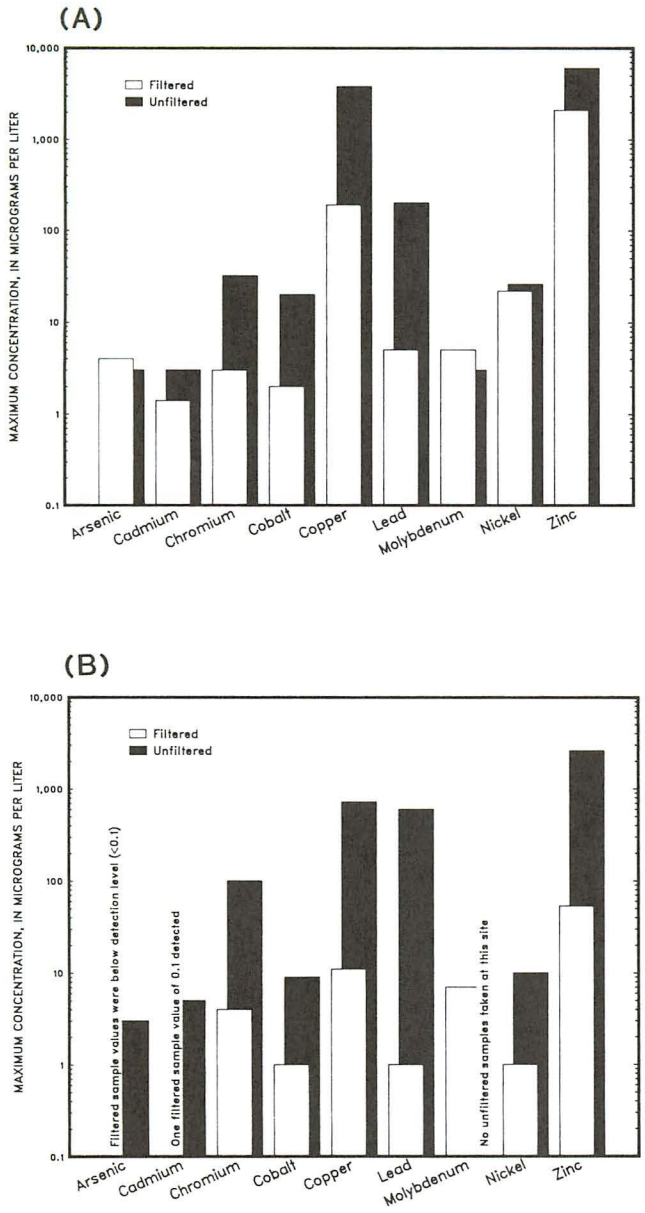


Figure 37.—Comparison of maximum concentrations of trace elements in filtered and unfiltered (A) runoff and (B) pond water at the Greenmount site.

concentrations of copper, lead, and zinc, indicating that high loadings of these metals enter the impoundment and possibly ground water in sporadic slugs. Extremely high concentrations were reported for chromium, copper, lead, and zinc that were associated with the unfiltered or suspended fraction of some pond-water samples (fig. 37); median concentrations were generally low or moderately elevated for these elements. The partitioning to the suspended phase in pond water was reflected in bottom materials by increases in concentrations of chromium, cobalt, lead, nickel, and zinc.

Concentrations of aluminum, iron, manganese, silica, strontium, and vanadium were reported for filtered samples only. The median values for manganese and strontium were nearly equivalent in runoff and pond water (Appendix B), and bottom-material abundance of these elements did not change appreciably. Pond water was depleted in iron and vanadium relative to runoff. The substantial increase of vanadium in bottom materials indicates that it was scavenged effectively by solid phases. Iron probably precipitated as an amorphous solid phase. Aluminum concentrations in pond water exceeded those in runoff because aluminum solubilities increased whenever pond-water pH approached or exceeded 9.0, and the median pH of pond water was 9.21.

Low concentrations of several volatile organic compounds were detected occasionally in storm-water samples, including benzene, trichlorofluoromethane, 1,2-dichloroethane, 1,2-dibromoethylene, and chloroform (Appendix B). Chloroform is likely to have been a laboratory contaminant (Larry Becker, U.S. Geological Survey, oral commun., 1987). The other contaminants were unique to the Greenmount study site and probably entered storm water as a result of site-specific sources, including dry-cleaning, automotive-repair, and meat-packing operations. Storm water was also contaminated with methylene blue active substances (MBAS), but concentrations never exceeded 1.3 mg/L. (The median concentration of dissolved organic carbon in impounded storm water was 7.5 mg/L.)

Water in the unsaturated zone.—Trace elements were analyzed mostly from filtered samples of water collected from the unsaturated zone (table 23, fig. 38A). Concentrations for most trace elements were less than those reported for storm water, including aluminum, boron, cadmium, copper, iron, vanadium, and zinc (table 23). This pattern contrasts with that of the major ions; even major ions with conservative characteristics (chloride and sulfate) were elevated in unsaturated-zone water with respect to storm water, demonstrating that constituent mobility through the unsaturated zone is impeded. Trace-element constituents could have been sequestered by solid phases in the unsaturated zone, and solution concentrations could have been lowered by this mechanism. On the other hand, movement of these constituents through the unsaturated zone may have been unimpeded but may have been undetected because of sample frequency. Barium concentrations were similar in storm and unsaturated-zone water.

Chromium, cobalt, manganese, and strontium concentrations in samples of unsaturated-zone water exceeded storm-water concentrations considerably. Native saprolite appeared to be a source of chromium and cobalt. Elevated concentrations of particulate chromium in native ground water (unfiltered) were approximately equivalent to concentrations of dissolved chromium in unsaturated-zone water (filtered) (table 23). Particulate chromium in some storm-water samples was found at much higher concentrations, however, and thus the impoundment also was a potential source of chromium. Storm water was not a source of cobalt, and equivalent cobalt concentrations were reported for unsaturated-zone water and native ground water; chromium and cobalt were depleted in beneath-pond and downgradient ground water.

Strontium concentrations in samples of unsaturated-zone water were more than three times greater than those in storm

Table 23.—Summary concentrations of selected trace constituents in rainwater, storm water, water from the unsaturated zone, and ground water at the Greenmount site

[Values in micrograms per liter (µg/L), unless otherwise indicated; mg/L, milligrams per liter; f, filtered sample (samples passed through a 0.1-micrometer filter); u, unfiltered sample[1]; <, below detection[2]; --, no data; MBAS, methylene blue active substances]

Chemical[3] constituent		Rainwater	Storm water[4]		Ground water						Unsaturated-zone water	
					Upgradient		Beneath pond		Downgradient[5]			
			Median	Maximum	Median	Maximum	Median	Maximum	Median	Maximum	Median	Maximum
Aluminum	(f)	--	80	190	10	100	20	50	45	160	--	20
Arsenic	(f)	--	<1	4	<1	<1	<1	6	<1	<1	--	<1
	(u)	<1	1	3	<1	1	<1	2	<1	<1	--	--
Barium	(f)	<2	12	54	--	47	57	100	61	100	28	46
	(u)	--	<100	300	--	--	<100	100	--	100	--	--
Boron	(f)	--	20	170	<10	10	<10	40	<10	10	--	<10
Cadmium	(f)	<1	<1	1.4	.6	2	2	16	.55	1	<.1	1
	(u)	<1	1	5	<1	2	1	26	<1	<1	--	--
Chromium	(f)	<5	<.5	4	1.1	<.5	<.5	1	<.5	2	6	25
	(u)	<1	6	100	2	30	9	22	8	20	--	1
Cobalt	(f)	<3	1	2	17	28	<.5	1	2.1	5.6	9	33
	(u)	<1	4	20	34	52	<1	2	4	10	--	--
Copper	(f)	<10	11	190	5	45	8.5	56	6.5	16	<10	24
	(u)	6	36	3,800	33	100	13.5	24	17.5	50	--	9
Iron	(f)	4	20	76	8.5	10	<10	60	4	26	7	9
Lead	(f)	<10	1	5	--	1.3	4.9	6.7	<5	2.6	<10	<10
	(u)	<5	18	600	14	33	<5	73	<5	10	--	<5
Lithium	(f)	<4	--	<4	7	8	<4	8	4.5	15	4	14
Manganese	(f)	5	67	820	280	620	49.5	190	86	220	13,000	37,000
Molybdenum	(f)	<10	1	7	1	2	1	10	<1	4	<1	<10
	(u)	--	--	3	--	6	1	8	1	5	--	--
Nickel	(f)	<10	4	22	20	28	7	12	5	8	<10	10
	(u)	<1	9.5	26	33.5	52	9	15	8	12	--	--

Table 23.—Summary concentrations of selected trace constituents in rainwater, storm water, water from the unsaturated zone, and ground water at the Greenmount site—Continued

Chemical[3] constituent	Rainwater	Storm water[4]		Ground water						Unsaturated-zone water	
				Upgradient		Beneath pond		Downgradient[5]			
		Median	Maximum	Median	Maximum	Median	Maximum	Median	Maximum	Median	Maximum
Strontium (f)	2	42	82	40	50	48.5	58	53	100	140	370
Vanadium (f)	<6	5	36	<1	<6	<1	13	<1	2	<6	<6
Zinc (f)	190	25	2,100	46	60	48.5	650	27	92	20	35
(u)	<10	590	6,000	105	160	80	1,300	35	110	--	20
Organic compounds[5] (µg/L)											
MBAS (mg/L)	--	0.42	1.3	0.09	0.14	0.09	1.3	0.08	0.11	0.16	0.34
Benzene	--	.2	.6	<.2	<.2	<.2	.4	<.2	<.2	--	--
Toluene	--	<.2	<.2	<.2	.2	<.2	.6	<.2	.8	--	--
Trichlorofluoromethane[4]	--	<.2	.4	<.2	<.2	<.2	<.2	<.2	<.2	--	--
1,2-Dichloroethane	--	<.2	.6	<.2	<.2	<.2	<.2	<.2	<.2	--	--
Chloroform	--	<.2	.5	<.2	<.2	<.2	<.2	<.2	<.2	--	--
1,2-Dibromoethylene	--	<.2	.5	<.2	<.2	<.2	<.2	<.2	<.2	--	--
1,2-Transdichloroethene	--	<.2	.5	<.2	<.2	<.2	<.2	<.2	<.2	--	--

[1] Concentrations of constituent for filtered samples may exceed those shown for unfiltered samples because filtered samples were collected more frequently than unfiltered samples.

[2] Value shown as below detection is the reporting limit set by the USGS National Water Quality Laboratory; detection/reporting limits depend upon the analytical methods requested, which varied as appropriate according to initial screening of constituent concentrations in the water source.

[3] See Appendix B for a comprehensive table of laboratory analyses.

[4] Data shown are for runoff and impounded storm water.

[5] The data shown are for samples collected from CL Bf 199. Concentrations of trichlorofluoromethene of 0.6 and 0.7 µg/L were found in samples collected from well CL Bf 200, which is next to CL Bf 199 but screened 60 ft deeper.

[6] The following compounds were found in ground-water samples upgradient: tetrachloroethylene; 1,1-dichloroethylene; 1,1,1-trichloroethane; and trichloroethylene. Although these contaminants were found at low concentrations in ground water beneath the pond and downgradient from the pond, they are not included in the table because the major source of contamination was from an upgradient source and not from storm water.

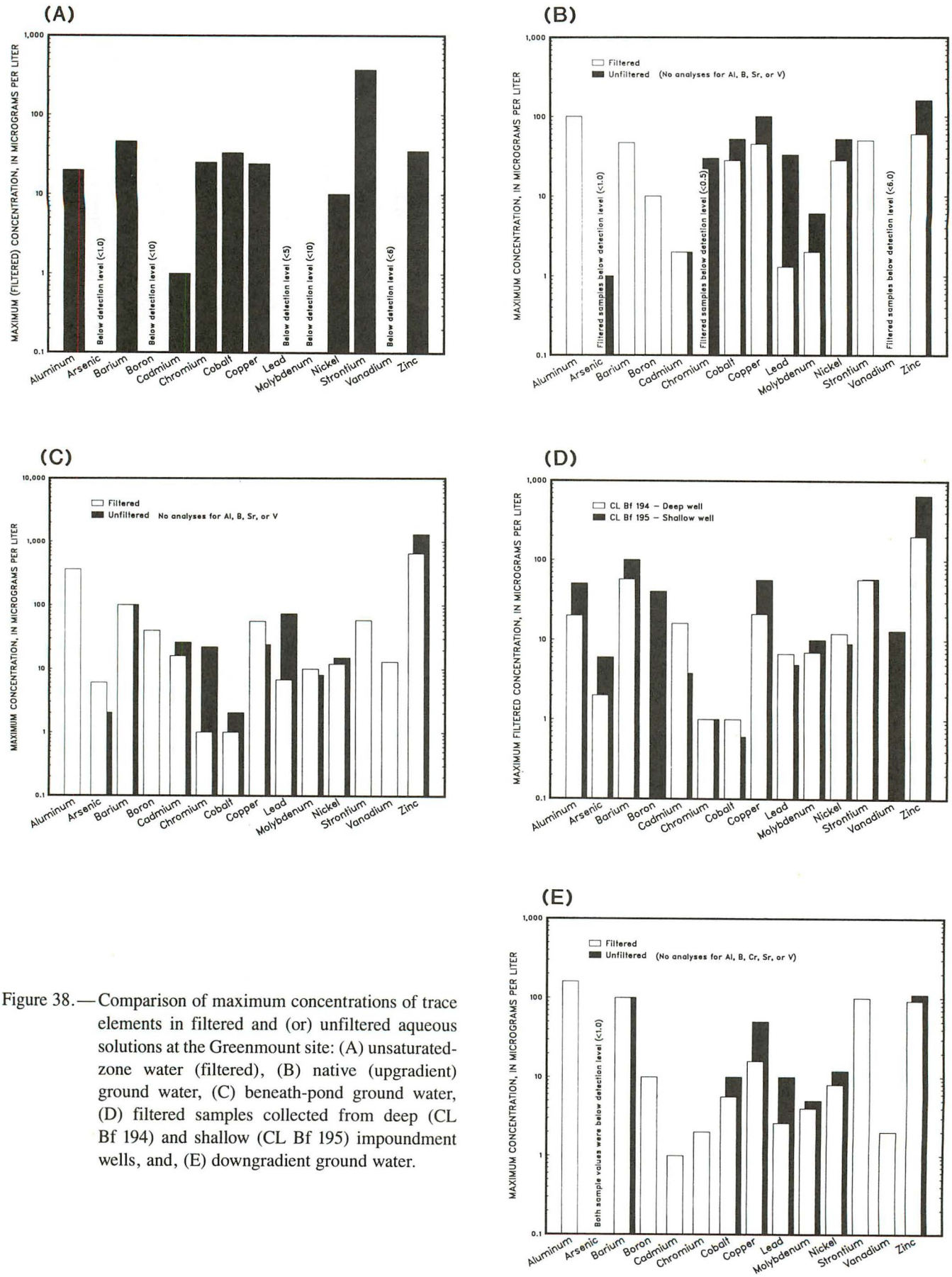


Figure 38.—Comparison of maximum concentrations of trace elements in filtered and (or) unfiltered aqueous solutions at the Greenmount site: (A) unsaturated-zone water (filtered), (B) native (upgradient) ground water, (C) beneath-pond ground water, (D) filtered samples collected from deep (CL Bf 194) and shallow (CL Bf 195) impoundment wells, and, (E) downgradient ground water.

water, following a pattern similar to calcium concentrations. Substitution of strontium for calcium and vice versa is common in carbonate minerals (aragonite), although the strontium ion is larger (Deer and others, 1978). Carbonate precipitation in the surface sediments was likely reversed with shallow burial: as carbon dioxide pressures increased, pH decreased, which possibly resulted in a downward flux of calcium, strontium, and bicarbonate. Precipitation and dissolution can occur repeatedly in the unsaturated zone. The processes controlling trace-element concentrations in unsaturated-zone water are not well understood and require further study.

Manganese concentrations in water from the unsaturated zone was nearly 200 times the concentrations reported in storm water. Native materials apparently have a large enough reservoir of ambient manganese to account for manganese concentrations in native ground water that were as high as 0.62 mg/L and had a median value of 0.28 mg/L in samples collected at the control well (table 23). Manganese concentrations in storm water which were as high as 0.82 mg/L (the median value was 0.067 mg/L), probably were controlled by mineral precipitation in pond water because the median pond pH was greater than 9.0. The median concentration of manganese recorded in unsaturated-zone water was 13 mg/L, however, and is difficult to reconcile with the known sources. Manganese precipitation from pond water at high pH could be a source of manganese that would undergo microbially-catalyzed dissolution at the lower pH of unsaturated-zone water. Manganese concentrations were not elevated in underlying ground water, and the geochemical and (or) biochemical controls on manganese concentrations in unsaturated-zone water at this site is not understood.

Hem (1963, 1985) states that manganese concentrations on the order of 1.0 mg/L are stable in oxygenated water, as long as the pH is not high (pH less than 7.8). It appears from stability diagrams that manganese concentrations of 100 mg/L are stable at a pH of around 5.7 (Hem, 1963). The pH of unsaturated-zone water would have had to have been at least 0.5 units lower than was measured to conform to the equilibrium predictions. Manganese dissolution could have been catalyzed by the presence of anaerobic bacteria in the reducing environment of the shallow unsaturated zone. Aerobic bacteria, such as *Hyphomicrobium,* in the deeper, oxygenated parts of the unsaturated zone and the water-table aquifer could catalyze the formation of manganese precipitates.

Ground water.—All of the trace elements that were reported in storm water and unsaturated-zone water were present in ground water that mixed with storm-water infiltrate. Concentrations for some trace elements, however, were also high in ground-water samples collected at the control well. For this reason, storm-water infiltrate could not be regarded as an important source of cobalt, lithium, manganese, nickel, and possibly strontium to ground water.

Trace constituents detected in ground-water samples collected at the upgradient well (CL Bf 198) could have been from several sources: ambient aquifer minerals, precipitation, and anthropogenic contaminants including commercial and agricultural substances. Cobalt, nickel, and lithium concentrations were consistent in upgradient ground-water samples, and the abundances of these constituents in ground water were attributed to ambient sources. Concentrations of particulate chromium, dissolved and particulate copper, and dissolved iron and manganese in upgradient ground-water samples fluctuated considerably, and the major sources for these constituents could have been anthropogenic.

Unsaturated-zone water had concentrations of filtered chromium, manganese, and strontium that substantially exceeded concentrations measured in samples collected of storm water and upgradient ground water. Unsaturated-zone processes beneath the impoundment appeared to mitigate transport of chromium and manganese to underlying ground water. Cadmium and strontium concentrations were substantially elevated in ground water beneath the impoundment. The effects on concentrations of other inorganic constituents were unclear. The data indicate that, at the Greenmount impoundment, complex geochemical and biochemical reactions in the unsaturated zone enhance or mitigate the transport of storm-water-borne constituents to ground water. Nevertheless, storm-water infiltrate was the major source of elevated arsenic, boron, cadmium, chromium, lead, molybdenum, vanadium, and zinc concentrations in beneath-pond and (or) downgradient ground water.

Differences in trace-element partitioning between upgradient and beneath-pond or downgradient ground water were few, and trace constituents were primarily present in the dissolved phase (fig. 38). Arsenic was detected in samples of unfiltered upgradient water only (fig. 38B), whereas the arsenic in beneath-pond water was detected in filtered samples as well (no arsenic was detected downgradient) (fig. 38C). Chromium may follow a similar pattern, but the data are sparse or nonexistent for unfiltered beneath-pond and downgradient ground water, and chromium was detected on only two occasions in downgradient samples (fig. 38E). Beneath-pond ground-water samples had higher dissolved concentrations relative to particulate concentrations of copper and lead than samples of upgradient ground water (fig. 38B, 38C).

Ground water beneath the pond had concentrations of aluminum, arsenic, boron, cadmium, lead, molybdenum, strontium, vanadium, zinc, and possibly barium and copper that were elevated in some samples compared with upgradient ground water (fig. 38B, 38C). The median concentrations of aluminum, cadmium, lead, copper, strontium, and zinc were elevated in beneath-pond ground-water samples compared to background; very high maximum concentrations were reported for aluminum, cadmium, lead, molybdenum, vanadium, and zinc. Beneath-pond ground-water samples from CL Bf 194 were collected 40 ft deeper than samples collected at the water-table surface from CL Bf 195. Mixing of the deeper ground water with upgradient ground water is shown by concentrations of cobalt, lithium, nickel, dissolved oxygen, and pH that were higher in CL Bf 194 than in the shallow ground water (CL Bf 195) (fig. 38D). Cadmium and lead concentrations in some deeper water samples exceeded concentrations in samples from near the water table, however (fig. 38D, Appendix B). Deeper ground water also had elevated concentrations of dissolved aluminum,

arsenic, molybdenum, strontium, vanadium, and zinc compared to background.

Concentrations in downgradient water were elevated for aluminum, barium, strontium, and possibly molybdenum and zinc, and median values of aluminum, barium, and strontium increased in comparison with concentrations in background and beneath-pond ground water (fig. 38E). Concentrations of most other constituents in downgradient ground water showed a pattern similar to those in upgradient ground water: arsenic, boron, cadmium, and vanadium were less concentrated, and cobalt, lithium, and manganese were more concentrated in downgradient and upgradient samples than in beneath-pond groundwater samples (fig. 38; table 23).

An increase or decrease in the abundance of contaminant elements in beneath-pond and downgradient ground water, compared with background, could not be circumstantially attributed to hydraulic transport of constituents in storm infiltrate and subsequent mixing. The factors controlling contaminant concentrations and mobility are examined in the section, "Factors Affecting Ground-Water Quality at the Study Sites." It is relevant, however, to consider some site-specific characteristics that might have affected trace-element concentrations in ground water at the Greenmount site.

Dilution at the downgradient well came, in part, from direct infiltration of precipitation. Water-level hydrographs did not substantiate an upward component of flow between downgradient wells CL Bf 199 and 200, so ground water from depth is not hypothesized to be a source of dilution; however, there may have been some contribution of native ground water from the east and from preferential flow channels through the saprolite. The dilution hypothesis does not explain the increase in aluminum, barium, and strontium, nor the downgradient trend toward a sodium chloride-type water. The downgradient increase in these constituents was accompanied by a marked depletion in copper, iron, lead, and possibly zinc with respect to upgradient and beneath-pond ground water. These data indicate that chemical processes were actively mediating the chemical composition of ground water.

Ground water was supersaturated with respect to iron oxide and was in equilibrium with kaolinite and amorphous silica; iron hydroxide precipitation is likely to have been accompanied by coprecipitation with other metals or sorption of metals. The tendency for lower pH values in downgradient water also could have been a result of hydroxide precipitation as follows:

$$\underset{\text{[almandine garnet]}}{Fe_3Al_2Si_3O_{12}} + 3H_2O \rightleftarrows \underset{\text{[iron hydroxide]}}{3FeOOH} + \underset{\text{[kaolinite]}}{Al_2[Si_2O_5](OH)_2} + \underset{\text{[silica]}}{SiO_2} + H^+,$$

thus, weathering of garnet in oxygenated solutions forms iron hydroxide, kaolinite, and amorphous silica phases, and an increase in acidity.

The lowering of ground-water pH to 5.0 beneath the pond and to 4.9 downgradient could have caused some increase in aluminum concentrations. Dissolution of aluminum solids increases slightly around pH 5 but increases exponentially in a pH of 4.9 and below and also at pH greater than 9.0. This results in increased concentrations of aluminum in the aqueous phase. Although dissolution kinetics are rapid for alumina minerals, precipitation is apparently a slower process (Hem, 1963), and this difference in reaction rates can result in elevated aluminum concentrations in solution. Storm-water infiltrate, enriched in aluminum, was a probable source of elevated concentrations in ground water.

The source of barium is less definable because barium data were sparse for native saprolite and upgradient ground water. The sole upgradient ground-water sample had a relatively low concentration (47 μg/L), but this value corresponded with the highest concentration reported for unsaturated-zone water (46 μg/L). Solid-phase data, however, showed that barium was being leached from bottom materials. In addition, barium concentrations occasionally were elevated substantially in storm water. Strontium concentrations were almost three times greater in unsaturated-zone water than in any other aqueous phase at the site; thus, unsaturated-zone water could have been the source of elevated strontium concentrations in beneath-pond and downgradient ground water.

Anthropogenic organic compounds that entered the subsurface hydrologic system in storm water included methylene blue active substances, benzene, and toluene. These compounds were not ubiquitous, but were detected in a few beneath-pond and (or) downgradient ground-water samples. Dissolved organic carbon (DOC) concentrations were consistently higher in samples of ground water collected beneath and downgradient from the pond compared to background DOC concentrations, reflecting elevated carbon concentrations in pond water.

Recapitulation of Greenmount Site Characteristics and Water Quality

The Greenmount storm-water management structure (fig. 23) was constructed in unconsolidated saprolite that overlies parent rock from the Prettyboy Schist. The depth to water table beneath the storm-water pond ranged from 2.5 to 10 ft. The average hydraulic gradient of the water-table surface from the control well to the downgradient end of the impoundment was 0.1 percent, but steepened beneath the pond to 2 percent. During periods of high rainfall, however, transient mounding in the water table caused a decrease or temporary reverse of hydraulic gradient. The rate of ground-water flow leaving the pond was not measured; estimates from the literature and from observation of the rate of movement of chloride entering the impoundment with runoff indicate rapid horizontal movement of 60 ft/d.

The percentage of silt- and clay-size particles in the bottom materials increased each year between 1986 and 1988 (fig. 39A). The cation-exchange capacity of the materials increased from 2.6 to 35 ppm during the same period. Calcium and magnesium concentrations in the bottom materials increased each year, while silica and sodium concentrations decreased (fig.

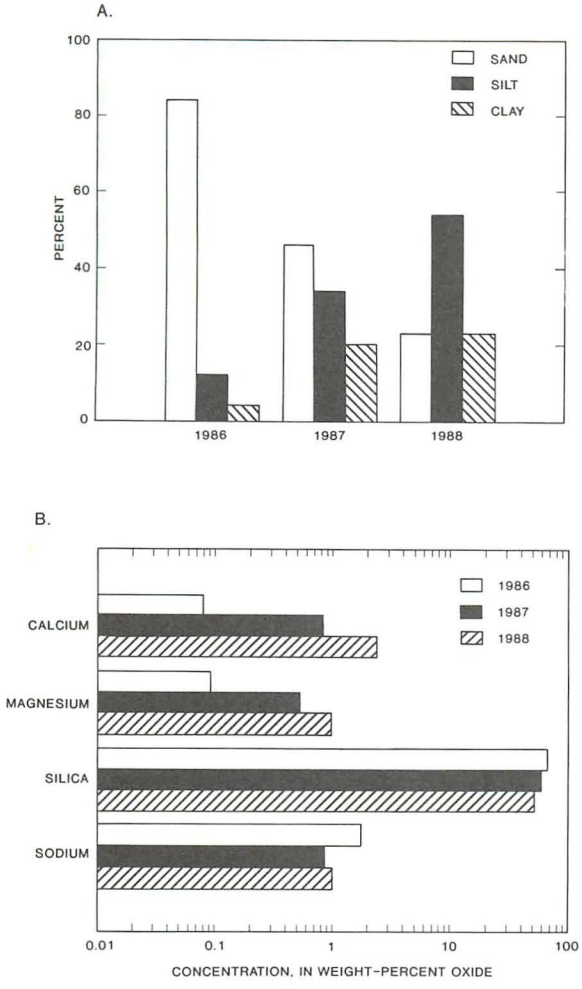


Figure 39.—Changes in pond-bottom materials at the Greenmount site for 1986–1988: (A) particle-size distribution, and (B) concentrations of calcium, magnesium, silica, and sodium.

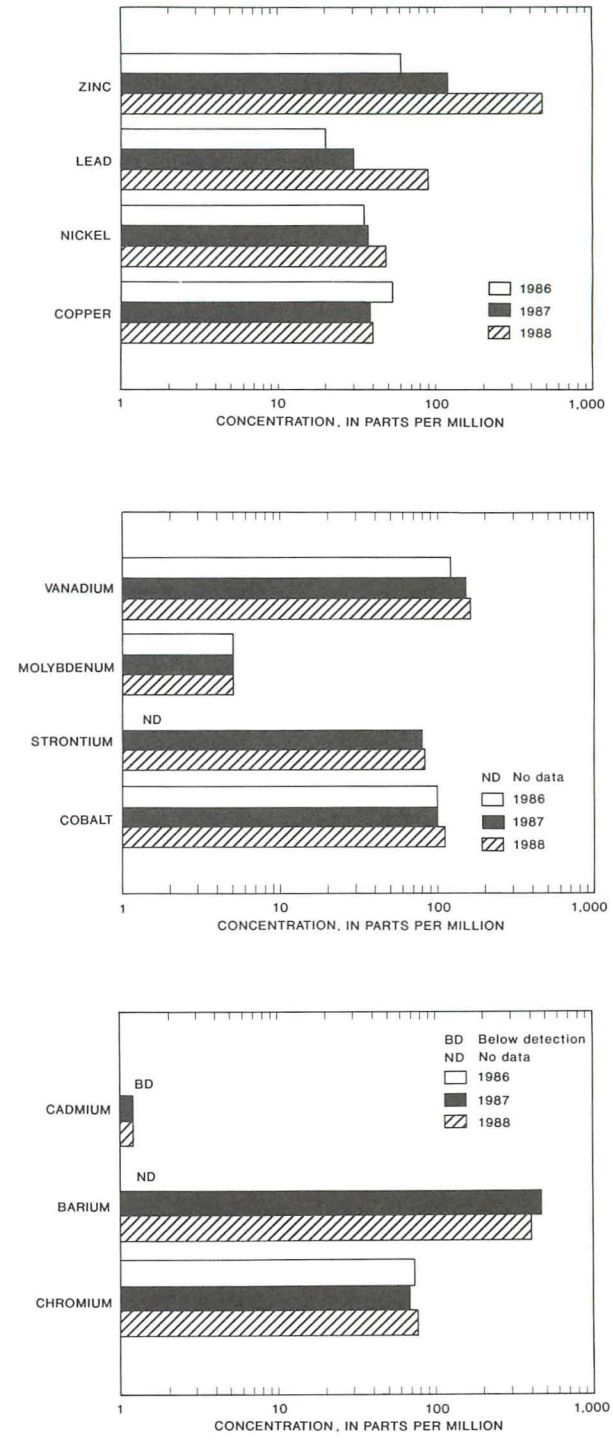


Figure 40.—Concentrations of heavy metals in Greenmount pond-bottom materials.

39B). Concentrations of lead, nickel, vanadium, and zinc in bottom materials increased appreciably, whereas concentrations of cadmium, chromium, cobalt, and strontium increased slightly during 1986–89 (fig. 40).

Certain effects of storm-water-infiltration practices on ground-water quality beneath and downgradient from the impoundment were persistent and showed no amelioration throughout the 3-year period of data collection: dissolved solids (estimated from specific-conductance measurements), chloride, and sodium concentrations were substantially elevated; pH values were consistently lower by about a tenth of a unit; and dissolved-oxygen concentrations decreased substantially.

Chloride was the simplest storm-water contaminant to trace to underlying ground water; deicing salt was the major source of chloride in runoff to the impoundment, and storm-water infiltration was the major source of elevated chloride concentrations to ground water. Specific conductance correlated highly with chloride in ground water and storm water. Chloride concentrations were substantially elevated in ground water receiving storm-water infiltrate, with chloride constituting 57 percent of major anions at the downgradient well compared with 32 percent in ambient ground water at the site (fig. 41).

The USEPA SMCL of 250 mg/L for chloride was exceeded in storm water whenever deicing salts were applied. In addition,

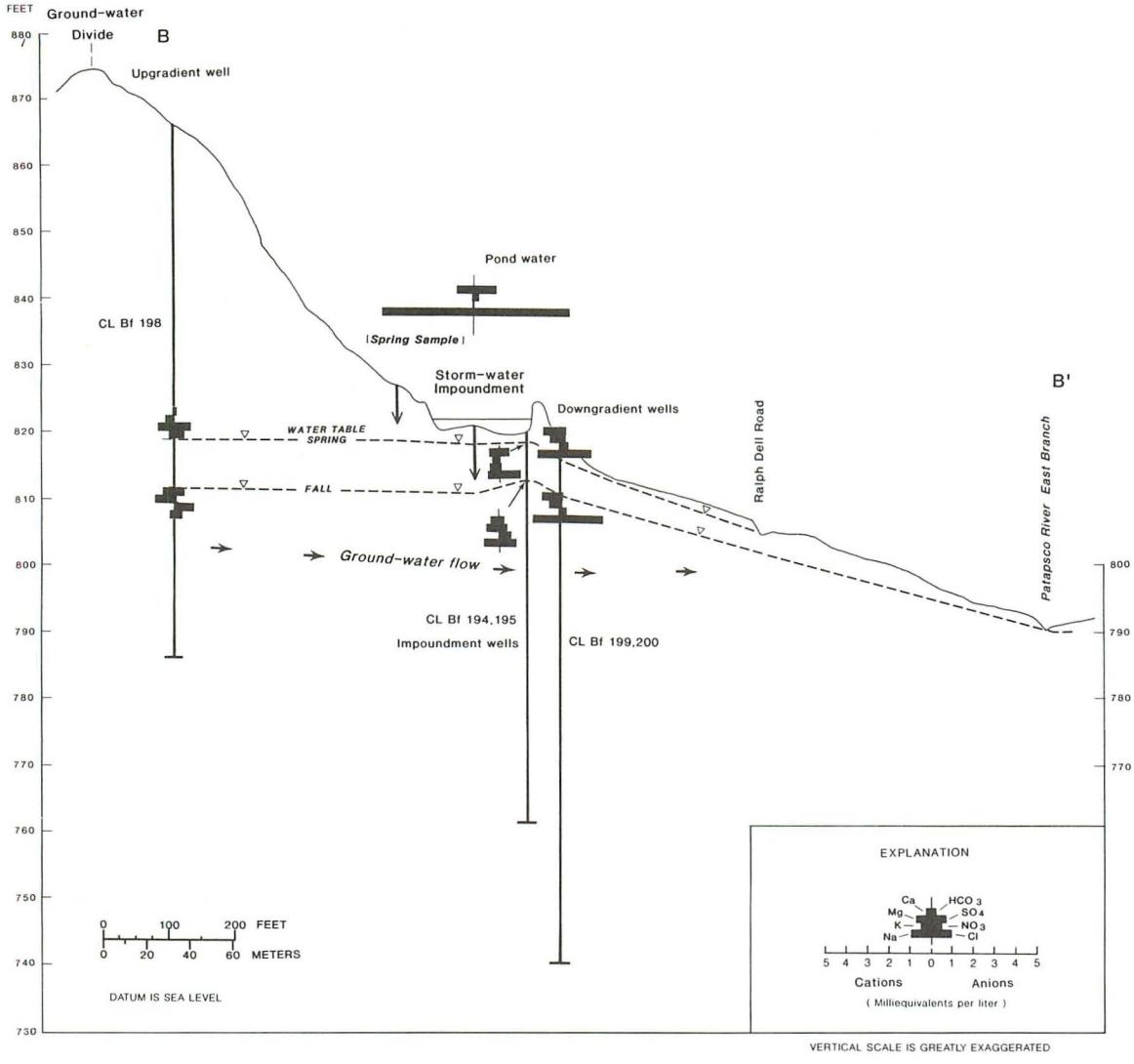


Figure 41.—Hydrogeologic section from upgradient (control) well to downgradient wells at the Greenmount site and showing the major-ion chemistry of ground water with respect to seasonal high and low water table. (Refer to line of section B-B′ in Fig. 23.)

chloride concentrations in unsaturated-zone water exceeded the SMCL and tended to build to higher concentrations in the unsaturated zone than were measured in storm water. Although the SMCL for chloride was never exceeded in ground-water samples, chloride concentrations were considerably elevated compared to background throughout the period of data collection. The highest chloride concentrations in ground water tended to occur in the late summer or early fall, during periods of high evapotranspiration. Elevated chloride concentrations during winter and early spring deicing episodes were somewhat muted by the volume of seasonal recharge. The high rate of ground-water flow helped mitigate chloride concentrations in ground water beneath and downgradient from the impoundment.

Nitrate contamination was caused by farming activities and was ubiquitous in upgradient as well as downgradient ground water. Nitrate concentrations regularly exceeded the USEPA MCL of 10 mg/L as nitrogen (table 21). Nitrate concentrations were generally lower in beneath-pond and downgradient ground water than in upgradient ground water, because of dilution by storm-water infiltrate.

Concentrations of inorganic and organic contaminants that entered the hydrogeologic system in runoff at the Greenmount site fluctuated considerably, resulting in fluctuating contaminant concentrations in ground water. Storm-water and ground-water concentrations of inorganic constituents periodically exceeded the MCL or SMCL for drinking water. Concentrations for some volatile organic compounds in ground water exceeded USEPA regulations; however, these compounds were introduced from an upgradient source and were not a result of storm-water infiltration. The data were insufficient to determine whether contaminant concentrations are increasing or will be detected with greater frequency over time.

Concentrations of aluminum, chromium, copper, lead, manganese, and zinc exceeded USEPA MCL's and SMCL's in some storm-water samples and generally were ubiquitous or present at high concentrations. Storm-water concentrations of barium, cadmium, and vanadium did not exceed MCL's or SMCL's, but their presence was ubiquitous. The potential for these contaminants to build to unacceptable levels in bottom materials and potentially remobilize as aqueous species is a credible concern. Indirect mechanisms also accounted for mobilization of ambient constituents. For example, dissolved aluminum in pond water periodically exceeded the SMCL; this was not related to input from runoff but to biochemical processes within the impoundment that increased pH sufficiently to cause aluminum mobilization.

Storm-water infiltrate was a source of aluminum, cadmium, and lead to ground water, and concentrations of these elements occasionally exceeded the USEPA MCL or SMCL; cadmium concentrations in downgradient ground-water samples did not exceed the MCL. In addition, ground-water samples collected from the impoundment or downgradient wells had elevated concentrations of arsenic, boron, copper, molybdenum, strontium, vanadium, zinc, and possibly barium and chromium, for which storm-water infiltration was the probable source (fig. 42).

Some ground-water samples collected from beneath-impoundment wells had cadmium concentrations that exceeded the MCL of 5 μg/L (fig. 42). Cadmium concentrations exceeding the MCL were not measured in the storm-water samples collected, but there appears to be no other source of aqueous or mineral-bound cadmium to ground water. Cadmium either entered the site in high concentrations at times when storm water was not being sampled, or low cadmium concentrations in storm water continually entered the infiltration system, resulting in a buildup of higher cadmium concentrations in ground water. (Mechanisms governing cadmium mobility are discussed in the section, "Factors Affecting Ground-Water Quality at the Study Sites.")

PRINCE FREDERICK SITE

The Route 231 Park-and-Ride lot in Prince Frederick, Calvert County, is located near the intersection of Maryland State Route 231 and a major highway (State Route 2/4) that bisects the county and leads northward toward Annapolis, Washington D.C., and Baltimore. The area is being developed rapidly because of the great demand for suburban housing by commuters to Washington; consequently, the volume of commuter traffic is large. The Park-and-Ride was constructed to alleviate traffic congestion. It ordinarily is filled to capacity during the week with cars and small trucks and is used for overflow traffic on weekends by St. Christopher's Church, located on the southeastern or upgradient side of the site (fig. 43).

The study site lies within the Mill Creek drainage basin and is just east of Maryland State Route 2/4 and approximately 700 ft east of major storm channels that discharge to Mill Creek. Mill Creek flows westward and empties into the Patuxent River, which eventually discharges to Chesapeake Bay. The land surrounding the Park-and-Ride is mostly paved on three sides. At its northwestern edge, the site is grassed and drops to a topographic low. The terrain between the study site and Mill Creek is wooded and hummocky, and it is improbable that the noninfiltrating portion of storm water that discharges from the impoundment to an adjacent riprap channel ever reaches Mill Creek. The total drainage area of the Park-and-Ride facility is 0.76 acre, 0.54 acre of which is perviously paved. Runoff from 0.13 acre of impervious surfaces constitutes 17 percent of the storm water entering the site.

The storm-water impoundment at the Prince Frederick study site is beneath the Park-and-Ride lot and had been used for about 1½ years before the start of this study (fig. 43B). The subsurface impoundment was constructed in Upland deposits sediments, is approximately 3 ft deep, and was filled with 2-in.-diameter rock course (figs. 3 and 43B). The impoundment was filled with rocks from the Hunting Hill Quarry near Rockville, Md., and was surfaced with 2 to 6 in. of porous-asphalt pavement. Fill material was used to level the site as the parking lot was built. The fill material consisted of native Upland deposits, excavated from a nearby lot. The thickness of the fill increases from 3 ft on

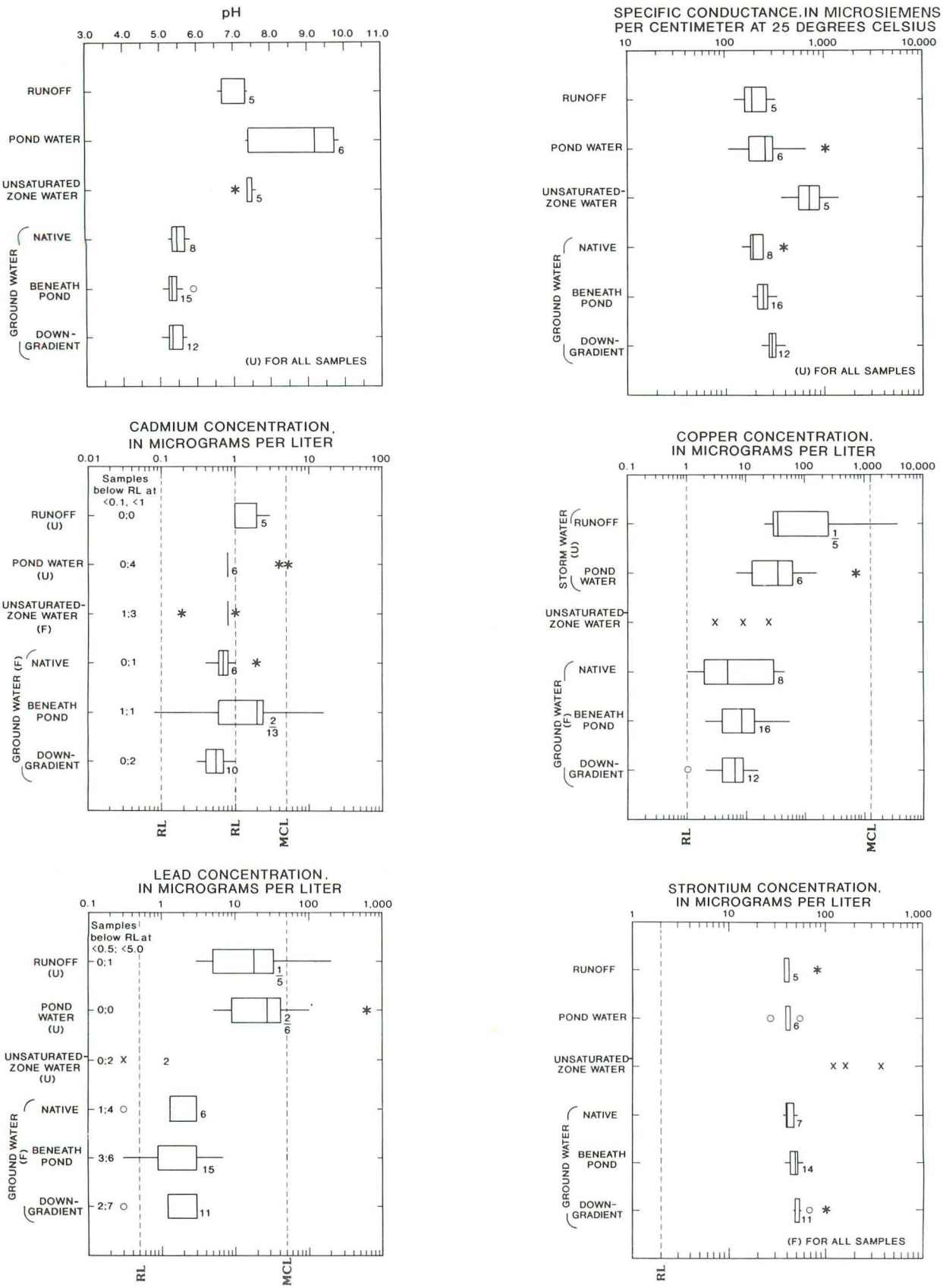
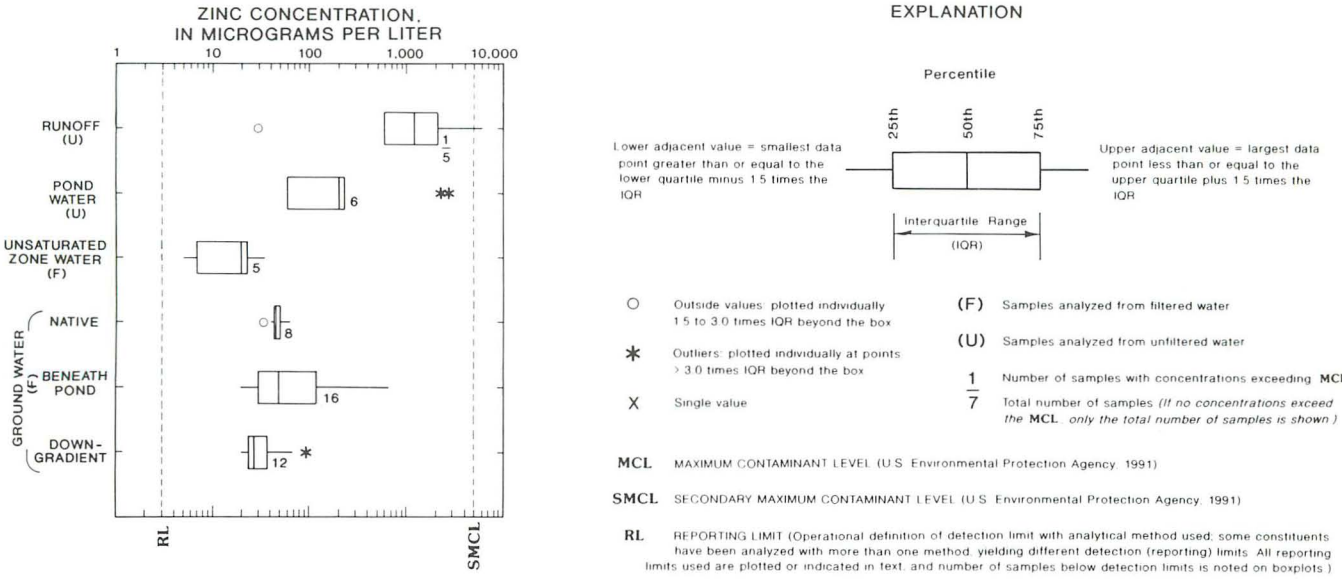


Figure 42.—Summary of pH, specific conductance, and aqueous concentrations of selected trace metals at the Greenmount site.



the southern and eastern sides to almost 10 ft near the western corner of the site.

The porous pavement structure deviated from State specifications in several respects. Instead of being completely level, the structure was built on a 2-percent grade that sloped toward the northern corner. Specifications advise no outlet from the impoundment; however, a 12-in. section of 2-in.-diameter pipe allowed external drainage of some of the impounded storm water to the riprap channel at the northern corner. Moreover, no percolation tests were run to determine suitability of the site for infiltration. Nevertheless, this was one of the few porous-pavement sites existing at the time of site selection that allowed some portion of the impounded storm water to percolate through the impoundment into the unsaturated zone. Storm water at the site consists of the precipitation (including snow) that falls directly on the parking lot and of runoff from Maryland State Route 231. The storm water percolates directly through the porous pavement to the subsurface impoundment.

Site Instrumentation and Hydrologic System

Instrumentation

The site map and site photograph (fig. 43) shows the location of data-collection stations. A double-notched weir plate was installed about 5 ft downstream from the point of storm-water discharge from the impoundment, and an ADR was installed on a standpipe at the weir plate to record stage. The amount of storm water discharging from the impoundment was determined to quantify the amount of noninfiltrating storm water. The rainwater sample collector and Belfort rain gage were housed with an Isco automatic sampler that collected samples of the discharging storm water. Samples of storm water were also withdrawn from a well-like porous-pavement percolate collector (CA Db 85) in the center of the parking lot that was screened in the rock aggregate (fig. 43B). The impoundment water collected in a Teflon vessel that extended beneath the screen. A Teflon suction lysimeter (CA Db 84) was installed in the unsaturated zone beneath the porous pavement at the northern corner of the study site.

Ten wells and nine piezometers were installed at this site during the summer of 1986 (fig. 43A and table 24). Nine of the wells were installed in clusters of three; two of which were screened at different depth intervals and monitored for water quality, and one of which was instrumented to record water-table levels. Wells CA Db 65, 66, and 67 were upgradient from the porous-pavement impoundment, near the church; wells CA Db 68, 69, and 70 were downgradient from the parking lot, and wells CA Db 71 and 72 were in the center of the parking lot. The water-quality monitoring wells—CA Db 66-67, 69-70, and 72-73—were screened at overlapping depth intervals to intersect the water-table surface during seasonal high and low levels. The nine piezometers were located to define the direction of ground-water flow beneath the site. ADR's were installed in wells CA Db 65, 68, and 71 and were operated throughout the period of data collection. A minimonitor was installed in CA Db 72 from July 1987 through September 1988, and was used to record pH and specific conductance at 15-minute intervals. Problems similar to those encountered at the Annapolis site for the pH measurements were found at the Prince Frederick site, and these data have not been reported because they are considered unreliable.

Hydrologic system

Rainfall at the Prince Frederick study site for the period October 1986 through March 1989 totaled 91.26 in.—an annual average of just 36.5 in., which was well below the average of 42.44 in. for the area (Calvert County, written commun., 1989). The total rainfall recorded during calendar years 1987 and 1988

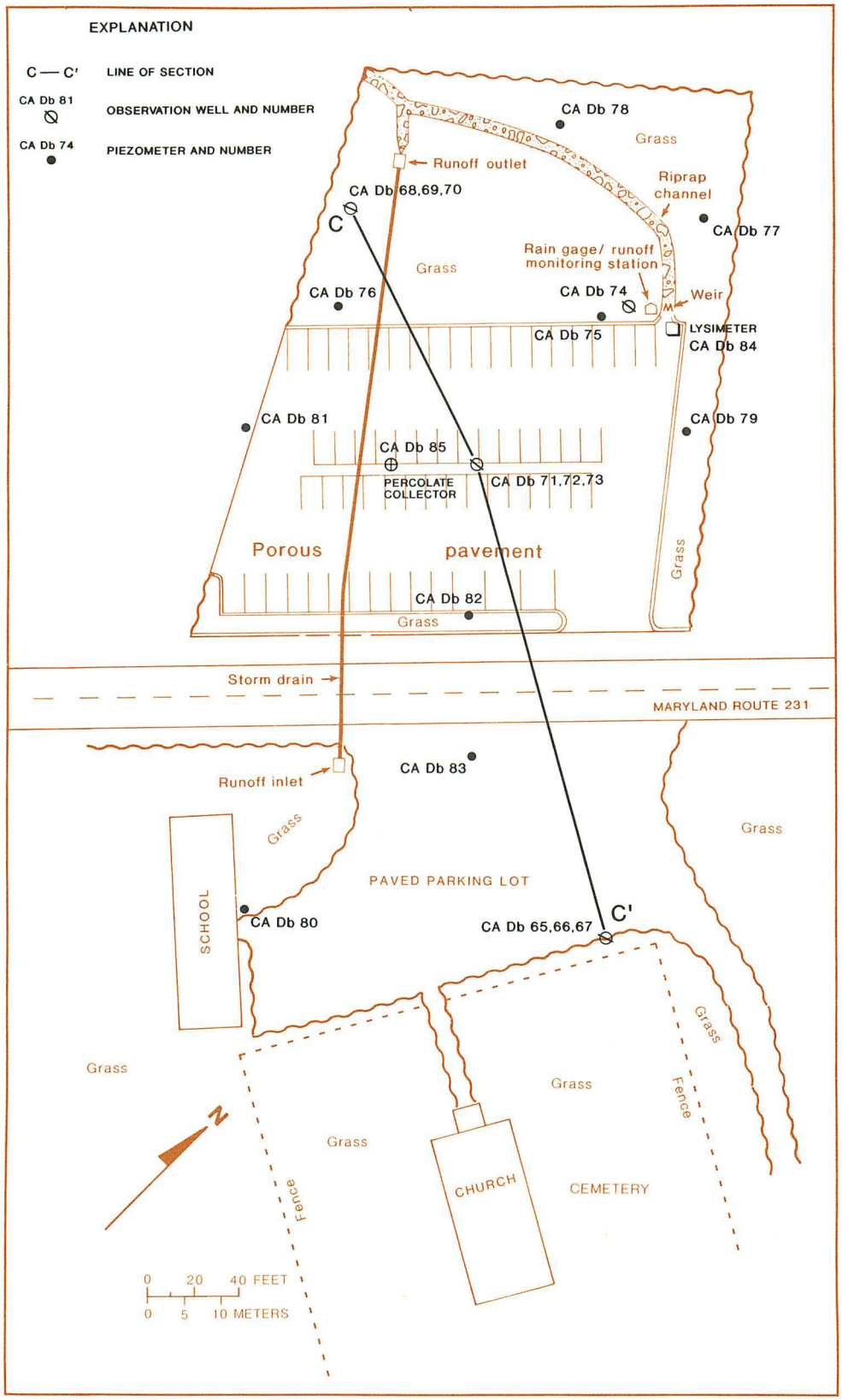


Figure 43.—(A) Location of wells, data-collection points, and line of section C-C′; (B) hydrologic section C-C′; and (C) photographs showing porous-pavement surface and profile at the Prince Frederick study site.

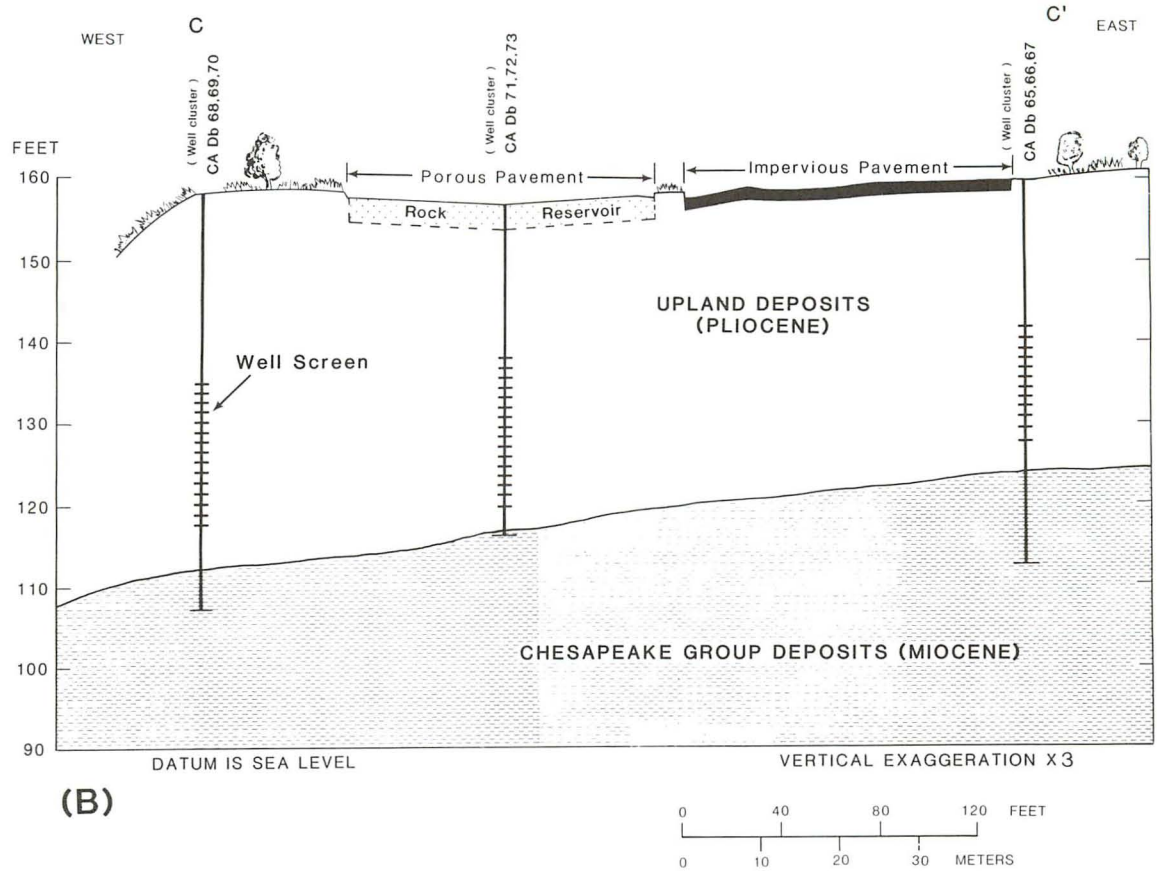


Figure 43.—Continued.

was 32.84 in. and 33.37 in., respectively (table 25). Calendar year 1989 was an unusually wet year, and 55.82 in. of precipitation was recorded at a nearby weather station in Mechanicsville, Md. The period of highest rainfall normally occurs during the spring, which corresponds to the period of regional recharge to the water table. Rainfall during the period of study was distributed relatively evenly over each year, however.

Evaporation data were not collected, but pan-evaporation data recorded at a nearby weather station (Upper Marlboro, Md.) was used for a rough estimate of evapotranspiration at the study site (table 25). Evaporation generally exceeded rainfall from May through August and sometimes in early fall. Rainfall was assumed to exceed evaporation from November through March.

Much of the storm water entering the impoundment discharged from the impoundment to a riprap channel near the northern corner of the parking lot. No simple relation was found between amounts of rainfall and runout (storm water discharged from the subsurface impoundment). The volume of storm water available to percolate through the impoundment generally depended on the amount, duration, and intensity of rainfall; antecedent weather conditions; and antecedent moisture conditions in the impoundment. Within the scope of this study, it was not possible to determine quantitatively the relations among these variables and the amount of discharging or infiltrating storm water. Comparison of the runout hydrograph with the rainfall hydrograph shows that, although storm-water discharge is nearly instantaneous for large storms of high intensity, the magnitude of runout does not always correspond with that of rainfall for a given storm (fig. 44). It was estimated that as much as 2 in. of storm water remained impounded after discharge ended. Because rainfall was distributed evenly throughout the year for the most part, water usually could be collected from the impoundment well (CA Db 85). Samples could not be collected from CA Db 85 during the drought period of late May through early June 1988; the absence of water in CA Db 85 indicated that the impoundment was dry.

In late June 1988, sodium-bromide powder was used to verify movement of storm water through the porous-pavement impoundment to ground water. Approximately 300 grams of dry sodium bromide powder was worked into a 30-square-foot section of porous pavement at the first two parking spaces near the Park-and-Ride entrance (fig. 45). Ground water collected from well CA Db 72, which is 25 ft downgradient from the area of bromide application, was monitored for bromide concentrations before and after the first rainfall. The first rainfall after bromide application was 0.27 in. on July 11. Bromide concentrations in ground-water samples collected from the same well the following day increased fivefold compared to background concentrations, and bromide concentrations continued to increase over the

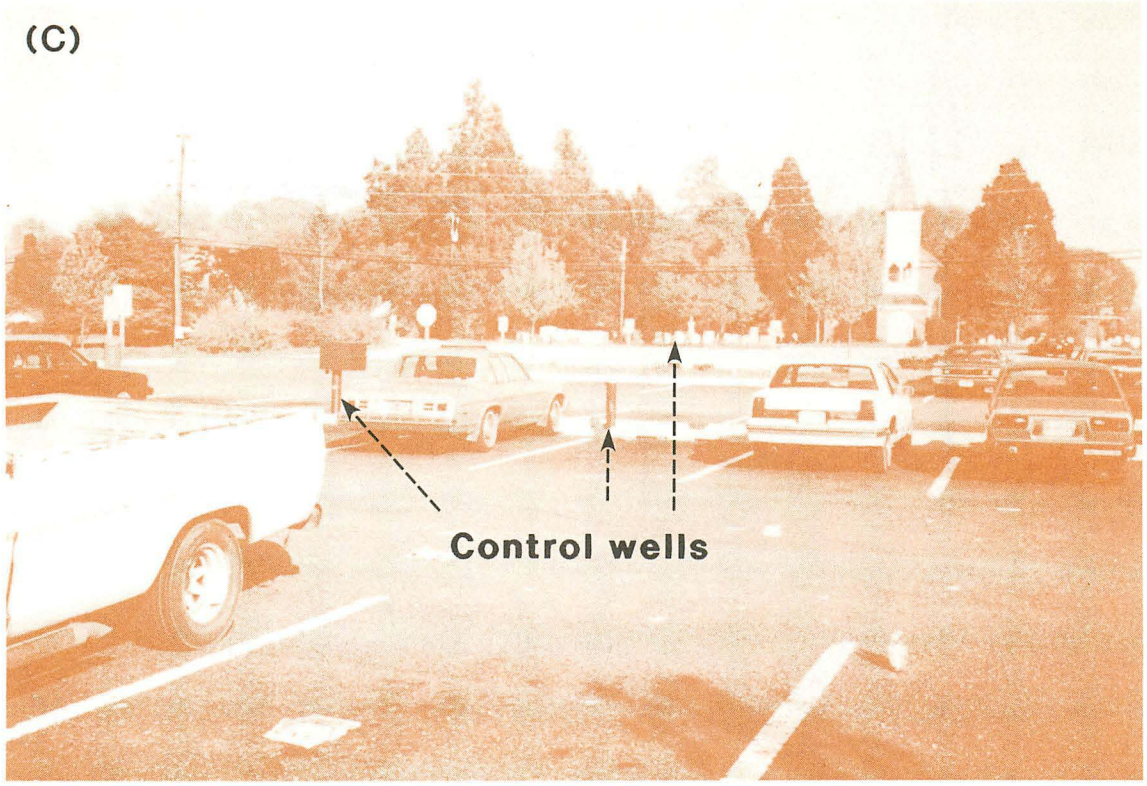


Figure 43.—Continued.

Table 24.—Records of wells at the Prince Frederick site

[ft, feet; in., inches; ft asl, feet above sea level; ft bls, feet below land surface; UPLD, Upland deposits aquifer; L, water-level data collected; Q, chemical data collected; *, lysimeter; #, porous-pavement percolate collector; --, not applicable;]

Well number	Latitude and longitude [1]	State permit number	Date well constructed	Altitude (ft asl)	Depth drilled (ft bls)	Well depth (ft bls)	Diameter of casing (in.)	Length of screen (ft)	Top of open interval (ft bls)	Hydro-geologic unit	Static water level (ft bls)	First date water level measured	Data type	Begin year of data collection
CA Db 65	3832160763515	CA-81-2415	07-16-86	159.33	50.5	49	3	10	22	UPLD	24.20	07-24-86	L	1986
CA Db 66	3832160763515	CA-81-2415	07-18-86	159.59	35	34	3	10	21	UPLD	24.26	07-24-86	QL	1986
CA Db 67	3832160763515	CA-81-2415	07-18-86	159.53	31.5	31	3	10	18	UPLD	24.08	07-24-86	QL	1986
CA Db 68	3832170763519	CA-81-2417	07-22-86	158.24	51	51	3	10	31	UPLD	29.10	07-23-86	L	1986
CA Db 69	3832170763519	CA-81-2418	07-24-86	157.91	39	39	3	10	26	UPLD	28.73	07-28-86	QL	1986
CA Db 70	3832170763519	CA-81-2418	07-24-86	157.38	36	35	3	10	22	UPLD	27.65	07-28-86	QL	1986
CA Db 71	3832170763517	CA-81-2416	07-30-86	156.78	40.5	40	3	10	27	UPLD	25.21	07-30-86	L	1986
CA Db 72	3832170763517	CA-81-2416	07-30-86	156.95	35	35	3	10	22	UPLD	25.80	08-25-86	QL	1986
CA Db 73	3832170763517	CA-81-2416	07-30-86	156.99	32	32	3	10	19	UPLD	25.97	08-25-86	QL	1986
CA Db 74	3832180763517	CA-81-2419	07-31-86	155.49	34	34	3	10	21	UPLD	23.47	08-25-86	L	1986
CA Db 75	3832180763518	CA-81-2419	03-13-86	156.39	34	29.8	1.25	5	24	UPLD	24.41	07-11-86	L	1986
CA Db 76	3832170763518	CA-81-2418	07-08-86	158.03	39.7	39.7	1.25	10	29	UPLD	28.56	07-11-86	L	1986
CA Db 77	3832180763519	CA-81-2418	07-09-86	150.53	32.5	30	1.25	10	20	UPLD	16.93	07-11-86	L	1986
CA Db 78	3832190763518	CA-81-2419	07-09-86	151.58	34.5	34.5	1.25	10	24	UPLD	20.73	07-11-86	L	1986
CA Db 79	3832180763517	CA-81-2417	07-10-86	156.64	35.3	35.3	1.25	10	25	UPLD	23.10	07-11-86	L	1986
CA Db 80	3832140763516	CA-81-2415	07-11-86	160.22	39	34.5	1.25	10	24	UPLD	25.52	07-11-86	L	1986
CA Db 81	3832150763518	CA-81-2417	07-08-86	158.70	39	32.9	1.25	10	22	UPLD	27.23	07-11-86	L	1986
CA Db 82	3832160763517	CA-81-2417	07-10-86	158.53	59	36	1.25	10	26	UPLD	24.98	07-11-86	L	1986
CA Db 83	3832160763516	CA-81-2415	07-07-86	159.07	45.5	45.5	1.25	10	35	UPLD	24.84	07-11-86	L	1986
* CA Db 84	3832180763517	--	06-26-87	155.69	2.6	2.1	2.38	.25	1.25	UPLD	--	--	Q	1987
# CA Db 85	3832170763517	--	04-10-87	157.46	2.5	2.1	6	.48	.5	--	--	--	Q	1987

[1] Symbols designating degrees (o), minutes(′), and seconds(″) have been omitted from latitude and longitude on table. Latitude precedes longitude and each longitude begins with 076 degrees. For example: latitude, 38°32′16″; longitude, 076°35′15″.

Table 25.—Monthly rainfall measured at the Prince Frederick site and monthly evaporation measured at the Upper Marlboro weather station, October 1986 through March 1989

[--, no data available; in., inches]

Year	Month	Precipitation		Evaporation[1]	Comments
		Number of storms	Number of inches	Number of inches	
1986	October	--	(3.22)	3.26	Source of October rainfall is the U.S. National Oceanic and Atmospheric Administration (1986).
	November	7	2.96	1.74	
	December	5	6.85	--	
1987	January	8	4.00	--	Amount of rainfall during 1987 calendar year totaled 32.84 in.
	February	3	2.26	--	
	March	4	1.69	--	
	April	4	4.35	3.49	
	May	6	3.39	5.68	
	June	6	2.55	7.13	Amount of rainfall during 1987 water year totaled 38.45 in.
	July	4	1.22	7.97	
	August	5	1.27	5.33	
	September	6	4.69	3.86	
	October	4	1.46	2.98	
	November	4	2.39	2.01	
	December	6	3.57	--	
1988	January	4	2.86	--	Amount of rainfall during 1988 calendar year totaled 33.37 in.
	February	6	4.05	--	
	March	4	2.19	--	
	April	6	2.46	4.37	
	May	9	3.27	5.68	
	June	3	.55	6.74	Amount of rainfall during 1988 water year totaled 32.73 in.
	July	7	4.91	6.87	
	August	5	2.65	6.30	
	September	5	2.37	4.02	
	October	4	1.85	3.08	
	November	6	5.42	2.09	
	December	6	.79	--	
1989	January	6	2.60	--	
	February	9	3.26	--	
	March	12	6.16	--	
	Total	192	67.81		
Data measured or compiled after March 1989:					
	April	7	4.38	4.92	
	May	6	6.89	5.13	
	June	10	10.59	6.08	
	July	3	1.59	6.23	

[1] Evaporation data compiled from climatological data summaries published by the U.S. National Oceanic and Atmospheric Administration (1986-88). Data were not adjusted for pan effects. Estimated annual pan coefficient for Class A pan is 0.75 (Fetter, 1988).

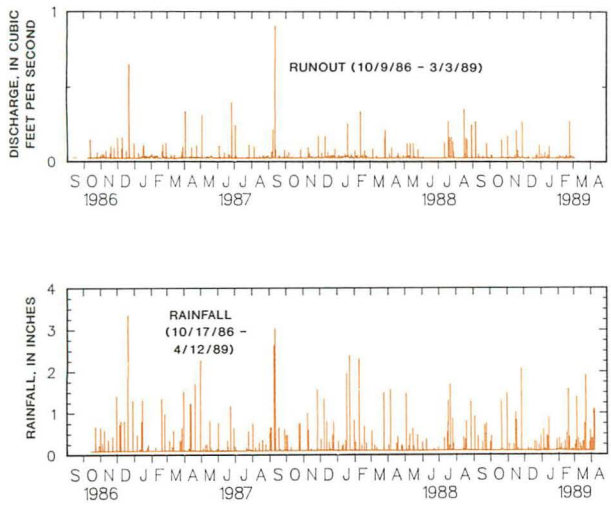


Figure 44.—Storm discharge (runout) from porous-pavement impoundment and total daily rainfall at the Prince Frederick site, October 1986–April 1989.

following 5 days. This test indicates an infiltration rate through the unsaturated zone to ground water of at least 1 ft/h. The infiltration rate, however, is highly dependent upon antecedent weather conditions and storm characteristics. Ground-water recharge often was not detected when rainfall was under ½ in. or was of low intensity during periods of sparse rainfall and high evapotranspiration. On the basis of the rise of the water table, infiltration rates ranged from 2 to greater than 9 ft/h for storms delivering ½ in. or more of rain.

The water-table aquifer at the study site is composed of a thin sequence of fluvially transported clays, silts, sands, and gravels known as Upland deposits (Glaser, 1971). The saturated thickness of the water-table aquifer is 10 to 20 ft. The water-table aquifer is not an important source of potable water in this area; although some dug wells still tap the aquifer for domestic use, most ground water in the area is withdrawn from deep, artesian aquifers (Otton, 1955; Drummond, 1984).

The inferred location of the southern surface-water and ground-water drainage divide is at the church, not more than 100 ft from the upgradient wells (CA Db 65, 66, 67). The direction of unconfined ground-water flow is to the west and northwest (fig. 45). Ground water discharges to Mill Creek and the Patuxent River.

The hydraulic conductivity of the water-table aquifer was estimated from published data on similar sediments to be within a range of 0.1 to 1 ft/d (Heath, 1984). Most of the wells at the site were pumped dry quickly, and water levels took approximately 5 hours to recover to initial levels. Recovery rates were on the order of 0.8 ft/d.

A bromide-tracer test was performed at the site to estimate the rate of ground-water flow. The tracer-test data, which were collected for 4 months, were not definitive, but they indicated a slow ground-water-flow rate estimated to be 0.05 to 2 ft/d (B.S. Smith, U.S. Geological Survey, written commun., 1990).

One liter of a 600-g/L sodium bromide solution was injected to the water table through well CA Db 73 on February 1, 1989. The tracer solution was prepared by dissolving 5 lb of bromide in 1 gal of a 5-gal composite of water collected from wells CA Db 72, 69, and 68. The remaining 4 gal of composited water sample was used to prepare stock and standard solutions for the calibration of bromide measurements. Samples were collected periodically from each well for bromide analysis just before introduction of the tracer solution on February 1 through June 28 (table 26). In general, field measurements made with a bromide-specific electrode corresponded qualitatively but not quantitatively with automatic-ion-chromatography laboratory analysis for concentrations exceeding laboratory value of 2 mg/L; below 2 mg/L, correspondence was unreliable between laboratory and field measurements.

The first possible breakthrough occurred on February 23 at CA Db 68, which is the downgradient well screened at the deeper aquifer interval. This breakthrough was coincident with an intense rainfall of nearly 2 in. the previous day. Field measurements were continued through June to look for marked changes in the relative concentrations. A substantial concentration increase was measured by electrode for samples collected on June 14 and 22; however, these results were not confirmed by analysis of archived samples that were filtered and run on the ion chromatograph more than 9 months later (M.M. Kennedy, U.S. Geological Survey, written commun., 1990).

It appears from the measurements of bromide concentrations in the injection well that major attenuation of bromide was occurring in the aquifer at a much higher rate than could be accounted for by the horizontal flow rate or by dilution from precipitation. It is possible that the breakthrough could have occurred sooner but was missed because flow was not direct from the injection well to well CA Db 68 or CA Db 69, and (or) samples from the downgradient wells were collected at too shallow a depth. The depth of sample collection was important; bromide breakthrough was observed only in the downgradient well screened in the lower section of the aquifer. It is unlikely that a significant amount of the bromide was lost to the underlying hydrogeologic unit because the water-table aquifer overlies a thick, areally extensive clay. The bromide test also demonstrated that the dilution effect from storms was transient, the major attenuation process apparently controlled by chemical-concentration gradients and hydraulic conductivity.

The position of the water table varied from 23 to 27 ft beneath the porous pavement (129.6 to 133.6 ft above sea level) during the period of data collection (figs. 46, 47). The annual fluctuation in water-table level during water year 1987[1] was about 3 ft, but was less than 1 ft during water year 1988, and approximately 4 ft during water year 1989 (1989 data not shown). Seasonal recharge of the water table generally occurred from January through May.

[1]Water year in U.S. Geological Survey reports is the 12-month period, October 1 through September 30. The water year is designated by the calendar year in which it ends and which includes 9 of the 12 months. Thus, the year ending September 30, 1986, is referred to as "water year 1987."

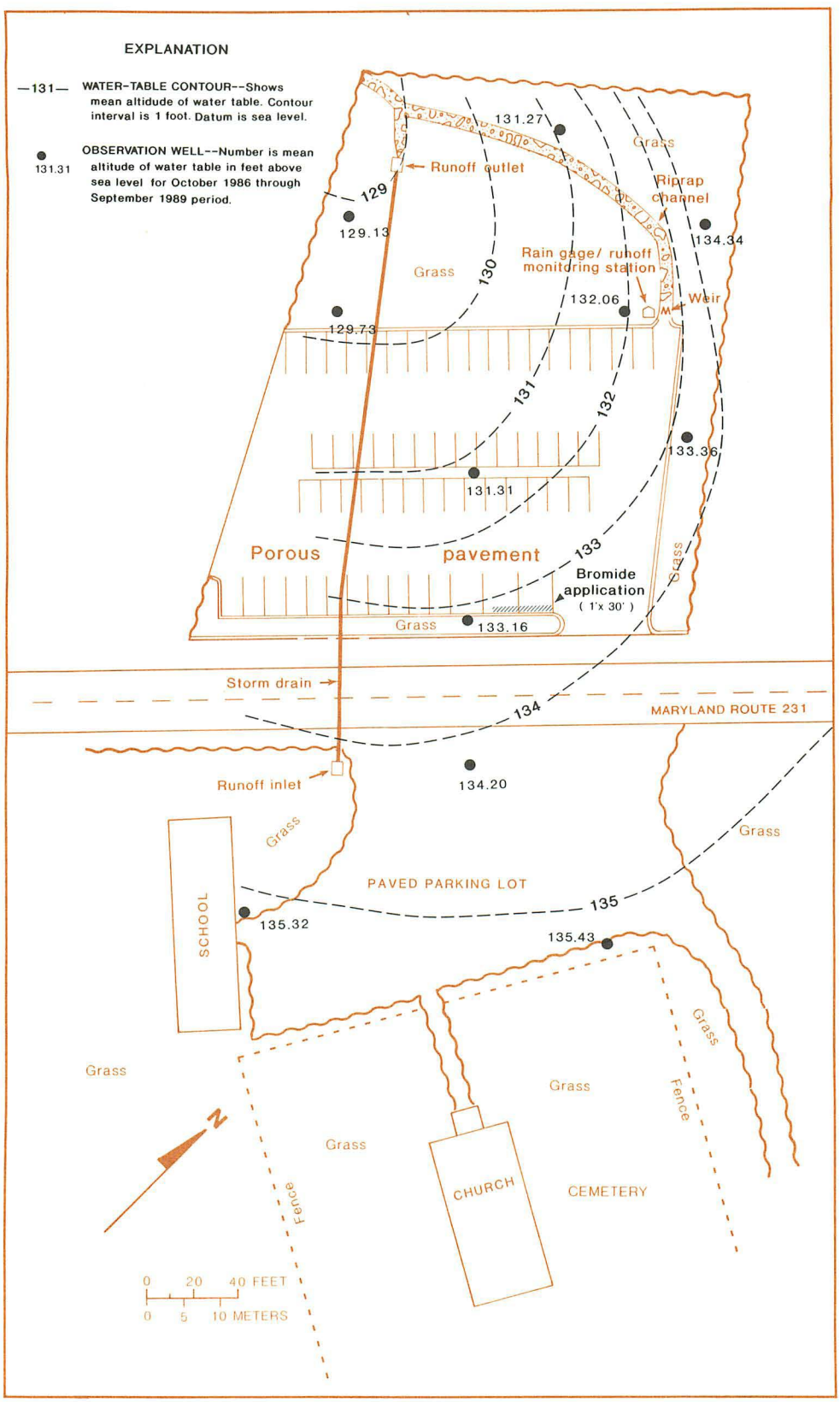


Figure 45.—Mean water-table configuration at the Prince Frederick site.

Table 26.—Results of bromide tracer test at the Prince Frederick site

[mg/L, milligrams per liter; --, no data]

Date (1989)	Rainfall (inches)	Beneath-Pavement: Injection well CA Db 73 Field	Injection well CA Db 73 Lab	Deep well CA Db 72 Field	Deep well CA Db 72 Lab	Downgradient: Shallow well CA Db 69 Field	Shallow well CA Db 69 Lab	Deep well CA Db 68 Field	Deep well CA Db 68 Lab
2-01	0.31	--	--	--	--	--	0.149	--	--
2-06	.47	24,000	25,500	1.06	0.496	1.45	1.56	1.0	0.421
2-07	.51	11,800	18,580	2.7	4.42	1.59	.498	1.06	.478
2-10	.51	11,000	22,400	1.0	1.04	1.30	--	1.11	.406
2-13	.83	7,400	--	1.1	--	1.2	.454	<1	.274
2-14	.83	13,800	14,400	1.15	--	1.6	.445	2.05	.464
2-15	1.28	5,700	5,730	1.11	--	1.4	.432	1.0	.348
2-21	0.0	4,150	--	1.43	--	1.25	.380	<1	.348
2-22	3.21	3,250	5,450	1.17	--	1.6	.413	.46	.238
2-23	0.0	3,400	--	.6	--	.78	--	2.80	2.23
5-31	18.65	500	--	1.64	--	1.01	--	1.28	1.33
6-07	23.3	278	--	1.55	--	.8	--	1.31	--
6-14	24.99	300	--	1.65	--	1.08	--	7.9	--
6-22	27.93	447	--	1.55	--	1.01	--	7.9	--
6-28	29.24	390	--	1.5	--	1.08	--	1.31	--

[1] Cumulative inches of rainfall recorded at site starting 2-1-89.

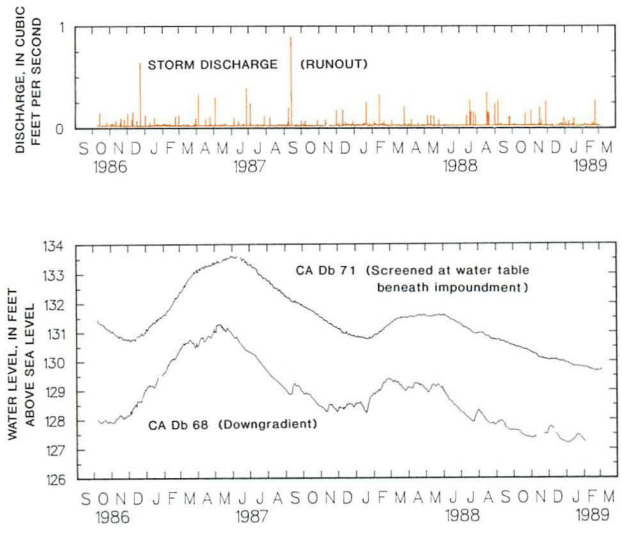


Figure 46.—Discharge (runout) through storm-water impoundment and water-table fluctuations beneath the impoundment and downgradient from the impoundment at the Prince Frederick site, October 1986–March 1989.

The hydrograph depicting water levels at well CA Db 71 is flattened and skewed to the right in comparison with hydrographs at the upgradient and downgradient wells. This reflects the effect of the porous-pavement structure. The upgradient and downgradient wells were located in vegetated areas where rainwater percolated directly to ground water, leaving event markers on the hydrograph (fig. 47). Much of the rainwater and runoff entering the porous-paved impoundment discharged offsite, however, and was not available for infiltration to ground water. Storm recharge resulted in a transient rise of water table on the order of tenths of a foot at well CA Db 68, but rises of water table beneath the impoundment at well CA Db 71 were on the order of hundredths of a foot (fig. 47). Infiltration of the impounded portion of the storm water probably was impeded by the filter fabric that lined the impoundment.

There was little evidence to substantiate water-table mounding beneath the site or at its periphery (fig. 48). Because transient recharge was greater through the grassy area (where wells CA Db 76 and CA Db 68 were located) than it was through the impoundment, the water table near the downgradient edges of the impoundment could possibly become higher than the water table beneath the impoundment. The consequent restriction to ground-water flow would have important implications for the interpretation of the aqueous geochemistry. The data, however, showed that, although the gradient on the water table tended to fluctuate more between wells CA Db 71, 76, and 68 than between CA Db 71 and the upgradient wells, a reverse gradient was never observed and is unlikely to have occurred (fig. 48). The

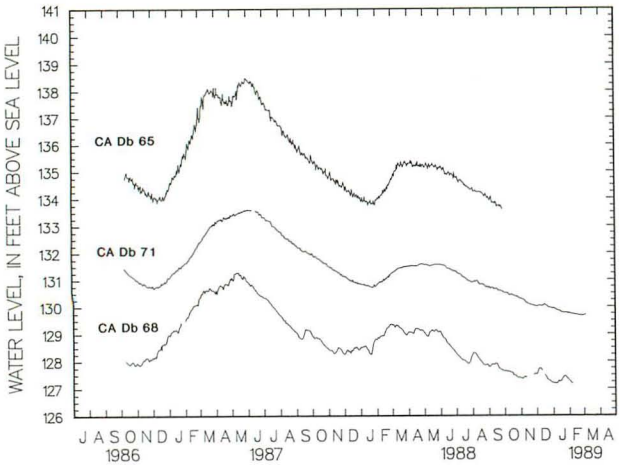


Figure 47.—Altitudes of water levels between the upgradient (control) well (CA Db 65), the impoundment well (CA Db 71), and the downgradient well (CA Db 68) at the Prince Frederick site, September 1986–March 1989.

mean water-table gradient from upgradient to downgradient wells was 1.7 percent; the mean gradient on the water table between wells CA Db 71 and 68 was 2 percent.

Native Geologic Materials

The Prince Frederick study site is within the Coastal Plain physiographic province in a poorly defined geologic unit known as the Upland deposits (table 1; Otton, 1955). The Upland deposits consist of a relatively thin sequence of unconsolidated Pliocene(?) sediments of fluvial origin. These rest in angular unconformity upon older geologic units of marine origin (Glaser, 1971). The underlying unit consists of soft green-gray and dense gray fossiliferous clays belonging to the St. Marys Formation of Miocene age.

Upland deposits at the study site were 30 to 40 ft thick (including fill material), with an increase in thickness toward well CA Db 68 at the northwestern corner of the site. The deposits were predominantly poorly sorted, yellow-to-orange-stained quartzose sands that contained stringers of clay and pockets of gravel. Sand-sized particles comprised from 71 to 94 percent of the Upland deposit samples (table 27). Sediments near the water-table tended to be lower in the sand-sized fraction (30 percent silt plus clay). Analyses of cation-exchange capacities, particle-size distribution (table 27), major-element composition (table 28), and trace-element composition (table 29) were performed on selected depth intervals of cored Upland deposits and St. Marys Formation.

Quartz, muscovite, gibbsite, kaolinite, hematite or goethite, and feldspar were identified by X-ray diffraction as the major minerals comprising Upland deposit sediments that were collected from split-spoon samples at the site. Quartz was the dominant mineral; silica comprised 87.54 to 94.67 percent of the major elements (table 28). Glaser (1971) reports that a zircon-tourmaline-staurolite mineral assemblage is typical of fluvial facies in the Maryland Coastal Plain province, and these trace minerals are the likely source for the trace-element composition of these sediments (table 29).

It is pertinent to the forthcoming discussion regarding ground-water chemistry to describe differences in the composition of native materials that were observed near the basal contact of Upland deposits and St. Marys Formation sediments at each well cluster. Shell fragments were found in sediment cores from the upgradient (CA Db 65-67) and impoundment (CA Db 71-73) wells, starting at 31 and 33 ft below land surface, respectively, but shell fragments were not found at the downgradient wells (CA Db 68-70). The St. Marys Formation at the site is composed of dense, gray-green to gray-blue clay with or without abundant shell material. At wells CA Db 65 and 71, there appeared to be a zone of reworked sediments near the top of the St. Marys Formation; this zone was characterized by tan and brown silty sands with shell fragments. No "reworked" zone was identified in cores collected during construction of the downgradient well. Shell material was more abundant in the basal zone of Upland deposits collected from upgradient well cores than from cores collected beneath the impoundment or downgradient from the impoundment. This abundance is reflected by the 8.84-percent calcium in upgradient sediments collected at 34 ft beneath land surface, compared with 2.64 percent from beneath-impoundment sediments collected at a depth of 39 ft, and 1.07 percent from downgradient sediments collected at a depth of 44.5 ft (table 28). Moreover, the bottom of the screen of the upgradient well (CA Db 66) from which aqueous samples were collected was positioned at the top of the "reworked" zone, whereas beneath-impoundment and downgradient wells were screened approximately 2 ft or more above the "reworked" zone or the St. Marys Formation.

Impoundment Materials

The mineralogy and chemistry of impoundment materials primarily consisted of Hunting Hill quarry rocks. The porous pavement filtered out sands, most silts, and the largest clay-sized particles, but presumably clays and colloids were able to pass to the impoundment. It was not possible to collect samples of the storm-water-borne material accumulating in the impoundment. Upland deposit sediments bounded the bottom and sides of the impoundment. It was apparent from chemical analysis of the impoundment water and water from the shallow unsaturated zone that the aqueous major-ion chemistry was dominated by the dissolution of the quarry rocks. Of concern was the potential for the quarry rock to be a source of toxic trace elements.

Hunting Hill rocks are mostly serpentinized dunites or serpentinites—ultramafic rocks of the Eastern Piedmont province. The mineral and chemical composition of the quarry aggregate contrasts sharply with that of native geologic materials (Upland deposits and St. Marys Formation) (table 29). In general, the aggregate is composed of magnesium-rich silicate and hydroxide minerals in which magnesium-carbonate veins are ubiq-

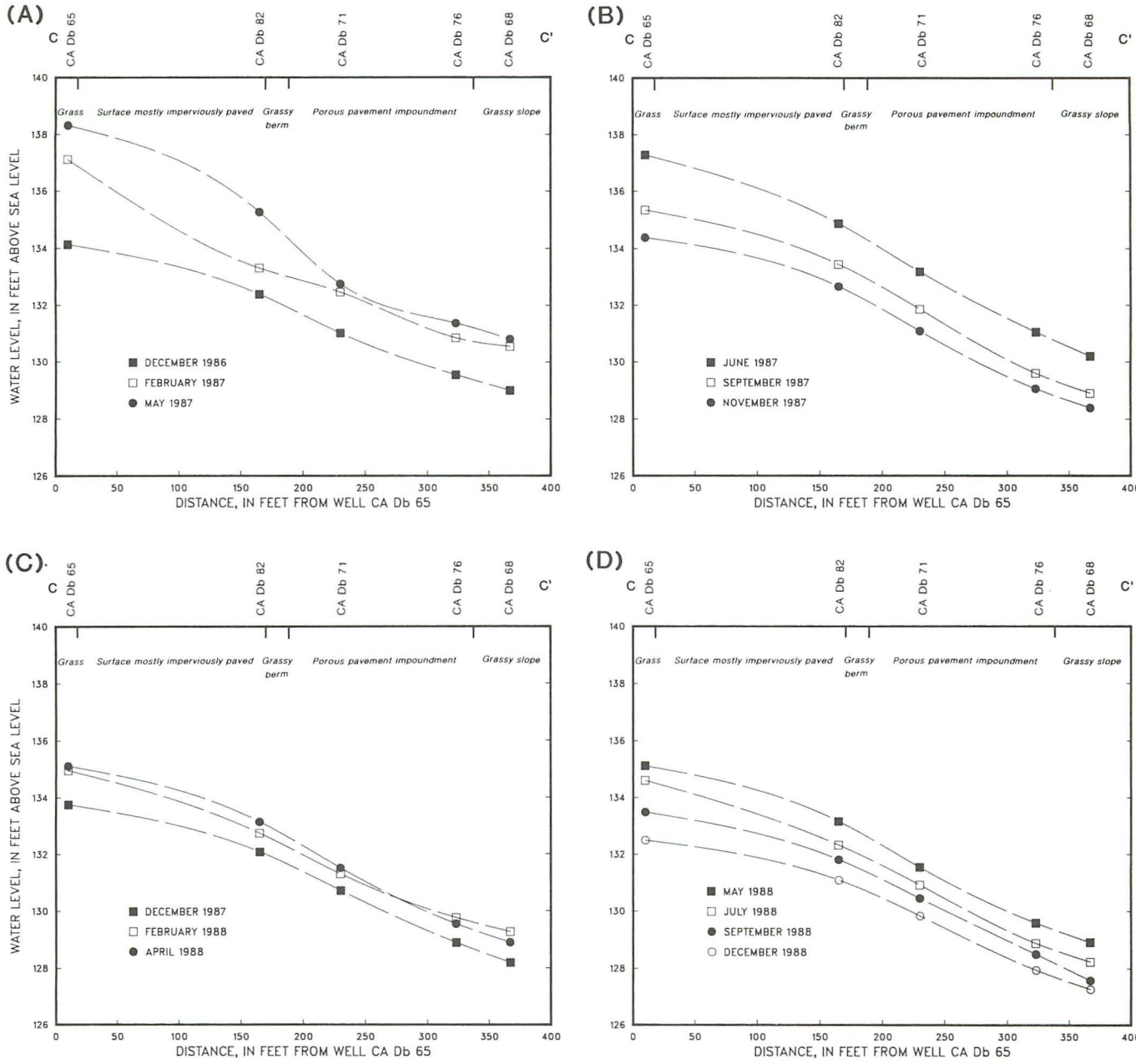


Figure 48.—Water-table gradients at the Prince Frederick site: (A) December 1986 through May 1987, (B) June 1987 through November 1987, (C) December 1987 through April 1988, and (D) May 1988 through December 1988. (Refer to Fig. 45 for map showing mean water-table configuration.)

Table 27.—Exchangeable base cations, cation-exchange capacities, and particle size of native geologic materials at the Prince Frederick site

[Ca^{2+}, calcium; Mg^{2+}, magnesium; K^{+}, potassium; Na^{+}, sodium; CEC, cation-exchange capacity; units are in milliequivalents per 100 grams of dry soil; UD, Upland deposits; SM, St. Marys Formation; sand, 0.062 millimeters; clay, 0.004 millimeters]

Well number	Geologic unit	Depth interval (feet below land surface)	Exchangeable base cations					Particle size (percent)		
			Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	CEC	Sand	Silt	Clay
CA Db 65[1]	UD	9 - 10	0.13	0.18	0.04	0.11	0.46	94	4	2
	UD	24 - 25.5	.54	.27	.04	.14	.99	91	4	5
	SM	34 - 35.5	1.78	.29	.12	.19	2.38	75	16	9
CA Db 68[2]	UD	19.5 - 26	.57	.24	.05	.11	.97	71	10	19
	SM	30.5 - 36.5	1.48	1.27	.09	.34	3.18	69	16	15
	SM	44.5 - 46	5.81	1.70	.15	.25	7.91	45	32	23
	SM	49.5 - 51	1.26	2.37	.24	.19	4.06	45	35	20
CA Db 71[3]	UD	3 - 4.5	.74	1.25	.07	.14	2.20	84	7	9
	SM	39 - 40	-	-	-	-	-	38	45	17
CA Db 72[3]	UD	.5 - 1	.52	.35	.05	.12	1.04	83	13	3
	UD	1 - 2	.52	.35	.05	.12	1.04	88	4	8
CA Db 73[3]	UD	1 - 1.8	.70	.52	.06	.13	1.41	85	8	7
	UD	1.8 - 2.5	.70	.52	.06	.13	1.41	87	6	7

[1] Upgradient (control) well.
[2] Downgradient well.
[3] Impoundment wells: CA Db 71, 72, and 73.

uitous (Larrabee, 1969). Minerals comprising the serpentinite group (table 30) are reactive and therefore relatively unstable when exposed to weathering from atmospheric, precipitation, and temperature conditions.

The quarry rocks can be expected to have low CEC's. CEC within the impoundment would have increased as mineral residues accumulated from weathering of Hunting Hill rocks, as well as from storm-water-borne material and hydroxide precipitates. Upland deposit sediments had low CEC's that generally reflected compositional characteristics: the particle-size distribution became finer in the downgradient direction, from 91 percent sand at CA Db 65 to 71 percent sand for the same depth interval at well CA Db 68 (table 27). The CEC was greatest in sediments beneath the impoundment, however, and was notably elevated with respect to background. This CEC increase was marked by increases in exchangeable magnesium and calcium. In theory, authigenic montmorillonite could be forming from weathering of the serpentinite, because the aqueous solution is rich in magnesium and infiltration is slow (Deer and others, 1978). Impoundment waters, however, are shown to be in equilibrium with kaolinite on clay-stability diagrams (fig. 49). Nevertheless, saturation-index calculations from WATEQF were negative for calcium-rich montmorillonite (indicating instability) but positive for sodic montmorillonite, magnesium carbonates, and iron and manganese hydroxides (indicating stability). Because there was clear evidence for dissolution of calcium and magnesium carbonates in quarry rocks and no initial hydroxide phase, precipitation of carbonate and hydroxide phases in the impoundment is inferred. Authigenically formed clays and hydroxides could be expected to accumulate on and in pores of the underlying Upland deposit sediments and could be expected to increase the CEC of the sediments.

Major elements

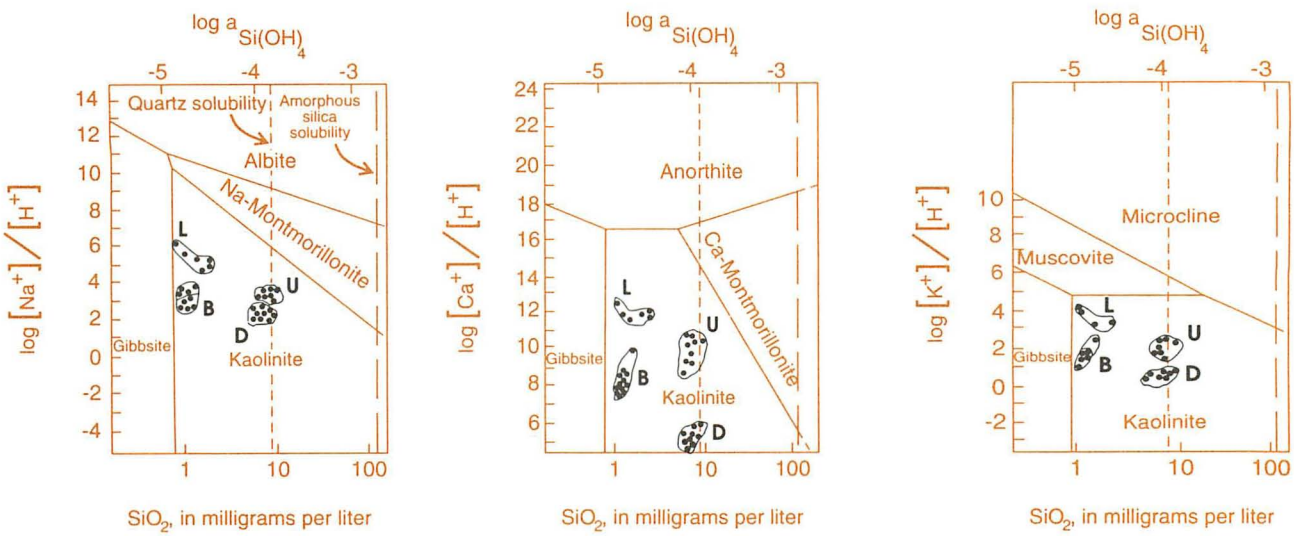
The quarry rocks dominated the major-element chemistry in the impoundment. The most common minerals found in the Hunting Hill serpentinite include serpentine (and its polymorphs

Table 28.—Major-element chemistry of native geologic materials at the Prince Frederick site

[Data are for the Upland deposits geologic formation, unless otherwise noted; reported in weight-percent oxide, normalized to 100 percent; ft bls, feet below land surface; LOI, loss on ignition; SM, St. Marys Formation; analytical method for elements was X-ray fluorescence]

Well number	Depth of sample (ft bls)	Calcium (CaO)	Magnesium (MgO)	Sodium (Na_2O)	Potassium (K_2O)	Phosphorus (P_2O_5)	Silica (SiO_2)	Aluminum (Al_2O_3)	Iron (Fe_2O_3)	Manganese (MnO)	Titanium (TiO_2)	Percent LOI	Final percentage
CA Db 65 [1]	9 - 10	0.03	0.01	0.11	0.25	0.04	93.74	3.16	1.34	0.01	0.25	1.06	100.00
	24 - 25.5	.06	.02	.13	.22	.06	94.67	2.10	1.51	.01	.41	.82	100.01
SM	34 - 35.5	8.84	1.26	.60	.92	.39	69.28	4.72	6.22	.18	.41	7.18	100.00
CA Db 71 [2]	3 - 4.5	.08	.36	.13	.38	.08	91.49	3.67	1.79	.01	.27	1.75	100.01
SM	39 - 40	2.64	1.01	.70	2.14	.15	71.78	9.96	5.48	.03	.82	5.30	100.01
CA Db 72	.5 - 2	.06	.09	.13	.35	.06	87.54	4.37	5.10	.01	.29	2.01	100.01
CA Db 73	1 - 2.5	.06	.02	.13	.34	.07	93.31	3.02	1.56	.01	.27	1.22	100.01
CA Db 68 [3]	19.5 - 26	.06	.11	.16	.72	.28	88.11	5.54	2.57	.01	.37	2.06	99.99
SM	30.5 - 36.5	.11	.14	.32	.82	.30	88.05	4.38	3.72	.02	.47	1.68	100.01
SM	44.5 - 46	1.07	.43	.66	1.66	.10	79.36	8.24	3.81	.02	.76	3.88	99.99
SM	49.5 - 51	1.60	.59	.64	1.98	.14	75.43	9.79	4.81	.02	.83	4.18	100.01

[1] Control (upgradient) well.
[2] Impoundment wells: CA Db 71, 72, and 73.
[3] Downgradient well.



EXPLANATION

L Unsaturated-zone water **U** Native ground water

D Downgradient ground water **B** Beneath-impoundment ground water

Figure 49.—Stability relations for clay minerals and aqueous solutions with respect to clay minerals at the Prince Frederick site. [log a $Si(OH)_4$ is log activity of silicic acid.]

Table 29.—Trace-element chemistry of native geologic materials at the Prince Frederick site

[Data are for the Upland deposits geologic formation, unless otherwise noted; reported in parts per million; ft bls, feet below land surface; <, below detection with analytical method used; SM, St. Marys Formation]

Well number	Depth of sample (ft bls)	Cadmium (Cd)	Chromium (Cr)	Cobalt (Co)	Copper (Cu)	Lead (Pb)	Molybdenum (Mo)	Nickel (Ni)	Vanadium (V)	Zinc (Zn)
CA Db 65 [1]	9 - 10	<1	16	170	9.5	12	5	6	28	12
	24 - 25.5	<1	20	270	6.5	10	8	5	20	15
SM	34 - 35.5	<1	32	140	5.5	10	10	67	48	230
CA Db 68 [2]	19.5- 26	<1	30	110	8.5	14	7	7	54	17
SM	30.5- 36.5	<1	28	210	7	12	8	11	40	56
SM	44.5- 46	4	54	140	10	18	12	52	72	97
SM	49.5- 51	1	68	71	11	18	9	54	90	96
CA Db 71 [3]	3 - 4.5	<1	80	170	10	16	6	54	34	16
SM	39 - 40	3	92	52	12	18	9	31	88	120
CA Db 72 [3]	.5- 2	<1	130	130	32	14	6	8	54	22
CA Db 73 [3]	1 - 2.5	<1	24	160	10	10	7	6	32	12

[1] Upgradient (control) well.
[2] Downgradient well.
[3] Impoundment wells: CA Db 71, 72, and 73.

Table 30.—Mineralogy and chemical composition of rocks from the Hunting Hill Quarry

[Data from Larrabee, 1969; ND, not determined]

	Hunting Hill Quarry	
	Serpentinite	Carbonate Veins
Mineral Phases:		
	Serpentine, antigorite, chrysotile $Mg_3[Si_2O_5](OH)_4$	Magnesite $MgCO_3$
	Olivine Mg_2SiO_4	Dolomite $CaMg(CO_3)_2$
	Chlorite $(Mg,Al,Fe)_{12}[(Si,Al)_8O_{20}](OH)_{16}$	Huntite $Mg_3Ca(CO_3)_4$
	Magnetite $Fe^{+2}Fe_2^{+3}O_4$	Calcite, aragonite $CaCO_3$
	Chromite $Fe^{+2}Cr_2O_4$	Brucite $Mg(OH)_2$
	Talc $Mg_6[Si_8O_{20}](OH)_4$	Coalingite $Mg_{10}Fe_2(CO_3)(OH)_{24}.2H_2O$
	Hematite Fe_2O_3	

Whole-Rock Chemistry:

(in weight-percent oxide)	Quarry sample W167341	Quarry sample W167342
Alumimum (Al_2O_3)	1.20	1.50
Calcium (CaO)	.35	.31
Carbon (CO_2)	.24	.11
Chromium (Cr_2O_3)	ND	ND
Iron (FeO)	2.50	2.50
Iron (Fe_2O_3)	5.10	4.90
Magnesium (MgO)	37.70	37.60
Manganese (MnO)	.12	.12
Phosphorus (P_2O_5)	.03	.02
Potassium (K_2O)	.11	.00
Silica (SiO_2)	39.40	40.00
Sodium (Na_2O)	.09	.10
Titanium (TiO_2)	.04	.06
Water (H_2O)	12.90	12.67
Sum	99.78	99.89

antigorite and chrysotile), magnetite, olivine, chromite, chlorite, hematite, and talc (table 30). Some of these minerals are weathering products of the original ultramafic assemblage. Minerals common in the carbonate veins are calcite, aragonite, dolomite, magnesite, huntite, brucite, and coalingite (Larrabee, 1969). Magnesium silicates comprise from 70 to 80 percent of the rock: thus, silica and magnesium are the most abundant elements. Iron and aluminum are the next most abundant elements, followed by calcium, carbon, manganese, potassium, and sodium, in that order. Titanium and phosphorus are minor components. Calcium-to-magnesium (Ca:Mg) and sodium-to-potassium (Na:K) ratios in Hunting Hill materials were 0.009:1 and 0.082:1, respectively.

The elemental abundances of major components in Upland deposits followed the order of silica (primarily from quartz, secondarily from clays), aluminum (mostly from clays), and iron (from iron oxides). Potassium and titanium (from clays), sodium (from feldspar), and calcium, magnesium, manganese, and phosphorus (possibly from accessory minerals) were minor components (table 28). Therefore, the primary distinction between elemental abundances of the quarry rocks and native sediments was the high percentage of magnesium in quarry rocks. The magnesium-to-silica (Mg:Si) ratio was 0.94:1 for Hunting Hill rock and 0.0001:1 for native Upland deposits; the Mg:Ca ratios were 121.3:1 and 0.33:1, respectively.

The effect of water-rock/sediment interaction on the sediment chemistry of the impoundment is apparent when ratios between relatively constant elements, such as sodium and potassium, are compared with magnesium-to-calcium or Mg:Na ratios. A decrease in the Na:K ratio from 0.44:1 to 0.22:1 noted between wells CA Db 65, CA Db 72, and CA Db 68 is consistent with the increase in kaolinite along that transect. Ratios of Ca:Mg also decreased along the same transect—from 3.0:1 to 0.54:1—but the decrease was much greater, and the Ca:Mg ratio was lowest (0.22:1) beneath the impoundment. Moreover, although exchangeable potassium and sodium remained constant in shallow native sediments along the transect, exchangeable calcium and magnesium and the CEC increased notably in sediments beneath the impoundment. The enrichment in core sediments from magnesium at CA Db 71 and CA Db 68 was consistent with modifications expected to result from impoundment-rock dissolution.

Trace elements

Spectrographic analyses of the serpentinite reported by Larrabee (1969) showed high nickel, chromium, and cobalt contents. Other trace elements reported were copper, vanadium, and minor amounts of strontium.

The trace-element composition of Upland deposits was notable in several respects (table 29): cadmium was uniformly undetected; lead, molybdenum, and zinc concentrations were low and relatively constant between sampling stations; and cobalt concentrations, which were relatively high in all samples, decreased somewhat between the upgradient and downgradient sample stations. Concentrations were elevated at shallow depth (0.5 to 4.5 ft below land surface) in native sediments beneath the impoundment for chromium (CA Db 72), copper (CA Db 72), nickel (CA Db 71), and vanadium (CA Db 71, 72).

Possible sources for the chromium, copper, nickel, and vanadium were the quarry rocks and (or) storm water. The concentration pattern was not uniform in sediments collected at the impoundment wells (CA Db 71, 72, 73) for these trace metals. If the quarry aggregate is assumed to be the source, this nonuniformity of concentration can be explained by the nonuniform occurrence of these elements in the rock aggregate; therefore, leaching, precipitation, and sequestering of the elements would not be uniform. There is no clear evidence that these metals were released from dissolution of the Hunting Hill rocks, however. The samples being compared were collected at different depth intervals, from 0.5 to 4.5 ft, and concentration discrepancies may be artifacts of mobilization and transport. The sediment samples at CA Db 68 were collected from a depth interval near the water table (19.5 to 26 ft) and were enriched only in vanadium, magnesium, and iron.

Aqueous Solutions

pH, specific conductance, and dissolved oxygen

The median pH of rainwater samples collected for 3 years at the Prince Frederick site was 4.26 (table 31). The volume-weighted mean pH, 4.19, was close to the median. Anomalous samples had pH values from 5.62 to 6.37. There were no farming or landscaping activities in the immediate proximity of the study site. The median specific conductance of rainwater was 34 μS/cm, but specific conductance ranged from 8 to 108 μS/cm. Low pH tends to correspond with high specific conductance (fig. 50A).

Runoff was not collected from the Prince Frederick site, because all the runoff and rainwater at the site percolated through the porous pavement and entered the subsurface impoundment. Storm water was collected from a well screened in the impoundment (impoundment water from CA Db 85) and from an automatic sampler at the weir where storm water (runout) discharged through the impoundment. The chemical composition of samples collected from the two storm-water sources exhibited few differences. The median pH of runout was 8.24 (the pH range was from 7.28 to 8.88); the median pH of impoundment water was 8.46 (the pH range was from 7.20 to 9.01) (table 31). The primary control on the pH of storm water appeared to be dissolution of minerals from the Hunting Hill rocks in the impoundment, which buffered the storm water to a pH of about 8.4; this pH decreased periodically because of rainwater dilution. Dissolution of the carbonate minerals that were present in veins throughout the rock aggregate was the primary buffering source; however, dissolution of silicate minerals apparently buffered the solution to higher pH when contact of storm water with rock aggregate was protracted.

Comparison of magnesium, bicarbonate, and silica concentrations in Prince Frederick storm water with Annapolis and Greenmount storm water (1) demonstrates that silicate dissolu-

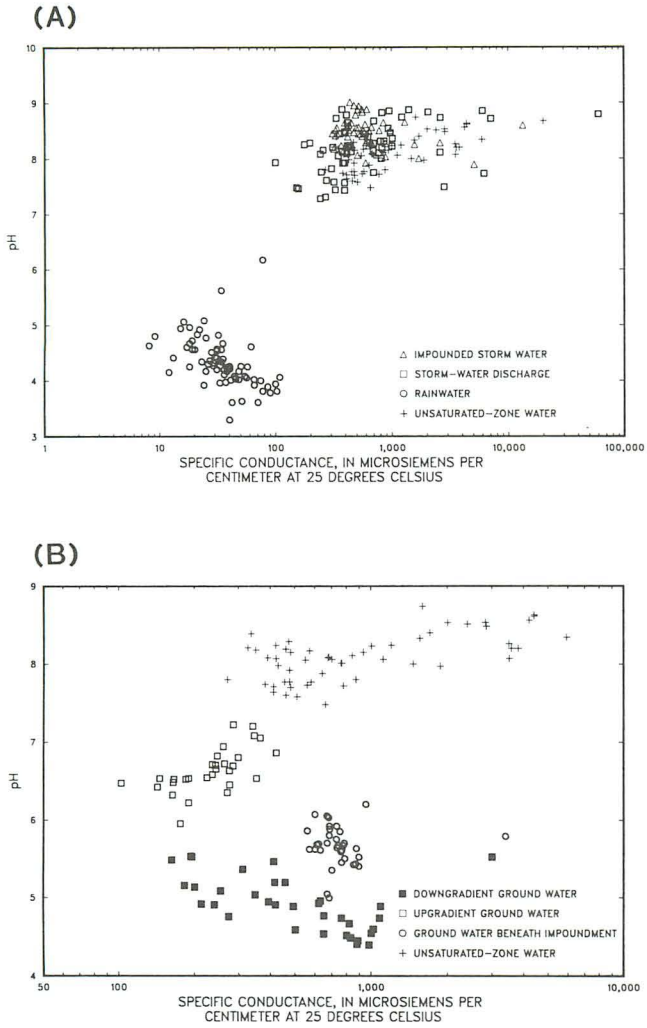


Figure 50.—Specific conductance and pH at the Prince Frederick site: (A) rainwater, storm water, and unsaturated-zone water; and (B) ground water and unsaturated-zone water.

tion was a minor source of alkalinity, and (2) indicates the relative effect that rock-aggregate dissolution can have on storm-water chemistry (table 32). Unlike impoundment water at the Annapolis and Greenmount sites, fluctuation in pH was not diurnal because algal growth was not a factor. The runoff component was only 17 percent of storm water entering the impoundment; therefore, 83 percent of the storm water was direct infiltration of acidic precipitation. Data from the Annapolis and Greenmount study sites and from National Urban Runoff Program (NURP) studies (U.S. Environmental Protection Agency, 1983) indicate that the pH of runoff is rarely greater than 7.5.

Specific conductance was often greater in impoundment water than in runout: the median for impoundment water was 520 μS/cm, compared with 442 μS/cm for runout. This difference was attributed to dissolution of minerals in the rock aggregate. Greatly elevated specific conductance was measured whenever road deicing occurred, and values as high as 60,000 and 5,100 μS/cm were recorded for runout and impoundment water, respectively. Chloride-concentration measurements were lower for samples of impoundment water than for samples of runout.

Dissolved-oxygen concentrations in impoundment water ranged from 6.94 to 10.78 mg/L (fig. 51) and generally were consistent with concentrations expected for oxygen saturation of the solution at the ambient temperature.

Water from the unsaturated zone was collected at shallow depth beneath the impoundment. Unsaturated-zone water plotted in a pH-specific conductance field similar to that of storm water (fig. 50), but the median pH (8.08) was lower and the median specific conductance was higher (680 μS/cm) for unsaturated-zone water. The highest value of specific conductance recorded for unsaturated-zone water, 20,000 μS/cm, was related to deicing. The redox potential of unsaturated-zone water was difficult to determine, but efforts to determine Eh by means of a platinum electrode and sulfide by means of an ion-specific electrode indicated that the water was well oxygenated at this depth.

Ground-water samples were collected with a point-source bailer from within the first foot of the water table. Upgradient ground-water chemistry was determined from samples collected primarily from well CA Db 66. The upgradient well cluster was near the ground-water divide, at the edge of church grounds that include a cemetery. The possibility was considered that chemical constituents leaching from the cemetery might affect the chemistry of the ground-water collected from these wells and that therefore samples might not be representative of the ground water entering the area overlain by the storm-water impoundment. Data from the literature were sparse for ground-water chemistry at nearby wells and at a roughly analogous depth interval, and the available data varied widely; nevertheless, the altitude, depth to water table, and ground-water chemistry at

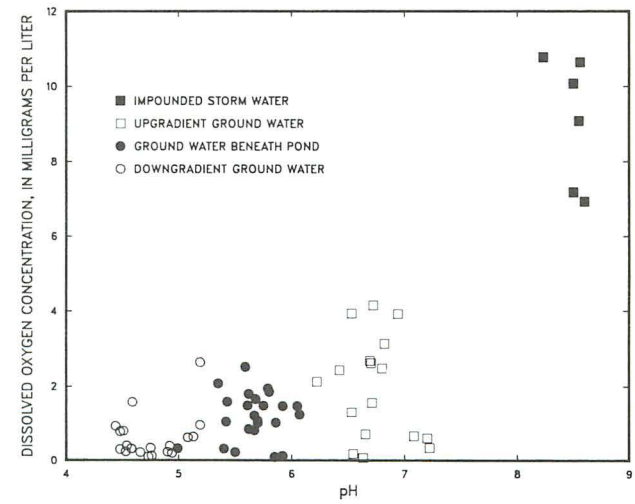


Figure 51.—Dissolved-oxygen concentrations and pH of impoundment water and ground water at the Prince Frederick site.

Table 31.— Median, minimum, and maximum values for specific conductance, pH, dissolved oxygen, and concentrations of major ions in filtered aqueous solutions at the Prince Frederick site

[Concentrations in milligrams per liter unless otherwise noted; µS/cm, microsiemens per centimeter at 25 degrees Celsius; --, no data; <, below detection at value shown; *, sole measurement shown as maximum concentration; >, greater than; #, median value for dissolved oxygen in impounded water is not meaningful; µm, micrometer]

Station description	Concentration	Specific conductance[1] (µS/cm)	pH[1]	Dissolved oxygen[1] (DO)	Dissolved organic carbon[2] (DOC)	Calcium[2] (Ca)	Magnesium[2] (Mg)	Sodium[2] (Na)	Potassium[2] (K)	Bicarbonate[1] (HCO_3)	Sulfate[2] (SO_4)	Chloride[1] (Cl)	Nitrate[2] (NO_3 as N)	Silica[2] (SiO_2)
Rainwater	Median	34	4.26	--	--	--	--	--	--	0	--	1.5	--	--
	Minimum	8	3.30	--	--	0.46	0.22	1.4	--	0	0.89	.3	0.09	0.11
	Maximum	108	6.37	--	--	.53	.32	1.4	--	1.83	2.50	2.8	.38	.93
Runout	Median	442	8.24	--	--	6.8	29.0	68.0	1.8	157	15.0	51.3	1.9	1.7
	Minimum	100	7.28	--	--	4.4	17.0	3.4	1.1	76.81	7.3	3.7	.78	1.5
	Maximum	60,000	8.88	--	--	9.4	39.0	200	3.2	318	27.0	>8,000	2.8	2.3
Impounded storm water	Median	520	8.46	#	5.0	5.7	52.0	10.5	2.55	279	16.5	15.8	1.1	1.65
	Minimum	310	7.20	6.94	3.3	3.8	47.0	5.9	1.6	67.3	13.0	1.0	.79	1.3
	Maximum	5,100	9.01	10.78	6.5	9.4	68.0	240	3.8	453	30.0	1,380	1.9	2.2
CA Db 66[3]	Median	279	6.71	1.13	1.4	53.5	2.85	3.05	1.4	150	15.0	3.4	.1	8.15
	Minimum	102	6.47	.07	.7	33.0	2.0	2.6	.6	44.5	11.0	2.0	< .1	6.4
	Maximum	421	7.22	4.15	1.7	71.0	7.1	8.0	2.5	260	24.0	5.0	.2	9.3
CA Db 67[4]	Median	165	6.42	3.18	--	20.0	3.8	5.6	4.6	65.22	17.0	4.7	--	7.6
	Minimum	102	5.95	1.30	1.2	16.0	3.0	4.2	.6	35.96	9.1	2.8	.10	6.8
	Maximum	275	6.53	5.43	1.5	24.0	6.6	10.0	4.9	114	19.0	10.0	.12	8.1
CA Db 69[5]	Median	650	4.80	.31	1.5	6.4	21.0	93.0	2.55	6.09	5.9	183	5.4	8.2
	Minimum	162	4.39	.10	1.0	1.9	6.0	40.0	1.3	1.21	4.2	55.0	3.9	7.7
	Maximum	3,000	5.52	.93	2.2	16.0	37.0	120	3.6	12.56	15.0	310	8.3	9.8
CA Db 70[6]	Median	413	5.17	.71	*	3.7	5.6	65.0	*	23.77	5.8	115	--	6.4
	Minimum	182	4.48	.24	*	3.5	5.1	55.0	*	12.68	5.0	9.9	2.7	6.3
	Maximum	1,400	5.53	2.64	1.0	9.3	5.9	67.0	2.4	46.93	8.2	308	2.7	7.7

Table 31.—Median, minimum, and maximum values for specific conductance, pH, dissolved oxygen, and concentrations of major ions in filtered aqueous solutions at the Prince Frederick site—Continued

Station description	Concentration	Specific conductance[1] (uS/cm)	pH[1]	Dissolved oxygen[1] (DO)	Dissolved organic carbon[2] (DOC)	Calcium[2] (Ca)	Magnesium[2] (Mg)	Sodium[2] (Na)	Potassium[2] (K)	Bicarbonate[1] (HCO_3)	Sulfate[2] (SO_4)	Chloride[1] (Cl)	Nitrate[2] (NO_3 as N)	Silica[2] (SiO_2)
CA Db 72[7]	Median	700	5.61	1.27	1.1	23.0	17.5	83.0	4.3	29.87	13.5	190	2.30	12.5
	Minimum	570	4.99	.22	1.1	19.0	12.0	74.0	3.3	10.36	10.0	135	1.90	12.0
	Maximum	954	6.20	2.51	1.2	69.0	22.0	93.0	8.3	173	21.0	220	2.80	14.0
CA Db 73[8]	Median	731	5.68	1.24	1.4	31.0	16.0	76.0	3.1	54.25	13.0	175	2.20	12.0
	Minimum	559	5.40	.09	1.0	28.0	8.8	49.0	.6	36.57	10.0	120	1.70	11.0
	Maximum	3,390	6.07	1.94	2.4	54.0	21.0	650	6.9	95.09	19.0	1,400	3.00	13.0
CA Db 84[9]	Median	680	8.08	--	*	7.6	40.0	82.0	1.8	203	13.0	130	1.60	2.0
	Minimum	270	7.48	--	*	5.7	31.0	30.0	1.4	97.54	6.5	13.0	< .10	.90
	Maximum	20,000	8.74	--	6.5	21.0	140	750	4.3	322	51.0	4,500	2.00	3.70

1 Data shown for specific conductance, pH, dissolved oxygen, bicarbonate, and chloride are for weekly or monthly samples that include samples sent to the laboratory (Appendix H).

2 Data shown are for laboratory analyses of dissolved organic carbon, calcium, magnesium, sodium, potassium, sulfate, nitrate, and silica concentrations (Appendix C). DOC samples passed through 0.45-μm-silver filter; cation and anion samples passed through 0.1-μm filters, except for bicarbonate samples (unfiltered) and nutrient samples (0.45-μm pore diameter).

3 Control well.

4 Auxiliary control well.

5 Downgradient well.

6 Auxiliary downgradient well.

7 Beneath-impoundment well screened approximately 2 to 7 feet below water-table surface.

8 Beneath-impoundment well screened at water-table surface.

9 Lysimeter.

Table 32.—Comparison of magnesium, bicarbonate, and silica concentrations in storm water at the Prince Frederick, Annapolis, and Greenmount study sites

[median concentrations, in milligrams per liter]

Study site	Magnesium	Bicarbonate	Silica
Prince Frederick			
Runout	29.0	158	1.70
Impounded storm water	52.0	279	1.65
Annapolis			
Runout	.77	27.43	.84
Impounded storm water	.87	22.86	.75
Greenmount			
Runout	1.20	65.04	1.20
Impounded storm water	1.02	62.48	.70

CA Bb 6 compared favorably with those of upgradient wells CA Db 66 and 67 (tables 24, 31, and 33). Some effect from dissolution of tombstones and other chemical degradation cannot be ruled out, but such an effect was not obvious.

The chemistry of ground water at the upgradient wells differed substantially from beneath-impoundment (CA Db 72, 73) and downgradient (CA Db 69) ground-water chemistry (table 31, fig. 50). Upgradient ground water (CA Db 66) had a median pH of 6.71 and a median specific conductance of 279 µS/cm. The median pH of beneath-impoundment ground water (CA Db 73) decreased to 5.68 and median specific conductance increased to 731 µS/cm. The median pH of ground water decreased further downgradient (CA Db 69) to 4.8 and specific conductance remained elevated, with a median of 650 µS/cm.

Elevated specific conductances of beneath-impoundment and downgradient ground water were caused by mixing with storm-water infiltrate that was characterized by much higher dissolved-solids concentrations. The specific conductance of ground water beneath the impoundment correlated well with chloride plus magnesium plus bicarbonate, whereas chloride and specific conductance in downgradient water correlated at the 94-percent confidence level.

Unimpeded infiltration of precipitation caused increases in dissolved-oxygen concentrations in ground water at the control and downgradient wells. This effect was absent at the impoundment wells, however, where recharge was impeded through the impoundment structure. Nevertheless, dissolved-oxygen concentrations in ground water at Prince Frederick decreased in the downgradient direction (fig. 51). Upgradient ground water had median concentrations of 1.13 mg/L (CA Db 66) and 3.18 mg/L (CA Db 67); median dissolved-oxygen concentrations in ground water beneath the impoundment of about 1.24 mg/L decreased in downgradient wells to less than 1 mg/L (0.31 mg/L in CA Db 69 and 0.71 mg/L in CA Db 70). Microbial consumption of oxygen is one possible cause for reduced concentrations of dissolved oxygen. On the other hand, there was some evidence that an unmonitored component of ground-water flow entered the beneath-impoundment and downgradient study system from the east; this unmonitored flow might have had ambient dissolved-oxygen concentrations that were low. (See discussion of pH on the following pages.)

Three causes were postulated to explain dramatic decreases in pH between upgradient, beneath-impoundment, and downgradient ground water: (1) The pH of upgradient ground water did not represent background but resulted from leaching of carbonates at the cemetery; (2) chemical reactions, such as iron oxyhydroxide precipitation and mixing of waters with different ionic strength, lowered pH; and (3) upgradient ground water from the south was buffered by carbonaceous aquifer sediments that were diminished beneath the impoundment, were absent downgradient, and might have been diminished in upgradient ground water from the east.

It is possible, given the acidity of rain at the site, that dissolution of exposed carbonate surfaces buffered the infiltrating solution and resulted in recharge of ground water by solution with a neutral pH. The pH of ground water sampled at well CA Db 82 (at the upgradient edge of the impoundment) was somewhat lower (6.2), which could have been the result of dilution by

Table 33.—Chemical analyses of ground water collected from wells screened in the Upland deposits near the Prince Frederick site[1] and field measurements of ground water collected from piezometers at the Prince Frederick site

[ft, feet; ft asl, ft above sea level; ft bls, feet below land surface; pH in standard units; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; filtered samples passed through 0.45-micrometer filters; --, no data]

Well number	Altitude (ft asl)	Water level (ft bls)	pH	Specific conductance (µS/cm)	Calcium, filtered (mg/L)	Magnesium, filtered (mg/L)	Sodium, filtered (mg/L)	Potassium, filtered (mg/L)	Alkalinity, as $CaCO_3$ (mg/L)	Sulfate, filtered (mg/L)	Chloride, filtered (mg/L)	Nitrate as nitrogen, filtered (mg/L)
CA Bb 1	144	27.87	5.1	116	5.5	2.7	5.2	7.3	2	14	7.8	4.70
CA Bb 6	140	21.20	7.3	171	27	.8	2.6	6.8	78	2	3.2	.20
CA Bb 12	160	75.00	8.1	219	33	4.4	--	--	94	--	9.0	--
CA Db 6	158	12.84	5.8	134	5.6	3.5	8.0	3.6	5	4.1	14	6.32
CA Ec 4	173	43.90	6.5	70	2.9	1.2	5.3	.2	10	2	9.5	1.42

[1] Weigle and Webb, 1970.

infiltrating rainwater. The data in table 33, however, indicate that ambient pH of ground water in Upland deposits can range from 5.1 to 8.1 and that pH of 6.2 to 6.7 is not anomalous for ground water from this aquifer. Furthermore, storm water percolating from the impoundment to ground water had an initial pH of about 8.5, but this elevated pH did not result in a higher pH of receiving ground water. Moreover, the upgradient area of recharge at the impoundment is small because the site is near the ground-water divide. Thus, it is not possible to account for a pH decrease from about 6.2 to 5.6 (CA Db 72, 73) because of dilution from precipitation or upgradient recharge.

The second cause postulated—precipitation of iron oxyhydroxide phases—is likely to be occurring because saturation indexes showed that impoundment water and ground water were supersaturated with respect to ferric mineral phases. Nevertheless, it is unlikely that these reactions would have been on a scale large enough to account for the magnitude of the pH reduction observed.

The third hypothesis is the best and simplest explanation, and it was alluded to in the section that described native geologic materials at Prince Frederick. Reworked shell material was present in aquifer sediments cored near the base of the Upland deposits at the upgradient wells. These wells (CA Db 65-67 and CA Db 80, 82, 83) were screened near the base of the aquifer. Considerably less shell material was found in cores from the impoundment wells, which were screened farther above geologic contact. No shell material was found in cores collected at CA Db 79 at the eastern edge outside the impoundment or in cores collected at the downgradient wells (CA Db 68-70). Moreover, the pH of the sole ground-water sample collected for reconnaissance purposes only from piezometer CA Db 79 was 5.18; this low pH indicates that there was likely to have been a substantial component of ground-water recharge from the east that had an ambient pH an order of magnitude less than that coming from the south-southeast or north. The effect of pH reductions caused by chemical reactions was superposed on the lithologic controls buffering ground-water pH, and probably account for pH measurements as low as 4.99 in beneath-impoundment samples and of 4.39 in downgradient samples. Mixing of ground water with infiltrating, acidic atmospheric deposition does not occur beneath the impoundment because deposition is buffered rapidly by surface and impoundment materials. Atmospheric deposition at the downgradient wells, however, probably is virtually unbuffered because it percolates directly through leached soils and sediments.

Major elements

Rainwater and storm water.—Concentrations of major ions and selected trace elements were analyzed in samples from two storms in which pH was 4.77 and 4.80 (Appendix C); however, laboratory determinations of the major ions for a sample collected on September 9, 1987, was questionable because of an ion imbalance that exceeded the 10-percent margin allowed for rainwater samples (37-percent imbalance). Comparison of the analytical data for the two samples reveals that the concentrations of the major cations were equivalent, but that large discrepancies in sulfate and nitrate concentrations can account for the imbalance of the first sample. The dominant cation was sodium in these rainwater samples; the dominant anion was sulfate, with concentrations of nitrate (in milliequivalents per liter) exceeding those of chloride. Field measurements and laboratory determinations for chloride were equivalent. Sodium concentrations were the same in both samples and were similar to the sodium concentrations measured in Annapolis and Greenmount rainwater samples.

Prince Frederick storm water plotted as a magnesium bicarbonate solution throughout most of the year but as a sodium chloride type whenever the roads were salted (fig. 52). Chloride concentrations in storm water ranged from 3.7 to greater than 8,000 mg/L (Appendix H). Sodium and chloride concentrations were generally greater in the runout than in impoundment water, although specific conductance tended toward higher values in impoundment water (table 31). Apparently, sodium and chloride are transported rapidly through the impoundment, and their effect upon the specific conductance of impoundment water is transient. Median concentrations of magnesium and bicarbonate in impoundment water, which were nearly double those in runout (table 31), demonstrate that the longer residence time of storm water in the impoundment enhanced dissolution of magnesium carbonate minerals in the Hunting Hill rocks and thus contributed substantially to specific conductance. Ca:Mg ratios (calculated from the median value in milliequivalents per liter) for runout and impoundment water were 0.14:1 and 0.07:1, respectively.

Concentrations of calcium, potassium, sulfate, and silica were similar for runout and impoundment water (table 31). The fact that median, minimum, and maximum concentrations of silica were similar in runout and impoundment water indicates that dissolution of mafic silicate minerals was minor compared with carbonate dissolution. The bicarbonate anion was balanced by magnesium and calcium cations.

Water in the unsaturated zone.—The major-ion composition of water samples collected from the unsaturated zone was similar to that of storm water, plotting as a magnesium or magnesium-plus-sodium bicarbonate solution for most of the year and occasionally as a sodium chloride solution during the winter and spring (fig. 52). The median concentration of magnesium was slightly lower in unsaturated-zone water than in impoundment water, but sodium and chloride concentrations were much greater and exceeded runout concentrations as well (table 31).

Concentrations of chloride in unsaturated-zone water generally followed the concentration pattern for storm water, but unsaturated-zone concentrations somewhat exceeded those in storm water during most of the data-collection period (fig. 53). Patterns of high chloride concentrations were similar for runout and unsaturated-zone water but not for impoundment water. Periods of strong evaporation and low rainfall (table 25) seemed to have a notable effect: chloride concentrations in runout generally were exceeded by those in unsaturated-zone water during June through December 1987 and 1988 (fig. 53). The data indicate that moderate rainfall during these periods resulted in an

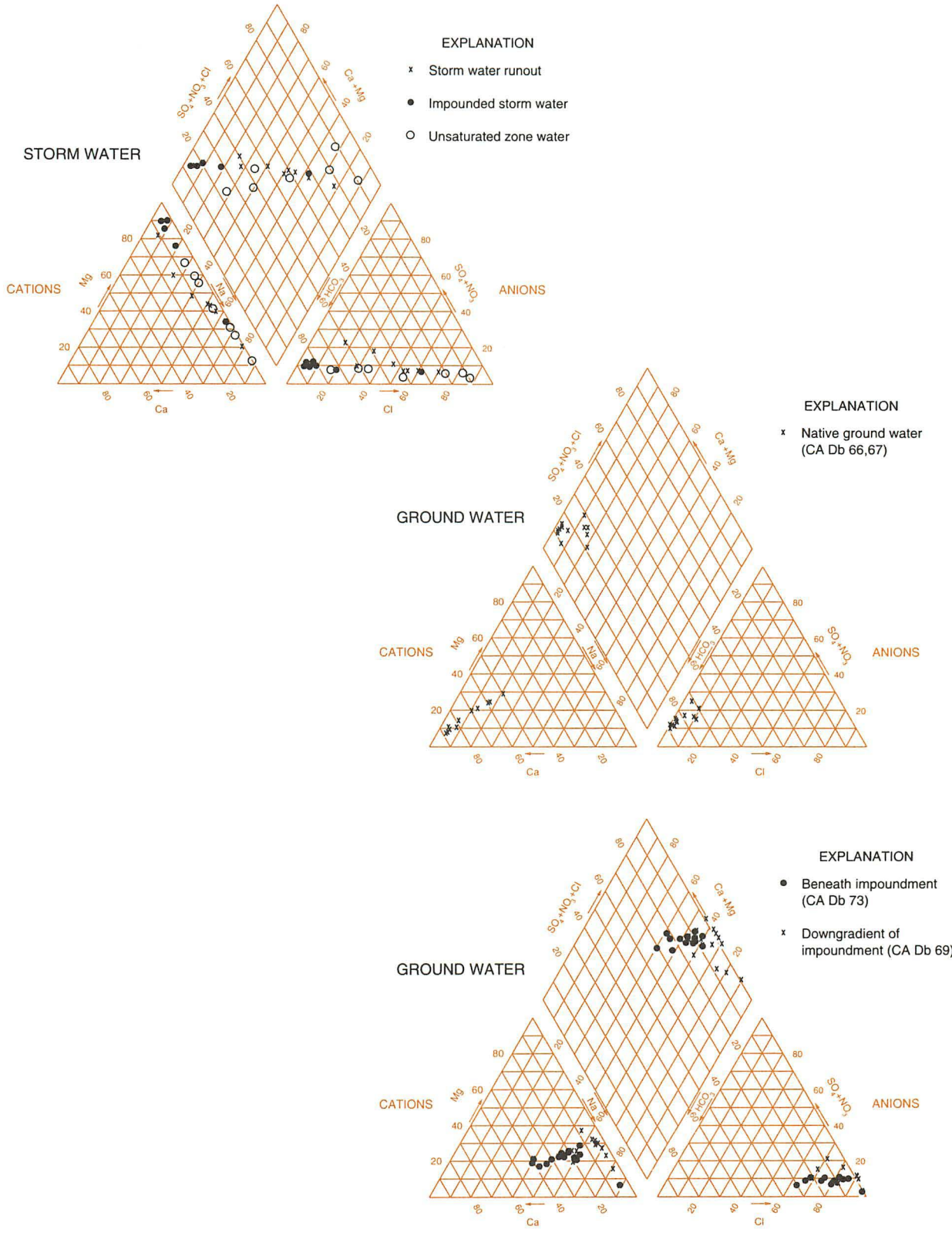


Figure 52.—Percentage of major ions in aqueous solutions at the Prince Frederick site. (Samples collected each spring, summer/fall, and winter of 1986–87, 1987–88, and 1988–89.)

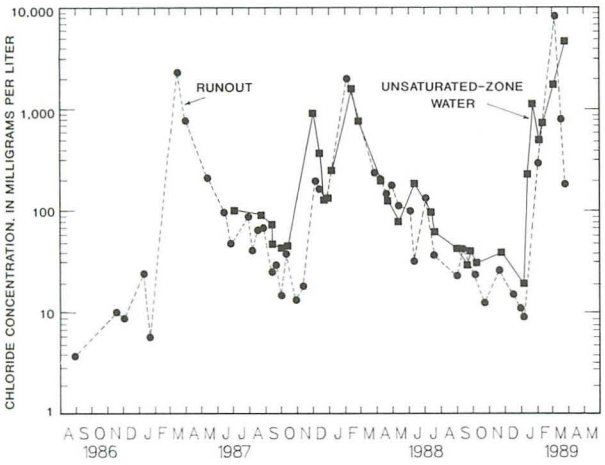


Figure 53.—Chloride concentrations in storm discharge (runout) and unsaturated-zone water at the Prince Frederick site, August 1986–March 1989.

increase in chloride concentrations in unsaturated-zone water, whereas greater amounts of rainfall diluted unsaturated-zone concentrations. This pattern indicates that dispersion and evaporative pumping impedes vertical transport of some of the chloride entering the unsaturated zone, which can become a source of chloride to ground water during subsequent recharge.

Median concentrations of calcium, potassium, sulfate, nitrate, and silica were similar in unsaturated-zone water and storm water; however, maximum concentrations of calcium, sulfate, and silica were higher in unsaturated-zone water. One sample only of unsaturated-zone water, from well CA Db 84, was analyzed for dissolved organic carbon (DOC). The DOC concentration (6.50 mg/L) equaled the maximum reported for impoundment water (table 31).

Ground water.—The chemical composition of native ground water collected from the control wells plotted as a calcium bicarbonate type water (fig. 52). Mean ratios of Ca:Mg and Ca:Na were 10.3:1 and 8.1:1, respectively, for water samples collected from well CA Db 66. These ratios remained fairly constant throughout the study period. The source of calcium and bicarbonate comprising this well-buffered solution was probably reworked shell material in the basal aquifer, which was mentioned in the discussion of ground-water pH.

Beneath and downgradient from the impoundment, the major-ion composition of ground water changed from a calcium bicarbonate type to a sodium chloride type (fig. 52). Ca:Na ratios were 0.26:1 and 0.06:1, respectively. Chloride comprised at least 88 percent of the major anions in beneath-impoundment ground-water samples, compared with only about 11 percent of the major anions in upgradient ground-water samples. The shift in chemical composition toward sodium chloride was caused primarily by a large, storm-water-borne input of sodium and chloride to the aquifer system. The shift away from calcium bicarbonate was caused, in part, by the diminished lithologic source of calcium- and carbonate-bearing minerals in aquifer materials downgradient and possibly to the east of the impoundment. In addition, the eastern component of ground-water recharge had a pH that was an order of magnitude lower than that measured at the control wells but similar to that of beneath-impoundment ground water: the upgradient area of recharge was greater from this direction than it was from the south-southeast, where the control wells were located. Calcium concentrations were lowest in ground-water samples collected downgradient; the downgradient concentrations were similar to those in storm water.

A storm-water imprint on ground-water chemistry was also seen as increases in magnesium concentrations and ratios: there was a sixfold concentration increase in samples of beneath-impoundment ground water and a sevenfold increase in downgradient ground water. The ratios for Ca:Mg were 1.4:1 and 0.3:1 for water collected from CA Db 73 and 69, respectively. These ratios were bracketed by those of native ground water (10.3:1) and impoundment water (0.07:1). Storm-water infiltrate was the only important source of magnesium to ground water and could have been a source of carbonate as well. Carbonic acid (H_2CO_3) is the stable species of inorganic carbon at the pH of beneath-pond and downgradient ground water, and most of the bicarbonate reaching ground water would have been converted to carbonic acid. The data indicate that dissolution of the magnesium-silicate minerals was minor compared to dissolution of the magnesium-rich carbonates as the source of magnesium and calcium.

The sole source of large concentrations of sodium and chloride in ground water was the storm-water infiltrate. Elevated chloride concentrations in beneath-impoundment ground water remained virtually constant throughout the study period (fig. 54). Chloride concentrations in downgradient water remained substantially elevated with respect to upgradient water, but fluctuated more than in upgradient water as a result of direct infiltration from rainwater. Chloride concentrations downgradient roughly followed concentration fluctuations in the unsaturated

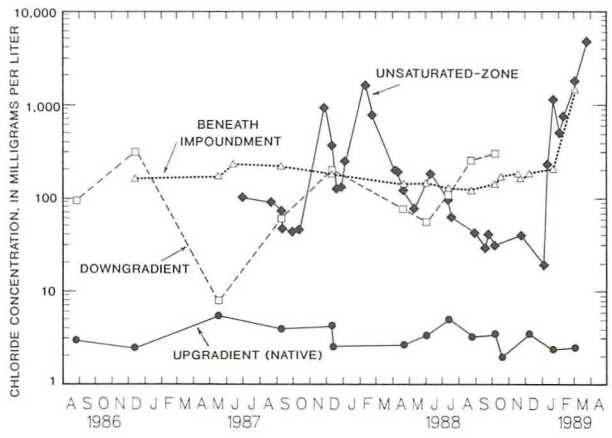


Figure 54.—Chloride concentrations in unsaturated-zone water and ground water at the Prince Frederick site, August 1986–March 1989.

zone and increased during periods of summer rainfall in 1988 and with winter road salting.

The plot of ground water on clay-stability diagrams indicates that samples collected upgradient, beneath the impoundment, and downgradient were in equilibrium with kaolinite (fig. 49). Beneath-impoundment ground water had the highest silica concentrations, and these concentrations exceeded quartz solubility. Downgradient ground water, on the other hand, had intermediate silica concentrations between those measured in upgradient and beneath-impoundment ground-water samples. The additional silica in beneath-impoundment ground water was from storm-water infiltrate. Although silica concentrations were much lower in storm water and the volume of storm-water infiltrate mixing with ground water was small, the ionic strength of the infiltrate solution was high. The effect on receiving ground water was additive, and the result was elevated silica concentrations because ground-water-flow velocity was slow. Dilution of ground water downgradient— probably from atmospheric deposition—mitigated the silica concentrations.

Trace elements and organic compounds

Rainwater and storm water.—The trace elements detected in rainwater at the Prince Frederick site included barium, cadmium, chromium, cobalt, copper, iron, lead, manganese, nickel, strontium, and zinc (table 34). (No determination was made for aluminum, antimony, arsenic, boron, or mercury.) The analytical methods used were probably not sufficiently sensitive for the detection of molybdenum or vanadium, nor for lead, nickel, and cobalt in some samples. The rainwater analyses confirm that precipitation can be a source of the constituents detected in runoff and ground water, but concentrations reported cannot be considered representative nor can the absence of other constituents be considered definitive.

Maximum concentrations of cadmium, chromium, copper, iron, lead, and zinc reported in filtered rainwater samples collected at the site exceeded maximum concentrations in filtered storm water (runout and impoundment water) (fig. 55). These trace elements can be expected to be dissolved in precipitation because rainwater was acidic. Storm-water pH was neutral to basic, and low dissolved concentrations of lead corresponded to high suspended concentrations in storm water compared with rainwater. There was no evidence of this relation between dissolved and suspended concentrations for the other constituents, however; mineral precipitation or sorption kinetics may have been sufficiently slow for removal of these metals from the dissolved phase.

Filtered storm-water concentrations of barium, cobalt, manganese, molybdenum, nickel, strontium, and vanadium exceeded rainwater concentrations (table 34). In addition, low concentrations of arsenic were detected in some samples of storm water, and aluminum concentrations were below or near detection. (Arsenic and aluminum were not analyzed for rainwater samples.) Much of the chromium, lead, molybdenum, and zinc in storm water was associated with particulates; however, lead was generally below detection and a high concentration of total molybdenum was found in one sample (fig. 56). Zinc was the sole constituent in Prince Frederick storm-water samples with constantly elevated concentrations.

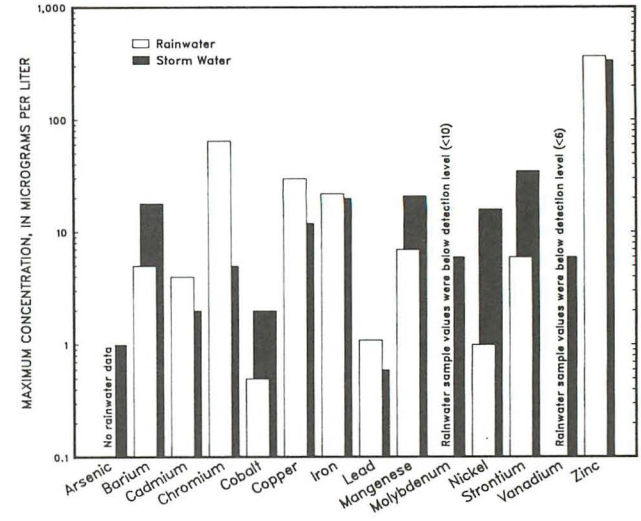


Figure 55.—Concentrations of selected trace elements in filtered rainwater and storm water at the Prince Frederick site.

Concentrations of trace constituents generally were equivalent for impoundment water and runout, although runout tended to have higher concentrations. Iron, copper, manganese, nickel, strontium, and zinc concentrations in runout generally were greater than impoundment-water concentrations. The elevated concentrations for these constituents in runout might be accounted for by an initial flushing of residual storm water from the impoundment. Constituent concentrations can increase in impounded storm water by evaporative concentration as well as by dissolution of Hunting Hill rocks.

Prince Frederick storm-water concentrations were generally lower with respect to most constituents than either storm water at the Annapolis and Greenmount sites or ground-water samples collected from the upgradient wells at Prince Frederick. The maximum concentration of dissolved organic carbon was 6.5 mg/L. Trace levels of toluene and tetrachloroethylene were reported in an analysis of one sample. Concentrations of methylene blue active substances were distinctively greater in storm water than in native ground water but never exceeded 1 mg/L.

Water in the unsaturated zone.—All the trace elements reported in storm water were detected in unsaturated-zone water, except for arsenic and lithium (fig. 57). Water from the unsaturated zone was depleted in zinc and possibly arsenic, compared to their median concentrations in storm water (table 34). Concentrations of barium, cadmium, chromium, cobalt, copper, iron, and strontium in some samples exceeded those in storm water, however. Median values were greater for barium, cadmium, cobalt, molybdenum, and strontium in unsaturated-zone water than in storm water.

Native sediments were probably a source of cobalt to unsaturated-zone water. Low concentrations of most other metals also were reported for Upland deposits (table 29), and the sedi-

Table 34.—Summary concentrations of selected trace constituents in rainwater, storm water, water from the unsaturated zone, and ground water at the Prince Frederick site

[Concentrations in micrograms per liter (ug/L), unless otherwise indicated; mg/L, milligrams per liter; f, filtered sample ("dissolved" constituents passed through 0.1-micrometer filter); u, unfiltered sample[1]; <, below detection[2]; --, no data; MBAS, methylene blue active substances]

Chemical[3] constituent		Rainwater		Storm water[4]		Ground water						Unsaturated-zone water	
						Upgradient		Beneath pond		Downgradient			
		Minimum	Maximum	Median	Maximum	Median	Maximum	Median	Maximum	Median	Maximum	Median	Maximum
Aluminum	(f)	--	--	<10	20	<10	20	85	190	820	1,200	--	20
Antimony	(f)	--	--	< 1	2	<1	<1	<1	<1	<1	<1	<1	<1
Arsenic	(f)	--	--	1	1	<1	2	<1	1	<1	<1	--	<1
	(u)	--	--	1	2	1	5	1	3	<1	2	--	<1
Barium	(f)	3	5	7	18	21.5	25	120	160	71	220	17	27
Boron	(f)	--	--	20	30	35	80	10	30	10	20	--	10
Cadmium	(f)	.3	4	.2	2	.3	2	1.2	8.4	.55	2	1	1
	(u)	--	--	<1	1	<1	2	1	2	<1	<1	--	--
Chromium	(f)	4.7	65	<.5	5	<.5	1	<.5	10	<.5	3	<1	9
	(u)	--	--	2.5	10	17	30	10	60	15	130	--	1
Cobalt	(f)	<3	.5	<.5	2	1.3	7	22	46	12	30	2.4	7
	(u)	--	--	1	2	6	12	29	58	27	45	--	--
Copper	(f)	20	30	6	12	3	4	3	9	7	9	6	30
	(u)	--	--	4.5	16	11	21	9	30	10.5	44	--	3
Iron	(f)	15	22	12.5	20	12	34	14.5	58	29	73	<10	31
Lead	(f)	1.1	--	<.5	.6	<.5	<5	<.5	5	1.1	2.7	--	.5
	(u)	--	--	<5	7	<7	12	<5	28	11	45	--	<5
Lithium	(f)	<4	<4	<4	6	<4	8	<4	8	<4	6	<4	<4
Manganese	(f)	4	7	1	21	67	230	660	1,200	140	350	8	24
Mercury	(u)	--	--	<.1	.1	.1	.3	.1	.2	--	.7	--	--

Table 34.—Summary concentrations of selected trace constituents in rainwater, storm water, water from the unsaturated zone, and ground water at the Prince Frederick site —Continued

Chemical[3] constituent	Rainwater		Storm water[4]		Ground water						Unsaturated-zone water	
					Upgradient		Beneath pond		Downgradient			
	Minimum	Maximum	Median	Maximum	Median	Maximum	Median	Maximum	Median	Maximum	Median	Maximum
Molybdenum (f)	<10	<10	<1	6	5.5	6	1	3	<1	3	1	1
(u)	--	--	1	32	5	8	2	8	<8	10	--	5
Nickel (f)	--	1	4	16	<5	7	28	46	10	36	4	7
(u)	--	--	4	8	8	20	38	70	26	47	--	--
Strontium (f)	1	6	19	35	190	420	210	470	80	190	35	41
Vanadium (f)	<6	<6	1	6	<1	1	1	3	<1	3	<6	6
Zinc (f)	66	370	57	340	11.5	39	65	320	32	97	19	55
(u)	--	--	140	670	60	90	110	420	90	370	--	<10
Organic compounds (u)												
MBAS (mg/L)	--	--	0.15	0.74	<0.01	0.02	0.05	4.3	0.05	4	--	--
Benzene	--	--	--	<.2	<.2	<.2	<.2	.3	<.2	<.2	--	--
Toluene	--	--	--	.8	<.2	<.2	<.2	<.2	<.2	<.2	--	--
Tetrachloroethylene	--	--	<.2	.2	<.2	<.2	<.2	<.2	<.2	<.2	--	--
1,1,1-Trichloroethane	--	--	--	<.2	<.2	<.2	<.2	3	<.2	<.2	--	--

[1] Concentrations of constituent for filtered samples may exceed those shown for unfiltered samples because filtered samples were analyzed more frequently than unfiltered samples.

[2] Value shown as below detection is the reporting limit set by the USGS National Water Quality Laboratory; detection/reporting limits depend upon the analytical methods requested, which varied as appropriate according to initial screening of constituent concentrations in the water source.

[3] See Appendix C for a comprehensive table of laboratory analyses.

[4] Data shown are for water impounded in and discharging from the subsurface porous-pavement reservoir.

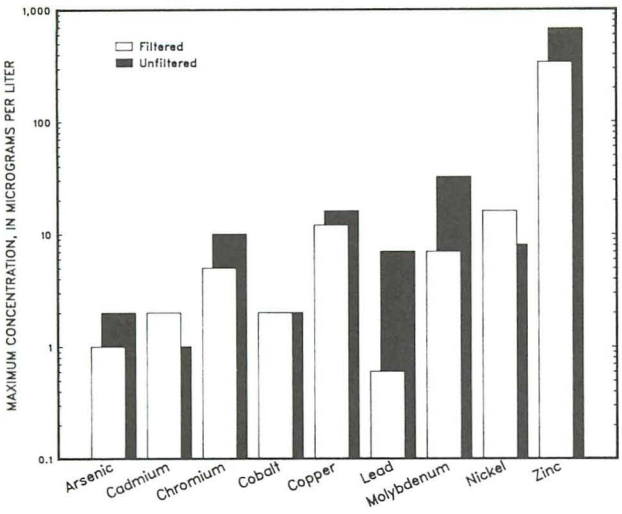


Figure 56.—Comparison of maximum filtered and unfiltered concentrations of trace elements in storm water at the Prince Frederick site.

ments cannot be ruled out as a possible source of these metals to associated solutions. Rainwater (and consequently, storm water) was the sole source of cadmium, however. The median cadmium concentration was higher in unsaturated-zone water than in storm water. At the ambient pH of the unsaturated zone, cadmium was expected to partition to particulates and out of solution.

Of the most abundant dissolved trace elements reported in unsaturated-zone water, barium, strontium, and zinc were common constituents of storm water, and storm water was the probable source of these constituents to the unsaturated zone. On the other hand, similar or greater concentrations of these constituents were reported in native ground-water samples collected from the upgradient wells (fig. 57B). Compared with filtered upgradient ground-water samples, trace-element concentrations generally were low in unsaturated-zone water: only chromium, copper, lead, vanadium, and zinc data indicated concentrations that were greater in some samples of filtered unsaturated-zone water (fig. 57A,B).

Ground water.—All of the trace elements that were reported in storm water and unsaturated-zone water were present in ground-water samples collected from the upgradient wells. Concentrations of cadmium and possibly iron, lithium, molybdenum, and nickel in upgradient ground water resembled rainwater concentrations. Concentrations of barium, cobalt, copper, lead, nickel, vanadium, and zinc were greater in storm and (or) unsaturated-zone water than in upgradient ground water.

There was no evidence that trace constituents leached to ground water from the cemetery. Concentrations of boron and strontium were greater in upgradient ground water than in beneath-impoundment and downgradient ground water (fig. 57). Boron and strontium concentrations were probably related to high calcium concentrations at the upgradient wells: dissolution of shell material in sediments near the Upland deposits—St. Marys Formation contact could have released calcium and strontium and produced an upward concentration gradient between the fossiliferous clay and calcium-poor Upland deposits. Boron is a common salinity indicator, and it is likely to have come from the St. Marys Formation; boron concentration decreased appreciably beneath the impoundment and downgradient. Strontium remained elevated beneath the impoundment but decreased more than 50 percent in downgradient ground water.

Concentrations of most trace elements increased appreciably between samples collected from upgradient, beneath-impoundment, and downgradient wells (fig. 57). Notable increases occurred in concentrations of aluminum, barium, cadmium, chromium, cobalt, copper, iron, lead, manganese, nickel, vanadium and zinc. These constituents can be grouped into two categories on the basis of source and process: those for which the source was internal to the aquifer but which were mobilized by biogeochemical processes that induced reduction in pH and redox; and those for which the predominant source of trace element was external to the aquifer and which were transported to ground water in storm-water infiltrate. In either case, processes that caused decreases in pH and redox seem to have been induced by biochemical reactions in the storm-water impoundment.

Decrease in pH was the major cause for mobilization of aluminum, cobalt, iron, manganese, and possibly barium. Aluminum, iron, and manganese are not stable as oxidized species at low pH; mineral phases that incorporate cobalt and barium are subject to corrosion under acidic conditions.

Elements for which ground-water concentrations were elevated because of direct transport in storm-water infiltrate were cadmium, chromium, nickel, lead, and zinc. Because no source other than storm water was determined for cadmium, it is postulated that elevated concentrations beneath the impoundment reflected an accumulation from storm-water infiltrate mixing with slow-moving ground water; in this respect, cadmium movement was similar to that of silica, sodium, and chloride. Ground-water enrichment in nickel and zinc beneath the impoundment followed a similar pattern. Dilution attenuated concentrations of silica, cadmium, nickel, and zinc in downgradient ground-water samples. Chromium and lead concentrations were most elevated in samples from the downgradient well but were strongly partitioned to suspended matter. Chromium and lead possibly moved as colloids through the aquifer. Although storm water entering the impoundment was the likely source of lead, chromium may have had an additional source from mineral dissolution.

Comparison of beneath-impoundment ground water collected at the water-table surface (well CA Db 73) with that ground water collected 5 ft deeper (well CA Db 72) shows equivalent concentrations of most trace elements; however, somewhat greater concentrations of aluminum, cadmium, chromium, and zinc were measured in water samples from the deeper well (Appendix C). Partitioning of trace elements between dissolved and suspended phases in ground water was similar for most constituents in upgradient, beneath-impoundment, and downgradient ground water. Cadmium and cobalt were

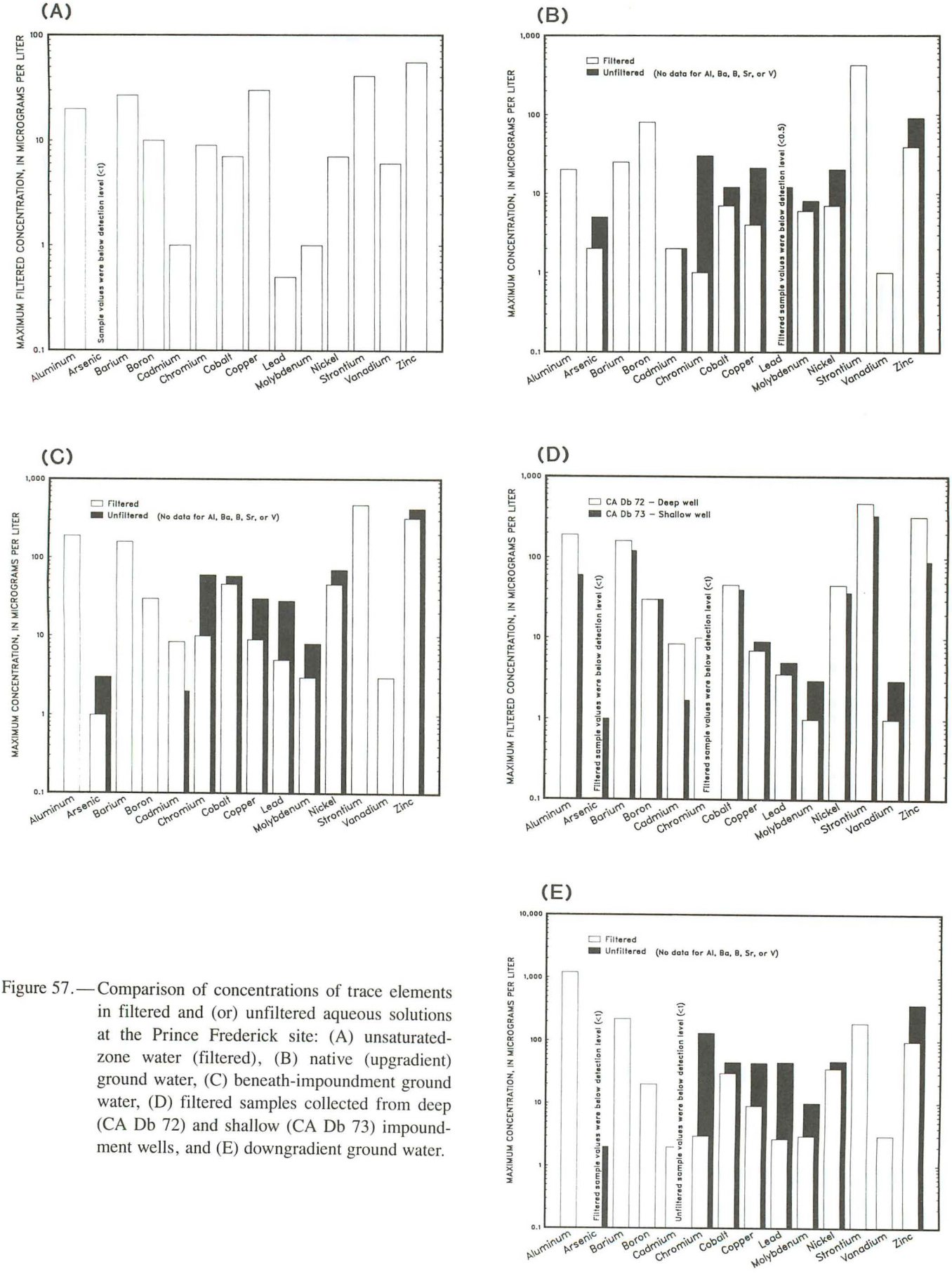


Figure 57.—Comparison of concentrations of trace elements in filtered and (or) unfiltered aqueous solutions at the Prince Frederick site: (A) unsaturated-zone water (filtered), (B) native (upgradient) ground water, (C) beneath-impoundment ground water, (D) filtered samples collected from deep (CA Db 72) and shallow (CA Db 73) impoundment wells, and (E) downgradient ground water.

found primarily in the filtered sample. Chromium, copper, and lead largely associated with the particulates in the unfiltered sample. Nickel and zinc were present as a dissolved phase in ground-water samples collected beneath the impoundment but were more partitioned in upgradient and downgradient ground-water samples.

Volatile organic compounds were not detected in ground-water samples collected upgradient. A trace amount of methylene blue active substances (MBAS) was detected once, and concentrations of dissolved organic carbon were around 1.4 mg/L. With the exception of MBAS, anthropogenic organic compounds were rarely detected in beneath-impoundment ground-water samples and were never detected in downgradient samples. Benzene and 1,1,1-trichloroethane were detected in beneath-impoundment ground water at slightly elevated concentrations once. MBAS concentrations were uniformly elevated in samples of beneath-impoundment and downgradient ground water; these waters were easily distinguished from upgradient ground water on this basis.

Recapitulation of Prince Frederick Site Characteristics and Water Quality

The Prince Frederick storm-water-management structure (fig. 43) was constructed in the unconsolidated Coastal Plain sediments of the Upland deposits. The depth to water beneath the storm-water structure (a rock-filled impoundment surfaced with porous asphalt paving) ranged from 23 to 27 ft. The average hydraulic gradient of the water-table surface from upgradient to downgradient across the site was 1.7 percent, and it steepened slightly to an average of 2 percent beneath the impoundment to downgradient. There was no evidence of mounding beneath the impoundment or at its perimeter. The rate of ground-water flow beneath the pond was estimated to be less than 1 ft/d from the literature and from the results reported for on-site bromide tracer tests.

Cores collected through the porous-pavement section at the beginning of the study confirmed that the rock aggregate used to fill the subsurface impoundment was a serpentinite containing carbonate veins characteristically rich in magnesium. Native geologic sediments underlying the impoundment were largely quartzose and were impoverished in magnesium. No subsequent coring was done, and the chemical nature of solid materials that passed through the porous asphalt surface to the impoundment remained undetermined.

Certain effects of storm-water-infiltration practices on ground-water quality were persistent and showed no amelioration throughout the 3-year period of data collection: dissolved solids (estimated from specific-conductance measurements), and chloride, magnesium, and sodium concentrations were substantially elevated, while dissolved-oxygen concentrations decreased substantially, in ground water beneath and downgradient from the impoundment. pH decreased by several orders of magnitude between the upgradient and downgradient wells, but

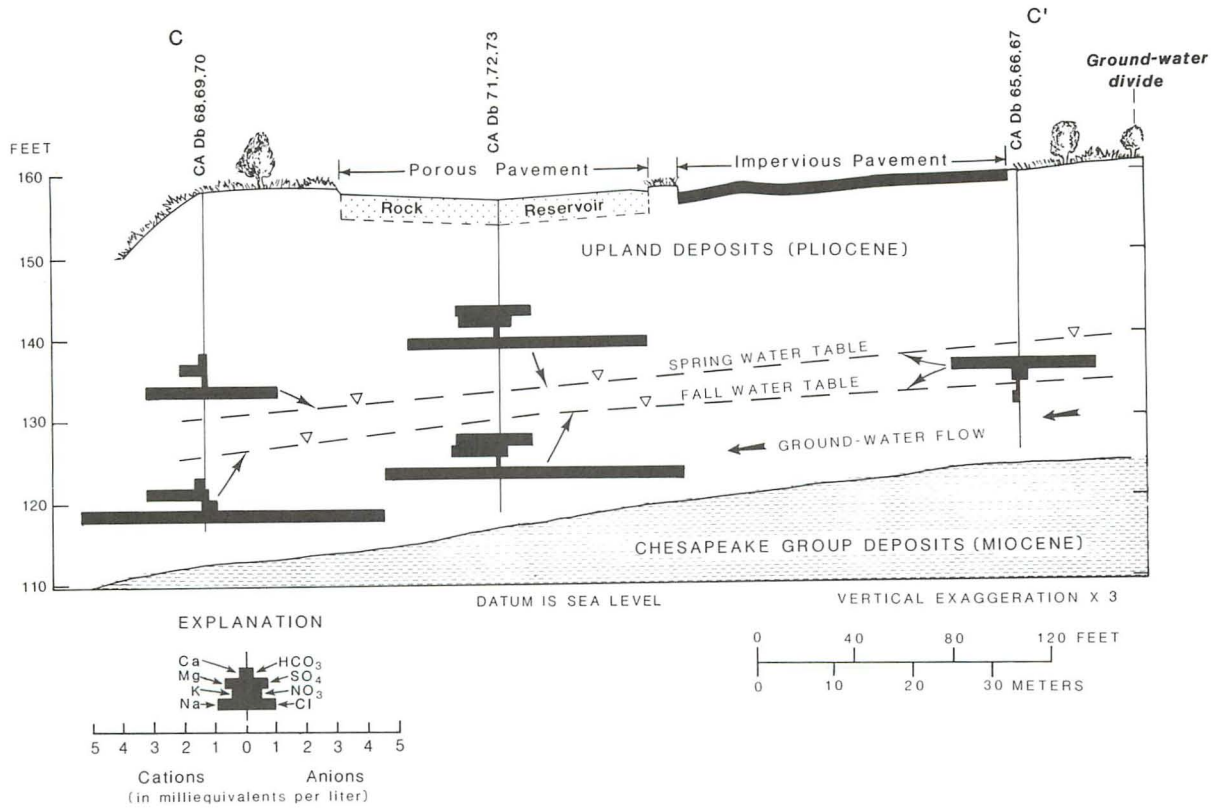


Figure 58.—Hydrogeologic section from upgradient (control) well to downgradient wells at the Prince Frederick site showing the major-ion chemistry of ground water with respect to seasonal high and low water table.

this decrease was attributable to compositional variations in native geologic materials.

Storm-water transport to the water table was the sole source of elevated concentrations of magnesium, sodium, and chloride in ground water beneath and downgradient from the impoundment. The magnesium imprint on ground water was from storm-water dissolution of magnesium-rich minerals composing the rock aggregate in the impoundment; dissolution of deicing salts was the sole source of sodium and chloride to the impoundment, and subsequent storm-water infiltration was the cause of elevated concentrations in ground water. Storm-water transport of these constituents resulted in persistent modification of the major-ion chemistry in ground water at the site, from a calcium carbonate-type water to a magnesium sodium chloride-type water (fig. 58). Chloride ions in ground water beneath the impoundment constituted 88 percent of major anions, compared with 11 percent in ambient ground water.

The USEPA SMCL of 250 mg/L for chloride was exceeded in storm water and in water from the unsaturated zone whenever deicing salts were applied. Chloride concentration periodically exceeded the SMCL in beneath-pond ground water, occasionally reaching a concentration close to that of brackish water. The highest chloride concentrations in ground water tended to occur in the late summer or early fall, during periods of evapotranspiration.

Nitrate concentrations in storm water or ground water did not exceed the USEPA MCL. Nevertheless, storm water was the source of nitrate concentrations that were elevated in ground water receiving infiltrate, compared with ambient concentrations measured in upgradient samples.

Contamination of storm water and ground water by trace elements was sporadic and minor at the Prince Frederick site: MCL's and SMCL's never were exceeded in samples of storm water analyzed; only zinc was found at moderately high concentrations in some samples. Nevertheless, barium, cadmium, chromium, cobalt, copper, lead, and molybdenum, nickel, and vanadium (as well as zinc) were ubiquitous components of storm-water chemistry in the impoundment, and storm-water infiltrate was the probable source of these constituents to underlying and downgradient ground water (fig. 59). Buildup of elevated concentrations of these constituents in ground water resulted from sluggish ground-water-flow rates, compared with the rapid rate of storm-water infiltration. MCL's and SMCL's were exceeded in some ground-water samples for chromium, lead, and cadmium. Aluminum concentrations exceeding the SMCL at the downgradient well were caused by a decrease in pH that was not related to storm-water management. The contaminant data were insufficient to determine whether, over time, contaminant concentrations would increase or would be detected with greater frequency.

FACTORS AFFECTING GROUND-WATER QUALITY AT THE STUDY SITES

The purpose of this section is to compare the general changes reported in ground-water quality at the storm-water-management sites and to examine some hydrologic and geochemical factors controlling contaminant concentrations and mobility. The central questions are, (1) which constituents contaminated the ground water, and (2) why were they not sequestered more effectively in pond-bottom and unsaturated-zone materials?

Ground-water quality can be assessed by comparing USEPA or State regulations pertaining to contaminant levels with constituent concentrations measured in ground-water samples. Such an assessment provides a snapshot of water quality at a given time, unless data were collected over a lengthy period and according to a strategy that minimized bias. The period of data collection and frequency of sample collection in this study generally were insufficient to determine temporal trends. The data were collected to determine whether contaminants entered the shallow ground-water system because of storm-water infiltration, to identify those that did, and to evaluate processes that could account for their presence in ground water. The process-focused approach is germane to the assessment of the potential for contaminant mobility over time.

Hydrologic and geochemical factors governed contaminant transport and concentration. Biochemical reactions mediated the ambient pond geochemistry and the fate of some constituents.

The data reveal striking similarities regarding the effects of storm-water infiltration on ground-water quality between the study sites. Ground water had elevated concentrations of metals and other inorganic and organic contaminants for which the storm-water infiltrate was the primary source at each study site. Concentrations of these contaminants exceeded USEPA drinking-water regulations periodically at each site, but at none of the sites did ground-water contamination chronically exceed USEPA regulations.

The contaminants for which concentrations exceeded or approached USEPA MCL's, proposed MCL's, SMCL's, or proposed SMCL's in ground water at two or more sites were aluminum, cadmium, chloride, chromium, and lead. The SMCL for chloride concentration was exceeded at each site. Cadmium concentration exceeded the MCL at Annapolis and Greenmount and nearly exceeded it at Prince Frederick. The median concentrations for chloride and cadmium at each site were substantially elevated with respect to background. MCL's or SMCL's for barium, copper, nickel, strontium, and zinc were not exceeded, but median concentrations were elevated in ground water receiving storm-water infiltration for at least two of the study sites.

Contaminant concentrations in storm water and beneath-impoundment and downgradient ground water (but not native ground water) fluctuated considerably from sample to sample.

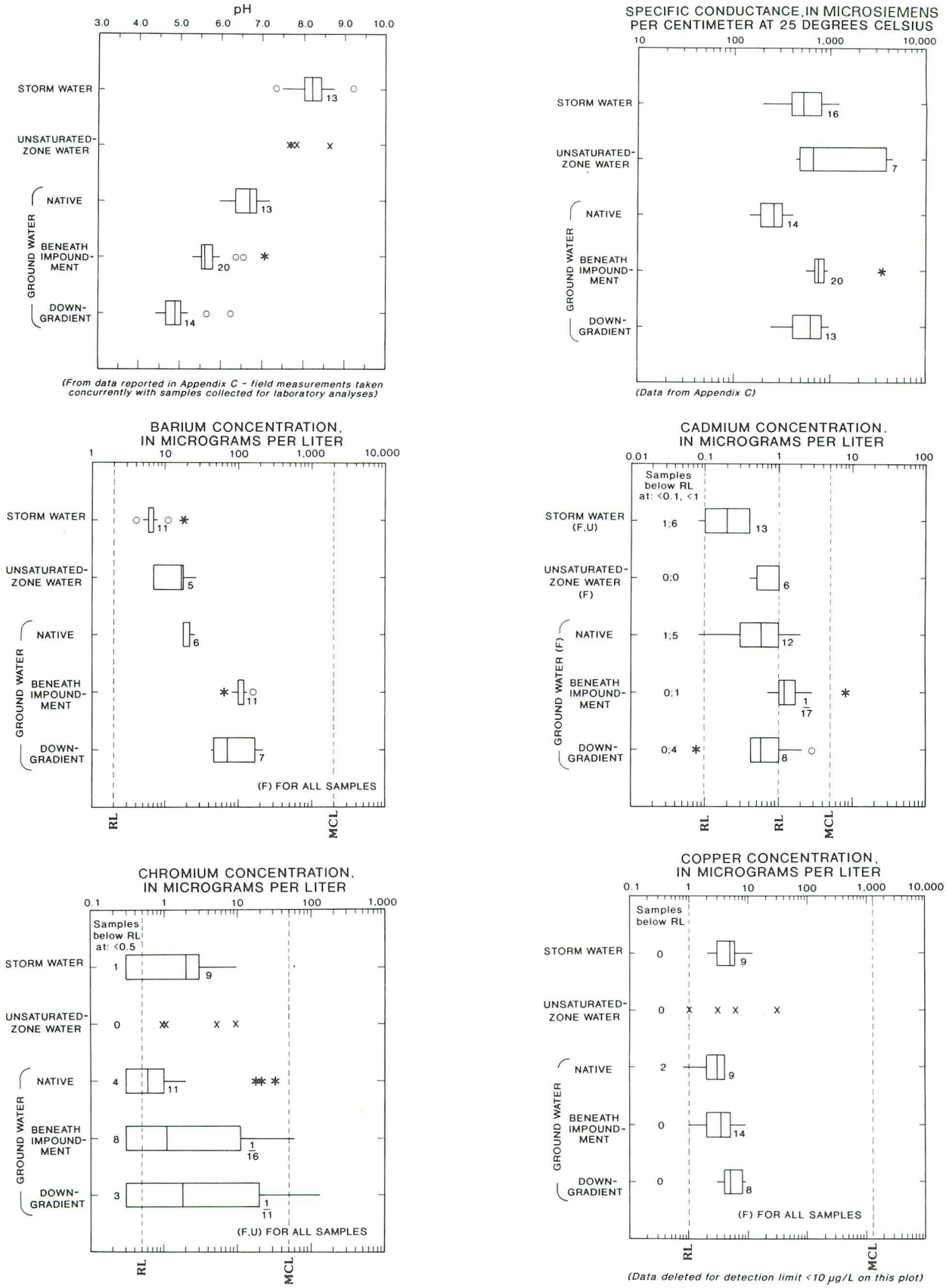
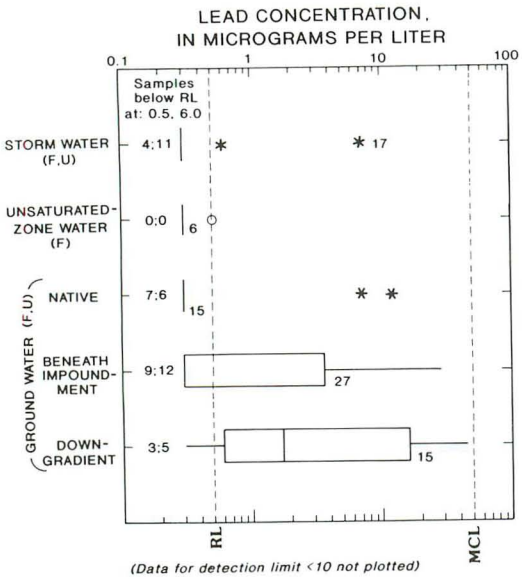
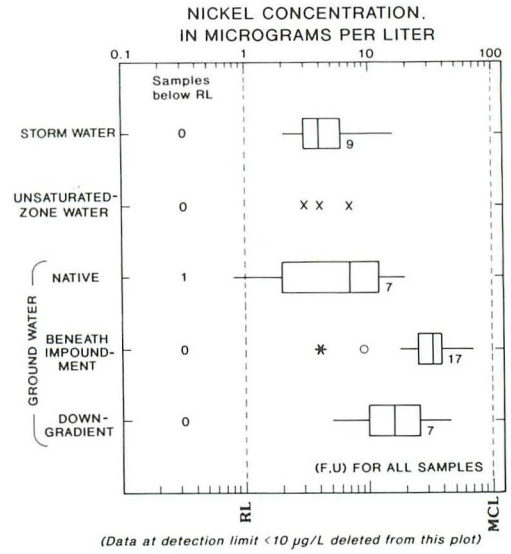
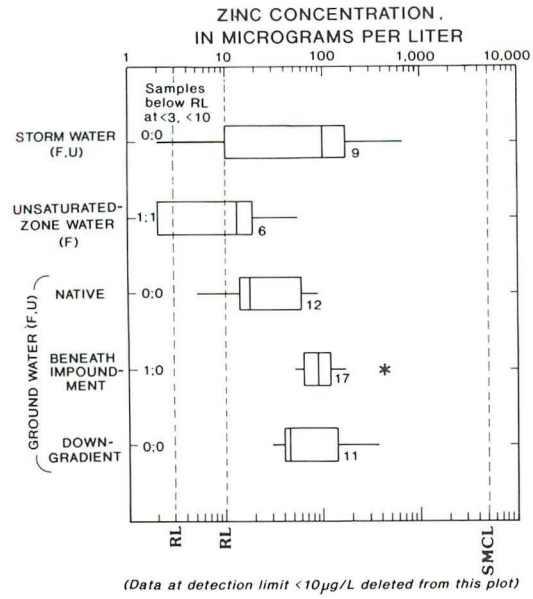
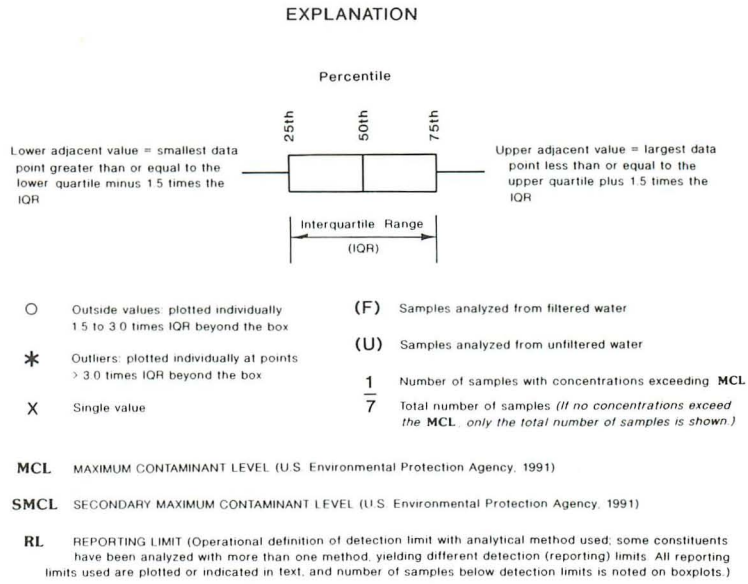


Figure 59.—Summary of pH, specific conductance, and aqueous concentrations of selected trace metals at the Prince Frederick site.









An influx of storm water with extremely high contaminant concentrations periodically discharged to the impoundments. These influxes caused occasional pulses of elevated contaminant levels in receiving ground water. Constituents that generally were at low concentrations in storm water and ground water, but for which pulses of high concentration typically occurred included chromium, lead, molybdenum, and vanadium.

HYDROLOGIC FACTORS AFFECTING CONTAMINANT CONCENTRATIONS

Hydrologic processes that mitigate elevated concentrations of contaminants in the unsaturated zone and ground water include simple mixing, dispersion, diffusion, and retardation. Dispersion and diffusion are the processes whereby contaminants can be diluted in time through space because concentrations are spread by moving ground water or by concentration gradients. Retardation is the loss of solute by chemical or biological reactions within impoundments, the unsaturated zone, or the aquifer. Dilution can result from hydrologic factors that include (1) the rate and amount of storm-water infiltration, (2) horizontal and vertical ground-water flow characteristics, (3) the area of ground-water (upgradient) recharge, and (4) the depth to water table. Dilution is caused also by direct recharge from rainfall. Evapotranspiration can have the opposite effect on contaminant concentrations in the shallow ground-water system. At some sites, the highest chloride concentrations were typically measured in ground-water samples collected in the summer or early fall; a heavy rainfall during this period seemed to flush residual chloride from the unsaturated zone, resulting in

elevated chloride concentrations. Chloride is commonly used as a tracer in aqueous solutions to monitor hydraulic rates and pathways (Davis and others, 1985), and the patterns of chloride concentration at the study sites were used to examine the effect of various hydrologic factors on contaminant concentrations.

An overall effect of storm-water infiltration on ground-water chemistry was a change in the ambient major-ion composition to a chloride-dominated water (fig. 60). This change constituted a threat to water quality at two sites—Annapolis and Prince Frederick—where chloride concentrations exceeded the SMCL in some samples. Elevated concentrations of chloride were accompanied by elevated sodium concentrations. The primary source of sodium and chloride was the dissolution of deicing salts in runoff.

The movement of chloride as a geochemically conservative (that is, relatively inert) element was important to investigate for two reasons. First, it could be used to distinguish between hydrologic and geochemical processes. Second, chloride was a ubiquitous and persistent contaminant in ground water at each study site. Chloride contamination of storm-infiltrate-receiving ground water was not surprising. The persistence of elevated concentrations was unexpected, however, because chloride entered a hydrologically dynamic system from three to eight times a year, at most, and dilution by upgradient ground water and storm recharge was expected. Nevertheless, the input of chloride was coincident with the major period of ground-water recharge. Dilution from recharge during the rest of the year was generally minor, and the upgradient ground-water drainage area was small. Evaporative pumping apparently enhanced chloride concentrations during periods of low rainfall, and moderate summer and fall rains could flush chloride from the unsaturated zone.

Storm-Water Infiltration Rate

Infiltration rates through the impoundments were low during dry weather—less than 0.04 ft/d. Infiltration rates were much greater during rainfall—as much as 38.4 ft/d at Annapolis, 130 ft/d at Greenmount, and 216 ft/d at Prince Frederick. Comparison of chloride concentrations in beneath-impoundment ground water before, during, and after a storm indicated that dilution was temporary. Chloride concentrations returned to prestorm levels or higher within a matter of days after recharge from the storm. Elevated chloride concentrations from deicing activities did not persist in impoundment water. Nevertheless, chloride concentrations tended to remain elevated in unsaturated-zone water compared with storm water, and slowed movement or pulses of chloride-enriched infiltrate may have been a continuing source of chloride to ground water. Elevated chloride concentrations persisted in ground water throughout the year. Thus, rapid infiltration rate was not a significant mitigating factor.

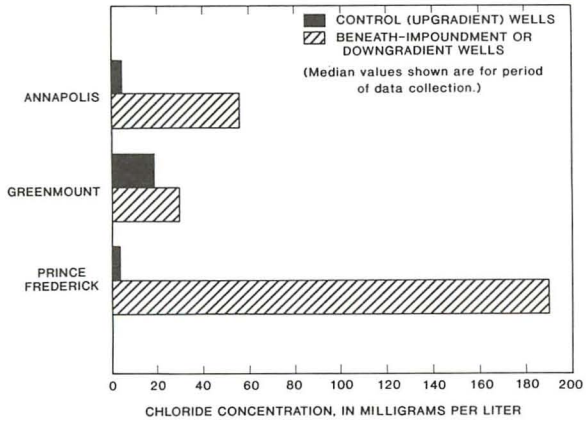


Figure 60.—Comparison of chloride concentrations in ground water at the three study sites.

Ground-Water-Flow Characteristics

The horizontal rate of ground-water flow was estimated at each site. Vertical flow rates were not determined. Hydrologic and geochemical lines of evidence, however, show that an upward component of ground-water flow at Annapolis mitigated contaminant concentrations. Ground-water-flow rates differed considerably between the sites; variation of rates at each site depended on hydrologic gradients.

Rate of ground-water flow

The horizontal rate of ground-water flow beneath the study sites was greatest at Greenmount (estimated to be 60 ft/d), followed by Annapolis (15 ft/d), and Prince Frederick (probably less than 1 ft/d). Application of chloride deicing salts was similar at Annapolis and Greenmount, and the maximum concentrations of chloride recorded in storm water were roughly equivalent. It is likely that deicing was more frequent at Greenmount because of more frequent snowfall. Chloride concentrations in ground water were smallest at Greenmount, occasionally exceeded the SMCL at Annapolis, and frequently exceeded the SMCL at Prince Frederick.

Much greater chloride concentrations were measured in Prince Frederick storm water because piles of road salt were deposited directly on the porous pavement. Unlike concentration patterns at Annapolis or Greenmount, which were characterized by considerable fluctuation, patterns of chloride concentrations for ground water beneath the Prince Frederick impoundment showed relatively little change throughout the year. (More typical concentration fluctuations occurred downgradient as a result of chloride dilution from direct rainfall.) High and constant chloride concentrations in ground water at Prince Frederick persisted because of slow horizontal ground-water flow.

This case illustrates that the rate of ground-water flow has an important effect on the persistence of contaminant concentrations: higher ground-water-flow rates relative to net storm-water infiltration can help spread contaminant concentrations over larger distances, whereas slower flow rates permit a buildup of contaminant concentrations.

Vertical component of flow

Vertical flow in ground water was downward beneath the impoundments because of head gradients from storm-water ponding; vertical flow had a strong downward component a relatively short downgradient distance from the impoundment, because this is near the area of ground-water discharge to the surface. Vertical mixing of ground water collected from the shallow (screened) section of the aquifer with deeper ground water occurred at the downgradient wells in Annapolis, where the hydrographs indicated an upward component of flow. Geochemical evidence for this mixing was an increase in pH and a shift in major-ion ratios that could not be explained by mixing with shallow upgradient ground water or rainwater. This mixing diluted the elevated concentrations of contaminants present in beneath-pond ground water. There also was geochemical evidence of downward flow of ground water beneath the impoundments, resulting in the downward transport of contaminants: at each site, concentrations of some contaminants were greater in some samples collected from a deeper interval in the aquifer than in samples collected at the water table.

Ground-Water Recharge Area

Each of these study sites was relatively near the local ground-water divide. Because the upgradient area of recharge was small, the potential for dilution from upgradient was correspondingly small. The small size of the upgradient recharge area restricted the ability of upgradient ground water to reduce contaminant concentrations by dilution in beneath-impoundment ground water at Prince Frederick and at Annapolis. The relative importance of the volumetric flow rates in dispersing contaminants could not be tested. Coincidentally, the site with the largest recharge area was Greenmount, where the ground-water-flow rate was also highest of the sites; Annapolis was intermediate with respect to recharge area and ground-water-flow rate; the Prince Frederick site, where the ground-water-flow rate was lowest, was less than 300 ft from the local ground-water divide to the south. Nevertheless, the fact that chloride concentrations remained elevated in downgradient ground water at all the sites indicates that the advective ground-water-flow rate could be the dominant hydrologic factor affecting dilution of conservatively transported contaminants.

Depth to Water Table

Storm-water regulations for the State of Maryland require a minimum depth to water table from the bottom of infiltration ponds to allow storm-water-borne contaminants to be "filtered out" or attenuated naturally before storm water enters the water table. Previous investigations at sites in the Midwestern United States, where unsaturated-zone thicknesses are on the order of hundreds of feet, have reported that contaminant concentrations from water percolating to the water table were diminished with depth to water table. In this study, in which unsaturated-zone thicknesses were less than 30 ft, comparison between sites of movement of major ions and contaminant constituents indicated that physical and hydraulic factors other than depth to water table were as important or of overriding importance in contaminant migration. These factors included preferential pathways of subsurface flow, such as macropores; contaminant loading and concentration gradients, such as heavy application of deicing salts; rate of ground-water flow relative to rate of storm-water infiltration; and capillary forces, especially within the unsaturated zone or zone of tension saturation.

Chloride and sodium/calcium from road salt moved readily to ground water, changing the major-ion chemistry of ground water to a chloride type at each study site. The magnitude of this effect could not be related to depth to the water table, as chloride concentrations in ground water were highest and most persistent at the Prince Frederick site, where the unsaturated zone was at least three times thicker but where chloride salts were applied in greater abundance each winter and spread directly on overlying porous pavement. Increases in ground-water concentrations of magnesium and sodium (from pavement and deicing salt dissolution, respectively) likewise were more pronounced and persistent at Prince Frederick compared with other sites. On the other hand, the bromide test conducted at Prince Frederick did indicate that the concentrations of bromide spread on the pavement were much diminished in underlying and downgradient ground water, probably resulting from dispersion, diffusion, and retardation.

Because of the small unsaturated thickness at the Greenmount site, unsaturated-zone water samples were collected near the interface of the aquifer and the unsaturated zone. The interface is tension-saturated (that is, aqueous phases respond to capillary forces) and can be a zone where the movement of solutes is retarded; tension saturation can account for elevated chloride concentrations that appeared to be increasing over time in unsaturated-zone water at Greenmount. Capillary forces in the tension-saturated zone could impede movement of chloride. The chloride data from the Greenmount and Prince Frederick sites indicate that nonreactive and possibly reactive and complexed solutes can accumulate at the capillary-zone/unsaturated-zone interface and thus become a source of solute to the shallow ground-water system (O.P. Bricker, U.S. Geological Survey, oral commun., 1987). Mobilization of solutes from the tension-saturated and unsaturated zones can be caused by vertical fluctuations of the water-table mound (Freeze, 1969). Freeze and Cherry (1979) and Freeze (1969) note that water-table mounding beneath recharge ponds can affect water chemistry at sites where the water table is normally shallow (less than 10 ft); however, there was no obvious relation between fluctuations of contaminant concentrations and water-table mounding at the Annapolis or Greenmount sites.

Chloride concentrations were very high (median, 130 mg/L) in water collected from the unsaturated zone at Prince Frederick also but fluctuated in a manner similar to the chloride-concentration fluctuations in storm water. This difference between chloride-concentration trends in unsaturated-zone water at Prince Frederick and Greenmount possibly can be explained by the relatively large unsaturated-zone thickness at Prince

Frederick and because Prince Frederick samples were collected well above the tension-saturated zone.

The thickness of the unsaturated zone beneath storm-water impoundments also can affect concentrations of constituents that are chemically reactive. In this case, geochemical factors that control contaminant concentrations reaching ground water depend on the chemical composition of unsaturated-zone materials as well as biochemical processes. Most reactive contaminants tend to partition out of aqueous transport when passing through materials with a large proportion of organic matter, manganese and iron hydroxides, and clays. Coarse, quartzose sands are a poor buffer between the impoundment and ground water, and contaminant concentrations can be expected to be controlled by hydraulic processes in such material.

Evapotranspiration and Rainfall

Evapotranspiration generally exceeded rainfall during the summer and early fall, although rainfall was unusually high during July 1988 and June 1989. The effect on chloride concentrations in ground water beneath the impoundment and downgradient from it was evident at each study site and depended on the amount of rainfall. Chloride concentrations were highest for the year during the summer and early fall when moderate rainfalls flushed residual chloride from the unsaturated zone; however, extremely high rainfall—such as 10 in. recorded in June 1989—resulted in temporary dilution of generally elevated chloride concentrations in ground water. The only known source of chloride to the system was from road salting in winter and early spring—a period that coincided with the period of major ground-water recharge; a rise in chloride concentrations in ground water occurred hours or days after road salting.

In a discussion of analogous conditions of artificial recharge, Freeze (1969) refers to the possibility of salinization of solid and aqueous phases at the tension-saturated zone caused by seasonal evaporation and transpiration. In this scenario, water-table fluctuations mobilize contaminants held by capillary forces and concentrated by evapotranspiration. Therefore, the mechanism by which transpiration increases contaminant concentrations in ground water can be direct or indirect and may depend on characteristics of geologic materials.

GEOCHEMICAL FACTORS AFFECTING CONTAMINANT MOVEMENT

The movement of trace constituents through the impoundment-unsaturated zone system can be conservative or nonconservative. Conservative contaminants are uncharged or negatively charged constituents, such as chlorides, nitrates, and anionic complexes. Their mobility is not expected to be retarded by pond-bottom or geologic materials. Concentrations of conservative constituents are mitigated mainly by dispersion, diffusion, and simple mixing, and their transport is controlled by the hydrologic factors discussed in the previous section.

Most metals are not conservative. Metal mobility is controlled by the ambient pH and (or) reduction-oxidation potential (redox state) of the solution and by the availability of ion exchange, sorption, and complex-forming media. These variables affected the way contaminants partitioned between dissolved and particulate phases at the study sites.

pH and Oxidation-Reduction Potential

The solubility of metal oxides and hydroxides generally strongly depends on pH and commonly on redox potential. For many metals, solubility increases as pH decreases (fig. 61). Redox is a change in the valence state of an element upon its oxidation or reduction. The redox state of natural waters is a

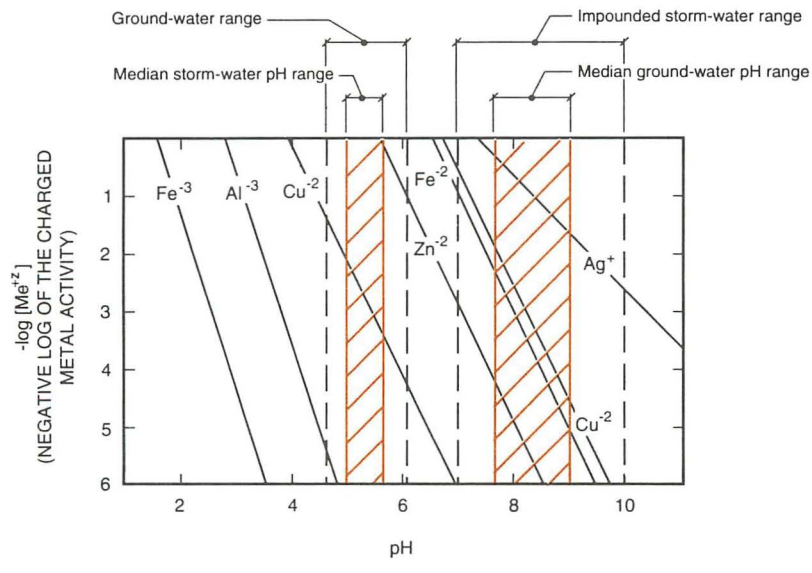


Figure 61.—Solubility of oxides and hydroxides for selected metals in freshwater systems. (Modified from Stumm and Morgan, 1981, p. 240.)

major control on the solubility equilibria for several trace metals. Measurements of Eh that define the redox state of a solution were not made in this study. Constituents for which redox is an essential factor are evaluated in general terms on the basis of measured dissolved-oxygen concentrations and physical evidence of oxidized species.

Impoundment water plotted in a pH-dissolved oxygen (pH-DO) field that was relatively high for pH considering its acidic source from rainwater: median pH ranged from 7.7 to 9.2. Concentrations of dissolved oxygen generally were greater than 8 mg/L (fig. 62). Concentrations of dissolved organic carbon generally were 5 to 12 mg/L, depending on the site, and also were in a range substantially greater than that for ground water. Beneath-impoundment ground water plotted in a pH-DO field that not only had much lower values than impoundment water but also had lower values than ground water sampled at the control wells. The dissolved organic carbon (DOC) concentrations of beneath-impoundment ground water were less than those of storm water but generally were higher than those in native ground water. The pH of ground water beneath the impoundment was reduced from the upgradient pH for each suite of samples collected; therefore, pH seems to have decreased in the downgradient direction at each site.

Dissolved-oxygen concentrations were not determined for water in the unsaturated zone. Unsaturated-zone water plotted in a pH-specific conductance field similar to the field for storm water, although the pH of unsaturated-zone water was consistently lower than that of storm water.

The pH of beneath-impoundment ground water could have been affected by iron and manganese equilibria. The presence of iron and manganese exerts important controls on aqueous chemistry and can affect the chemistry of the ambient solution and of other trace constituents. The chemistry of iron and manganese is somewhat similar, although manganese chemistry is much more complex (Hem, 1985). Each constituent strongly depends on pH and redox potential. For each, the +2 state is the common dissolved species in most natural waters, and ions with higher charge are less soluble (fig. 63).

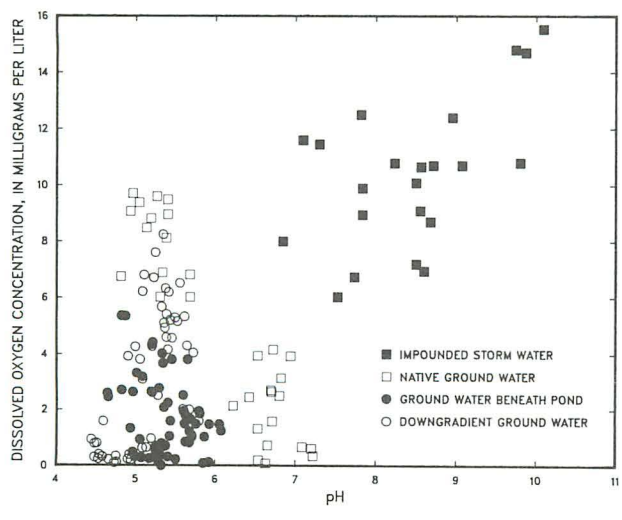


Figure 62.—Dissolved-oxygen concentrations and pH for storm water and ground water at study sites.

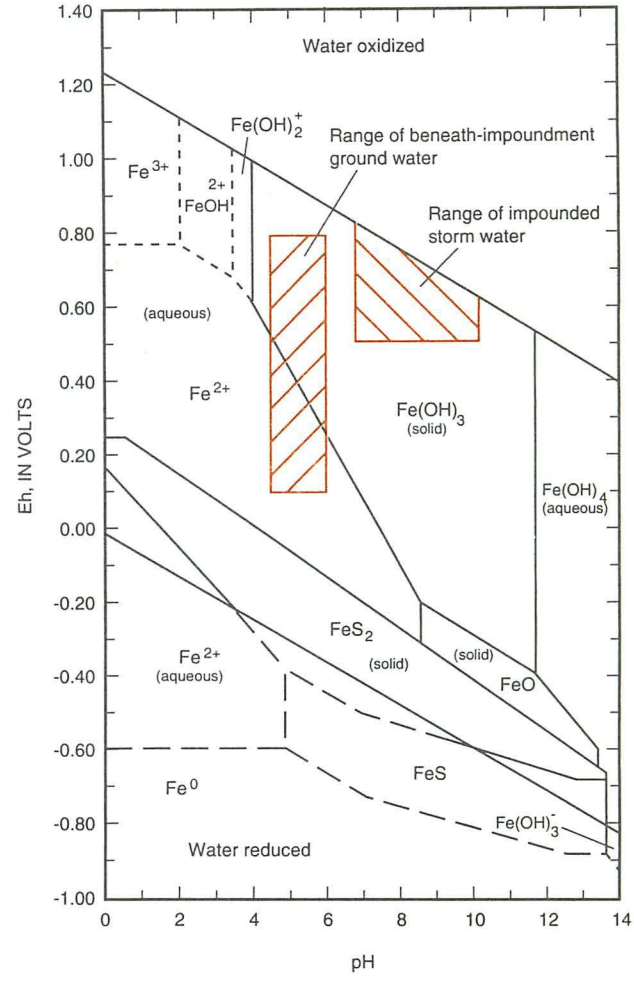


Figure 63.—Stability fields for solid and dissolved species of iron as a function of Eh and pH (125° Celsius and 1 atmosphere). (Modified from Hem, 1985, p. 80.)

Ground water at Greenmount and Annapolis was saturated with respect to iron and manganese hydroxides according to saturation indexes calculated by use of WATEQF and plotted in a field where manganese and some iron could be stable as reduced species (fig. 64). Oxidation reactions of manganese and iron can sequentially lower pH because the reactions add acidity to the aqueous system as follows (modified from Ball and others, 1981, p. 6):

$$Mn^{2+} + 1/2\ O_2 + H_2O \rightleftarrows MnO_2 + 2H^+$$
(Hem, 1985, p. 87)

and

$$Fe^{3+} + 2H_2O \rightleftarrows FeOOH + 3H^+.$$

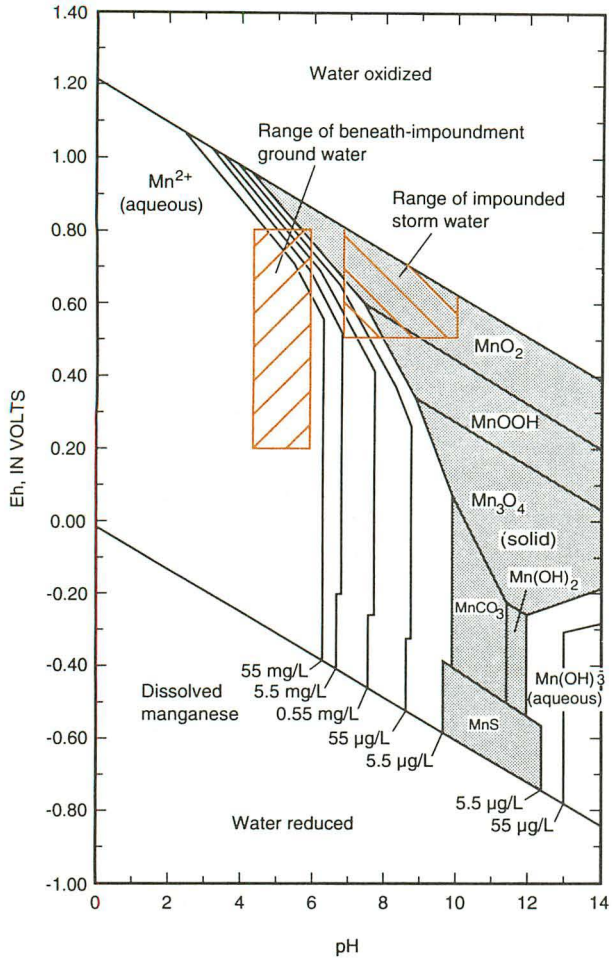


Figure 64.—Stability fields for solid and dissolved species of manganese as a function of Eh and pH (125° Celsius and 1 atmosphere). (Modified from Hem, 1985, p. 87.)

Precipitation of hydroxides could help to account for the depletion of dissolved iron and manganese in ground water beneath the ponds at Annapolis and Greenmount (figs. 65 and 66), because dissolved oxygen was always detected in ground water at each site (figs. 62 and 64). In contrast, manganese and iron concentrations increased at Prince Frederick in beneath-impoundment and downgradient ground water, but they were low in unsaturated-zone water. The increases were driven in part by decreases in the redox state. The concentrations of manganese in Prince Frederick ground water far exceeded predictions from equilibrium and were matched only by concentrations in unsaturated-zone water at Greenmount.

There was evidence for the development of anaerobic conditions in bottom materials of the unsaturated zone in Greenmount. The shaded area on figure 64 shows the stability field hypothesized for interstitial water in pond-bottom materials and (or) the unsaturated zone at Greenmount, in which sulfide was reported. Decreases in pH and Eh beneath the sediment-water interface in the ponds could result in mobilization of manganese well before iron would be mobilized. It is possible that the basal unsaturated zone at Prince Frederick was also sufficiently anaerobic to mobilize manganese. Anaerobic conditions and manganese chemistry were likely to have been microbially mediated.

Cation Exchange, Sorption, and Complexation

Cation-exchange reactions exert important controls on the aqueous chemistry, and exchangeable ions can buffer solution composition (Drever, 1988). Clay minerals, oxyhydroxides, and organic compounds are subject to ion exchange and to sorption. Cation exchange most commonly involves substitution of major ions, and sorption pertains to the scavenging of trace elements from solution by solid phases. Removal of trace metals from solution also can be a result of ion exchange, however, because some ion exchangers are highly selective for a specific metal ion even when the metal concentration is not very high. Thus, halloysite (Al_2O_3) strongly sorbs lead at pH of 5.5 to 7.0, although the substrate is charged positively within this pH range (Stumm and Morgan, 1981; Hem, 1976).

Cation-exchange capacities in clay minerals vary as a function of the ions that occupy the exchange sites and as a function of pH; at high pH the predominant surface charge is negative. Oxides and organic matter commonly form gels, or coatings, on clay minerals; the exchange capacities of these coatings which can be considerable, also are strongly pH dependent (Jenne, 1977). The direction in which a cation-exchange reaction proceeds depends on the ratio of the adsorbed mole fractions at the initial condition and on the concentration ratio of the two ions in solution (Drever, 1988). Divalent ions, such as calcium and magnesium, normally have a stronger affinity for clay phases than do monovalent ions, such as potassium and sodium, depending on the concentration of ions in solution and the exchange medium. Moreover, the smaller the hydrated ion, the greater its ability to fill exchange sites. The general affinity sequence for exchange, from stronger to weaker, is

barium > strontium > calcium > magnesium > potassium > sodium > lithium.

Adsorption of trace elements onto mineral surfaces and organic compounds is a rapid and readily reversible process that results from the mutual attraction between the charges on ions in solution and small residual surface charges on solid phases. Horowitz (1985) summarized studies on affinity sequences of solid phases and elements as

Solid phases: manganese oxides > organic matter > iron oxides > clay minerals;
Elements: lead > copper > nickel > cobalt > zinc > cadmium > iron > manganese.

Elemental affinity, however, is dependent upon the nature and abundance of the available substrate, competition between the substrates, and pH. Adsorption and desorption are pH-

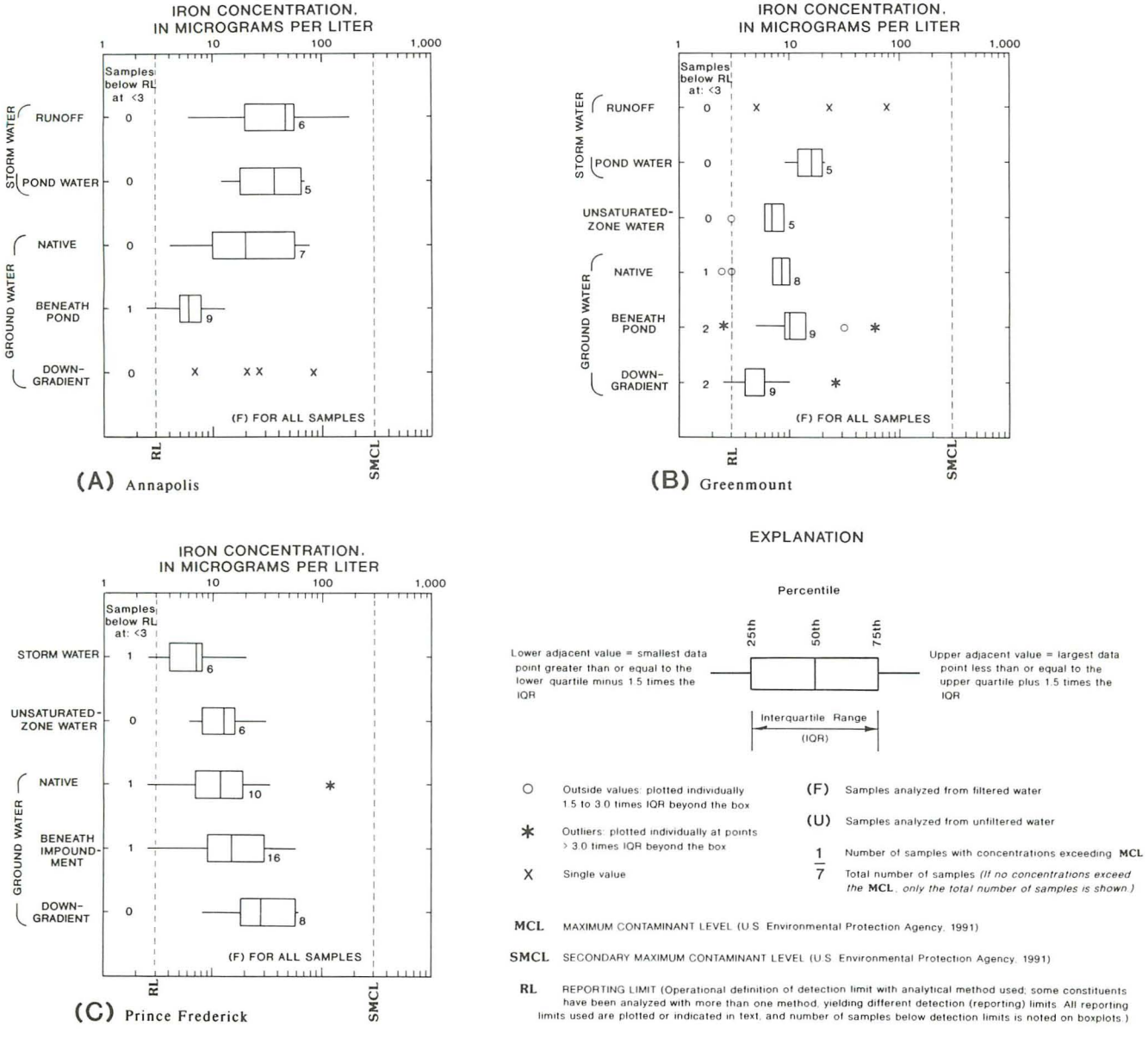


Figure 65.—Summary of changes in concentrations of iron at (A) Annapolis, (B) Greenmount, and (C) Prince Frederick.

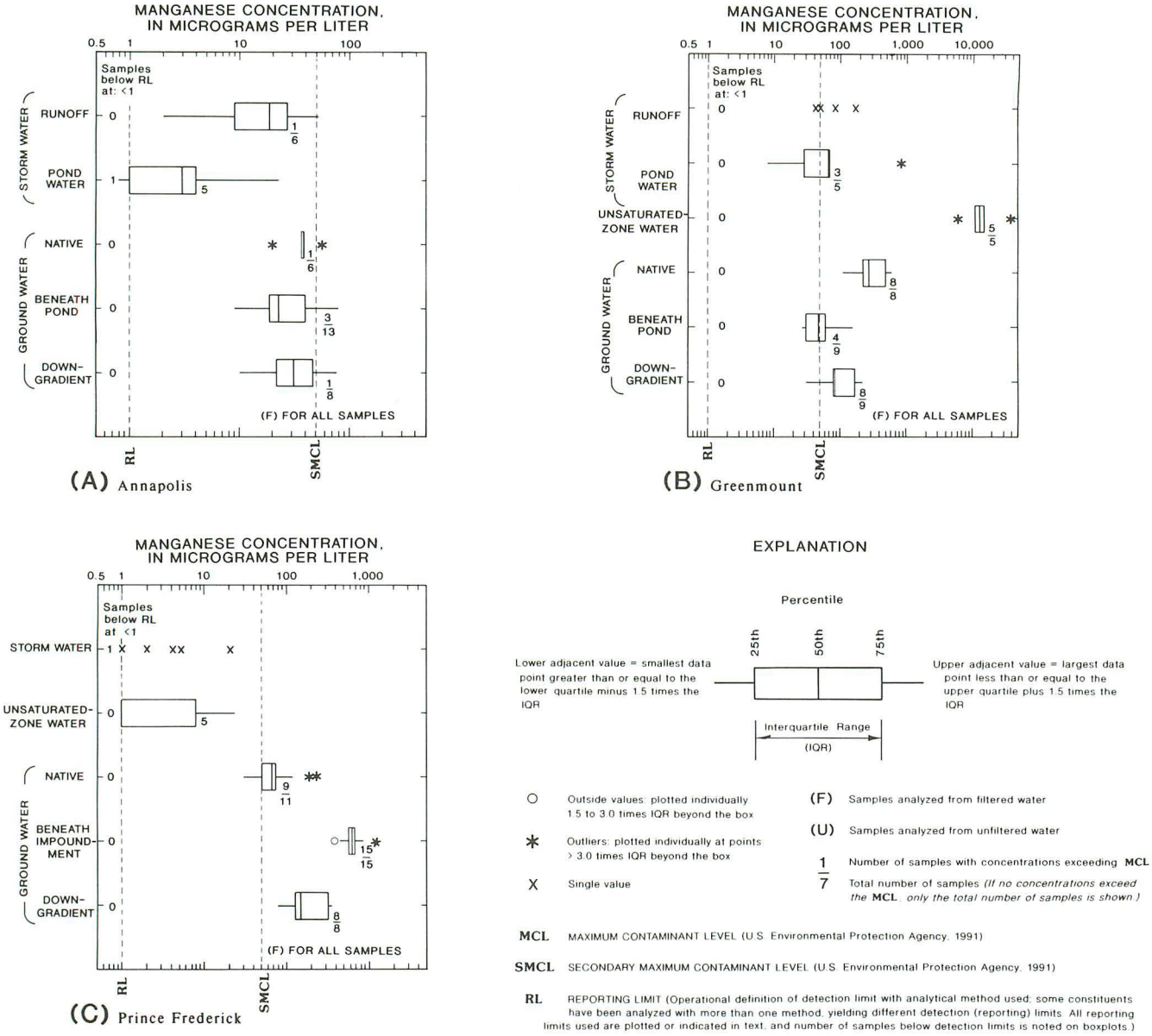


Figure 66.—Summary of changes in concentrations of manganese at (A) Annapolis, (B) Greenmount, and (C) Prince Frederick.

dependent: as pH increases, adsorption of cations tends to increase, although some adsorption of elements is amphoteric (capable of reactions either as an acid or a base) at high pH (typically, greater than 9.0). The pH range from no sorption to complete sorption is relatively narrow and different for each adsorbant, and the pH at which significant sorption occurs is the pH at which dissolved cations undergo hydrolysis to hydroxy complexes (Drever, 1988). Manganese oxides are usually negatively charged, but amorphous iron oxyhydroxides can be either positively or negatively charged (Elder, 1988). The negative surface charge of iron and manganese oxides has been shown to increase as the solution pH increases (Jenne, 1977).

Complexes consist of a metal cation and an electron-donating ligand or chelate that are covalently bonded (Stumm and Morgan, 1981). Complex formation is important because it can alter the behavior that ordinarily would be predicted for a metal cation. Contrary to sorption, complexation provides a mechanism for metal transport by forming a stable, uncharged or negatively charged entity that remains in solution. Electron-donating ligands can be inorganic or organic, and metallo-organic complexation can be an important mechanism for metal transport to ground water from storm-water ponds.

A hypothesis of storm-water management is that many contaminants—especially metals—that enter the management system will be sequestered by bottom materials in impoundments or by unsaturated-zone materials and will be removed from aqueous transport to ground water. The data presented in this report have shown that substantial quantities of zinc, copper, nickel, and lead were sequestered by solid phases accumulating in pond-bottom materials. The potential for ion exchange and sorption in bottom materials and suspended phases in the impoundments was high, and it increased each year. The median pH of impoundment water generally favored partitioning to solid materials, and the increases in available organic matter and manganese and iron oxyhydroxides enhanced the scavenging potential of the impoundments for most metals. Nevertheless, elevated concentrations of these and other constituents accumulating in bottom materials were measured in samples of ground water collected beneath and (or) downgradient from the impoundments. In addition, beneath-pond concentrations of chloride, aluminum, and cadmium in ground water were elevated.

The factors that could have limited the efficacy for impoundment scavenging of trace constituents were kinetic constraints, critical fluctuations in the ambient chemical environment, competition for exchange sites, sorption capacities, and complexation with anionic compounds. Kinetic constraints may have been unfavorable to the oxidation, precipitation, or sorption of trace elements entering the impoundment in the dissolved phase. For many metals, the dissolved fraction may have moved rapidly through the impoundment system to ground water, especially during a sizeable storm. Critical fluctuations in pH and dissolved-oxygen concentrations in the Annapolis and Greenmount pond could have mobilized pH-dependent constituents, such as aluminum, copper, nickel, and zinc. Again, the process may not reverse itself rapidly enough to hinder transport of mobilized metals to the shallow aquifer. One of the most puzzling results was the fate of cadmium. Cadmium was expected to be scavenged effectively by bottom materials, but it was not. The presence of elevated cadmium concentrations in some ground-water samples possibly indicates that cadmium competed unfavorably with other metals for sorption sites and might have moved unimpeded to ground water as a dissolved ion or anionically complexed species.

Mobility of Selected Contaminants

Aluminum

The chemistry of aluminum is largely controlled by pH and kinetics (Brown and Hem, 1975; Lind and Hem, 1975). Aluminum is amphoteric, with solubility increasing exponentially at a pH of less than 5.0 and greater than 9.0 (fig. 67). This property of aluminum is important in understanding its concentrations in beneath-impoundment ground water. Ground-water pH beneath the impoundments was near and sometimes less than the lower solubility limit for aluminum; it is likely that this low pH caused the elevated aluminum concentrations reported. Likewise, aluminum concentrations in storm water impounded at the Annapolis and Greenmount sites responded to rises in pond pH that exceeded 9.0.

Aluminum concentrations exceeded the proposed USEPA SMCL (50 μg/L) in some ground-water samples at each site. Because aluminum chemistry is governed by pH and kinetic constraints, impoundment processes that cause large fluctuations in pH and Eh consequently cause chemical gradients that indirectly can affect ground-water chemistry. For example, the periodic mobilization of iron to oxygenated ground water, dur-

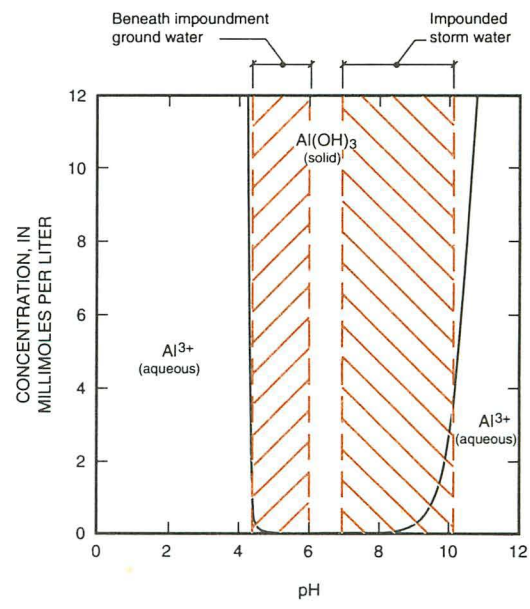


Figure 67.—Solubility of aluminum hydroxide in freshwater systems. (Modified from Mason and Moore, 1982, p. 164.)

ing which ferrous iron oxidizes and precipitates, can reduce the pH sufficiently at these sites to temporarily mobilize aluminum.

Aluminum concentration reached the 50 μg/L SMCL in beneath-pond ground water at Annapolis once, when ground-water pH was 4.82 for that sample, but was 5.40 μg/L in a concurrently collected sample of upgradient ground water. Aluminum concentrations in samples of beneath-pond ground water did not differ much from concentrations measured in samples of native ground water because the pH of native ground water was kept low by recharge from acidic precipitation. The median pH for the samples of pond water collected at Annapolis was 7.7, and, although algal photosynthesis occasionally increased pH to above 9.0, such high pH was not frequent enough to maintain elevated aluminum concentrations in pond water. Moreover, a 10-ft thickness of unsaturated zone provided a buffer between the impoundment and ground water that was sufficient to mitigate aluminum transport to ground water when aluminum concentrations in pond water were high. The pH of upper unsaturated-zone water was not conducive to aluminum mobility.

Aluminum concentrations at Greenmount were substantially elevated in ground water receiving storm-water infiltrate, and samples of ground water collected downgradient had a median concentration that was close to the SMCL for aluminum. Pond water had a median pH of 9.2, which maintained aluminum concentrations above the proposed SMCL. Elevated aluminum concentrations in pond water correlated directly with pH greater than 9.0. Increases in aluminum concentrations followed a general pH decrease between the beneath-pond and downgradient wells. Moreover, ground-water levels beneath the impoundment were within 3 to 4 ft of pond bottom during the spring, when pH and aluminum concentrations were high in the pond; these periods of high water table enhanced aluminum movement to ground water.

Aluminum concentrations in ground water were controlled by downgradient pH decreases at Prince Frederick, where low aluminum concentrations in storm water and upgradient ground water rose exponentially in the direction of ground-water flow and decreasing pH.

Cadmium

Cadmium concentrations in some beneath-impoundment ground-water samples exceeded the 1991 USEPA MCL of 5 μg/L at Annapolis and Greenmount and in one downgradient sample at Prince Frederick. Storm water was the sole source of cadmium to ground water; cadmium was not detected in geologic materials of the unconfined aquifer at any of the sites. Cadmium entered the impoundments in the suspended storm-water fraction and was expected to partition to pond-bottom materials. On the basis of data from the sorption experiments performed with Annapolis and Greenmount pond-bottom materials and information from the literature (Horowitz, 1985), cadmium should have partitioned to solid phases in the impoundment. Nevertheless, cadmium concentrations were low or below detection in pond-bottom materials and in unsaturated-zone water. Moreover, cadmium concentrations were elevated in beneath-impoundment and (or) downgradient ground water at each site (fig. 68) and were partitioned to the dissolved phase. Although the storm-water samples analyzed normally had cadmium concentrations of a few micrograms per liter or less, median concentrations of cadmium in ground water generally were elevated with respect to background, and maximum concentrations far exceeded those in native ground water.

Cadmium solubility depends on pH and redox potential, and it may be controlled by the solubilities of carbonates and sulfides (figs. 61 and 68). In the presence of sulfide, cadmium is virtually immobile. Sulfide was nonuniformly detected in Greenmount pond water; no effect was evident on cadmium concentrations in pond water or ground water, perhaps because sulfide was nonuniform. On the other hand, the biological uptake of cadmium is also important and may control sorption and release of cadmium (and other metals) at the sediment-solution interface (Elder, 1988).

Cadmium solubility is low at impoundment-water pH (fig. 68), and cadmium in solution would have a strong affinity for

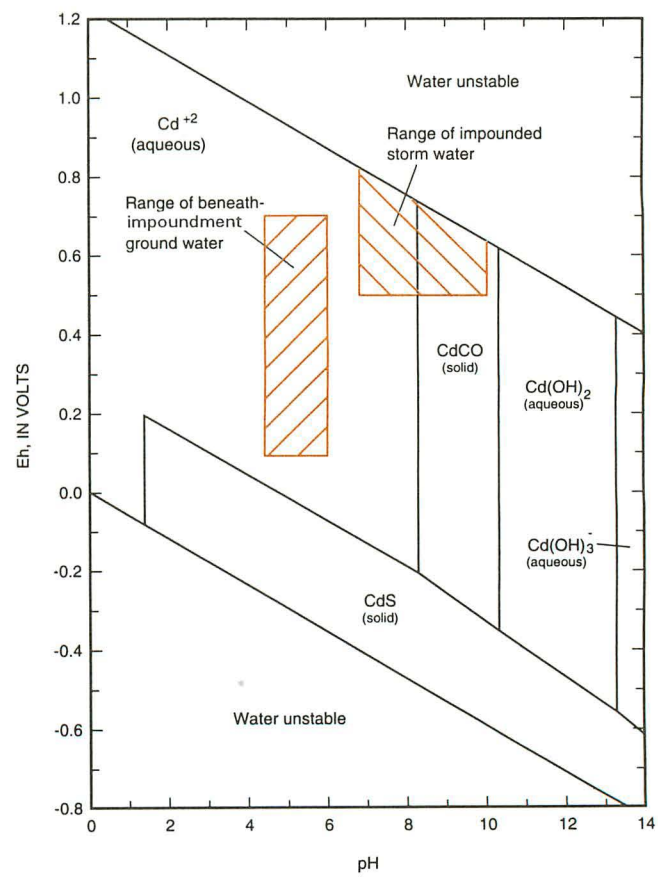


Figure 68.—Solubility of cadmium in freshwater systems. (Dissolved cadmium activity, $10^{-7.05}$ moles per liter; dissolved carbon dioxide and sulfur species, 10^{-3} moles per liter; 25° Celsius and 1 atmosphere pressure; modified from Hem, 1972, p. 667.)

forming complexes of low solubility. Below pH 7.0, however, cadmium solubility is high (Hem, 1972); the Cd^{2+} ion is the predominant species in solutions of pH less than 8.0. Cadmium may remain more mobile than other divalent contaminant metals because it has lower sorption affinity and because of unfavorable competition with other metals for sorption sites. On the other hand, cadmium complexes readily with organic and inorganic ligands (Rubin, 1974). According to Callahan and others (1979), the preferential order of complex formation is

humic acids > carbonate > hydroxide
> chloride > sulfate.

Cadmium entering the impoundments may form hydrophilic complexes with humic acids or chloride and may be effectively transported to ground water. Cadmium complexing with chloride is significant with 10^{-3} M (350 mg/L) or more chloride in solution (Rubin, 1974). The data previously presented confirm that chloride concentrations were easily this high or substantially greater during winter and spring because of road salting. The negatively charged cadmium-chloride complex behaves conservatively, and this conservative behavior would account for the elevated concentrations of dissolved cadmium in ground water receiving storm-water infiltrate. Hem (1972) notes that cadmium concentrations greater than 10 μg/L may be stable in water with low pH and low concentrations of total solute.

Zinc, copper, and nickel

Zinc was an indicator of ground-water contamination at the three storm-water management sites: concentrations of zinc in beneath-impoundment ground water were substantially elevated at each study site, although the USEPA SMCL (5 mg/L) was not exceeded.

Zinc partitioned strongly to solid phases in the impoundments, but it was present almost entirely in a dissolved phase in ground water. Water collected from the shallow unsaturated zone was depleted in zinc relative to storm water and underlying ground water and was depleted or had concentrations that were equivalent to native ground water. Concentrations of dissolved zinc commonly reported in rainwater at the study sites and in the literature are of the same magnitude as those measured in storm-water samples and in ground-water samples beneath the impoundments. Particulate zinc concentrations entering the impoundments were substantial in most samples, including two concentrations that exceeded the SMCL. These data indicate the likelihood that the SMCL was exceeded more frequently.

Copper and nickel concentrations did not exceed proposed USEPA MCL's (1,300 μg/L and 100 μg/L, respectively) in ground water at the study sites, but they generally were elevated in ground water compared to background. Concentrations exceeded the proposed MCL for copper in storm water only at Greenmount and were moderately elevated in ground water at Annapolis and Prince Frederick. Nickel concentrations were elevated in storm water (one sample exceeded the proposed MCL) and ground water at Annapolis, and concentrations in ground water were clearly related to storm-water infiltration. Concentrations of nickel were not elevated at Greenmount in storm water or ground water. The nickel concentrations measured in storm-water samples could have been from dissolution of impoundment materials (Hunting Hill rocks) at Prince Frederick (O.P. Bricker, U.S. Geological Survey, oral commun., 1988); elevated concentrations in underlying ground water were maintained by the pH controls on nickel chemistry.

Zinc is an amphoteric metal; however, its upper solubility limit (greater than 10.0) may have had significance at the Greenmount site only. $ZnCO_3$ (smithsonite) and $Zn(OH)_2$ (crystalline zinc hydroxide) are the stable phases of zinc within the pH and redox conditions of impoundment water (fig. 69). Below a pH of about 7.7, the mobile Zn^{2+} and (or) $ZnOH^+$ species are stable in solution (fig. 70). Therefore, at the pH and Eh of beneath-pond ground water, no particulate phase is expected to be stable, and dissolved zinc can be expected to remain mobile. The only source of elevated zinc concentrations to ground water at the sites was from impounded storm water.

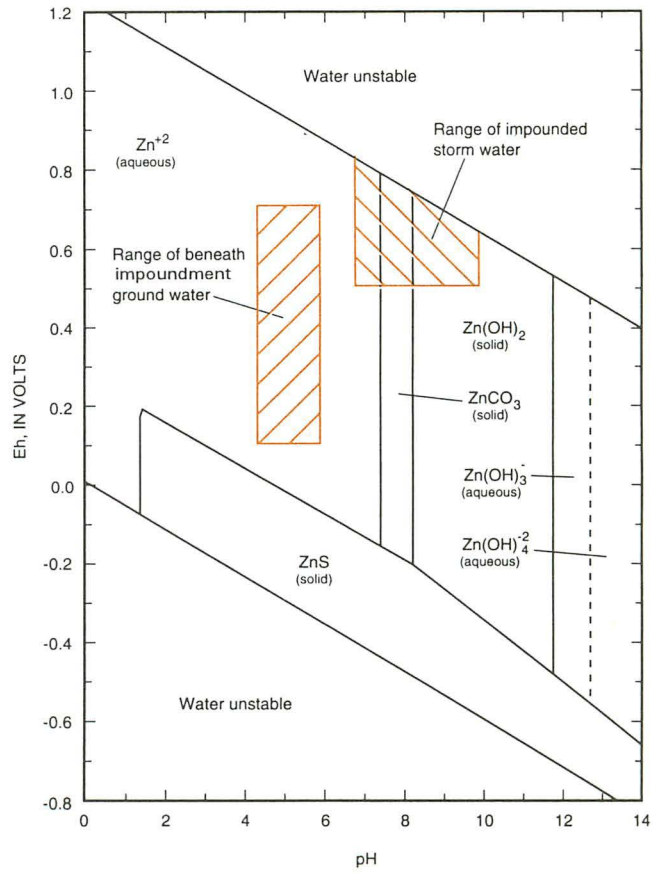


Figure 69.—Stability field of solids and predominant dissolved species of zinc. (Dissolved cadmium activity, 10^{-5} moles per liter; dissolved carbon dioxide and sulfur species, 10^{-3} moles per liter; 25° Celsius and 1 atmosphere pressure; modified from Hem, 1972, p. 667.)

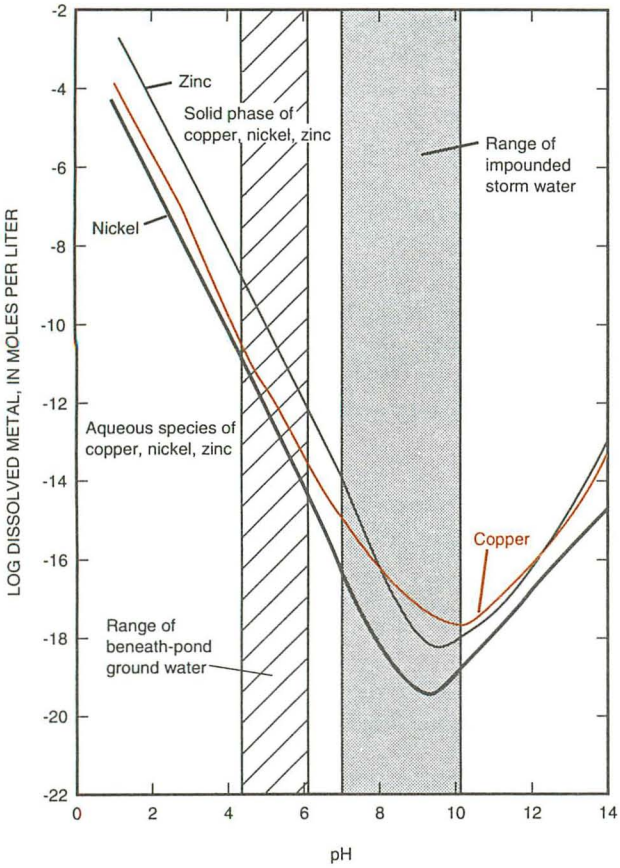


Figure 70.—Solubility of copper, nickel, and zinc in the presence of ferric hydroxide and fixed total bicarbonate in freshwater systems. (Bicarbonate species activity 10^{-3} moles per liter at 25° Celsius and 1 atmosphere pressure. Dissolved metal concentrations include free metal ions and hydroxide and carbonate complexes; $10^{-7.0}$ moles per liter = 6.4 micrograms per liter nickel or 6.5 micrograms per liter zinc; modified from Hem, 1977, p. 535.)

Median zinc concentrations in ground water were higher at Annapolis than at Greenmount. These differences can be accounted for by examining the pH of impounded water at each site. The similarity between the sites with respect to pH explains the mechanism of zinc mobilization from the impoundment to ground water: pH decreases in pond water that were caused by algal respiration and dilution from runoff resulted in periodic pH values as low as 6.8 at Annapolis. The reduced zinc species is stable at pH less than 7.4 (fig. 69); however, the Greenmount pond biota were more prolific because nitrogen and phosphorus nutrients were abundant. Biological activity resulted in a much higher median pH of 9.21 at Greenmount, compared with 7.7 at Annapolis. The lowest pH value measured in Greenmount pond water was 7.3. Generally higher pH was likely to have limited zinc mobility at Greenmount. The presence of sulfide in interstitial water at Greenmount could have been another limitation on zinc mobility.

Although some biological mediation occurred, the chemistry of impoundment water at Prince Frederick appeared to be controlled primarily by carbonate equilibria. Median pH of Prince Frederick impoundment water was 8.46, and zinc concentrations in ground water were intermediate compared to Annapolis and Greenmount concentrations.

Zinc chemistry is not as simple as portrayed in the preceding paragraphs, however. For example, partial pressures of carbon dioxide exert a major influence on zinc solubility (Hem, 1972 and 1977), and major differences occur between the dissolved carbon dioxide concentrations of impoundment water, unsaturated-zone water, and ground water. Moreover, conditions in the unsaturated zone were not well defined and probably have significant effects. Zinc silicates or phases other than those shown in figure 69 may exert a more realistic control on zinc solubility in natural waters than has been presented (Hem, 1972). Aqueous zinc concentrations can be limited by coprecipitation with other minerals, cation-exchange adsorption, biochemical activities, and complexation and sorption with organic and inorganic substances (Hem, 1972 and 1977).

The chemistry of copper and nickel are similar to that of zinc. Solubility controls on copper and nickel follow patterns analogous with zinc (fig. 70). Copper solubility begins at a higher pH than that of zinc or nickel but does not increase as rapidly. Iron that complexes with copper exerts an important solubility control, but copper ions form complexes with a variety of ligands, and coprecipitation by oxides and sorption also exert controls on copper mobility (Hem, 1977 and 1985). It is noteworthy that the relative abundances of zinc, copper, and nickel in beneath-impoundment ground water followed a sequence that would have been predicted by their relative sorption affinities: zinc exceeded nickel, which exceeded copper. At Greenmount, nickel abundance was exceeded by copper, but only small concentrations of nickel were entering the system.

Chromium and lead

Chromium concentrations in suspended phases exceeded the 1989 MCL (50 μg/L) in a few storm-water and ground-water samples at each site. Chromium and lead were strongly partitioned to suspended phases in storm water. The elevated chromium and lead concentrations measured in ground-water samples collected beneath the impoundments or downgradient also were partitioned to particulates. Dissolved chromium and lead generally were not reported near contaminant concentrations in ground water, but concentrations tended to be elevated compared to native ground water.

Particulate concentrations of chromium in ground water were much lower than in storm water. Chromium (unfiltered) met or exceeded regulatory standards in ground water four times at Annapolis (Appendix A), never at Greenmount, and twice at Prince Frederick (fig. 59). The chromium detected in beneath-impoundment ground water at Prince Frederick was attributed to dissolution of chromium-bearing minerals in the impoundment. The MCL for lead changed from 50 μg/L to 5 μg/L (proposed) during 1990–91, and the analytical detection limit most

commonly requested was at the 5 μg/L concentration. Lead concentrations exceeded the proposed 1991 MCL in most unfiltered storm-water samples from Annapolis and Greenmount, but only once at Prince Frederick (fig. 59); lead concentrations in unfiltered ground water equaled or exceeded 5 μg/L in most downgradient samples at Annapolis and Prince Frederick, and in all upgradient and about half of the beneath-impoundment samples at Greenmount. Data presented in earlier sections show that lead concentrations occasionally exceeded the current proposed MCL in other aqueous samples as well. The lead MCL was exceeded in the filtered sample fraction occasionally in storm water but rarely in ground water.

A major difference between the fate of chromium and lead was that chromium did not increase substantially in bottom materials, whereas lead accumulation was substantial. Lead tends to bind with organic matter, coprecipitate with manganese oxides, and readily sorbs to organic and inorganic surfaces, keeping aqueous concentrations low (Lovering, 1976; Hem, 1976a). In addition, lead mobility is kept low by cation-exchange sorption (Hem, 1976b).

Chromium chemistry is complex, and transport controls are not well understood (N.S. Simon, U.S. Geological Survey, oral and written communs., 1988). Data from Hem (1977) indicate that the dissolved chromium species that could have been stable consisted of the chromate ion (CrO_4^{2-}) in impoundment waters, and the dichromate ($Cr_2O_7^{2-}$) in ground water (fig. 71). Concentrations of dissolved chromium ions were the same or larger in receiving ground waters than in the overlying storm water. This pattern may be the result of direct infiltration of the dissolved species, as negatively charged compounds tend to be conservative. Hem notes that chromium tends to be immobilized where iron is abundant because chromate reduction can be coupled to ferrous ion oxidation (Hem, 1977). It was postulated previously that iron oxidation caused depletion of iron concentrations in beneath-pond ground water at Annapolis and Greenmount.

Lead solubility is largely governed by formation of lead hydroxide, carbonate, sulfide, and sulfate compounds of low solubility (Hem, 1976b). The solubility of lead would be extremely small in the pH-Eh environment of the Greenmount and Prince Frederick storm-water impoundments, and $Pb(OH)_2$ would be the stable solid phase (fig. 72). Within the stability field of $PbSO_4$ (pH < 5.2), lead solubility is a function of sulfate concentration, especially at low pH and high sulfate concentration. Sulfate concentrations were not high enough nor pH low enough in the ground waters studied for this to have played a major role.

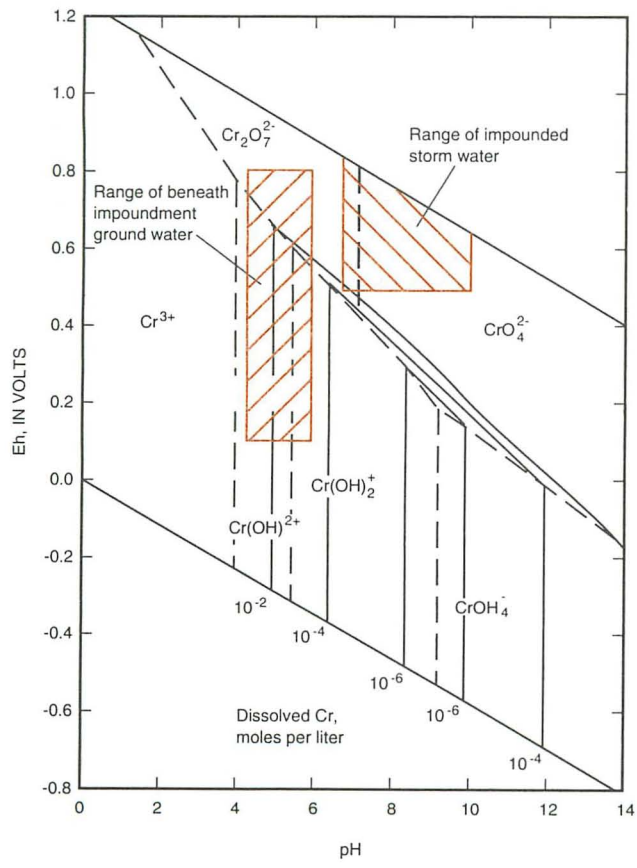


Figure 71.—Solubility of chromium in freshwater systems. (Total activity of sulfur $10^{-4.00}$ moles per liter and carbon $10^{-3.00}$ moles per liter at 25° Celsius and 1 atmosphere pressure; modified from Hem, 1977, p. 531.)

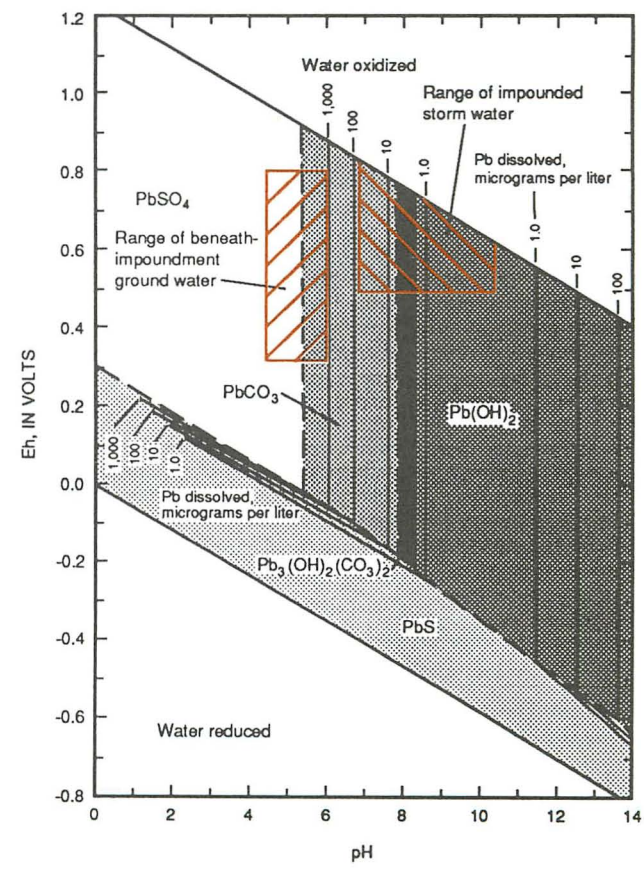


Figure 72.—Solubility of lead in freshwater systems. (25° Celsius and 1 atmosphere pressure; ionic strength 0.005; modified from Hem *in* Lovening, ed., 1976b, p. 7.)

Within the intermediate stability field that is governed by $PbCO_3$, lead solubility is complex, and lead could be relatively mobile at pH less than 6.5 in the absence of sulfur (Hem, 1976b). This pH was not unusual for runoff entering the impoundments, and it is possible that sporadic transport of lead occurred through this mechanism.

The presence of elevated concentrations of particulate chromium and lead in ground water presented a puzzle. Storm water was the only evident source of chromium at Annapolis (chromium was absent from beneath-pond ground water at Greenmount) and of lead at Annapolis, Greenmount, and Prince Frederick. Particulate chromium and lead concentrations increased in downgradient ground water at Annapolis and Prince Frederick. A possible mechanism of transport is the formation of hydrophilic colloids or anionic complexes (Stumm and Morgan, 1981).

SUMMARY AND CONCLUSIONS

SUMMARY

This is the final report of a 5-year study undertaken to determine the effects of storm-water infiltration on ground-water quality at three representative management facilities in Maryland. The purpose of this report is to describe the storm-water-management study sites, present the hydrologic and geochemical data collected, and on the basis of these data, assess the relation between the chemistry and quality of ground water and the infiltration of storm water at the study sites.

Infiltration of runoff through storm-water management structures was based on the hypothesis that heavy metals and organic contaminants would be removed from transport by being sequestered in impoundment and unsaturated-zone materials. It was also believed that conservative constituents that would not be sequestered with solid phases would be attenuated by ground-water and storm-water dilution. The major- and trace-element geochemistry at the sites and the consequences for ground-water quality were analyzed with respect to source, concentration, and mobility. The data were not sufficient to determine contamination trends or long-term effects; to do so would require a continued program of data collection.

The data showed that contaminants were transported to ground water as either a direct or indirect result of storm-water infiltration. Contaminants were transported directly to ground water because (1) the fate of negatively charged species is characteristically conservative, (2) partitioning of some metals to solid materials was impeded by preferential exclusion caused by the presence of an abundance of metals with greater partitioning affinities, (3) chemical concentration gradients increased, and (4) vertical hydraulic gradients increased during storm events. Contaminants reached ground water indirectly because of (1) biochemical reactions in the impoundments that ultimately affected unsaturated-zone and ground-water pH and redox or that caused solubilization of metals from time to time, and (2) dissolution of the rock aggregate used in subsurface impoundments that released trace metals to solution.

The potential of pond-bottom materials to sequester contaminants was substantially enhanced at the Annapolis and Greenmount sites during the period of data collection. This enhancement was reflected by increases in cation-exchange capacities by factors of 3 and 13.4 at Annapolis and Greenmount, respectively; the amount of exchangeable calcium underwent the largest increase. Cation-exchange capacities were increased by the influx of clays into the impoundments, by the increase in organic matter, and by precipitation of amorphous phases of iron and manganese oxyhydroxides. Trace-metal concentrations that increased substantially in bottom materials included cobalt, lead, nickel, strontium, and zinc: increases were from 4.5 to 28 times for lead, and from 6 to 8 times for zinc. At Annapolis, barium, copper, and molybdenum also increased in bottom materials. Chromium and vanadium concentrations increased moderately in bottom materials at Greenmount. A similar suite of anthropogenic organic compounds was detected at low concentrations in bottom materials that accumulated in the Annapolis and the Greenmount storm-water impoundments.

Contaminant concentrations and mobility in ground water at the study sites depended upon hydrologic and geochemical factors. Pertinent hydrologic factors that affected contaminant concentrations included the magnitude and rate of recharge, ground-water-flow rate, the vertical component of ground-water flow, the area of ground-water recharge, the amount and season of rainfall and evapotranspiration, and depth to water table. Geochemical factors governed the mobility as well as the concentrations of contaminants. Ion exchange, mineral precipitation, and sorption processes in the impoundments helped to sequester contaminants. These are reversible processes, however (kinetic constraints can limit reversibility), and biochemical reactions can produce conditions favorable or unfavorable to exchange, sorption, and precipitation. Moreover, divalent metals that complex with negatively charged organic or inorganic ligands or are bound in an anionic colloidal phase can move unimpeded to ground water. Metal solubilities were constrained by the pH and (or) redox environment of storm water, water in the unsaturated zone, and ground water.

Rainwater at the sites was acidic (pH less than 4.5) but was rapidly buffered; the typical pH of runoff entering the storm-water impoundments exceeded 7.0. Biological activity was greatest in the ponds (Annapolis and Greenmount) and caused large fluctuations in pH and dissolved-oxygen concentrations. The net result was a median pond-water pH of 7.7 at Annapolis and 9.2 at Greenmount. The higher pH of the Greenmount pond resulted from uninhibited biological activity; nutrients to the impoundment were plentiful. Dissolution of the rock aggregate

used to fill the impoundment buffered the water at Prince Frederick and resulted in a median pH of 8.46. Impoundment water generally was well oxygenated, although sulfide was detected in a few pond-water samples collected at Greenmount; the presence of sulfide was evidence of developing anaerobic conditions in interstitial waters of pond-bottom and (or) unsaturated-zone materials. The pH of water collected from the shallow unsaturated zone, 7.0 at Greenmount and 8.0 at Prince Frederick, was reduced from that of impoundment water.

The major-ion chemistry of storm water plotted in two compositional fields on trilinear diagrams for each site. Throughout most of the year, storm water was a bicarbonate type (the cation component tended to be site-dependent). In the winter and early spring, storm water occasionally was a sodium chloride type because of the presence of deicing salts in runoff. Bicarbonate was associated with calcium from dissolved materials in runoff at Annapolis and Greenmount. At Prince Frederick, the bicarbonate was associated with magnesium from the dissolution of impoundment rocks that produced high magnesium concentrations in storm water. Dissolution of magnesium minerals in the rock aggregate resulted in magnesium concentrations in storm water that persisted in unsaturated-zone water and ground water.

A large number of contaminants was reported in storm water at each site; contaminants were fewest and in lowest concentrations (except for chloride) in storm water at Prince Frederick. Trace elements tended to be partitioned to the suspended fraction of storm water at all the sites. USEPA MCL's and SMCL's for drinking water were exceeded with respect to aluminum, barium, cadmium, chromium, copper, lead, manganese, and zinc in some storm-water samples at one or more of the study sites. The pH of pond water was a solubility constraint on chromium, copper, lead, nickel, and zinc as long as pH remained between 8.0 and 10.0. Pond-water pH was biologically mediated, however, and fluctuations of pH to less than neutral created the potential for metal mobilization. Periodically low pH was less likely to occur at Prince Frederick, where the impoundment was subsurface and impoundment-water chemistry was controlled by carbonate equilibria from dissolution of the rocks.

Water collected from the shallow unsaturated zone usually plotted as a calcium/sodium chloride type at Greenmount; Prince Frederick unsaturated-zone water was a magnesium or sodium/magnesium bicarbonate type through most of the year, but was a sodium chloride type after influxes of storm water carrying deicing salts. Chloride concentrations seemed to increase over time in the unsaturated-zone water at the Greenmount site. Unsaturated-zone thickness at Greenmount varied seasonally, and depth to water table was usually within 5 ft of pond bottom; therefore, the thickness of unsaturated-zone materials available to attenuate concentrations of contaminants was small. Capillary forces in the tension-saturated zone could have impeded chloride movement. The data for chloride indicate that nonreactive and possibly reactive complexed solutes can accumulate at the capillary-zone/unsaturated-zone interface, becoming a source of solute to the shallow ground-water system.

Chloride and manganese were the only constituents that exceeded USEPA SMCL's in unsaturated-zone water, but elevated manganese concentrations were not related directly to storm-water infiltration. Water collected from the shallow unsaturated zone beneath the impoundments at Greenmount and Prince Frederick was generally depleted in most trace elements compared with storm water. Chromium, cobalt, manganese, and strontium were more abundant in unsaturated-zone water than in storm water, but the source of these constituents could have been geologic materials. Copper, nickel, and zinc seem to have been sequestered by pond-bottom materials (and, therefore, possibly by unsaturated-zone materials), and this sequestering could account for depleted concentrations in unsaturated-zone water. Most of the cadmium, vanadium, and arsenic were transported rapidly through the unsaturated zone to ground water. (Arsenic concentrations were always below or near detection.) The data collected from the unsaturated zone generally raised more questions than they answered, but they provided insight as to the complexity of the processes controlling contaminant transport to ground water. Chemical data collected from several depths in the unsaturated zone might help to elucidate the controls on contaminant transport.

Although the specific conductance, pH, and dissolved-oxygen concentrations of ground water differed considerably between the sites because of differences in background chemistry, similar patterns were detected in the changes recorded for ground-water chemistry beneath the impoundments. Elevated specific conductance was a uniform pattern in ground water beneath and downgradient from impoundments at each study site, compared with upgradient samples collected from control wells. Elevated specific conductance was caused by typically high concentrations of dissolved solids in infiltrating storm water. Although specific conductance fluctuated on the order of 150 μS/cm during the period of study, the data do not indicate a decrease in specific conductance values over time. Therefore, specific conductance was an immediate and gross indicator of the effect of storm-water infiltration on ground-water composition.

The complexity of the chemical changes that occurred because of storm-water infiltration from impoundments to ground water was previewed by patterns that emerged from measurements of pH and dissolved-oxygen concentrations. Dissolved-oxygen concentrations and pH were consistently lower in ground-water samples collected beneath storm-water impoundments than in samples collected from the control wells, and were considerably lower than dissolved-oxygen concentrations in unsaturated-zone water and storm water. The difference in pH between storm water and beneath-impoundment ground water was 2 to 4 orders of magnitude. The differences in pH between upgradient and beneath-impoundment ground water were generally within one-tenth of a pH unit at Annapolis and Greenmount but appeared to be consistent and significant. A large decrease in ground-water pH between the control wells, impoundment wells, and downgradient wells at Prince Frederick was mostly attributed to a diminishing amount of shell material observed in the downgradient geologic section.

Ground water beneath the impoundments and downgradient was modified to a chloride type at each site, although background compositions were quite different: native ground water

was a mixed-cation/mixed-anion type at Annapolis, a magnesium-nitrate chloride type at Greenmount, and a calcium bicarbonate type at Prince Frederick. The persistence of elevated sodium and chloride concentrations in beneath-impoundment and downgradient ground waters was related to rates of ground-water recharge and ground-water flow. Ground-water recharge predominantly occurred during the winter and spring and coincided with the period when road salting modified storm water to a sodium chloride-type water. Road salt was the only significant source of chloride at each site. The mixing of ground water with storm-water infiltrate throughout the rest of the year was evidenced by changes in major-ion concentrations and ratios as well as by the trace-element chemistry; the relatively minor effect from this recharge was emphasized by the magnitude and persistence of the sodium and chloride concentrations. Chloride concentrations in ground water beneath impoundments increased in the winter and early spring following road salting, and in late summer through late autumn if rainfall was low and evapotranspiration was high relative to rainfall.

Inorganic contaminants reported in beneath-impoundment ground water at elevated concentrations in some samples compared to background levels included aluminum, barium, cadmium, chloride, chromium, copper, lead, molybdenum, nickel, strontium, vanadium, and zinc. Median values were generally elevated for concentrations of barium, cadmium, chloride, chromium, copper, nickel, strontium, and zinc. Except for chromium and lead, the trace elements reported in ground water were present primarily in the dissolved phase. USEPA MCL's and SMCL's were approached or exceeded in ground water for aluminum, cadmium, chloride, chromium, and lead; cadmium concentration exceeded the MCL and chloride concentrations exceeded the SMCL in some samples at all three sites.

Most of the contaminant metals reaching ground water were solubilized or remained in solution because ground-water pH was less than 5.0 beneath the impoundments. Iron could have been mobilized from the impoundments to ground water and subsequently precipitated as hydroxide, because this process increases acidity by increasing hydrogen ion activity, and it can account for reduced pH in ground water beneath the Annapolis and Greenmount impoundments. Copper, nickel, and zinc chemistry follow analogous patterns with respect to solubility controls. Low ground-water pH and fluctuations of pond-water pH account for the occurrence of copper, nickel, and zinc in beneath-impoundment ground water despite substantial accumulation of these metals in pond-bottom materials.

Dissolved cadmium was a contaminant of concern in ground water because median values were elevated and concentrations in some samples exceeded the MCL. Cadmium, which is stable as a divalent cation under the ambient aqueous pH and redox conditions, was expected to sorb effectively to pond-bottom materials. In laboratory experiments, cadmium sorbed to solid-phase materials collected from bottom materials at the sites; however, cadmium was not detected in bottom materials at Annapolis and was just at the detection level in bottom materials at Greenmount. It is possible that unfavorable competition for sorption sites with other metals excluded cadmium from the solid phase. Cadmium could have moved through the unsaturated zone by being complexed with organic ligands. Cadmium also complexes with chloride at chloride concentrations exceeding 350 mg/L; however, cadmium was not associated with chloride in the unsaturated zone.

Elevated concentrations of chromium and lead occurred in the particulate phase in ground water. Rare pulses of high concentrations of chromium and lead in ground water may have been related to similar concentration pulses in storm water. Laboratory data and solubility diagrams indicated that chromium would be transported more readily than lead; thus, infrequent detection of chromium reflects sporadic presence in storm runoff. Infrequent detection of lead in ground water also was a function of low concentrations in runoff. Although lead strongly partitioned to solid phases, the pond pH and redox were sometimes favorable to lead mobilization. The data indicate either that the transport of chromium and lead was as part of a colloidal phase or that dissolved lead and chromium entering the aquifer flocculated or sorbed to particulates.

CONCLUSIONS

This study showed that the quality of ground water can be affected adversely by storm-water infiltration at storm-water management sites, but that the degree and extent of contamination can be controlled by adequate design, maintenance, and siting criteria. Nevertheless, the quantity of contaminant entering the system in runoff is an overriding factor; it is likely that sudden large loads and generally high concentrations of virtually any contaminant will find its way to ground water. Concentrations can build up in ground water if a contaminant source is persistent, even if input is infrequent.

The results presented would appear to be typical of storm-water-management sites with similar land use and design. The findings of this investigation with respect to storm-water-management concerns indicate that ground-water quality can be protected by developing criteria and implementing practices that target hydrologic, geochemical, and biochemical controls governing contaminant concentrations and mobility.

The following hydrologic considerations can aid in the development of criteria for storm-water management that minimize adverse effects on ground-water quality.

1. Rates of horizontal ground-water flow are typically very low compared with infiltration rates; the slow ground-water-flow rate of 1 ft/d or less estimated for the Prince Frederick site is not unusual in ground-water systems. The lower the rate of ground-water flow, the greater the potential for long-term aquifer contamination. Therefore, knowledge of flow rates or aquifer transmissivities would be useful for siting purposes.

2. Siting of storm-water-management structures at considerable distance downgradient from the ground-water divide may enhance the dilution potential by increasing the amount of upgradient water available for mixing and dilution.

3. A thick unsaturated zone above the water table can reduce contaminant concentrations in ground water by means of dispersion, sorbing solid phases of contaminants, and increasing infiltration distance and thus slowing infiltration rates. The efficacy of the unsaturated zone to sequester contaminants depends largely on the mineralogic and geologic nature of the materials and the chemical nature of the contaminant, as well as on dispersion through the unsaturated thickness. Sands and gravels or fractured rock can be expected to have less attenuation potential than silts, clays, and organic-rich sediments.

The following geochemical and biochemical considerations can aid in the development of criteria for storm-water management that minimize adverse effects on ground-water quality.

1. Transport of neutral or negatively charged contaminants to ground water will not be excluded by the type of impoundments studied in this investigation. These include widespread and predictable contaminants, such as chlorides and nitrates.

2. Data were not conclusive but indicated that the chemically stable environment of the subsurface impoundment limited contaminant mobility.

3. Some constituents, notably magnesium and possibly chromium and nickel, were transported to ground water as a result of dissolution of the rock aggregate used in the Prince Frederick porous-pavement impoundment; however, dissolution of the rock aggregate at Prince Frederick generally had an ameliorating effect on contaminant mobility by buffering the impounded water to a pH of about 8.4.

4. Generally, a pH of 7.0 to 9.0 and aerobic conditions provide geochemical constraints on the solubility, mobility, and concentrations of metals entering impoundments; ion exchange, sorption, and mineral precipitation provide further controls. Biologic activity (for example, algal photosynthesis and respiration in the ponds) causes large fluctuations in pH and redox that can result in mobilization of some contaminants.

Other conclusions reached by this investigation that specifically address the study objectives and hypotheses are as follows:

1. The major-ion chemistry of ground water beneath the storm-water impoundments was modified to a chloride-dominated solution at each site throughout the period of study because of seasonal pavement deicing; the magnitude and persistence of the chloride contamination indicate that the ground-water systems are not readily purged, even if horizontal flow rates are relatively high.

2. The trace-element composition of ground water beneath storm-water impoundments contained heavy metals; storm-water infiltrate was the sole or predominant source. Concentrations were modest and usually did not exceed USEPA drinking-water regulations; nevertheless, concentrations of cadmium, chromium, and lead exceeded USEPA MCL's in some ground-water samples, and concentrations of barium, copper, nickel, strontium, and zinc commonly were elevated above background concentrations.

3. Concentrations of anthropogenic organic compounds were usually below detection limits in storm water and ground water.

4. Constraints on contaminant mobility that might have resulted from differences between geologic materials of the Piedmont at Greenmount compared with the Coastal Plain (Aquia Formation) at Annapolis were not distinguishable in this study. Effects of differing geology were difficult to determine in part, because the sites were not otherwise comparable; for example, differences in unsaturated-zone thicknesses were large between sites. Moreover, pond-bottom geochemical and biochemical processes appeared to be of overriding importance.

5. Geologic materials that were native or used in site construction were a source of some metals to ground water; in some cases, concentrations of these metals exceeded USEPA drinking-water regulations.

6. Geochemical controls on the fate of trace elements were superimposed on hydrologic factors that governed the mobility and concentrations of conservative chemical constituents. Cadmium probably moved to ground water because of complexation, either with an anionic organic ligand or possibly with chloride. In addition, cadmium may have been excluded from sorption because of competition from other elements that were more abundant and had higher sorption affinities.

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APPENDIXES

Appendix A.—Chemical analyses of rainwater, storm water, water from the unsaturated zone, and ground water at the Annapolis site

[°, degrees; ' seconds; ", minutes; µS/cm, microsiemens per centimeter at 25 degrees Celsius; deg. C, degrees Celsius; --, no data available; $CaCO_3$, calcium carbonate; mg/L, milligrams per liter; µg/L, micrograms per liter; <, less than; for filtered samples: µm, micrometer, mm, millimeter; values shown for pH and dissolved oxygen are field measurements; values shown for specific conductance and alkalinity are field or laboratory measurements; values shown in parentheses (360) are of questioned validity and were not used in the text or for data analysis or interpretation]

Sample type	Pore diameter	Filter diameter	Filter composition
Nitrogen and phosphorus	.45 µm	144 mm	Polycarbonate
Major ions, metals, and trace elements[1]	.10 µm	144 mm	Polycarbonate
Organic carbon	.45 µm	47 mm	Silver

[1] Prior to 1987, only aluminum, iron, and manganese samples were filtered through 0.1 µm pores; other constituents filtered through 0.45 µm pores.

For the convenience of the reader, the sampling stations are categorized as follows:

Rainwater	Rainwater (precipitation)
Storm-water impoundment inlet (runoff).....	01589903
Storm-water impoundment outlet.....	01589906
Control well (upgradient).....	AA De 140
Downgradient wells.....	AA De 142, AA De 143, and AA De 159
Beneath-impoundment wells.....	AA De 155, AA De 156, and AA De 157
Unsaturated zone (lysimeter).....	AA De 160

Appendix A.—Chemical analyses of rainwater, storm water, water from the unsaturated zone, and ground water at the Annapolis site—Continued

Station name or number	Latitude (° ' ")	Longitude (° ' ")	Date	Specific conductance (µs/cm)	pH (standard units)	Temperature, water (deg. C)	Oxygen, dissolved (mg/L)
Rainwater	38 59 28	76 32 21	05-27-87	27	4.50	--	--
			09-09-87	18	4.64	--	--
			06-09-88	124	3.70	--	--
			08-16-88	68	3.96	--	--
01589903	38 59 26	76 32 21	09-26-85	--	7.40	23.0	--
			12-10-86	57	7.20	9.1	--
			05-27-87	48	7.17	20.1	--
			09-09-87	126	7.22	25.0	--
			01-18-88	116	6.76	5.1	--
			06-09-88	79	6.35	--	--
			08-16-88	84	6.48	25.5	--
			02-01-89	304	7.11	18.1	--
01589906	38 59 28	76 32 20	05-01-87	137	8.71	21.0	10.7
			05-27-87	57	8.20	21.1	--
			09-01-87	96	8.95	26.5	12.4
			09-11-87	72	8.81	--	--
			06-03-88	65	7.83	23.4	8.95
			08-17-88	71	6.84	26.0	8.00
			10-07-88	83	6.90	--	--
			01-19-89	95	7.09	5.2	11.63
			03-29-89	109	9.07	17.3	10.69
AA De 140	38 59 19	76 32 21	09-04-86	43	4.81	12.0	6.73
			12-11-86	36	4.95	11.0	--
			04-29-87	30	5.26	13.9	9.58
			05-04-87	44	5.36	12.7	--
			09-09-87	36	5.07	14.5	--
			12-07-87	30	5.40	13.7	8.94
			08-17-88	36	5.40	14.6	9.47
			01-19-89	33	5.13	14.2	8.46
AA De 142	38 59 28	76 32 21	09-02-86	67	5.08	16.0	6.21
			12-12-86	93	4.91	13.7	--
			04-29-87	64	5.41	16.5	6.19
AA De 143	38 59 28	76 32 21	12-12-86	120	5.06	15.3	--
			12-07-87	77	5.37	14.8	6.32
			06-10-88	94	5.22	15.3	6.70
			08-16-88	80	5.34	14.4	8.24
			08-17-88	71	5.80	--	--
AA De 155	38 59 28	76 32 21	12-12-86	74	4.86	12.1	--
			12-07-87	68	4.92	15.2	2.94
AA De 156	38 59 28	76 32 21	09-03-86	185	4.82	12.0	5.35
			12-12-86	230	4.63	13.8	--
			04-29-87	372	4.87	13.8	5.34
			06-10-88	320	4.93	14.4	1.32
			01-18-89	156	5.33	16.8	4.01
			03-29-89	154	4.96	15.3	.47
AA De 157	38 59 28	76 32 21	09-03-86	975	4.18	12.0	--
			12-10-86	345	4.86	17.1	--
			04-29-87	135	5.21	13.5	4.41
			05-04-87	140	5.16	12.2	--
			09-09-87	630	4.65	16.5	2.44
			09-11-87	600	4.64	17.9	2.58
			12-07-87	480	4.82	17.9	2.69
			06-10-88	251	5.20	13.7	4.33
			08-16-88	225	5.34	18.3	3.66
			08-17-88	176	5.50	--	--
			01-18-89	148	5.29	16.2	2.76
			03-29-89	101	4.96	15.2	2.62
AA De 159	38 59 28	76 32 21	12-07-87	110	6.41	14.8	3.07
AA De 160	38 59 26	76 32 22	08-16-88	53	6.19	--	--

Calcium, filtered (mg/L)	Magnesium, filtered (mg/L)	Sodium, filtered (mg/L)	Potassium, filtered (mg/L)	Alkalinity, as CaCO3 (mg/L)	Sulfide, unfiltered (mg/L)	Sulfate, filtered (mg/L)	Station name or number
--	--	--	--	--	--	--	Rainwater
--	--	--	--	--	--	1.7	
2.2	0.44	1.2	--	--	--	13	
1.1	.18	1.3	--	--	--	--	
25	1.9	3.7	--	--	--	--	01589903
--	--	--	--	20.5	--	--	
6.8	.6	.9	0.7	16.0	--	5.0	
18	1.2	4.2	2.4	29.2	--	13	
18	.72	4.6	1.3	24.0	--	21	
8.8	.69	.8	1.0	9.0	<0.5	15	
9.6	.77	3.6	1.4	16.0	--	19	
44	2.4	7.3	2.8	40.0	--	61	
11	1.2	11	1.3	27.6	--	12	01589906
--	--	--	--	19.0	--	--	
12	1.3	.2	--	19.3	--	16	
9.3	.86	1.4	1.3	18.5	--	13	
7.7	1.1	1.8	2.5	17.2	<.5	9.6	
10	.85	1.6	1.2	17.5	<.5	13	
--	--	--	--	--	--	--	
12	.75	3.4	.8	17.5	--	7.8	
12	.87	8.2	.8	16.2	--	8.8	
2.7	.70	1.6	2.1	2.9	--	1.8	AA De 140
1.9	.80	1.5	2.2	3.0	--	2.8	
1.3	.90	2.1	1.6	3.7	--	.3	
3.5	.70	1.8	1.7	3.1	--	6.3	
.95	.60	1.9	1.7	1.0	--	.4	
.93	.55	1.7	1.7	1.4	--	.5	
1.2	.50	1.8	1.6	2.0	--	1.9	
.96	.56	1.6	4.8	1.0	--	.5	
3.6	1.8	3.1	2.1	3.2	--	.5	AA De 142
6.9	3.1	4.0	2.5	2.6	--	5.8	
3.4	2.4	3.8	1.9	4.6	--	.3	
8.2	3.5	4.9	4.0	3.0	--	4.5	AA De 143
3.3	2.2	4.0	2.9	2.6	--	.7	
4.1	2.6	4.4	3.4	3.2	--	.8	
3.0	1.7	7.5	4.0	4.5	--	4.8	
3.0	1.9	4.8	2.6	4.0	--	1.2	
4.6	1.5	3.5	2.8	3.0	--	14	AA De 155
3.3	1.6	3.6	2.7	--	--	8.3	
9.3	5.6	6.9	5.0	3.0	--	2.1	AA De 156
15	9.4	10	5.8	4.0	--	1.4	
--	--	--	--	1.6	--	--	
16	10	14	6.2	2.4	--	.5	
8.6	5.4	9.7	5.7	4.0	--	2.8	
7.5	4.8	11	4.4	3.0	<.5	<.2	
69	25	40	12	3.0	--	2.4	AA De 157
24	8.3	22	6.0	4.0	--	3.8	
6.5	2.5	10	2.9	5.1	--	.4	
7.1	2.7	11	3.1	4.0	--	.4	
29	10	44	6.2	2.0	--	1.5	
31	12	49	7.6	2.0	--	.6	
25	9.4	42	6.7	3.0	--	.7	
11	4.4	21	3.6	3.4	--	.8	
8.6	3.2	21	3.6	5.0	<.5	.7	
6.7	2.4	20	3.3	5.0	--	.5	
4.8	1.7	16	3.7	5.0	--	.7	
3.3	1.2	12	2.2	7.0	.8	.3	
9.8	2.1	1.6	2.1	40.5	--	12	AA De 159
--	--	--	--	16	--	--	AA De 160

Appendix A.—Chemical analyses of rainwater, storm water, water from the unsaturated zone, and ground water at the Annapolis site—Continued

Station name or number	Date	Chloride, filtered (mg/L)	Fluoride, filtered (mg/L)	Bromide, filtered (mg/L)	Iodide, filtered (mg/L)
Rainwater	05-27-87	--	--	--	--
	09-09-87	2.1	0.05	<0.01	--
	06-09-88	.8	.16	<.01	--
	08-16-88	--	--	--	--
01589903	09-26-85	--	--	--	--
	12-10-86	--	--	--	--
	05-27-87	1.1	<.1	<.01	<0.001
	09-09-87	6.3	.1	--	--
	01-18-88	7.7	<.1	<.01	--
	06-09-88	1.4	.2	--	--
	08-16-88	2.0	.1	--	--
	02-01-89	13	.1	--	--
01589906	05-01-87	11	.1	<.01	.005
	05-27-87	1.0	--	--	--
	09-01-87	1.5	.1	--	--
	09-11-87	2.2	.1	--	--
	06-03-88	3.3	.3	--	--
	08-17-88	1.4	<.1	--	--
	10-07-88	--	--	--	--
	01-19-89	9.9	<.1	<.01	--
	03-29-89	18	<.1	--	--
AA De 140	09-04-86	5.1	<.1	--	--
	12-11-86	10	<.1	--	--
	04-29-87	4.3	<.1	.024	.001
	05-04-87	4.4	<.1	.025	<.001
	09-09-87	4.9	.1	--	--
	12-07-87	6.1	.2	--	--
	08-17-88	3.8	<.1	--	--
	01-19-89	3.8	.1	.019	--
AA De 142	09-02-86	12	<.1	--	--
	12-12-86	22	<.1	--	--
	04-29-87	13	<.1	.012	.001
AA De 143	12-12-86	28	.2	--	--
	12-07-87	18	.2	--	--
	06-10-88	20	.2	--	--
	08-16-88	17	<.1	--	--
	08-17-88	15	<.1	--	--
AA De 155	12-12-86	8.8	.1	--	--
	12-07-87	14	.2	--	--
AA De 156	09-03-86	46	.2	--	--
	12-12-86	72	<.1	--	--
	04-29-87	--	--	--	--
	06-10-88	85	.2	--	--
	01-18-89	45	<.1	.015	--
	03-29-89	47	.1	--	--
AA De 157	09-03-86	270	.1	--	--
	12-10-86	100	<.1	--	--
	04-29-87	30	<.1	.027	.005
	05-04-87	42	<.1	.026	.004
	09-09-87	170	.1	--	--
	09-11-87	170	.1	--	--
	12-07-87	150	.2	--	--
	06-10-88	65	.3	--	--
	08-16-88	55	<.1	--	--
	08-17-88	45	<.1	--	--
	01-18-89	35.7	<.1	.03	--
	03-29-89	23.8	<.1	--	--
AA De 159	12-07-87	4.0	.6	--	--
AA De 160	08-16-88	3.0	--	--	--

Silica, filtered (mg/L)	Nitrate + nitrite, as N, filtered (mg/L)	Nitrogen, ammonia, filtered (mg/L)	Nitrogen, ammonia + organic, as N, filtered (mg/L)	Phosphorus, as P, unfiltered (mg/L)	Phosphorus, ortho as P, filtered (mg/L)	Aluminum, filtered (μg/L)	Station name or number
--	--	--	--	--	--	--	Rainwater
<0.01	<0.01	--	--	--	--	--	
.16	1.6	--	--	--	--	--	
.25	--	--	--	--	--	--	
--	--	--	--	--	--	--	01589903
--	--	--	--	--	--	--	
--	--	--	--	--	--	--	
1.5	--	--	--	--	--	--	
.52	1.1	--	--	--	<0.01	20	
.29	--	--	2.5	0.1	--	40	
.84	.79	0.30	.7	39	.54	30	
.95	4.1	2.9	10	--	<.01	--	
--	--	--	--	--	--	--	01589906
--	--	--	--	--	--	--	
2.7	--	--	--	--	--	--	
1.2	<.10	.04	.5	.04	<.01	--	
.75	<.10	.08	.7	.09	<.01	30	
1.1	.16	.02	.5	.41	<.01	20	
--	--	--	--	--	--	--	
.17	.47	--	--	--	<.01	<10	
.3	<.10	.02	<.2	<.01	<.01	60	
14	.66	.01	<.2	.72	<.01	40	AA De 140
14	--	--	--	--	--	40	
--	--	--	--	--	--	--	
--	--	--	--	--	--	--	
13	--	--	--	--	--	--	
14	.70	<.01	<.2	--	<.001	30	
13	1.2	<.01	.4	.06	<.01	30	
14	1.2	--	--	--	<.01	30	
13	.31	.01	<.2	.18	<.01	30	AA De 142
--	--	--	--	--	--	20	
14	--	--	--	--	--	--	
17	--	--	--	--	--	--	AA De 143
16	.24	.01	<.2	--	<.001	20	
16	.38	.05	1.3	<.01	<.01	10	
14	.32	.06	.6	.06	.01	20	
15	--	--	--	--	--	20	
18	--	--	--	--	--	--	AA De 155
18	.31	<.01	<.2	--	<.001	40	
17	.31	.04	<.2	.09	.02	--	AA De 156
19	--	--	--	--	--	40	
--	--	--	--	--	--	--	
17	.13	.02	.4	.03	<.01	40	
18	<.10	--	--	--	<.01	20	
19	<.10	.01	.3	.08	.02	20	
16	--	--	--	--	--	--	AA De 157
16	--	--	--	--	--	--	
--	--	--	--	--	--	--	
--	--	--	--	--	--	--	
12	--	--	--	--	--	--	
16	.52	.04	.4	<.01	<.01	--	
15	.99	.03	<.2	--	.003	50	
14	.32	.02	.7	<.01	<.01	20	
15	.36	.01	.4	.02	<.01	20	
15	--	--	--	--	--	20	
15	.55	--	--	--	<.01	10	
14	.47	.02	.2	.09	<.01	<10	
17	.30	.04	.3	--	.018	<10	AA De 159
--	--	--	--	--	--	--	AA De 160

Appendix A.—Chemical analyses of rainwater, storm water, water from the unsaturated zone, and ground water at the Annapolis site—Continued

Station name or number	Date	Antimony, filtered (µg/L)	Antimony, unfiltered (µg/L)	Arsenic, filtered (µg/L)	Arsenic, unfiltered (µg/L)
Rainwater	05-27-87	--	--	--	--
	09-09-87	--	--	--	--
	06-09-88	--	--	--	--
	08-16-88	--	--	--	--
01589903	09-26-85	<1	2	1	6
	12-10-86	--	--	--	--
	05-27-87	--	--	--	<1
	09-09-87	<1	--	1	--
	01-18-88	--	--	--	--
	06-09-88	<1	<1	<1	<1
	08-16-88	<1	<1	7	7
	02-01-89	--	2	1	<1
01589906	05-01-87	--	--	--	--
	05-27-87	--	--	--	--
	09-01-87	--	--	--	3
	09-11-87	1	--	1	--
	06-03-88	<1	4	1	3
	08-17-88	<1	<1	1	2
	10-07-88	--	<1	--	6
	01-19-89	--	--	--	--
	03-29-89	<1	<1	<1	<1
AA De 140	09-04-86	<1	1	<1	5
	12-11-86	<1	<1	<1	2
	04-29-87	--	--	--	--
	05-04-87	--	--	--	--
	09-09-87	<1	<1	<1	<1
	12-07-87	--	--	<1	--
	08-17-88	--	--	2	1
	01-19-89	--	--	--	--
AA De 142	09-02-86	<1	<1	<1	3
	12-12-86	--	--	--	--
	04-29-87	<1	<1	<1	2
AA De 143	12-12-86	--	--	<1	--
	12-07-87	--	--	<1	--
	06-10-88	--	--	<1	--
	08-16-88	--	--	1	1
	08-17-88	--	--	<1	--
AA De 155	12-12-86	--	--	<1	--
	12-07-87	--	--	<1	--
AA De 156	09-03-86	<1	<1	<1	<1
	12-12-86	<1	<1	<1	<1
	04-29-87	--	--	--	--
	06-10-88	--	--	<1	--
	01-18-89	--	--	--	--
	03-29-89	--	--	<1	<1
AA De 157	09-03-86	<1	--	<1	--
	12-10-86	--	--	<1	--
	04-29-87	--	--	--	--
	05-04-87	--	--	--	--
	09-09-87	<1	<1	4	<1
	09-11-87	<1	<1	<1	<1
	12-07-87	--	--	<1	--
	06-10-88	--	--	<1	--
	08-16-88	--	--	<1	2
	08-17-88	--	--	<1	--
	01-18-89	--	--	--	--
	03-29-89	--	--	<1	<1
AA De 159	12-07-87	--	--	<1	--
AA De 160	08-16-88	--	1	--	--

Barium, filtered (μg/L)	Barium, unfiltered (μg/L)	Beryllium, filtered (μg/L)	Boron, filtered (μg/L)	Boron, unfiltered (μg/L)	Cadmium, filtered (μg/L)	Cadmium, unfiltered (μg/L)	Station name or number
--	--	--	--	10	--	<1	Rainwater
--	--	--	--	--	--	--	
5	--	<0.5	--	--	2	--	
4	--	<.5	--	--	<1	--	
--	<100	<.5	--	--	<1	<1	01589903
--	--	--	--	--	--	<1	
--	--	<.5	10	--	<1	1	
19	<100	--	30	40	.4	<1	
--	--	--	--	--	--	--	
7	100	--	30	20	.7	1	
8	<100	<.5	20	40	<.2	1	
28	<100	--	60	70	1	1	
--	--	<.5	10	50	<.1	<1	01589906
--	--	--	--	50	--	<1	
18	<100	--	20	60	.6	2	
8	--	--	10	--	<1	--	
7	<100	--	10	40	<.1	2	
16	<100	<.5	10	80	1.2	2	
--	600	--	--	370	--	16	
--	--	--	--	--	--	--	
6	100	<.5	20	30	.3	1	
--	--	<.5	10	--	<1	<1	AA De 140
--	--	.9	10	--	1	<1	
--	--	<.5	10	20	.3	<1	
--	--	<.5	10	30	.6	2	
15	<100	--	10	20	.3	<1	
--	--	--	10	--	<1	--	
9	--	<.5	10	--	<1	--	
--	--	--	--	--	--	--	
--	--	<.5	20	--	<1	<1	AA De 142
--	--	<.5	<10	--	1	<1	
--	--	<.5	<10	20	.7	1	
--	--	--	20	--	7	--	AA De 143
--	--	--	10	--	4	--	
33	--	--	10	--	5	--	
26	--	<.5	20	--	9	12	
25	--	<.5	10	--	2	--	
--	--	--	10	--	9	--	AA De 155
--	--	--	<10	--	7	--	
--	--	<.5	10	--	9	9	AA De 156
--	--	<.5	20	--	15	13	
--	--	--	--	--	--	--	
160	--	--	10	--	23	--	
--	--	--	--	--	--	--	
69	--	<.5	20	--	9	7	
--	--	3.3	<10	--	27	--	AA De 157
--	--	--	20	--	8	--	
--	--	<.5	<10	20	2.3	2	
--	--	<.5	10	20	2.5	5	
130	200	--	30	20	12	12	
180	200	--	20	--	12	13	
--	--	--	20	--	10	--	
63	--	--	10	--	5	--	
50	--	<.5	20	--	5	4	
38	--	<.5	20	--	3	--	
--	--	--	--	--	--	--	
19	--	<.5	40	--	1	1	
--	--	--	20	--	1	--	AA De 159
--	100	--	--	40	--	<1	AA De 160

Appendix A.—Chemical analyses of rainwater, storm water, water from the unsaturated zone, and ground water at the Annapolis site—Continued

Station name or number	Date	Chromium, filtered (µg/L)	Chromium, unfiltered (µg/L)	Cobalt, filtered (µg/L)	Cobalt, unfiltered (µg/L)
Rainwater	05-27-87	--	20	--	7
	09-09-87	--	--	--	--
	06-09-88	28	--	<3	--
	08-16-88	<5	--	<3	--
01589903	09-26-85	--	110	<3	9
	12-10-86	--	10	--	3
	05-27-87	<1	14	<1	<1
	09-09-87	<.5	<10	<.5	2
	01-18-88	--	--	--	--
	06-09-88	<.5	5	2.0	--
	08-16-88	.6	3	2.0	--
	02-01-89	< .5	3	2.0	--
01589906	05-01-87	<1	<10	<.5	<1
	05-27-87	--	<10	--	<1
	09-01-87	1.2	30	.5	1
	09-11-87	<1	--	<1	--
	06-03-88	<.5	58	3.0	--
	08-17-88	<.5	58	1.0	--
	10-07-88	--	750	--	--
	01-19-89	--	--	--	--
	03-29-89	.5	4	<1	--
AA De 140	09-04-86	<1	70	2.0	1
	12-11-86	3.0	50	3.0	2
	04-29-87	1.9	20	1.3	2
	05-04-87	1.9	<10	1.6	<1
	09-09-87	2.0	40	1.7	2
	12-07-87	2.3	--	1.3	--
	08-17-88	3.0	--	1.0	--
	01-19-89	--	--	--	--
AA De 142	09-02-86	<1	60	2.0	1
	12-12-86	<1	40	<1	2
	04-29-87	.7	20	<.5	1
AA De 143	12-12-86	4.0	--	<1	--
	12-07-87	1.4	--	2.9	--
	06-10-88	2.0	--	2.0	--
	08-16-88	<1	15	1.0	--
	08-17-88	3.0	--	<1	--
AA De 155	12-12-86	3.0	--	5.0	--
	12-07-87	4.5	--	2.1	--
AA De 156	09-03-86	<1	130	3.0	3
	12-12-86	8.0	<10	3.0	3
	04-29-87	--	--	--	--
	06-10-88	3.0	--	<1	--
	01-18-89	--	--	--	--
	03-29-89	4.0	5.0	3.0	--
AA De 157	09-03-86	<2	--	5.0	--
	12-10-86	<1	--	2.0	--
	04-29-87	.8	<10	<.5	1
	05-04-87	.9	<10	<.5	<1
	09-09-87	<.5	30	1.8	2
	09-11-87	1.3	30	1.7	3
	12-07-87	<.5	--	1.7	--
	06-10-88	2.0	--	1.0	--
	08-16-88	1.0	4.0	1.0	--
	08-17-88	3.0	--	1.0	--
	01-18-89	--	--	--	--
	03-29-89	2.0	45	1.0	--
AA De 159	12-07-87	<.5	--	.9	--
AA De 160	08-16-88	--	3	--	--

Copper, filtered (µg/L)	Copper, unfiltered (µg/L)	Iron, filtered (µg/L)	Lead, filtered (µg/L)	Lead, unfiltered (µg/L)	Lithium, filtered (µg/L)	Manganese, filtered (µg/L)	Station name or number
--	16	--	--	<5	--	--	Rainwater
--	--	--	--	--	--	--	
70	--	50	<10	--	<4	26	
<10	--	110	<10	--	<4	9	
10	12	180	<10	15	--	9	01589903
--	12	--	--	5	--	--	
4	24	20	<5	29	--	2	
11	18	--	<5	5	<4	--	
--	--	6	--	--	--	13	
7	13	39	.8	12	<4	27	
3	21	60	<.5	11	<4	52	
18	19	56	<.5	<5	<4	50	
2	6	65	<5	<5	--	<1	01589906
--	5	--	--	<5	--	--	
--	36	--	--	82	<4	--	
5	--	--	<5	--	<4	--	
2	30	37	<.5	55	<4	3	
5	38	69	.6	74	<4	23	
--	380	--	--	800	--	--	
--	--	18	--	--	--	4	
4	4	12	<.5	7	<4	1	
6	11	21	<5	12	<4	57	AA De 140
6	14	77	<5	<5	6	--	
<1	9	56	<5	<5	--	39	
2	8	10	<5	20	--	37	
5	9	--	<5	<5	<4	--	
3	--	20	<.5	--	<4	20	
3	--	10	.7	--	--	39	
--	--	4	--	--	--	38	
1	12	6	<5	10	<4	44	AA De 142
2	9	12	<5	6	5	47	
<1	5	10	<5	<5	--	18	
2	--	21	<5	--	6	78	AA De 143
2	--	<10	<.5	--	<4	10	
3	--	7	1.1	--	--	27	
9	27	90	<.5	6	--	37	
3	--	27	<5	--	--	22	
4	--	5	<5	--	4	81	AA De 155
2	--	100	.8	--	<4	20	
4	6	6	<5	<5	10	--	AA De 156
5	15	6	<5	<5	4	59	
--	--	--	--	--	--	--	
32	--	--	2.3	--	--	40	
--	--	5	--	--	--	27	
35	10	6	2	<5	--	19	
10	--	13	5	--	15	--	AA De 157
9	--	6	<5	--	<4	66	
1	3	7	<5	<5	--	18	
1	3	5	<5	7	--	21	
6	11	--	<5	<5	<4	--	
8	8	--	5	<5	<4	--	
5	--	<10	1	--	<4	80	
24	--	5	.7	--	--	27	
3	7	12	1.1	<5	--	23	
3	--	8	<5	--	--	22	
--	--	<3	--	--	--	18	
13	3	6	1	<5	--	9	
1	--	4,600	6.9	--	5	260	AA De 159
--	8	--	--	<5	--	--	AA De 160

Appendix A.—Chemical analyses of rainwater, storm water, water from the unsaturated zone, and ground water at the Annapolis site—Continued

Station name or number	Date	Mercury, filtered (µg/L)	Mercury, unfiltered (µg/L)	Molybdenum, filtered (µg/L)	Molybdenum, unfiltered (µg/L)
Rainwater	05-27-87	--	--	--	<1
	09-09-87	--	--	--	--
	06-09-88	--	--	<10	--
	08-16-88	--	--	<10	--
01589903	09-26-85	--	--	<10	<1
	12-10-86	--	--	--	--
	05-27-87	--	--	<1	--
	09-09-87	--	--	1	1
	01-18-88	--	--	--	--
	06-09-88	--	<0.1	3	11
	08-16-88	--	.2	1	1
	02-01-89	--	--	2	5
01589906	05-01-87	<0.1	.1	1	<1
	05-27-87	--	--	--	<10
	09-01-87	--	--	--	1
	09-11-87	--	--	<1	--
	06-03-88	--	<.1	2	6
	08-17-88	--	<.1	1	1
	10-07-88	--	--	--	7
	01-19-89	--	--	--	--
	03-29-89	--	.2	<1	3
AA De 140	09-04-86	--	--	<1	3
	12-11-86	--	--	<1	2
	04-29-87	<.1	.1	1	<1
	05-04-87	<.1	.1	<1	<1
	09-09-87	--	--	<1	<1
	12-07-87	--	--	<1	--
	08-17-88	--	<.1	<1	--
	01-19-89	--	--	--	--
AA De 142	09-02-86	--	--	<1	3
	12-12-86	--	--	2	5
	04-29-87	<.1	.1	<1	<1
AA De 143	12-12-86	--	--	2	--
	12-07-87	--	--	<1	--
	06-10-88	--	<.1	1	--
	08-16-88	--	<.1	<1	--
	08-17-88	--	--	<1	--
AA De 155	12-12-86	--	--	2	--
	12-07-87	--	--	<1	--
AA De 156	09-03-86	--	--	4	2
	12-12-86	--	--	2	1
	04-29-87	--	<.1	--	--
	06-10-88	--	--	2	--
	01-18-89	--	.1	--	--
	03-29-89	--	--	<1	--
AA De 157	09-03-86	--	--	2	--
	12-10-86	--	--	<1	--
	04-29-87	<.1	.8	<1	<1
	05-04-87	<.1	.1	<1	<1
	09-09-87	--	--	<1	<1
	09-11-87	--	--	<1	<1
	12-07-87	--	--	<1	--
	06-10-88	--	<.1	2	--
	08-16-88	--	<.1	<1	--
	08-17-88	--	--	<1	--
	01-18-89	--	--	--	--
	03-29-89	--	.1	1	--
AA De 159	12-07-87	--	--	<1	--
AA De 160	08-16-88	--	--	--	5

Nickel, filtered (µg/L)	Nickel, unfiltered (µg/L)	Selenium, filtered (µg/L)	Silver, filtered (µg/L)	Strontium, filtered (µg/L)	Thallium, filtered (µg/L)	Vanadium, filtered (µg/L)	Station name or number
--	4	--	--	--	--	--	Rainwater
--	--	--	--	--	--	--	
<10	--	--	<1	5	--	<6	
<10	--	--	<1	3	--	<6	
<100	2	<1	--	--	--	10	01589903
--	10	--	--	--	--	--	
2	12	--	--	19	--	2	
9	10	<1	<1	47	--	19	
--	--	--	--	--	--	--	
2	5	--	--	22	--	4	
7	13	--	--	26	--	--	
20	18	--	<1	130	--	12	
<1	1	--	--	33	<1	1	01589906
--	2	--	--	--	--	--	
--	17	--	--	32	--	3	
2	--	<1	<1	24	--	1	
3	20	--	--	21	--	3	
5	29	--	--	26	--	4	
--	200	--	--	--	--	--	
--	--	--	--	--	--	--	
1	1	--	--	59	--	2	
4	8	<1	--	7	--	<1	AA De 140
8	11	<1	<1	5	--	<1	
3	4	--	--	5	<1	<1	
8	7	--	<1	12	<1	<1	
3	1	<1	<1	4	--	<1	
3	--	<1	--	3	--	<1	
2	--	--	--	4	--	<1	
--	--	--	--	--	--	--	
4	10	<1	--	18	--	<1	AA De 142
6	9	<1	<1	32	--	<1	
5	5	--	--	18	<1	<1	
25	--	<1	<1	31	--	<1	AA De 143
69	--	<1	--	18	--	<1	
14	--	--	--	19	--	<1	
13	--	--	--	22	--	<1	
8	--	--	--	17	--	<1	
15	--	<1	<1	15	--	<1	AA De 155
7	--	<1	--	13	--	<1	
20	32	<1	--	38	--	<1	AA De 156
48	44	<1	<1	60	--	<1	
--	--	--	--	--	--	--	
50	--	--	--	67	--	<1	
--	--	--	--	--	--	--	
28	--	--	--	31	--	<1	
62	--	<1	--	210	--	1	AA De 157
28	--	<1	<1	74	--	<2	
9	7	--	--	20	<1	<5	
7	11	--	--	23	<1	<4	
31	37	<1	<1	81	--	2	
37	39	<1	<1	98	--	1	
27	--	<1	--	80	--	<1	
15	--	--	--	37	--	<1	
10	--	--	--	28	--	<1	
9	--	--	--	21	--	<1	
--	--	--	--	--	--	--	
7	--	--	--	13	--	<1	
3	--	<1	--	26	--	<1	AA De 159
--	8	--	--	--	--	--	AA De 160

Appendix A.—Chemical analyses of rainwater, storm water, water from the unsaturated zone, and ground water at the Annapolis site—Continued

Station name or number	Date	Zinc, filtered (µg/L)	Zinc, unfiltered (µg/L)	Carbon, organic, filtered (mg/L)	Carbon, organic, unfiltered (mg/L)
Rainwater	05-27-87	--	230	--	--
	09-09-87	--	--	--	--
	06-09-88	160	--	--	--
	08-16-88	230	--	--	--
01589903	09-26-85	28	220	--	--
	12-10-86	--	40	--	8.6
	05-27-87	61	250	--	--
	09-09-87	110	160	64	72
	01-18-88	--	--	--	--
	06-09-88	180	240	--	8.7
	08-16-88	150	290	--	--
	02-01-89	280	270	--	--
01589906	05-01-87	33	30	7.4	7.5
	05-27-87	--	30	--	--
	09-01-87	110	790	15	27
	09-11-87	17	--	--	--
	06-03-88	3	730	12	13
	08-17-88	7	90	--	--
	10-07-88	--	9,300	--	--
	01-19-89	--	--	--	--
	03-29-89	8	80	4.1	5.8
AA De 140	09-04-86	49	140	.5	2.8
	12-11-86	97	110	1.0	.9
	04-29-87	26	30	1.0	.8
	05-04-87	24	20	2.3	2.1
	09-09-87	40	40	1.6	1.1
	12-07-87	18	--	.8	.9
	08-17-88	42	--	--	--
	01-19-89	--	--	--	--
AA De 142	09-02-86	24	110	.6	2.3
	12-12-86	30	60	1.6	1.4
	04-29-87	16	20	1.2	1.0
AA De 143	12-12-86	83	--	1.2	1.8
	12-07-87	66	--	1.0	.6
	06-10-88	54	--	1.8	1.6
	08-16-88	53	--	--	--
	08-17-88	35	--	--	--
AA De 155	12-12-86	43	--	1.0	1.0
	12-07-87	26	--	.5	.3
AA De 156	09-03-86	120	120	.9	.5
	12-12-86	170	200	1.3	1.4
	04-29-87	--	--	1.0	1.0
	06-10-88	200	--	1.0	1.0
	01-18-89	--	--	--	--
	03-29-89	110	--	1.1	1.1
AA De 157	09-03-86	200	--	--	--
	12-10-86	80	--	1.4	1.9
	04-29-87	18	20	1.1	1.6
	05-04-87	26	20	1.6	.7
	09-09-87	97	100	1.6	1.2
	09-11-87	85	90	1.3	.6
	12-07-87	69	--	1.3	.8
	06-10-88	32	--	1.3	1.0
	08-16-88	33	--	--	--
	08-17-88	26	--	--	--
	01-18-89	--	--	--	--
	03-29-89	18	--	1.2	1.3
AA De 159	12-07-87	53	--	1.1	.9
AA De 160	08-16-88	--	50	--	--

Cyanide, unfiltered (mg/L)	Methylene blue active substances (mg/L)	Oil and grease, unfiltered (mg/L)	Benzene, unfiltered (µg/L)	Toluene, unfiltered (µg/L)	Trichloro-fluoro-methane, unfiltered (µg/L)	1,1,1,-trichloro-ethane, unfiltered (µg/L)	Station name or number
--	--	--	--	--	--	--	Rainwater
--	--	--	--	--	--	--	
--	--	--	--	--	--	--	
--	--	--	--	--	--	--	
--	--	--	--	--	--	--	01589903
--	--	--	--	--	--	--	
--	0.10	--	--	--	--	--	
--	.93	--	--	--	--	--	
--	--	--	--	--	--	--	
--	.28	--	--	--	--	--	
--	.90	--	--	--	--	--	
--	2.6	--	--	--	--	--	
--	.23	--	<0.2	<0.2	<0.2	<0.2	01589906
--	.12	--	--	--	--	--	
--	.19	<1	<.2	<.2	<.2	<.2	
--	--	--	--	--	--	--	
--	.55	--	--	--	--	--	
--	.49	--	--	--	--	--	
--	--	--	--	--	--	--	
--	--	--	--	--	--	--	
<0.01	.10	--	--	--	--	--	
--	.01	--	<3	<3	<3	<3	AA De 140
--	.04	--	--	--	--	--	
--	.01	<1	<.2	<.2	<.2	<.2	
--	.01	--	<.2	<.2	<.2	<.2	
--	.01	--	--	--	--	--	
--	.02	--	--	--	--	--	
--	.01	--	--	--	--	--	
--	--	--	--	--	--	--	
--	.01	--	--	--	--	--	AA De 142
--	.04	--	.2	.6	<.2	<.2	
--	.02	<1	<.2	<.2	<.2	<.2	
--	.05	--	--	--	--	--	AA De 143
--	.03	--	--	--	--	--	
--	.03	--	--	--	--	--	
--	.02	--	--	--	--	--	
--	.03	--	--	--	--	--	
--	.04	--	--	--	--	--	AA De 155
--	.02	--	--	--	--	--	
--	.04	--	<3	<3	5.2	<3	AA De 156
--	.05	--	<.2	.3	<.2	<.2	
--	.03	--	<.2	<.2	<.2	<.2	
--	.04	<1	--	--	--	--	
--	--	--	--	--	--	--	
<.01	.05	--	--	--	--	--	
--	--	<1	--	--	--	--	AA De 157
--	.07	--	<.2	<.2	.2	.2	
--	.03	<1	<.2	<.2	<.2	<.2	
--	.03	--	<.2	<.2	<.2	<.2	
--	.02	--	<.2	<.2	<.2	<.2	
--	.02	--	--	--	--	--	
--	.05	--	--	--	--	--	
--	.03	--	--	--	--	--	
--	.03	--	--	--	--	--	
--	.03	--	--	--	--	--	
--	--	--	--	--	--	--	
<.01	.08	--	--	--	--	--	
--	.02	--	--	--	--	--	AA De 159
--	--	--	--	--	--	--	AA De 160

Appendix B.— Chemical analyses of rainwater, storm water, water from the unsaturated zone, and ground water at the Greenmount site

[°, degrees; ' seconds; ", minutes; µS/cm, microsiemens per centimeter at 25 degrees Celsius; deg. C, degrees Celsius; --, no data available; $CaCO_3$, calcium carbonate; mg/L, milligrams per liter; µg/L, micrograms per liter; <, less than; for filtered samples: µm, micrometer, mm, millimeter; values shown for pH and dissolved oxygen are field measurements; values shown for specific conductance and alkalinity are field or laboratory measurements; values shown in parentheses [Example (360)] are of questioned validity and were not used in the text or for data analysis or interpretation]

Sample type	Pore diameter	Filter diameter	Filter composition
Nitrogen and phosphorus	.45 µm	144 mm	Polycarbonate
Major ions, metals, and trace elements[1]	.10 µm	144 mm	Polycarbonate
Organic carbon	.45 µm	47 mm	Silver

[1] Prior to 1987, only aluminum, iron, and manganese samples were filtered through 0.1 µm pores; other constituents filtered through 0.45 µm pores.

For the convenience of the reader, the sampling stations are categorized as follows:

Rainwater	Rainwater (precipitation)
Storm-water impoundment inlet (runoff).....	01585680
Storm-water impoundment outlet.....	01585681
Beneath-impoundment wells.....	CL Bf 194 and CL Bf 195
Control well (upgradient).....	Cl Bf 198
Downgradient wells.....	CL Bf 199 and CL Bf 200
Unsaturated zone (lysimeter).....	CL Bf 201

Appendix B.— Chemical analyses of rainwater, storm water, water from the unsaturated zone, and ground water at the Greenmount site—Continued

Station name or number	Latitude (° ' ")	Longitude (° ' ")	Date	Specific conductance (µs/cm)	pH (standard units)	Temperature, water (deg. C)	Oxygen, dissolved (mg/L)
Rainwater	39 38 13	76 52 07	06-04-87	37	4.10	--	--
			03-26-88	10	5.31	--	--
01585680	39 38 13	76 52 07	05-20-86	265	6.70	--	--
			06-04-87	125	7.33	--	--
			09-10-87	320	6.59	--	--
			03-26-88	189	7.38	--	7.96
			05-06-88	160	7.30	--	--
01585681	39 38 11	76 52 11	06-01-87	216	7.41	--	--
			06-05-87	175	7.34	23.2	--
			03-23-88	1,030	9.74	10.0	14.8
			03-24-88	--	--	--	--
			03-31-88	655	9.87	14.3	14.7
			09-28-88	106	9.80	18.3	10.8
			03-30-89	303	8.68	15.2	8.70
CL Bf 194	39 38 11	76 52 11	06-25-86	190	5.86	12.4	5.70
			12-17-86	230	5.52	11.1	--
			12-10-87	211	5.60	12.0	1.93
			09-28-88	255	5.29	15.9	3.92
			03-30-89	269	5.32	11.8	.64
CL Bf 195	39 38 11	76 52 11	06-19-86	270	5.45	14.1	3.80
			06-01-87	246	5.23	14.0	--
			06-04-87	239	5.32	16.4	0
			06-05-87	250	5.15	15.5	--
			09-10-87	245	5.08	14.9	3.18
			12-10-87	194	5.40	13.6	2.23
			03-23-88	210	5.32	11.5	.78
			03-24-88	--	--	--	--
			03-26-88	210	5.37	11.5	.69
			03-31-88	230	5.25	11.1	.68
			09-28-88	335	5.07	15.3	.28
			03-30-89	289	5.28	9.7	.18
CL Bf 198	39 38 17	76 52 08	06-25-86	147	5.68	15.5	6.00
			12-17-86	190	5.41	11.2	--
			06-02-87	178	5.80	18.0	--
			06-04-87	181	5.63	15.0	--
			12-10-87	201	5.53	--	--
			03-24-88	188	5.33	14.2	6.87
			09-29-88	242	5.30	12.6	6.00
			03-30-89	290	5.25	12.0	--
CL Bf 199	39 38 10	76 52 10	06-20-86	250	5.43	13.4	5.20
			12-17-86	230	5.08	11.1	--
			06-02-87	275	5.32	15.3	--
			06-04-87	276	5.25	14.6	--
			06-05-87	285	5.23	14.8	--
			09-10-87	360	5.05	14.6	3.81
			12-10-87	400	5.61	12.6	5.33
			03-23-88	322	5.35	8.5	5.10
			03-26-88	300	5.67	9.0	2.00
			03-31-88	319	5.27	9.4	2.50
			09-29-88	320	5.55	13.4	6.51
			03-30-89	260	5.72	8.3	4.05
CL Bf 200	39 38 10	76 52 10	06-20-86	196	5.64	14.7	4.30
			06-02-87	145	5.39	12.0	--
			06-04-87	147	5.28	15.0	--
			06-05-87	150	5.28	14.8	--
			09-10-87	144	5.32	12.0	5.67
			12-10-87	159	5.45	11.7	4.57
CL Bf 201	39 38 11	76 52 11	09-10-87	570	7.03	--	--
			12-10-87	560	7.50	--	--
			03-23-88	987	7.50	--	--
			03-31-88	905	7.38	--	--
			09-29-88	1,410	7.70	--	--
			03-30-89	366	7.60	--	--

Calcium, filtered (mg/L)	Magnesium, filtered (mg/L)	Sodium, filtered (mg/L)	Potassium, filtered (mg/L)	Alkalinity as CaCO3 (mg/L)	Sulfide, unfiltered (mg/L)	Sulfate, filtered (mg/L)	Station name or number
--	--	--	--	--	--	--	Rainwater
0.88	0.11	0.7	--	1.5	--	--	
19	1.1	7.6	2.5	30.0	--	49	01585680
17	.7	2.7	1.9	25.0	--	13	
53	2.5	7.9	5.9	66.0	--	66	
8.9	7.7	14	1.5	64.0	--	22	
21	1.2	3.4	.9	28.5	--	22	
36	1.4	3.3	2.5	99.3	--	6.6	01585681
29	1.1	2.3	1.9	65.0	--	13	
21	1.1	180	2.5	84.0	--	15	
--	--	--	--	--	--	--	
16	.79	100	1.5	53.0	--	11	
19	.55	1.5	.8	45.0	1.6	9.5	
19	.94	38	1.0	44.0	.8	8.0	
8.9	7.2	11	1.7	15.0	--	3.5	CL Bf 194
8.4	8.1	21	1.6	20.5	--	6.9	
9.7	8.1	12	1.5	12.0	--	5.5	
11	9.5	19	1.8	15.0	1	7.5	
8.8	9.3	22	1.7	13.0	--	5.2	
11	8.8	18	1.5	10.0	--	14	CL Bf 195
13	7.3	16	1.9	11.0	--	18	
8.8	8.1	16	.9	9.0	--	16	
11	8.2	17	1.5	10.0	--	20	
8.8	7.7	17	1.6	9.5	--	16	
7.8	7.0	14	1.6	8.5	--	18	
8.4	7.2	14	1.5	8.7	--	18	
--	--	--	--	--	--	--	
20	1.1	11	1.6	8.8	--	21	
9.0	7.2	17	1.9	8.6	--	24	
11	9.2	24	1.8	8.0	.6	16	
9.9	19	14	4.2	8.4	--	<.2	
6.2	7.1	6.2	1.5	12.5	--	1.0	CL Bf 198
7.8	7.8	12	1.6	9.5	--	7.1	
7.4	8.5	7.3	2.6	12.7	--	2.1	
7.0	8.8	7.1	1.9	13.5	--	1.7	
7.2	11	10	2.3	10.0	--	1.0	
5.1	9.1	9.1	1.9	5.4	--	<.2	
15	5.3	32	1.0	6.0	<.5	.4	
10	8.5	27	1.5	7.5	--	24	
14	6.0	18	1.0	11.5	--	6.5	CL Bf 199
14	5.9	16	1.1	7.5	--	7.0	
13	5.9	18	1.5	9.2	--	9.3	
13	6.0	19	.5	8.6	--	6.8	
16	5.9	22	1.0	10.0	--	11	
17	6.0	29	1.0	7.0	--	5.0	
26	5.5	40	1.3	19.0	--	34	
16	6.0	29	1.1	9.1	--	11	
16	5.8	25	1.1	13.1	--	12	
--	--	--	1.0	6.5	--	--	
8.0	16	9.3	2.5	14.0	<.5	16	
15	4.5	26	.9	16.2	<.5	19	
8.7	7.2	13	2.1	12.0	--	--	CL Bf 200
6.7	5.9	6.1	1.4	6.3	--	.3	
6.6	6.0	6.0	.6	5.5	--	.3	
7.0	6.0	6.8	1.2	7.0	--	.4	
6.6	5.8	5.8	1.2	5.5	--	.6	
7.5	6.9	10	1.5	6.5	--	2.1	
--	--	--	--	43.0	--	93	CL Bf 201
83	9.0	12	--	222	--	45	
46	4.1	110	--	116	--	12	
47	4.1	110	--	108	--	10	
170	18	69	1.8	229	--	47	
33	3.3	39	1.1	81.0	--	5.0	

Appendix B.— Chemical analyses of rainwater, storm water, water from the unsaturated zone, and ground water at the Greenmount site—Continued

Station name or number	Date	Chloride, filtered (mg/L)	Fluoride, filtered (mg/L)	Bromide, filtered (mg/L)	Iodide, filtered (mg/L)
Rainwater	06-04-87	--	--	--	--
	03-26-88	0.5	--	--	--
01585680	05-20-86	8.8	0.2	--	--
	06-04-87	12	.2	<0.01	0.003
	09-10-87	16	.2	--	--
	03-26-88	27	.1	--	--
	05-06-88	4.2	.3	--	--
01585681	06-01-87	6.5	<.1	<.01	.018
	06-05-87	6.0	.2	<.01	.011
	03-23-88	300	.2	--	--
	03-24-88	--	--	--	--
	03-31-88	160	.2	--	--
	09-28-88	2.3	.1	--	--
	03-30-89	58	.1	--	--
CL Bf 194	06-25-86	18	<.1	--	--
	12-17-86	29	<.1	--	--
	12-10-87	26	.3	--	--
	09-28-88	28	<.1	--	--
	03-30-89	35	<.1	--	--
CL Bf 195	06-19-86	33	<.1	--	--
	06-01-87	30	<.1	.57	.007
	06-04-87	28	<.1	1	.007
	06-05-87	30	<.1	2.70	.009
	09-10-87	28	<.1	--	--
	12-10-87	23	.2	--	--
	03-23-88	27	.1	--	--
	03-24-88	--	--	--	--
	03-26-88	16	.2	--	--
	03-31-88	29	.1	--	--
	09-28-88	61	<.1	--	--
	03-30-89	24	<.1	--	--
Cl Bf 198	06-25-86	10	<.1	--	--
	12-17-86	22	<.1	--	--
	06-02-87	17	<.1	.046	.003
	06-04-87	14	<.1	.045	.005
	12-10-87	24	.3	--	--
	03-24-88	17	.1	--	--
	09-29-88	20	<.1	--	--
	03-30-89	54	<.1	--	--
CL Bf 199	06-20-86	38	<.1	--	--
	12-17-86	39	<.1	--	--
	06-02-87	43	<.1	.37	.005
	06-04-87	35	<.1	.31	.002
	06-05-87	50	.3	.37	.003
	09-10-87	74	.2	--	--
	12-10-87	79	.3	--	--
	03-23-88	64	.1	--	--
	03-26-88	53	.1	--	--
	03-31-88	72	--	--	--
	09-29-88	60	.1	--	--
	03-30-89	48	<.1	--	--
CL Bf 200	06-20-86	26.2	--	--	--
	06-02-87	14	<.1	.22	.004
	06-04-87	15	<.1	.20	.002
	06-05-87	19	<.1	.26	.002
	09-10-87	21	.1	--	--
	12-10-87	20	.2	--	--
CL Bf 201	09-10-87	23	--	<.01	--
	12-10-87	14	.7	.40	--
	03-23-88	230	.2	--	--
	03-31-88	210	.2	--	--
	09-29-88	310	.1	--	--
	03-30-89	60	.2	--	--

Silica, filtered (mg/L)	Nitrate + nitrite, as N, filtered (mg/L)	Nitrogen, ammonia, filtered (mg/L)	Nitrogen, ammonia + organic, filtered (mg/L)	Phosphorus, as P, filtered (mg/L)	Phosphorus, as P, filtered (mg/L)	Aluminum, filtered (µg/L)	Station name or number
--	--	--	--	--	--	--	Rainwater
0.4	--	--	--	--	--	--	
1.1	1.5	1.3	2.6	0.28	0.37	80	01585680
1.2	--	--	--	--	--	--	
2.6	--	--	--	--	--	--	
6.6	--	--	1.9	--	--	10	
.8	--	--	1.6	--	.04	30	
.7	--	--	--	--	--	--	01585681
.7	--	--	--	--	--	--	
.66	<.10	.03	1.1	--	--	180	
--	--	--	--	--	--	--	
.83	<.10	.09	1.1	--	--	190	
1.0	<.10	<.01	.6	--	--	90	
.6	.11	.01	<.2	--	.05	40	
6.8	9.3	.14	.7	.02	.02	<10	CL Bf 194
7.8	--	--	--	--	--	20	
7.1	10	.17	.2	<.01	<.01	<10	
7.7	12	.03	.7	--	--	<10	
7.3	12	--	--	--	--	20	
6.8	11	.05	.6	<.01	.05	30	CL Bf 195
6.1	--	--	--	--	--	(360)	
6.7	--	--	--	--	--	--	
6.7	--	--	--	--	--	--	
7.3	--	--	--	--	--	--	
7.0	4.9	.03	.4	.01	.02	20	
6.5	4.7	.03	.5	--	--	10	
--	--	--	--	--	--	--	
.97	4.4	.03	1.8	--	--	50	
6.5	3.9	.09	--	--	--	20	
6.6	4.4	<.01	.5	--	--	20	
5.8	27	--	--	--	--	20	
5.9	9.0	.06	.7	<.01	.31	<10	CL Bf 198
6.2	--	--	--	--	--	60	
6.0	--	--	--	--	--	<10	
5.9	--	--	--	--	--	--	
6.1	13	.06	.3	<.01	.31	<10	
5.9	11	--	--	--	--	10	
6.2	20	.01	.4	--	--	100	
6.0	3.1	--	--	--	--	20	
6.0	7.9	.08	.3	.01	.20	20	CL Bf 199
6.2	--	--	--	--	--	20	
6.2	--	--	--	--	--	60	
6.1	--	--	--	--	--	--	
6.4	--	--	--	--	--	--	
6.9	--	--	--	--	--	--	
6.8	3.4	.02	.4	<.01	.03	160	
6.0	--	--	--	--	--	--	
5.5	5.4	.02	.3	--	--	40	
--	--	--	--	--	--	90	
6.0	3.4	.03	.5	--	--	50	
5.5	2.8	.03	.4	--	.06	40	
--	9.1	.04	1.1	1.0	.19	20	CL Bf 200
7.0	--	--	--	--	--	<10	
7.0	--	--	--	--	--	--	
7.0	--	--	--	--	--	--	
7.0	--	--	--	--	--	--	
7.1	9.0	--	--	<.01	--	10	
--	.13	--	--	--	--	--	CL Bf 201
2.1	--	--	--	--	--	--	
1.3	<.10	--	--	--	--	--	
1.7	<.10	--	--	--	--	--	
3.5	<.10	--	--	--	--	<10	
1.7	<.10	--	--	--	--	20	

Appendix B.— Chemical analyses of rainwater, storm water, water from the unsaturated zone, and ground water at the Greenmount site—Continued

Station name or number	Date	Antimony, filtered (µg/L)	Antimony, unfiltered (µg/L)	Arsenic, filtered (µg/L)	Arsenic, unfiltered (µg/L)
Rainwater	06-04-87	--	--	--	<1
	03-26-88	--	--	--	--
01585680	05-20-86	<1	--	<1	<1
	06-04-87	<1	--	<1	3
	09-10-87	2	1	4	3
	03-26-88	--	--	<1	<1
	05-06-88	--	--	<1	1
01585681	06-01-87	<1	--	<1	1
	06-05-87	<1	--	<1	3
	03-23-88	--	--	<1	2
	03-24-88	--	--	--	--
	03-31-88	--	--	<1	1
	09-28-88	--	--	<1	1
	03-30-89	--	--	<1	<1
CL Bf 194	06-25-86	6	10	2	2
	12-17-86	<1	<1	<1	<1
	12-10-87	--	--	<1	--
	09-28-88	--	--	<1	1
	03-30-89	--	--	--	--
CL Bf 195	06-19-86	<1	<1	<1	<1
	06-01-87	<1	--	<1	<1
	06-04-87	<1	--	<1	<1
	06-05-87	<1	--	<1	--
	09-10-87	<1	<1	<1	<1
	12-10-87	--	--	<1	--
	03-23-88	--	--	<1	<1
	03-24-88	--	--	--	--
	03-26-88	--	--	1	1
	03-31-88	--	--	<1	<1
	09-28-88	--	--	6	<1
	03-30-89	--	--	--	--
Cl Bf 198	06-25-86	<1	1	<1	1
	12-17-86	<1	<1	<1	<1
	06-02-87	<1	--	<1	<1
	06-04-87	<1	--	<1	<1
	12-10-87	--	--	<1	--
	03-24-88	--	--	<1	--
	09-29-88	--	--	<1	<1
	03-30-89	--	--	--	--
CL Bf 199	06-20-86	<1	<1	<1	<1
	12-17-86	<1	<1	<1	<1
	06-02-87	<1	--	<1	<1
	06-04-87	<1	--	<1	<1
	06-05-87	--	--	<1	--
	09-10-87	<1	<1	<1	<1
	12-10-87	--	--	<1	--
	03-23-88	--	--	<1	--
	03-26-88	--	--	--	--
	03-31-88	--	--	--	--
	09-29-88	--	--	<1	<1
	03-30-89	--	--	<1	<1
CL Bf 200	06-20-86	2	12	<1	1
	06-02-87	<1	--	<1	<1
	06-04-87	<1	--	<1	<1
	06-05-87	<1	--	<1	--
	09-10-87	<1	<1	<1	<1
	12-10-87	--	--	<1	--
CL Bf 201	09-10-87	--	--	--	--
	12-10-87	--	--	--	--
	03-23-88	--	--	--	--
	03-31-88	--	--	--	--
	09-29-88	--	--	<1	--
	03-30-89	--	--	--	--

Barium, filtered (µg/L)	Barium, unfiltered (µg/L)	Beryllium, filtered (µg/L)	Boron, filtered (µg/L)	Cadmium, filtered (µg/L)	Cadmium, unfiltered (µg/L)	Chromium, filtered (µg/L)	Station name or number
--	--	--	--	--	<1	--	Rainwater
<2	--	<0.5	--	<1	--	<5	
--	--	<.5	60	<1	1	<1	01585680
--	--	--	30	<1	3	3.0	
29	<100	--	170	1.4	1	<.5	
54	<100	--	<10	1.4	2	<.5	
13	<100	--	20	1.2	2	<.5	
--	--	--	20	<1	<1	4.0	01585681
--	--	--	<10	<1	<1	3.0	
12	300	--	10	<.2	5	<.5	
--	--	--	--	--	--	--	
8	200	--	10	<.1	4	<.5	
<2	<100	--	20	.1	<1	<.5	
5	<100	--	10	--	<1	--	
--	--	<.5	<10	16	26	1.0	CL Bf 194
--	--	<.5	<10	2.0	3	<1	
--	--	--	<10	--	--	.5	
57	<100	--	<10	6.2	7	<.5	
--	--	--	--	--	--	--	
--	--	.7	<10	<1	<1	<1	CL Bf 195
--	--	--	<10	2.3	2	<.5	
--	--	--	<10	<.3	<1	1.0	
--	--	--	<10	.2	--	<.5	
56	<100	--	<10	.8	<1	<.5	
--	--	--	<10	--	--	<.5	
52	100	--	<10	2.3	<1	<.5	
--	--	--	--	--	--	--	
12	<100	--	40	.6	2	<.5	
100	100	--	<10	.5	1	<.5	
70	<100	--	<10	3.8	<1	<.5	
--	--	--	--	2.4	--	<.5	
--	--	1.0	<10	2.0	2	<1	CL Bf 198
--	--	<.5	<10	1.0	<1	<1	
--	--	--	<10	.6	<1	<.5	
--	--	--	<10	.6	<1	<.5	
--	--	--	<10	--	--	1.1	
47	--	<.5	10	<1	--	<5	
--	--	--	--	.4	--	<.5	
--	--	--	--	--	--	--	
--	--	<.5	<10	<1	<1	<1	CL Bf 199
--	--	<.5	10	1.0	<1	<1	
--	--	--	<10	.4	<1	<.5	
--	--	--	<10	.7	<1	<.5	
--	--	--	<10	.6	--	<.5	
100	100	--	<10	.5	<1	<.5	
--	--	--	<10	--	--	1.0	
--	--	--	<10	<1	--	2.0	
61	--	<.5	--	.4	--	<.5	
--	--	--	--	.3	--	<.5	
--	--	--	10	.5	--	<.5	
49	100	--	10	--	<1	--	
--	--	<.5	--	9.0	9	4.0	CL Bf 200
--	--	--	<10	.2	<1	<.5	
--	--	--	<10	.4	<1	<.5	
--	--	--	10	.1	--	<.5	
26	<100	--	<10	.2	<1	<.5	
--	--	--	<10	--	--	<.5	
--	--	--	--	--	--	--	CL Bf 201
10	--	<.5	--	<1	--	25	
29	--	<.5	--	<1	--	6.0	
27	--	<.5	--	<1	--	<5	
46	--	<.5	<10	1.0	--	9.0	
--	--	--	--	<.2	--	<.5	

Appendix B.— Chemical analyses of rainwater, storm water, water from the unsaturated zone, and ground water at the Greenmount site—Continued

Station name or number	Date	Chromium, unfiltered (µg/L)	Cobalt, filtered (µg/L)	Cobalt, unfiltered (µg/L)	Copper, filtered (µg/L)
Rainwater	06-04-87	<1	--	<1	--
	03-26-88	--	<3	--	<10
01585680	05-20-86	<10	<3	2	30
	06-04-87	32	<1	20	70
	09-10-87	20	<.5	4	190
	03-26-88	4	--	--	15
	05-06-88	2	2.0	--	12
01585681	06-01-87	<1	1.0	2	3
	06-05-87	5	<1	9	11
	03-23-88	100	--	--	5
	03-24-88	--	--	--	--
	03-31-88	93	--	--	2
	09-28-88	6	--	--	2
	03-30-89	3	--	--	11
CL Bf 194	06-25-86	<10	1.0	2	10
	12-17-86	<10	<1	2	9
	12-10-87	--	--	--	6
	09-28-88	4	--	--	10
	03-30-89	--	--	--	21
CL Bf 195	06-19-86	<10	<1	<1	4
	06-01-87	<1	<.5	<1	14
	06-04-87	<1	.6	<1	8
	06-05-87	--	<.5	--	4
	09-10-87	<10	<.5	<1	5
	12-10-87	--	--	--	2
	03-23-88	2	--	--	12
	03-24-88	--	--	--	--
	03-26-88	22	--	--	22
	03-31-88	3	--	--	4
	09-28-88	9	--	--	4
	03-30-89	--	--	--	56
Cl Bf 198	06-25-86	30	28	52	2
	12-17-86	<10	22	48	1
	06-02-87	2	17	19	6
	06-04-87	<1	19	21	4
	12-10-87	--	--	--	1
	03-24-88	--	9.0	--	30
	09-29-88	--	--	--	6
	03-30-89	--	--	--	45
CL Bf 199	06-20-86	20	2.0	9	5
	12-17-86	<10	<1	4	3
	06-02-87	2	1.7	3	6
	06-04-87	<1	2.2	<1	8
	06-05-87	--	3.1	--	2
	09-10-87	<10	5.6	10	8
	12-10-87	--	--	--	4
	03-23-88	--	<1	--	9
	03-26-88	2	<3	--	16
	03-31-88	--	--	--	7
	09-29-88	--	--	--	1
	03-30-89	8	--	--	12
CL Bf 200	06-20-86	40	3.0	9	9
	06-02-87	<1	<.5	<1	3
	06-04-87	<1	<.5	<1	6
	06-05-87	--	<.5	--	4
	09-10-87	20	<.5	3	2
	12-10-87	--	--	--	4
CL Bf 201	09-10-87	--	--	--	--
	12-10-87	--	4.0	--	<10
	03-23-88	--	9.0	--	<10
	03-31-88	<10	9.0	--	<10
	09-29-88	1	33	--	<10
	03-30-89	--	--	--	24

Copper, unfiltered (µg/L)	Iron, filtered (µg/L)	Lead, filtered (µg/L)	Lead, unfiltered (µg/L)	Lithium, filtered (µg/L)	Manganese, filtered (µg/L)	Mercury, filtered (µg/L)	Station name or number
6	--	--	<5	--	--	--	Rainwater
--	4	<10	--	<4	5	--	
30	76	<10	33	<4	83	--	01585680
3,800	23	<5	200	--	170	<.1	
250	--	5.0	18	<4	--	--	
36	5	<5	<5	--	42	--	
21	23	.9	5	--	49	--	
13	20	<5	9	--	820	<.1	01585681
63	--	<5	42	--	--	--	
160	16	<.5	100	--	70	--	
--	--	--	--	--	--	--	
720	9	<.5	600	--	8	--	
19	21	1.0	18	--	29	--	
7	12	--	5	--	67	--	
24	3	6.0	15	8	140	--	CL Bf 194
15	15	<5	15	6	61	--	
--	<10	6.7	--	--	30	--	
21	7	5.4	6	--	33	--	
--	<3	--	--	--	31	--	
9	14	<5	<5	4	49	--	Cl Bf 195
13	60	<5	9	<4	40	<.1	
6	<3	<5	<5	<4	27	<.1	
--	--	<5	--	<4	--	--	
11	--	<5	<5	<4	--	--	
--	<10	<.5	--	--	30	--	
14	9	<.5	<5	--	51	--	
--	--	--	--	--	--	--	
--	31	.9	73	--	97	--	
6	<10	<.5	<5	--	50	--	
20	12	4.9	<5	--	160	--	
--	5	1.1	--	--	190	--	
100	3	<5	33	8	490	--	Cl Bf 198
42	(150)	<5	15	7	370	--	
24	<10	<5	13	7	240	<.1	
15	7	<5	8	7	320	<.1	
--	10	<.5	--	--	620	--	
--	9	<10	--	<4	110	--	
--	8	1.3	--	--	230	--	
--	<3	--	--	--	160	--	
50	<3	<5	10	5	83	--	CL Bf 199
16	6	<5	<5	4	31	--	
19	26	<5	<5	5	86	<.1	
7	4	<5	<5	<4	75	<.1	
--	--	<5	--	5	--	--	
15	--	<5	10	15	--	--	
--	<10	1.2	--	--	140	--	
--	4	<5	--	<4	220	--	
22	<3	<.5	<5	<4	170	--	
23	--	<.5	<5	--	--	--	
--	5	2.6	--	--	84	--	
12	4	--	5	--	170	--	
52	9	7.0	62	10	120	--	CL Bf 200
8	<3	15	<5	6	26	<.1	
10	6	<5	<5	8	25	<.1	
--	--	<5	--	7	--	--	
6	--	<5	<5	<4	--	--	
--	<10	3.0	--	--	20	--	
--	--	--	--	--	--	--	Cl Bf 201
--	6	<10	--	6	11,000	--	
--	7	<10	--	<4	15,000	--	
3	3	<10	<5	<4	13,000	--	
9	9	<10	<5	14	37,000	--	
--	9	<.5	--	--	5,900	--	

Appendix B.— Chemical analyses of rainwater, storm water, water from the unsaturated zone, and ground water at the Greenmount site—Continued

Station name or number	Date	Mercury, unfiltered (µg/L)	Molybdenum, filtered (µg/L)	Molybdenum, unfiltered (µg/L)	Nickel, filtered (µg/L)
Rainwater	06-04-87	--	--	--	--
	03-26-88	--	<10	--	<10
01585680	05-20-86	--	<10	<1	5
	06-04-87	<.1	5	--	4
	09-10-87	--	3	3	22
	03-26-88	--	<1	--	--
	05-06-88	--	1	--	--
01585681	06-01-87	<.1	1	--	<1
	06-05-87	--	--	--	1
	03-23-88	--	7	--	--
	03-24-88	--	--	--	--
	03-31-88	--	1	--	--
	09-28-88	--	<1	--	--
	03-30-89	--	<1	--	--
CL Bf 194	06-25-86	--	<1	1	10
	12-17-86	--	7	8	12
	12-10-87	--	<1	--	--
	09-28-88	--	<1	--	--
	03-30-89	--	<1	--	--
CL Bf 195	06-19-86	--	<1	1	9
	06-01-87	<.1	1	--	6
	06-04-87	<.1	5	--	5
	06-05-87	--	7	--	5
	09-10-87	--	<1	<1--	7
	12-10-87	--	<1	--	--
	03-23-88	--	1	--	--
	03-24-88	--	--	--	--
	03-26-88	--	1	--	--
	03-31-88	--	10	--	--
	09-28-88	--	1	--	--
	03-30-89	--	<1	--	--
Cl Bf 198	06-25-86	--	<1	1	28
	12-17-86	--	2	6	21
	06-02-87	<.1	2	--	17
	06-04-87	<.1	1	--	17
	12-10-87	--	<1	--	--
	03-24-88	--	<10	--	20
	09-29-88	--	<1	--	--
	03-30-89	--	<1	--	--
CL Bf 199	06-20-86	--	<1	1	8
	12-17-86	--	2	5	5
	06-02-87	<.1	<1	--	5
	06-04-87	<.1	4	--	5
	06-05-87	--	<1	--	6
	09-10-87	--	<1	<1	8
	12-10-87	--	1	--	--
	03-23-88	--	<1	--	4
	03-26-88	--	1	--	<10
	03-31-88	--	1	--	--
	09-29-88	--	<1	--	--
	03-30-89	--	<1	--	--
CL Bf 200	06-20-86	--	1	1	11
	06-02-87	<.1	<1	--	7
	06-04-87	<.1	4	--	7
	06-05-87	--	2	--	9
	09-10-87	--	<1	<1	10
	12-10-87	--	<1	--	--
CL Bf 201	09-10-87	--	--	--	--
	12-10-87	--	<10	--	10
	03-23-88	--	--	--	<10
	03-31-88	--	<10	--	<10
	09-29-88	--	<1	--	<10
	03-30-89	--	<1	--	--

Nickel, unfiltered (µg/L)	Selenium, filtered (µg/L)	Silver, filtered (µg/L)	Strontium, filtered (µg/L)	Thallium, filtered (µg/L)	Vanadium, filtered (µg/L)	Zinc, filtered (µg/L)	Station name or number
<1	--	--	--	--	--	--	Rainwater
--	--	<1	2	--	<6	190	
9	<1	--	38	--	36	390	01585680
18	--	--	38	--	6	1,000	
26	<1	<1	82	--	29	2,100	
--	<1	<1	42	--	<1	25	
--	<1	--	38	--	5	620	
10	--	--	53	--	<5	<3	01585681
7	--	--	42	--	<1	16	
--	<1	<1	43	--	6	53	
--	--	--	--	--	--	--	
--	<1	<1	39	--	6	<3	
--	<1	<1	27	--	2	8	
2	<1	1	55	--	<1	8	
9	<1	--	45	--	<1	81	CL Bf 194
15	<1	<1	48	--	<1	120	
--	--	--	51	--	<1	200	
--	<1	<1	57	--	<1	120	
--	--	--	--	--	<1	50	
14	1	--	52	--	<1	40	CL Bf 195
8	--	--	48	<1	<1	53	
5	--	--	43	<1	<1	35	
--	--	--	49	<1	<1	26	
3	4	<1	42	--	<1	30	
--	--	--	38	--	<1	22	
--	1	<1	40	--	<1	24	
--	--	--	--	--	--	--	
--	<1	<1	58	--	13	650	
--	<1	1	50	--	<1	20	
11	<1	<1	51	--	<1	47	
--	--	--	--	--	<1	140	
52	<1	--	38	--	<1	47	CL Bf 198
41	<1	<1	44	--	<1	46	
26	--	--	40	<1	<1	43	
23	--	--	39	<1	<1	44	
--	--	--	50	--	<1	46	
--	--	<1	40	--	<6	60	
--	<1	<1	47	--	--	50	
--	--	--	--	--	<1	35	
11	<1	--	54	--	<1	67	CL Bf 199
6	<1	<1	47	--	<1	24	
10	--	--	48	<1	<1	25	
5	--	--	47	<1	<1	25	
--	--	--	54	<1	<1	29	
12	<1	<1	53	--	<1	37	
--	--	--	100	--	<1	31	
--	<1	<1	53	--	<1	32	
--	--	<1	52	--	<6	20	
--	--	--	--	--	--	20	
--	<1	<1	68	--	2	92	
3	<1	1	51	--	<1	21	
23	<1	--	46	--	--	190	CL Bf 200
9	--	<1	29	<1	<1	54	
12	--	--	29	<1	<1	65	
--	--	--	30	<1	<1	52	
10	<1	<1	28	--	<1	58	
--	--	--	170	--	<1	21	
--	--	--	--	--	--	--	CL Bf 201
--	--	5	160	--	<6	7	
--	--	2	120	--	<6	23	
--	--	1	120	--	<6	5	
--	<1	9	370	--	<5	20	
--	--	--	--	--	<1	35	

Appendix B.— Chemical analyses of rainwater, storm water, water from the unsaturated zone, and ground water at the Greenmount site—Continued

Station name or number	Date	Zinc, unfiltered (µg/L)	Carbon organic, filtered (mg/L)	Carbon organic, unfiltered (mg/L)	Methylene blue active substances (mg/L)
Rainwater	06-04-87	<10	--	--	--
	03-26-88	--	--	--	--
01585680	05-20-86	590	--	44	.94
	06-04-87	6,000	8.6	11	.42
	09-10-87	2,100	--	--	1.30
	03-26-88	30	1.5	1.9	.05
	05-06-88	1,200	--	--	.45
01585681	06-01-87	60	7.2	18	.11
	06-05-87	230	--	--	.14
	03-23-88	2,600	8.5	9.9	1.10
	03-24-88	--	1.3	.6	--
	03-31-88	2,300	7.9	55	.78
	09-28-88	180	9.3	9.9	.21
	03-30-89	60	5.5	6.1	.16
CL Bf 194	06-25-86	80	2.1	1.7	.12
	12-17-86	210	1.2	1.3	.14
	12-10-87	--	1.4	.8	.11
	09-28-88	140	1.3	1.1	.21
	03-30-89	--	--	--	--
CL Bf 195	06-19-86	30	1.3	19	--
	06-01-87	100	2.8	2.1	.10
	06-04-87	30	2.2	2.4	.09
	06-05-87	--	--	--	.08
	09-10-87	110	1.5	2.0	.04
	12-10-87	--	1.6	.7	.08
	03-23-88	20	1.2	.8	.07
	03-24-88	--	7.4	16	--
	03-26-88	1,300	7.4	7.5	1.30
	03-31-88	20	1.4	1.5	.07
	09-28-88	40	1.7	3.8	.08
	03-30-89	--	--	--	--
Cl Bf 198	06-25-86	160	1.9	29	.10
	12-17-86	140	.9	4.0	.08
	06-02-87	70	1.3	6.1	.08
	06-04-87	60	1.0	.8	.08
	12-10-87	--	1.5	2.1	.09
	03-24-88	--	.5	<.1	.10
	09-29-88	--	.6	1.5	.14
	03-30-89	--	--	--	--
CL Bf 199	06-20-86	110	1.7	1.5	.11
	12-17-86	70	.7	2.7	.07
	06-02-87	40	2.2	2.1	.08
	06-04-87	20	2.3	2.5	.09
	06-05-87	--	--	--	.07
	09-10-87	40	1.2	.6	.05
	12-10-87	--	1.5	.6	.08
	03-23-88	--	--	--	--
	03-26-88	20	1.1	1.1	.05
	03-31-88	20	--	--	--
	09-29-88	--	1.3	2.2	.09
	03-30-89	30	1.3	1.8	.05
CL Bf 200	06-20-86	290	1.5	--	.14
	06-02-87	70	2.1	2.2	.07
	06-04-87	70	2.2	2.1	.07
	06-05-87	--	--	--	--
	09-10-87	70	1.1	.2	.06
	12-10-87	--	.8	.3	.10
CL Bf 201	09-10-87	--	--	--	.16
	12-10-87	--	--	--	.34
	03-23-88	--	--	--	.13
	03-31-88	<10	--	--	--
	09-29-88	20	--	--	--
	03-30-89	--	--	--	--

Oil and grease, unfiltered (mg/L)	Benzene, unfiltered (µg/L)	Toluene, unfiltered (µg/L)	Trichloro-fluoro-methane, unfiltered (µg/L)	Chloroform, unfiltered (µg/L)	1,2-Di-chloro-ethane, unfiltered (µg/L)	1,2-Transdi-chloroethene unfiltered (µg/L)	1,2-Dibromo-ethylene, unfiltered (µg/L)	Station name or number
--	--	--	--	--	--	--	--	Rainwater
--	--	--	--	--	--	--	--	
--	0.6	<0.2	0.4	0.5	0.6	0.2	0.5	01585680
<1	<.2	<.2	<.2	--	<.2	<.2	<.2	
--	--	--	--	<.2	--	--	--	
--	--	--	--	--	--	--	--	
--	--	--	--	--	--	--	--	
<1	.2	<.2	<.2	--	<.2	<.2	.2	01585681
--	--	--	--	<.2	--	--	--	
--	--	--	--	--	--	--	--	
--	--	--	--	--	--	--	--	
--	--	--	--	--	--	--	--	
--	--	--	--	<.2	--	--	--	
--	--	--	--	--	--	--	--	
<1	--	--	--	--	--	--	--	CL Bf 194
--	<.2	.6	<.2	<.2	<.2	<.2	<.2	
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<1	--	--	--	--	--	--	--	CL Bf 195
<1	.4	<.2	<.2	<.2	<.2	<.2	<.2	
<1	<.2	<.2	<.2	<.2	<.2	<.2	<.2	
--	<.2	<.2	<.2	<.2	<.2	<.2	<.2	
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3	--	--	--	--	--	--	--	CL Bf 198
--	<.2	.2	<.2	<.2	<.2	<.2	<.2	
1	<.2	<.2	<.2	<.2	<.2	<.2	<.2	
<1	<.2	<.2	<.2	<.2	<.2	<.2	<.2	
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<1	--	--	--	--	--	--	--	CL Bf 199
--	<.2	.8	<.2	<.2	<.2	<.2	<.2	
<1	<.2	<.2	<.2	<.2	<.2	<.2	<.2	
<1	<.2	<.2	<.2	<.2	<.2	<.2	<.2	
--	<.2	<.2	<.2	<.2	<.2	<.2	<.2	
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--	--	--	--	--	--	--	--	
<1	--	--	--	--	--	--	--	CL Bf 200
<1	<.2	<.2	.6	<.2	<.2	<.2	<.2	
--	<.2	<.2	.7	<.2	<.2	<.2	<.2	
--	<.2	<.2	.6	<.2	<.2	<.2	<.2	
--	--	--	--	--	--	--	--	
--	--	--	--	--	--	--	--	
--	--	--	--	--	--	--	--	CL Bf 201
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Appendix C.— Chemical analyses of rainwater, storm water, water from the unsaturated zone, and ground water at the Prince Frederick site

[°, degrees; ' seconds; ", minutes; µS/cm, microsiemens per centimeter at 25 degrees Celsius; deg. C, degrees Celsius; --, no data available; $CaCO_3$, calcium carbonate; mg/L, milligrams per liter; µg/L, micrograms per liter; <, less than; for filtered samples: µm, micrometer, mm, millimeter; values shown for pH and dissolved oxygen are field measurements; values shown for specific conductance and alkalinity are field or laboratory measurements; values shown in parentheses [Example (360)] are of questioned validity and were not used in the text or for data analysis or interpretation]

Sample type	Pore diameter	Filter diameter	Filter composition
Nitrogen and phosphorus	.45 µm	144 mm	Polycarbonate
Major ions, metals, and trace elements[1]	.10 µm	144 mm	Polycarbonate
Organic carbon	.45 µm	47 mm	Silver

[1] Prior to 1987, only aluminum, iron, and manganese samples were filtered through 0.1 µm pores; other constituents filtered through 0.45 µm.

For the convenience of the reader, the sampling stations are categorized as follows:

Rainwater	Rainwater (precipitation)
Storm-water impoundment outlet.....	01594680
Control wells (upgradient).....	CA Db 66 and CA Db 67
Downgradient wells.....	CA Db 69 and CA Db 70
Beneath-impoundment wells.....	CA Db 72 and CA Db 73
Unsaturated zone (lysimeter).....	CA Db 84
Storm-water impoundment well (reservoir).....	CA Db 85

Appendix C.— Chemical analyses of rainwater, storm water, water from the unsaturated zone, and ground water at the Prince Frederick site—Continued

Station name or number	Latitude (° ' ")	Longitude (° ' ")	Date	Specific conductance (µs/cm)	pH (standard units)	Temperature, water (deg. C)	Oxygen, dissolved (mg/L)
Rainwater	38 32 18	76 35 17	09-09-87	9	4.80	--	--
			12-11-87	25	4.77	--	--
01594680	38 32 18	76 35 17	08-28-86	198	8.28	25.5	--
			06-13-87	644	8.28	27.0	--
			10-09-87	382	7.92	14.5	--
			12-11-87	814	8.00	--	--
			04-20-88	694	8.14	11.5	--
			05-09-88	823	8.19	--	--
			07-12-88	396	7.43	26.9	--
			08-23-88	244	7.28	--	--
			02-01-89	1,220	8.74	15.4	--
CA Db 66	38 32 16	76 35 15	08-27-86	421	6.86	--	--
			12-15-86	351	6.53	15.9	--
			12-11-87	260	6.94	15.5	3.92
			12-14-87	246	6.82	15.2	3.13
			04-21-88	242	6.70	15.7	2.62
			08-24-88	263	6.72	14.7	4.15
			10-19-88	320	--	--	--
			01-20-89	345	7.08	15.5	.66
			03-01-89	340	7.20	15.3	.60
CA Db 67	38 32 16	76 35 15	08-27-86	269	6.35	--	--
			12-15-86	175	5.95	14.3	--
			05-18-87	163	6.32	15.0	--
			12-11-87	189	6.22	15.6	2.12
			12-14-87	145	6.53	15.6	3.93
CA Db 69	38 32 17	76 35 19	08-28-86	418	4.90	15.0	--
			12-16-86	980	4.39	15.8	--
			09-09-87	240	4.90	14.4	.23
			12-11-87	763	4.73	15.3	.10
			12-14-87	650	4.76	14.9	.13
			04-20-88	392	4.94	14.4	.20
			08-23-88	887	4.44	15.4	.93
			10-19-88	630	4.95	--	--
			01-20-89	830	4.48	15.4	.30
			03-01-89	820	4.66	15.0	.22
CA Db 70	38 32 17	76 35 19	12-16-86	347	5.33	15.8	--
			12-11-87	457	5.19	15.0	2.64
			12-14-87	415	5.19	15.3	.96
CA Db 72	38 32 17	76 35 17	08-27-86	954	6.20	18.5	--
			12-16-86	874	5.63	15.5	--
			12-11-87	784	5.70	17.2	1.01
			12-14-87	742	5.67	17.3	.81
			04-21-88	787	5.50	16.0	.22
			08-24-88	700	5.35	16.2	2.07
			01-20-89	630	5.61	16.9	1.48
			03-01-89	761	5.59	16.9	2.51
CA Db 73	38 32 17	76 35 17	08-27-86	--	--	--	--
			12-15-86	686	5.88	15.3	--
			05-18-87	734	5.64	15.0	--
			06-13-87	896	5.52	18.4	--
			09-09-87	869	5.43	16.5	1.58
			09-11-87	853	5.42	17.5	1.04
			12-11-87	753	5.85	17.2	.09
			12-14-87	731	5.92	17.1	.12
			04-21-88	669	6.05	16.0	1.47
			08-23-88	559	5.86	16.4	1.02
			10-19-88	630	--	--	--
			01-20-89	776	5.67	17.1	1.21
			03-01-89	3,390	5.79	16.9	1.94
CA Db 84	38 32 18	76 35 17	09-02-87	640	7.88	27.6	--
			09-11-87	480	7.70	30.6	--
			12-11-87	1,460	8.00	--	--
			04-20-88	661	7.80	--	--
			08-23-88	456	7.77	27.4	--
			01-20-89	3,810	8.20	--	--
			03-01-89	3,580	8.20	--	--
CA Db 85	38 32 17	76 35 17	09-02-87	571	8.50	--	--
			09-09-87	330	8.41	25.3	7.19
			12-14-87	395	8.64	--	9.09
			04-20-88	540	8.44	12.2	10.65
			08-23-88	430	8.60	27.1	6.94
			10-19-88	510	8.87	--	--
			03-01-89	970	8.50	4.8	10.08

Calcium, filtered (mg/L)	Magnesium, filtered (mg/L)	Sodium, filtered (mg/L)	Potassium, filtered (mg/L)	Alkalinity, as CaCO3 (mg/L)	Sulfide, unfiltered (mg/L)	Sulfate, filtered (mg/L)	Station name or number
0.46	0.32	1.4	--	--	--	0.89	Rainwater
.53	.22	1.4	--	--	--	2.5	
4.8	20	3.4	1.1	86.0	--	7.3	01594680
6.9	30	68	2.2	131	--	13	
4.9	29	24	1.6	117	--	12	
4.8	29	110	1.7	125	--	15	
6.8	30	86	1.3	125	--	13	
7.7	39	93	3.2	166	--	17	
9.4	21	35	2.9	94.0	--	27	
7.5	17	14	3.0	73.8	--	18	
4.4	26	200	1.8	139	--	23	
71	7.1	8.0	.6	213	--	16	CA Db 66
66	4.5	3.8	2.5	138	--	19	
44	3	5.1	1.4	124	--	13	
43	2.7	3.0	--	107	--	14	
33	2	2.6	1.1	101	--	11	
46	2.4	2.9	1.8	116	--	12	
--	--	--	--	156	--	--	
61	2.7	3.4	1.5	148	--	22	
65	2.9	3.7	1.3	155	--	24	
20	6.6	10	.6	94.0	--	18	CA Db 67
20	4.5	6.3	4.9	64.0	--	19	
16	3.8	5.6	4.6	58.0	--	9.1	
24	3.7	4.5	--	67.0	--	17	
17	3	4.2	--	53.0	--	10	
16	7.8	49	3.6	32.0	--	11	CA Db 69
15	37	110	3.2	5.0	--	4.2	
1.9	6	40	1.3	10.3	--	15	
6.4	23	93	2.6	1.0	--	5.9	
4.9	18	81	--	--	--	6.6	
3.7	9.5	43	1.5	7.0	--	6.5	
9.8	29	110	2.5	--	--	5.3	
--	--	--	--	3.5	--	--	
6.4	23	120	2.6	--	--	4.8	
5.9	21	110	2.5	--	--	5.1	
9.3	5.1	55	2.4	27.0	--	8.2	CA Db 70
3.7	5.9	67	--	10.4	--	5.0	
3.5	5.6	65	--	11.0	--	5.8	
69	19	78	8.3	142	--	10	CA Db 72
51	19	93	4.1	75.5	--	21	
26	18	83	4.5	42.0	--	13	
20	17	80	--	25.0	--	14	
19	22	91	3.3	27.0	--	13	
19	16	83	4.8	19.0	--	13	
20	12	74	3.6	24.0	--	15	
26	16	87	4.3	22.5	--	18	
--	--	--	--	--	--	--	CA Db 73
54	14	61	4.0	78.0	--	18	
28	16	69	5.0	52.0	--	19	
28	21	95	.6	46.0	--	15	
28	19	86	3.0	39.0	--	12	
30	20	94	3.1	38.0	--	13	
34	16	76	--	44.5	--	11	
31	16	76	--	45.0	--	10	
41	12	65	2.2	75.0	--	15	
38	8.8	49	2.2	56.5	7	13	
--	--	--	--	30.5	--	--	
29	18	80	3.2	30.0	--	10	
41	17	650	6.9	31.0	--	13	
7.7	40	57	--	193	--	12	CA Db 84
7.6	44	51	--	164	--	13	
5.7	35	200	--	145	--	19	
6.4	31	82	1.4	136	--	9.3	
6.6	37	30	1.6	167	--	6.5	
21	140	620	4.3	228	--	51	
8.7	47	750	2.0	161	--	43	
4.3	68	11	2.9	269	--	20	CA Db 85
3.8	56	10	--	203	--	17	
5.5	48	5.9	--	199	--	16	
6.6	48	23	1.6	192	--	13	
5.9	47	9.8	3.8	190	--	16	
--	--	--	--	271	--	--	
9.4	66	240	2.2	241	--	30	

Appendix C.— Chemical analyses of rainwater, storm water, water from the unsaturated zone, and ground water at the Prince Frederick site—Continued

Station name or number	Date	Chloride, filtered (mg/L)	Fluoride, filtered (mg/L)	Bromide, filtered (mg/L)	Iodide, filtered (mg/L)
Rainwater	09-09-87	0.41	0.06	0.03	--
	12-11-87	.32	.02	<.01	--
01594680	08-28-86	3.7	<.1	--	--
	06-13-87	95.0	<.1	<.01	0.012
	10-09-87	38.0	.1	--	--
	12-11-87	160	.1	--	--
	04-20-88	130	.1	--	--
	05-09-88	150	.2	--	--
	07-12-88	46.0	<.1	18.0	--
	08-23-88	15.0	.1	--	--
	02-01-89	290	.1	--	--
CA Db 66	08-27-86	3.0	.1	--	--
	12-15-86	2.5	.1	--	--
	12-11-87	4.3	.2	--	--
	12-14-87	2.6	.2	.023	--
	04-21-88	2.7	.2	--	--
	08-24-88	3.3	.1	--	--
	10-19-88	2.0	--	--	--
	01-20-89	2.4	.1	--	--
	03-01-89	2.5	.2	--	--
CA Db 67	08-27-86	3.9	<.1	--	--
	12-15-86	2.8	<.1	--	--
	05-18-87	5.5	<.1	.019	.001
	12-11-87	6.0	.2	.031	--
	12-14-87	4.7	.1	.012	--
CA Db 69	08-28-86	93.0	<.1	--	--
	12-16-86	310	.3	--	--
	09-09-87	60.0	.1	--	--
	12-11-87	200	.2	--	--
	12-14-87	170	.2	.25	--
	04-20-88	85.0	.2	--	--
	08-23-88	260	.2	--	--
	10-19-88	183	--	--	--
	01-20-89	250	.2	--	--
	03-01-89	240	.2	--	--
CA Db 70	12-16-86	83.0	<.1	--	--
	12-11-87	120	.1	.17	--
	12-14-87	110	.2	.21	--
CA Db 72	08-27-86	200	<.1	--	--
	12-16-86	220	.2	--	--
	12-11-87	190	.2	--	--
	12-14-87	190	.2	.20	--
	04-21-88	200	.2	--	--
	08-24-88	190	.2	--	--
	01-20-89	160	.2	--	--
	03-01-89	200	.2	--	--
CA Db 73	08-27-86	--	--	--	--
	12-15-86	160	.2	--	--
	05-18-87	170	<.1	.16	.005
	06-13-87	230	.2	.20	.010
	09-09-87	220	.2	--	--
	09-11-87	220	.2	--	--
	12-11-87	180	.2	.16	--
	12-14-87	180	.2	.17	--
	04-21-88	140	.2	--	--
	08-23-88	120	.1	--	--
	10-19-88	166	--	--	--
	01-20-89	200	.1	--	--
	03-01-89	1,400	.1	--	--
CA Db 84	09-02-87	67.6	--	--	--
	09-11-87	73.0	.2	.015	--
	12-11-87	360	.2	.054	--
	04-20-88	120	.1	--	--
	08-23-88	27.0	.1	--	--
	01-20-89	1,050	.1	--	--
	03-01-89	1,030	.1	--	--
CA Db 85	09-02-87	15.0	.1	--	--
	09-09-87	13.0	.1	<.01	--
	12-14-87	8.2	.1	<.01	--
	04-20-88	38.0	.1	--	--
	08-23-88	16.0	.1	--	--
	10-19-88	15.8	--	--	--
	03-01-89	330	.1	--	--

Silica, filtered (mg/L)	Nitrate + nitrite, as N, filtered (mg/L)	Nitrogen, ammonia, filtered (mg/L)	Nitrogen, ammonia + organic, as N, filtered (mg/L)	Phosphorus, ortho as P, orthophosphate filtered (mg/L)	Phosphorus as P, unfiltered (mg/L)	Aluminum, filtered (μg/L)	Station name or number
0.93	0.09	--	--	<0.1	--	--	Rainwater
.11	.38	--	--	<.1	--	--	
1.6	.78	0.02	<0.2	<.01	0.02	20	01594680
--	--	--	--	--	--	--	
2.1	--	--	--	--	--	--	
1.6	1.40	.15	.7	.02	--	--	
1.8	2.80	.21	1.1	.01	.03	<10	
1.6	2.70	.46	1.7	.01	.05	<10	
2.1	--	--	1.3	--	--	<10	
2.3	2.10	.36	1.3	.07	.13	20	
1.5	1.70	.26	1.1	.03	--	<10	
6.4	.15	.04	<.2	.01	.72	<10	CA Db 66
6.7	--	--	--	--	--	<10	
8.2	.10	.02	<.2	.01	--	10	
8.7	.10	--	--	--	--	--	
9.3	.20	.06	.6	.01	.03	<10	
8.1	.12	.01	.4	.02	.02	<10	
--	--	--	--	--	--	--	
7.9	<.10	--	--	<.01	--	20	
8.2	<.10	.04	.4	.01	.58	20	
7.3	--	--	--	--	--	--	CA Db 67
6.8	--	--	--	--	--	--	
--	--	--	--	--	--	--	
8.1	.12	--	--	--	--	--	
7.9	.10	--	--	--	--	--	
9.8	4.40	.06	.8	<.01	6.0	40	CA Db 69
8.5	--	--	--	--	--	820	
8.1	--	--	--	--	--	--	
8.5	5.70	.01	<.2	<.01	--	840	
8.7	5.40	--	--	--	--	--	
7.7	3.90	.04	.6	.01	.01	260	
7.7	8.30	<.01	1.4	<.01	.11	1,200	
--	--	--	--	--	--	--	
7.8	5.60	--	--	<.01	--	870	
8.2	4.90	.02	1.0	<.01	.17	810	
7.7	--	--	--	--	--	--	CA Db 70
6.3	2.70	--	--	--	--	--	
6.4	2.70	--	--	--	--	--	
14	2.30	.05	.3	<.01	4.0	--	CA Db 72
13	--	--	--	--	--	20	
13	2.30	.02	<.2	<.01	--	110	
12	2.80	--	--	--	--	--	
12	2.70	.04	1.1	<.01	.05	190	
12	2.30	.02	.5	<.01	.04	130	
12	2.00	--	--	<.01	--	120	
13	1.90	.03	.5	<.01	.39	110	
--	--	--	--	--	--	--	CA Db 73
13	--	--	--	--	--	--	
--	--	--	--	--	--	--	
--	--	--	--	--	--	--	
11	--	--	--	--	--	--	
12	2.70	.04	.7	<.01	.01	--	
13	2.20	--	--	--	--	--	
12	2.20	--	--	--	--	--	
12	1.70	.04	.7	.01	.02	30	
13	1.80	.02	.6	<.01	.09	20	
--	--	--	--	--	--	--	
12	3.00	--	--	<.01	--	40	
13	2.70	.05	1.4	<.01	.07	60	
3.7	1.90	--	--	<.01	--	--	CA Db 84
3.7	1.60	--	--	<.01	--	--	
1.2	2.00	--	--	--	--	--	
2.0	<.10	.02	.4	<.01	--	20	
3.0	--	--	--	--	--	--	
.9	1.00	--	--	<.01	--	20	
1.2	--	--	--	--	--	--	
1.8	--	--	--	--	--	--	CA Db 85
2.2	1.90	--	--	<.01	--	--	
1.3	.82	.02	<.2	<.01	--	--	
1.5	1.10	.10	.3	<.01	--	<10	
1.8	1.70	<.01	--	.01	--	10	
--	--	--	--	--	--	--	
1.3	.79	<.01	.3	<.01	<.01	10	

Appendix C.— Chemical analyses of rainwater, storm water, water from the unsaturated zone, and ground water at the Prince Frederick site—Continued

Station name or number	Date	Antimony, filtered (µg/L)	Antimony, unfiltered (µg/L)	Arsenic, filtered (µg/L)	Arsenic, unfiltered (µg/L)
Rainwater	09-09-87	--	--	--	--
	12-11-87	--	--	--	--
01594680	08-28-86	<1	<1	<1	<1
	06-13-87	--	--	--	2
	10-09-87	2	<1	1	<1
	12-11-87	--	--	--	--
	04-20-88	1	--	<1	1
	05-09-88	<1	--	<1	--
	07-12-88	<1	--	1	1
	08-23-88	<1	--	--	--
	02-01-89	2	--	1	1
Ca Db 66	08-27-86	<1	<1	<1	5
	12-15-86	<1	<1	<1	<1
	12-11-87	--	--	--	--
	12-14-87	--	--	--	--
	04-21-88	<1	--	<1	1
	08-24-88	<1	--	--	--
	10-19-88	--	--	--	--
	01-20-89	--	--	--	--
	03-01-89	<1	--	<1	5
CA Db 67	08-27-86	<1	--	<1	--
	12-15-86	--	--	2	--
	05-18-87	--	--	--	--
	12-11-87	--	--	--	--
	12-14-87	--	--	--	--
CA Db 69	08-28-86	<1	3	<1	(21)
	12-16-86	<1	1	<1	2
	09-09-87	<1	<1	<1	<1
	12-11-87	--	--	--	--
	12-14-87	--	--	--	--
	04-20-88	<1	--	<1	<1
	08-23-88	<1	--	--	--
	10-19-88	--	--	--	--
	01-20-89	--	--	--	--
	03-01-89	<1	--	<1	--
CA Db 70	12-16-86	--	--	<1	--
	12-11-87	--	--	--	--
	12-14-87	--	--	--	--
CA Db 72	08-27-86	<1	1	<1	(15)
	12-16-86	<1	1	<1	3
	12-11-87	--	--	--	--
	12-14-87	--	--	--	--
	04-21-88	<1	--	<1	1
	08-24-88	<1	--	--	--
	01-20-89	--	--	--	--
	03-01-89	<1	--	<1	1
CA Db 73	08-27-86	--	--	--	--
	12-15-86	--	--	<1	--
	05-18-87	--	--	--	--
	06-13-87	--	--	--	--
	09-09-87	<1	<1	<1	<1
	09-11-87	<1	1	<1	1
	12-11-87	--	--	--	--
	12-14-87	--	--	--	--
	04-21-88	<1	--	<1	<1
	08-23-88	<1	--	--	--
	10-19-88	--	--	--	--
	01-20-89	--	--	--	--
	03-01-89	<1	--	1	1
CA Db 84	09-02-87	--	--	--	--
	09-11-87	--	--	--	--
	12-11-87	--	--	--	--
	04-20-88	<1	--	<1	<1
	08-23-88	<1	--	--	--
	01-20-89	--	--	--	--
	03-01-89	<1	--	<1	--
CA Db 85	09-02-87	1	--	1	--
	09-09-87	--	--	--	--
	12-14-87	--	--	--	--
	04-20-88	<1	--	1	<1
	08-23-88	<1	--	--	--
	10-19-88	--	--	--	--
	03-01-89	<1	--	1	1

Barium, filtered (µg/L)	Barium, unfiltered (µg/L)	Beryllium, filtered (µg/L)	Boron, filtered (µg/L)	Boron, unfiltered (µg/L)	Cadmium, filtered (µg/L)	Cadmium, unfiltered (µg/L)	Station name or number
3	--	<0.5	--	--	4	--	Rainwater
5	--	<.5	--	--	.3	--	
--	--	<.5	20	--	<1	<1	01594680
--	--	.9	30	--	<1	<1	
7	<100	--	20	30	.1	<1	
--	--	--	--	--	<.1	<1	
7	--	--	10	--	.4	--	
11	--	--	20	--	.2	--	
4	--	--	20	--	.3	--	
8	--	<.5	--	--	.2	--	
7	--	--	10	--	<.1	--	
--	--	<.5	40	--	<1	<1	CA Db 66
--	--	<.5	20	(2,400)	<1	<1	
--	--	<.5	--	--	.3	--	
22	--	<.5	--	--	<.4	--	
18	--	--	<10	--	.3	2	
21	--	<.5	--	--	.4	--	
--	--	--	--	--	--	--	
--	--	--	--	--	--	--	
25	--	<.5	--	--	<.1	1	
--	--	<.5	80	--	2	--	CA Db 67
--	--	--	50	--	<1	--	
--	--	<.5	30	--	.2	<1	
24	--	<.5	--	--	.3	--	
18	--	<.5	--	--	<.3	--	
--	--	<.5	20	--	<1	<1	CA Db 69
--	--	2.2	10	--	2	<1	
43	<100	--	20	20	.4	<1	
--	--	<.5	--	--	.5	--	
140	--	<.5	--	--	<.4	--	
71	--	--	10	--	.6	--	
220	--	<.5	--	--	1	--	
--	--	--	--	--	--	--	
--	--	--	--	--	--	--	
170	--	<.5	--	--	.4	--	
--	--	--	10	--	<1	--	CA Db 70
50	--	<.5	--	--	.4	--	
46	--	<.5	--	--	<.3	--	
--	--	<.5	30	--	1	1	CA Db 72
--	--	<.5	10	--	2	1	
--	--	<.5	--	--	8.4	--	
130	--	<.5	--	--	2.8	--	
160	--	--	<10	--	1.4	--	
120	--	<.5	--	--	1.8	--	
--	--	--	--	--	--	--	
130	--	<.5	--	--	1	2	
--	--	--	--	--	--	--	CA Db 73
--	--	--	10	--	<1	--	
--	--	<.5	30	--	.7	<1	
--	--	1	10	30	1.2	1	
120	200	--	10	<10	1.4	1	
120	200	--	10	<10	1.1	<1	
100	--	<.5	--	--	1.2	--	
110	--	<.5	--	--	.8	--	
82	--	--	<10	--	.9	--	
62	--	<.5	--	--	1.7	--	
--	--	--	--	--	--	--	
--	--	--	--	--	--	--	
100	--	<10	--	--	1.1	2	
18	--	<.5	--	--	1	--	CA Db 84
17	--	<.5	--	--	1	--	
27	--	4.3	--	--	1	--	
7	--	--	10	--	.4	--	
7	--	<.5	--	--	1	--	
--	--	--	--	--	--	--	
--	--	<10	<10	--	.5	--	
18	<100	--	30	40	<1	<1	CA Db 85
7	--	<.5	--	--	2	--	
5	--	<.5	--	--	.1	<1	
6	--	--	30	--	.2	--	
8	--	<.5	--	--	.2	--	
--	--	--	--	--	--	--	
--	--	<10	--	--	<.1	1	

Appendix C.— Chemical analyses of rainwater, storm water, water from the unsaturated zone, and ground water at the Prince Frederick site—Continued

Station name or number	Date	Chromium, filtered (µg/L)	Chromium, unfiltered (µg/L)	Cobalt, filtered (µg/L)	Cobalt, unfiltered (µg/L)
Rainwater	09-09-87	65	--	<3.0	--
	12-11-87	4.7	--	.5	--
01594680	08-28-86	5.0	<10	1.0	<1
	06-13-87	<1.0	<1	2.0	2
	10-09-87	<.5	<10	<.5	<1
	12-11-87	<.5	2	<.5	2
	04-20-88	<.5	<1	<.5	--
	05-09-88	<.5	1	<.5	--
	07-12-88	<.5	5	<.5	--
	08-23-88	<.5	--	<.5	<1
	02-01-89	.6	3	--	--
CA Db 66	08-27-86	1.0	20	4.0	12
	12-15-86	<1.0	<10	<1.0	7
	12-11-87	<.5	--	.9	--
	12-14-87	<.5	--	<.5	--
	04-21-88	<1.0	2	3.0	1
	08-24-88	.6	--	<1.0	--
	10-19-88	--	--	--	--
	01-20-89	--	--	--	--
	03-01-89	<2.0	17	<1.0	6
CA Db 67	08-27-86	1.0	--	7.0	--
	12-15-86	<1.0	--	4.0	--
	05-18-87	<.5	30	.8	5
	12-11-87	<5.0	--	1.3	--
	12-14-87	<.5	--	<.7	--
CA Db 69	08-28-86	1.0	130	19	27
	12-16-86	<1.0	10	30	45
	09-09-87	<.5	20	2.6	6
	12-11-87	<.5	--	14	--
	12-14-87	<.5	--	12	--
	04-20-88	<.5	4	7.0	--
	08-23-88	.8	--	22	--
	10-19-88	--	--	--	--
	01-20-89	--	--	--	--
	03-01-89	<.5	--	18	--
CA Db 70	12-16-86	3.0	--	6.0	--
	12-11-87	<5.0	--	5.1	--
	12-14-87	<.5	--	4.4	--
CA Db 72	08-27-86	10	60	34	58
	12-16-86	<1.0	10	46	32
	12-11-87	<.5	--	22	--
	12-14-87	<.5	--	21	--
	04-21-88	<.5	4	22	--
	08-24-88	<.5	--	22	--
	01-20-89	--	--	--	--
	03-01-89	<.5	11	25	30
CA Db 73	08-27-86	--	--	--	--
	12-15-86	<1.0	--	40	--
	05-18-87	<.5	<10	17	24
	06-13-87	<.5	30	33	37
	09-09-87	<.5	<10	21	25
	09-11-87	<.5	30	25	28
	12-11-87	<5.0	--	17	--
	12-14-87	<.5	--	17	--
	04-21-88	<.5	8	15	--
	08-23-88	<.5	--	10	--
	10-19-88	--	--	--	--
	01-20-89	--	--	--	--
	03-01-89	<.5	9	16	20
CA Db 84	09-02-87	9.0	--	<3.0	--
	09-11-87	<5.0	--	<3.0	--
	12-11-87	5.0	--	7.0	--
	04-20-88	<1.0	1	<1.0	--
	08-23-88	<1.0	--	<1.0	--
	01-20-89	--	--	--	--
	03-01-89	.9	--	2.4	--
CA Db 85	09-02-87	3.0	10	<1.0	1
	09-09-87	<5.0	--	<3.0	--
	12-14-87	<5.0	3	<.5	1
	04-20-88	<.5	<1	<.5	--
	08-23-88	<.5	--	<.5	<1
	10-19-88	--	--	--	--
	03-01-89	<.5	2	<1.0	1

Copper, filtered (µg/L)	Copper, unfiltered (µg/L)	Iron, filtered (µg/L)	Lead, filtered (µg/L)	Lead, unfiltered (µg/L)	Lithium, filtered (µg/L)	Manganese, filtered (µg/L)	Station name or number
30	--	15	<10	--	<4	7	Rainwater
20	--	22	1.1	--	<4	4	
3	3	7	<5.0	<5	<4	<1	01594680
12	16	--	<5.0	<5	--	--	
6	5	--	<5.0	<5	6	--	
5	4	--	<.5	<5	--	--	
4	4	<3	.6	<5	--	1	
6	10	6	<.5	<5	--	6	
8	11	20	<.5	7	--	21	
6	--	16	<.5	--	--	4	
2	8	4	<.5	<5	--	2	
2	11	7	<5.0	12	<4	230	CA Db 66
3	11	19	<5.0	7	8	190	
4	--	20	<.5	--	--	80	
<10	--	8	<.5	--	<4	30	
<1	4	<3	<.5	<5	--	75	
3	--	6	<.5	--	--	62	
--	--	--	--	--	--	--	
--	--	14	--	--	--	51	
<1	10	(120)	<.5	<5	--	47	
4	--	--	<5.0	--	5	--	CA Db 67
3	--	--	<5.0	--	<4	--	
4	21	--	--	--	--	54	
<10	--	34	<.5	--	<4	120	
<10	--	10	<.5	--	<4	67	
7	44	18	<5.0	45	<4	350	CA Db 69
9	11	27	<5.0	6	6	320	
4	10	--	<5.0	16	<4	--	
3	--	60	1.1	--	--	130	
<10	--	29	<.8	--	<4	120	
5	5	8	.6	<5	--	80	
8	--	35	2.7	--	--	210	
--	--	--	--	--	--	--	
--	--	16	--	--	--	140	
4	--	58	<.5	--	--	160	
4	--	73	<5.0	--	<4	230	CA Db 70
<10	--	29	<.5	--	<4	72	
<10	--	12	<.5	--	<4	59	
4	30	--	<5.0	28	5	--	CA Db 72
7	10	23	<5.0	<5	8	--	
4	--	30	3.6	--	--	630	
<10	--	15	<.5	--	<4	570	
5	7	18	<.5	<5	--	580	
3	--	11	<.5	--	--	570	
--	--	7	--	--	--	610	
1	7	14	<.5	<5	--	820	
--	--	--	--	--	--	--	CA Db 73
9	--	30	<5.0	--	6	1,200	
8	16	9	5.0	14	--	570	
6	12	58	<5.0	9	--	840	
3	6	--	<5.0	<5	<4	--	
2	16	--	<5.0	16	<4	--	
<10	--	33	<.5	--	<4	790	
<10	--	11	<.5	--	<4	660	
2	6	8	<.5	<5	--	670	
2	--	8	<.5	--	--	460	
--	--	--	--	--	--	--	
--	--	<3	--	--	--	410	
2	8	40	<.5	<5	--	670	
<10	--	31	<10	--	<4	3	CA Db 84
<10	--	16	<10	--	<4	24	
30	--	20	<10	--	<4	8	
1	3	6	<.5	<5	--	1	
3	--	8	<5.0	--	--	1	
--	--	<10	--	--	--	<10	
6	--	10	.5	--	--	<10	
5	4	--	<5.0	<5	<4	--	CA Db 85
<10	--	8	<10	--	<4	1	
<10	5	8	<.5	<5	<4	<1	
1	3	3	<.5	<5	--	<1	
7	--	7	<.5	--	--	1	
--	--	--	--	--	--	--	
1	3	<10	<.5	<5	--	<10	

Appendix C.— Chemical analyses of rainwater, storm water, water from the unsaturated zone, and ground water at the Prince Frederick site—Continued

Station name or number	Date	Mercury, filtered (µg/L)	Mercury, unfiltered (µg/L)	Molybdenum, filtered (µg/L)	Molybdenum, unfiltered (µg/L)
Rainwater	09-09-87	--	--	<10	--
	12-11-87	--	--	<10	--
01594680	08-28-86	--	--	6	1
	06-13-87	<0.1	0.1	<1	--
	10-09-87	--	--	<1	1
	12-11-87	--	--	<1	<1
	04-20-88	--	<.1	<1	<1
	05-09-88	--	--	3	4
	07-12-88	--	.1	<1	3
	08-23-88	.1	<.1	1	3
	02-01-89	--	--	1	5
CA Db 66	08-27-86	--	--	5	4
	12-15-86	--	--	6	8
	12-11-87	--	--	1	--
	12-14-87	--	--	<10	--
	04-21-88	--	--	1	1
	08-24-88	.2	<.1	6	--
	10-19-88	--	--	--	--
	01-20-89	--	--	--	--
	03-01-89	--	.3	2	7
CA Db 67	08-27-86	--	--	6	--
	12-15-86	--	--	3	--
	05-18-87	<.1	.1	<1	5
	12-11-87	--	--	<10	--
	12-14-87	--	--	<10	--
CA Db 69	08-28-86	--	--	3	10
	12-16-86	--	--	<1	8
	09-09-87	--	--	<1	<1
	12-11-87	--	--	<1	--
	12-14-87	--	--	<10	--
	04-20-88	--	.7	<1	<1
	08-23-88	.6	.3	<1	--
	10-19-88	--	--	--	--
	01-20-89	--	--	--	--
	03-01-89	--	--	<1	--
CA Db 70	12-16-86	--	--	3	--
	12-11-87	--	--	<10	--
	12-14-87	--	--	<10	--
CA Db 72	08-27-86	--	--	<1	7
	12-16-86	--	--	1	8
	12-11-87	--	--	<1	--
	12-14-87	--	--	<10	--
	04-21-88	--	.1	1	<1
	08-24-88	.1	<.1	<1	--
	01-20-89	--	--	--	--
	03-01-89	--	.1	<1	5
CA Db 73	08-27-86	--	--	--	--
	12-15-86	--	--	3	--
	05-18-87	<.1	.2	1	<10
	06-13-87	<.1	<.1	<1	1
	09-09-87	--	--	<1	<1
	09-11-87	--	--	<1	2
	12-11-87	--	--	<10	--
	12-14-87	--	--	<10	--
	04-21-88	--	--	1	<1
	08-23-88	--	.2	<1	--
	10-19-88	--	--	--	--
	01-20-89	--	--	--	--
	03-01-89	--	--	1	6
CA Db 84	09-02-87	--	--	<10	--
	09-11-87	--	--	<10	--
	12-11-87	--	--	<10	--
	04-20-88	--	--	1	5
	08-23-88	--	--	<1	--
	01-20-89	--	--	--	--
	03-01-89	--	--	1	--
CA Db 85	09-02-87	--	--	<1	1
	09-09-87	--	--	<10	--
	12-14-87	--	--	<10	1
	04-20-88	--	<.1	<1	<1
	08-23-88	--	--	<1	4
	10-19-88	--	--	--	--
	03-01-89	--	<.1	2	32

Nickel, filtered (µg/L)	Nickel, unfiltered (µg/L)	Selenium, filtered (µg/L)	Silver, filtered (µg/L)	Strontium, filtered (µg/L)	Thallium, filtered (µg/L)	Vanadium, filtered (µg/L)	Station name or number
<10	--	--	1	1	--	<6	Rainwater
1	--	--	4	6	--	<6	
1	3	<1	--	15	--	<1	01594680
1	8	--	--	28	--	<2	
7	5	<1	<1	19	--	<1	
4	6	<1	--	27	--	<1	
3	--	--	--	26	--	<1	
9	--	--	--	31	--	<1	
16	--	--	--	35	--	6	
3	--	--	--	31	--	2	
2	--	--	--	19	--	2	
7	20	1	--	420	--	<1	CA Db 66
<1	12	<1	<1	330	--	1	
6	--	<1	--	220	--	<1	
<5	--	--	<1	210	--	<6	
4	7	--	--	170	--	<1	
2	--	--	--	230	--	<1	
--	--	--	--	--	--	--	
--	--	--	--	--	--	--	
5	8	--	--	340	--	<1	
7	--	<1	--	81	--	1	CA Db 67
5	--	<1	<1	130	--	<1	
<1	5	--	--	95	<1	<2	
<10	--	--	<2	97	--	<6	
<2	--	--	<1	79	--	<6	
10	26	<1	--	92	--	<1	CA Db 69
30	47	<1	<1	190	--	<3	
5	10	<1	<1	28	--	<1	
15	--	<1	--	110	--	<1	
<10	--	--	<1	80	--	<6	
5	--	--	--	51	--	<1	
21	--	--	--	150	--	2	
--	--	--	--	--	--	--	
--	--	--	--	--	--	--	
16	--	--	--	110	--	3	
36	--	<1	<1	49	--	<1	CA Db 70
<10	--	--	1	40	--	<6	
<5	--	--	<1	36	--	<6	
30	70	<1	--	470	--	1	CA Db 72
46	26	<1	<1	330	--	<2	
33	--	<1	--	200	--	<1	
37	--	--	1	170	--	<6	
24	--	--	--	170	--	<1	
26	--	--	--	160	--	1	
--	--	--	--	--	--	--	
33	44	--	--	210	--	1	
--	--	--	--	--	--	--	CA Db 73
4	--	<1	<1	330	--	1	
24	37	--	--	230	<1	<16	
34	40	--	--	200	<1	<2	
20	26	<1	<1	190	--	1	
28	36	<1	<1	200	--	3	
30	--	--	<1	230	--	<6	
25	--	--	1	210	--	<6	
9	--	--	--	260	--	<1	
18	--	--	--	220	--	<1	
--	--	--	--	--	--	--	
--	--	--	--	--	--	--	
37	39	--	--	300	--	--	
<10	--	--	1	36	--	<6	CA Db 84
<10	--	--	<1	34	--	<6	
<10	--	--	<1	41	--	6	
4	--	--	--	28	--	<1	
3	--	--	--	26	--	<1	
--	--	--	--	--	--	--	
7	--	--	--	40	--	--	
2	<1	1	<1	18	--	1	CA Db 85
<10	--	--	<1	11	--	<6	
<10	4	--	<1	14	--	<6	
6	--	--	--	19	--	<1	
4	--	--	--	19	--	<1	
--	--	--	--	--	--	--	
3	4	--	--	20	--	3	

Appendix C.— Chemical analyses of rainwater, storm water, water from the unsaturated zone, and ground water at the Prince Frederick site—Continued

Station name or number	Date	Zinc, filtered (µg/L)	Zinc, unfiltered (µg/L)	Carbon organic, filtered (mg/L)	Carbon organic, unfiltered (mg/L)
Rainwater	09-09-87	370	--	--	--
	12-11-87	66	--	--	--
01594680	08-28-86	5	10	3.3	2.6
	06-13-87	100	390	5.0	5.1
	10-09-87	97	170	6.5	8.9
	12-11-87	57	110	--	7.0
	04-20-88	60	200	--	12
	05-09-88	140	250	--	--
	07-12-88	230	250	--	--
	08-23-88	100	--	--	--
	02-01-89	340	670	--	--
CA Db 66	08-27-86	14	90	--	--
	12-15-86	8	70	1.1	3.4
	12-11-87	16	--	1.7	2.6
	12-14-87	16	--	--	1.9
	04-21-88	10	20	.7	1.2
	08-24-88	5	--	--	--
	10-19-88	--	--	--	--
	01-20-89	--	--	--	--
	03-01-89	7	60	--	--
CA Db 67	08-27-86	39	--	--	--
	12-15-86	14	--	1.2	4.8
	05-18-87	9	50	1.5	10
	12-11-87	13	--	--	5.4
	12-14-87	10	--	--	2.0
CA Db 69	08-28-86	63	370	1.5	11
	12-16-86	97	140	1.0	.8
	09-09-87	19	30	1.6	1.5
	12-11-87	46	--	2.2	1.2
	12-14-87	32	--	--	.6
	04-20-88	22	40	1.2	1.2
	08-23-88	44	--	--	--
	10-19-88	--	--	--	--
	01-20-89	--	--	--	--
	03-01-89	46	--	--	--
CA Db 70	12-16-86	31	--	1.0	1.7
	12-11-87	26	--	--	1.0
	12-14-87	22	--	--	1.7
CA Db 72	08-27-86	320	420	--	2.7
	12-16-86	110	130	1.1	1.4
	12-11-87	73	--	1.2	3.1
	12-14-87	65	--	--	1.2
	04-21-88	70	90	1.1	1.7
	08-24-88	83	--	--	--
	01-20-89	--	--	--	--
	03-01-89	5	140	--	--
CA Db 73	08-27-86	--	--	2.4	--
	12-15-86	55	--	1.2	1.4
	05-18-87	50	100	1.4	7.6
	06-13-87	87	100	1.6	1.5
	09-09-87	78	120	1.3	2.2
	09-11-87	65	170	1.7	4.0
	12-11-87	64	--	--	.6
	12-14-87	51	--	--	.7
	04-21-88	43	60	1.0	1.7
	08-23-88	<3	--	--	--
	10-19-88	--	--	--	--
	01-20-89	--	--	--	--
	03-01-89	90	100	--	--
CA Db 84	09-02-87	19	--	--	--
	09-11-87	25	--	6.5	5.1
	12-11-87	9	--	--	3.0
	04-20-88	<3	<10	--	3.5
	08-23-88	55	--	--	--
	01-20-89	--	--	--	--
	03-01-89	<10	--	--	--
CA Db 85	09-02-87	5	40	--	--
	09-09-87	25	--	--	--
	12-14-87	6	<10	--	2.1
	04-20-88	<3	<10	--	6.4
	08-23-88	10	--	--	--
	10-19-88	--	--	--	--
	03-01-89	<10	<10	--	--

Cyanide, unfiltered (mg/L)	Methylene blue active substances (mg/L)	Oil and grease, unfiltered (mg/L)	Benzene, unfiltered (µg/L)	Toluene, unfiltered (µg/L)	Trichloro-fluoro-methane unfiltered (µg/L)	1,1,1,-tri-chloroethene, unfiltered (µg/L)	Station name or number
--	--	--	--	--	--	--	Rainwater
--	--	--	--	--	--	--	
--	0.06	--	<3.0	<3.0	<3.0	<3.0	01594680
--	.27	<1	<.2	.8	<.2	<.2	
--	.07	--	--	--	--	--	
--	.11	--	--	--	--	--	
--	.19	--	--	--	--	--	
--	.18	--	--	--	--	--	
--	.74	--	--	--	--	--	
--	.33	--	--	--	--	--	
--	.23	--	--	--	--	--	
--	--	--	--	--	--	--	CA Db 66
--	<.01	--	<.2	<.2	<.2	<.2	
--	.02	--	--	--	--	--	
--	.02	--	--	--	--	--	
--	.01	--	--	--	--	--	
--	.02	--	--	--	--	--	
--	--	--	--	--	--	--	
--	--	--	--	--	--	--	
<0.01	<.01	--	--	--	--	--	
--	--	--	<3.0	<3.0	<3.0	<3.0	CA Db 67
--	<.01	--	<.2	<.2	<.2	<.2	
--	<.01	--	<.2	<.2	<.2	<.2	
--	<.01	--	--	--	--	--	
--	.02	--	--	--	--	--	
--	.08	--	--	--	--	--	CA Db 69
--	.09	--	<.2	<.2	<.2	<.2	
--	.02	--	--	--	--	--	
--	.04	--	--	--	--	--	
--	.07	--	--	--	--	--	
--	4.00	<1	--	--	--	--	
--	.05	--	--	--	--	--	
--	--	--	--	--	--	--	
--	--	--	--	--	--	--	
--	.07	--	<.2	<.2	<.2	<.2	
--	.05	--	<.2	<.2	<.2	<.2	CA Db 70
--	.06	--	--	--	--	--	
--	.03	--	--	--	--	--	
--	--	<1	--	--	--	--	CA Db 72
--	.05	--	<.2	<.2	<.2	<.2	
--	.03	--	--	--	--	--	
--	.04	--	--	--	--	--	
--	.05	--	--	--	--	--	
--	.11	--	--	--	--	--	
--	--	--	--	--	--	--	
<.01	.05	--	<.2	.2	<.2	<.2	
--	--	--	<3.0	<3.0	<3.0	3.0	CA Db 73
--	.04	--	<.2	<.2	<.2	<.2	
--	.05	--	<.2	<.2	<.2	<.2	
--	.05	2	.3	<.2	<.2	<.2	
--	.02	--	<.2	<.2	<.2	<.2	
--	<.01	--	--	--	--	--	
--	.06	--	--	--	--	--	
--	.06	--	--	--	--	--	
--	.05	<1	--	--	--	--	
--	.02	--	--	--	--	--	
--	--	--	--	--	--	--	
--	--	--	--	--	--	--	
<.01	4.30	--	--	--	--	--	
--	--	--	--	--	--	--	CA Db 84
--	--	--	--	--	--	--	
--	--	--	--	--	--	--	
--	--	--	--	--	--	--	
--	--	--	--	--	--	--	
--	--	--	--	--	--	--	
--	--	--	--	--	--	--	
--	.09	--	--	--	--	--	CA Db 85
--	--	--	<.2	<.2	<.2	<.2	
--	.06	--	--	--	--	--	
--	.08	--	--	--	--	--	
--	.07	--	--	--	--	--	
--	--	--	--	--	--	--	
<0.01	.18	--	--	--	--	--	

Appendix D.— Detection limits for organic-compound analyses of storm-water and ground-water samples collected at the study sites

[Detection limits refer to reportable levels of concentration and not to the lowest limits of detection with the method used; *, compound was detected in at least one sample--refer to Appendixes A, B, C, and to text]

Organic compound	Detection limit(s) (in micrograms per liter)
*Dichlorobromomethane	0.2
Carbontetrachloride	.2
1,2-Dichloroethane	.2
Bromoform	.2
Chlorodibromomethane	.2
*Chloroform	.2
*Toluene	.2
*Benzene	.2
Acenaphthylene	5
Acenaphthene	5
Anthracene	5
Benzo B Fluoranthene	10
Benzo K Fluoranthene	10
Benzoapyrene	10
Bis (2-Chloroethyl) Ether	5
Bis (2-Chloroethoxy) Methane	5
Bis (2-Chloroisopropyl) Ether	5
N-Butyl Benzyl Phthalate	5
Chlorobenzene	.2
*Chloroethane	.2
Chrysene	10
Diethyl Phthalate	5
Dimethyl Phthalate	5
Ethylbenzene	.2
Fluoranthene	5
Fluorene	5
Hexachlorocyclopentadiene	5
Hexachloroethane	5
Indeno (1,2,3-Cd) Pyrene	10
Isophorone	5
Methylbromide	.2
Methylchloride	.2
Methylene Chloride	.7 - .2
N-Nitrosodi-N-Propylamine	5
N-Nitrosodiphenylamine	5
N-Nitrosodimethylamine	5
Nitrobenzene	5
Parachlorometa Cresol	30
Phenanthrene	5
Pyrene	5
*Tetrachloroethylene	.2
*Trichlorofluoromethane	.2

Appendix D.— Detection limits for organic-compound analyses of storm-water and ground-water samples collected at the study sites—Continued

Organic compound	Detection limit(s) (in micrograms per liter)
*1,1,-Dichloroethane	.2
1,1-Dichloroethylene	.2
*1,1,1-Trichloroethane	.2
1,1,2-Trichloroethane	.2
1,1,2,2 Tetrachloroethane	.2
Benzogh I Perylene1,12-Benzoperylene	10
Benzo A Anthracene1,2-Benzanthracene	10
1,2-Dichlorobenzene	5 - .2
1,2-Dichloropropane	.2
*1,2-Transdichloroethene	.2
1,2,4-Trichlorobenzene	5
1,2,5,6-Dibenzanthracene	10
1,3-Dichloropropene	.2
1,3-Dichlorobenzene	5 - .2
1,4-Dichlorobenzene	5 - .2
2-Chloroethylvinylether	.2
2-Chloronaphthalene	6
2-Chlorophenol	6
2-Nitrophenol	6
Di-N-Octyl Phthalate	10
2,4-Dichlorophenol	6
2,4-Dimethylphenol	6
2,4-Dinitrotoluene	5
2,4-Dinitrophenol	20
2,4,6-Trichlorophenol	20 - 5
2,6-Dinitrotoluene	5
4-Bromophenyl Phenyl Ether	5
4-Chlorophenyl Phenyl Ether	5
4-Nitrophenol	30
4,6-Dinitroorthocresol	30
Dichlorodifluoromethane	.2
Phenol(C_6H_5OH)	6
Naphthalene	5
Trans-1,3-Dichloropropene	.2
Cis 1,3-Dichloropropene	.2
Pentachlorophenol	30
*1,2-Dibromoethylene	.2
Bis(2-Ethyl Hexyl)Phthalate	5
Di-N-Butylphthalate	5
Vinyl Chloride	.2
*Trichloroethylene	.2
Hexachlorobenzene	5
Hexachlorobutadiene	5
Styrene	.2
Xylene	.2

Appendix E.— Detection limits for organic-compound analyses of bottom materials collected from storm-water ponds at the Annapolis and Greenmount sites

[Detection limits refer to reportable concentration levels and not to the lowest level of detection with the methods used]

Organic compound	Analytical detection limit (in micrograms per kilogram)
Acenaphthylene	200
Acenaphthene	200
Anthracene	200
Benzo B Fluoranthene	400
Benzo K Fluoranthene	400
Benzo A Pyrene	400
Bis (2-Chloroethyl) Ether	200
Bis (2-Chloroethoxy) Methane	200
Bis (2-Chloroisopropyl) Ether	200
N-Butyl Benzyl Phthalate	200
Chrysene	400
Diethyl Phthalate	200
Dimethyl Phthalate	200
Fluoranthene	200
Fluorene	200
Hexachlorocyclopentadiene	200
Hexachloroethane	200
Indeno (1,2,3-CD) Pyrene	400
Isophorone	200
N-Nitrosodi-N-Propylamine	200
N-Nitrosodiphenylamine	200
N-Nitrosodimethylamine	200
Naphthalene	200
Nitrobenzene	200
Parachlorometa Cresol	600
Phenanthrene	200
Pyrene	200
Benzoh I Perylene 1,12-Benzo Erylene	400
Benzo A Anthracene1,2-Benzanthracene	400
1,2-Dichlorobenzene	200
1,2,4-Trichlorobenzene	200
1,2,5,6-Dibenzanthracene	400
1,3-Dichlorobenzene	200
1,4-Dichlorobenzene	200
2-Chloronaphthalene	200
2-Chlorophenol	200
2-Nitrophenol	200
Di-N-Octyl Phthalate	400
2,4-Dichlorophenol	200
2,4-Dimethylphenol	200

Appendix E.— Detection limits for organic-compound analyses of bottom materials collected from storm-water ponds at the Annapolis and Greenmount sites—Continued

Organic compound	Analytical detection limit (in micrograms per kilogram)
2,4-Dinitrotolue	200
2,4-Dinitrophenol	600
2,4,6-Trichlorophenol	600
2,6-Dinitrotoluene	200
4-Bromophenyl Phenyl Ether	200
4-Nitrophenol	600
4,6-Dinitroorthocresol	600
Phenol (C_6H_5OH)	200
Pentachlorophenol	600
Bis(2-Ethyl Hexyl) Phthalate	200
Di-N-Butyl Phthalate	200
Hexachlorobenzene	200
Hexachlorobutadience	200

Appendix F.— Measurements of specific conductance, pH, alkalinity, chloride, and dissolved oxygen in samples collected at the Annapolis site

[Specific conductance in microsiemens per centimeter at 25 degrees Celsius; pH in standard units; alkalinity in milligrams per liter as calcium carbonate; chloride and dissolved oxygen in milligrams per liter; --, no data]

Date	Specific conductance	pH	Alkalinity	Chloride	Dissolved oxygen
			Rainfall		
19861026	22	4.64	--	--	--
19861104	69	3.83	--	--	--
19861120	25	4.46	--	--	--
19861126	25	4.55	--	--	--
19861209	25	4.26	--	--	--
19861224	9	5.28	--	--	--
19870109	--	5.01	--	--	--
19870118	15	3.59	--	--	--
19870327	42	4.20	--	--	--
19870416	29	4.40	--	--	--
19870504	27	4.35	--	--	--
19870508	120	3.85	--	--	--
19870527	27	4.50	--	--	--
19870626	24	4.61	--	--	--
19870710	43	4.23	--	--	--
19870725	119	3.74	--	--	--
19870805	83	3.40	--	--	--
19870822	79	6.23	--	--	--
19870828	90	3.81	--	--	--
19870909	18	4.64	--	2.1	--
19870912	91	4.11	--	--	--
19870918	46	4.04	--	--	--
19870930	20	4.66	--	--	--
19871027	14	5.17	--	--	--
19871110	24	4.77	--	--	--
19871118	21	5.01	--	--	--
19871203	72	4.04	--	--	--
19871210	33	4.36	--	--	--
19871214	36	4.43	--	--	--
19871222	31	4.33	--	--	--
19880110	25	4.71	--	--	--
19880117	26	5.15	--	--	--
19880119	12	4.66	--	--	--
19880127	44	4.23	--	--	--
19880211	14	4.85	--	--	--
19880219	--	4.40	--	--	--
19880304	32	4.32	--	--	--
19880309	59	4.52	--	--	--
19880326	16	4.82	--	--	--
19880406	35	4.24	--	--	--
19880427	33	4.40	--	--	--
19880503	30	4.61	--	--	--
19880510	63	4.02	--	--	--
19880517	36	4.24	--	--	--
19880518	34	4.26	--	--	--
19880524	37	4.15	--	--	--
19880609	124	3.70	--	.8	--
19880712	19	5.94	--	--	--
19880717	35	4.84	--	--	--
19880719	21	6.37	1.39	--	--
19880726	43	4.23	--	--	--
19880816	68	3.96	--	--	--
19880824	17	4.94	--	--	--
19880909	15	5.38	--	--	--
19880924	22	4.63	--	--	--

Appendix F.— Measurements of specific conductance, pH, alkalinity, chloride, and dissolved oxygen in samples collected at the Annapolis site —Continued

Date	Specific conductance	pH	Alkalinity	Chloride	Dissolved oxygen
		Rainfall--Continued			
19881011	37	4.65	--	--	--
19881021	12	5.11	--	--	--
19881101	12	5.15	--	--	--
19881116	20	4.47	--	--	--
19881127	14	4.78	--	--	--
19881231	29	4.44	--	--	--
19890101	26	4.51	--	--	--
19890106	45	4.03	--	--	--
19890112	30	4.44	--	--	--
19890126	50	4.69	--	--	--
19890203	45	4.17	--	--	--
19890207	--	4.00	--	--	--
19890309	26	4.93	--	--	--
19890318	35	4.28	--	--	--
19890323	8	5.30	--	--	--
		Storm runoff			
19850926	--	7.40	--	--	--
19861026	78	6.93	23.5	--	--
19861126	45	7.09	--	2.1	--
19861210	57	7.20	20.5	--	--
19861224	41	6.78	--	--	--
19870118	50	6.65	6.7	.3	--
19870330	205	6.87	27.2	5.5	--
19870416	80	6.35	20.1	4.2	--
19870508	93	7.64	18.0	2.2	--
19870527	48	7.17	16.0	1.1	--
19870626	46	7.23	18.5	1.2	--
19870710	55	6.33	--	--	--
19870725	57	6.32	9.0	1.3	--
19870805	217	5.98	5.0	1.3	--
19870822	119	6.88	29.2	3.0	--
19870828	116	6.78	23.0	--	--
19870909	126	7.22	29.2	6.3	--
19870912	200	7.10	29.5	2.0	--
19870915	254	6.68	41.4	--	--
19870918	76	7.31	18.0	1.1	--
19870930	75	7.10	20.0	1.1	--
19871027	58	7.47	21.0	1.2	--
19871110	125	6.83	17.0	--	--
19871118	212	7.24	79.6	--	--
19871203	700	7.24	23.0	--	--
19871210	315	7.31	18.0	71.0	--
19871214	481	6.98	21.0	108	--
19871222	391	7.45	29.5	94.0	--
19880117	--	--	24.0	6.3	--
19880118	116	6.76	24.0	7.7	--
19880127	--	7.20	20.5	--	--
19880211	--	6.70	14.0	--	--
19880219	249	7.02	32.0	33.4	--
19880304	85	7.27	15.7	10.5	--
19880326	95	6.76	25.3	20.0	--
19880406	88	7.45	25.3	13.0	--
19880510	142	7.20	--	--	--
19880517	72	7.28	27.0	--	--
19880518	70	6.88	15.3	4.6	--
19880524	36	6.91	10.5	--	--

Appendix F.— Measurements of specific conductance, pH, alkalinity, chloride, and dissolved oxygen in samples collected at the Annapolis site —Continued

Date	Specific conductance	pH	Alkalinity	Chloride	Dissolved oxygen
		Storm runoff--Continued			
19880525	90	6.70	--	--	--
19880609	79	6.35	9.0	1.4	--
19880628	131	6.84	41.0	5.0	--
19880717	158	6.91	44.0	7.0	--
19880719	100	7.00	27.5	8.0	--
19880726	59	6.66	--	1.0	--
19880816	84	6.48	16.0	2.0	--
19880825	75	6.94	20.5	4.0	--
19880909	140	6.50	44.5	22.0	--
19881002	--	7.05	22.5	--	--
19881116	77	7.31	32.0	2.0	--
19881119	96	7.12	31.5	3.5	--
19881127	66	7.32	27.0	1.7	--
19881231	505	7.07	31.3	--	--
19890103	1,280	6.81	21.5	170	--
19890106	2,600	7.23	16.0	550	--
19890112	116	6.76	24.0	12.6	5.1
19890201	304	7.11	40.0	13.0	--
19890203	153	6.94	--	--	--
		Impoundment (pond) storm water			
19870501	137	8.71	27.6	11	10.7
19870527	57	8.20	19.0	1.0	--
19870901	96	8.95	19.3	1.5	12.4
19870911	72	8.81	18.5	2.2	--
19880603	65	7.83	17.2	3.3	8.95
19880726	63	7.22	--	3.2	--
19880817	71	6.84	17.5	1.4	8.0
19881007	83	6.90	--	--	--
19881011	58	7.83	19.5	.3	9.89
19881206	49	7.29	20.3	1.0	11.45
19890119	95	7.09	17.5	9.9	11.63
19890308	94	6.82	17.5	11.0	--
19890322	230	7.57	19.5	60.0	--
19890329	109	9.07	16.2	18.0	10.69
		Unsaturated-zone water AA De 160			
19880621	100	--	--	10.0	--
19880622	7	5.12	--	--	--
19880816	53	6.19	16.0	3.0	--
19880823	25	5.82	5.0	3.4	--
19880913	--	7.68	--	--	--
19881101	580	7.77	--	--	--
		Ground water AA De 140 (control well)			
19860904	43	4.81	2.9	5.1	6.73
19861211	36	4.95	3.0	10.0	--
19870429	30	5.26	3.7	4.3	9.58
19870504	44	5.36	3.1	4.4	--
19870909	36	5.07	1.0	4.9	--
19870917	30	5.13	--	--	--
19871207	30	5.40	1.4	6.1	8.94
19880610	33	4.96	--	4.1	9.69
19880726	33	4.93	2.0	--	9.05
19880817	36	5.40	2.0	3.8	9.47
19881011	32	5.04	2.5	5.2	9.36
19881207	30	5.19	3.5	6.1	8.80
19890119	33	5.13	1.0	3.8	8.46
19890329	24	5.38	2.0	4.2	8.10
19890803	41	5.19	2.7	6.0	--

Appendix F.— Measurements of specific conductance, pH, alkalinity, chloride, and dissolved oxygen in samples collected at the Annapolis site —Continued

Date	Specific conductance	pH	Alkalinity	Chloride	Dissolved oxygen
		Ground Water--Continued			
		AA De 142 (downgradient well)			
19860902	67	5.08	3.2	12.0	6.21
19861212	93	4.91	2.6	22.0	--
19870429	64	5.41	4.6	13.0	6.19
19870917	33	5.51	4.0	--	--
19880610	52	5.24	3.3	12.5	7.60
19880719	50	5.35	3.0	10.5	--
		AA De 143 (downgradient well)			
19860914	--	--	--	12.0	--
19861212	120	5.06	3.0	28.0	--
19870422	119	5.24	3.0	--	--
19870917	58	5.41	3.8	18.2	--
19871207	77	5.37	2.6	18.0	6.32
19880610	94	5.22	3.2	20.0	6.70
19880816	80	5.34	4.5	17.0	8.24
19880817	71	5.80	4.0	15.0	--
19881011	87	5.10	3.5	23.8	6.80
19881206	72	5.36	4.5	15.4	4.93
19890118	59	5.38	3.0	14.5	4.59
19890329	38	5.52	6.0	5.4	5.16
19890803	24	--	6.0	4.0	--
		AA De 156 (deep beneath-impoundment well)			
19860903	185	4.82	3.0	46.0	5.35
19861212	230	4.63	4.0	72.0	--
19870429	372	4.87	1.6	--	5.34
19880314	--	--	1.9	--	--
19880610	320	4.93	2.4	85.0	1.32
19881011	235	5.05	3.5	63.8	.92
19881206	--	5.34	3.4	--	--
19890118	156	5.33	4.0	45.0	4.01
19890329	154	4.96	3.0	47.0	.47
19890803	70	--	7.5	16.0	--
		AA De 157 (shallow beneath-impoundment well)			
19860903	975	4.18	3.0	270	--
19861210	345	4.86	4.0	100	--
19870429	135	5.21	5.1	30.0	4.41
19870504	140	5.16	4.0	42.0	--
19870909	630	4.65	2.0	170	2.44
19870911	600	4.64	2.0	170	2.58
19870917	610	4.74	--	160	--
19871203	420	4.93	--	--	--
19871207	480	4.82	3.0	150	2.69
19880610	251	5.20	3.4	65.0	4.33
19880719	238	5.01	2.3	57.6	3.31
19880816	225	5.34	5.0	55.0	3.66
19880817	176	5.50	5.0	45.0	--
19881011	175	5.20	5.5	49.3	2.60
19881206	--	5.32	7.5	--	--
19890118	148	5.29	5.0	35.7	2.76
19890329	101	4.96	7.0	23.8	2.62
19890803	69	--	9.0	14.0	--

Appendix G.—Measurements of specific conductance, pH, alkalinity, chloride, and dissolved oxygen in samples collected at the Greenmount site

[Specific conductance in microsiemens per centimeter at 25 degrees Celsius; pH in standard units; alkalinity in milligrams per liter as calcium carbonate; chloride and dissolved oxygen in milligrams per liter; --, no data]

Date	Specific conductance	pH	Alkalinity	Chloride	Dissolved oxygen
			Rainfall		
19861026	37	4.23	--	--	--
19861102	12	5.88	--	--	--
19861105	31	4.10	--	--	--
19861118	37	4.31	--	--	--
19861124	21	4.40	--	--	--
19861208	38	4.02	--	--	--
19870102	62	3.71	--	--	--
19870110	58	5.41	--	--	--
19870114	16	3.95	--	--	--
19870129	40	3.93	--	--	--
19870328	12	4.96	--	--	--
19870402	39	4.76	--	--	--
19870416	25	4.42	--	--	--
19870512	49	5.80	--	--	--
19870604	37	4.10	--	--	--
19870630	41	6.25	--	--	--
19870906	46	6.37	--	--	--
19870909	8	5.94	--	--	--
19871127	22	4.44	--	--	--
19871204	70	4.01	--	--	--
19871215	33	4.64	--	--	--
19880117	11	5.07	--	--	--
19880125	37	6.50	--	--	--
19880211	15	4.91	--	--	--
19880219	24	4.66	--	--	--
19880303	42	4.15	--	20.0	--
19880326	10	5.31	1.5	.5	--
19880404	31	4.65	--	3.0	--
19880418	--	5.43	1.7	1.0	--
19880423	54	3.43	--	2.0	--
19880429	38	4.06	--	.2	--
19880504	35	4.39	--	--	--
19880510	37	4.47	--	--	--
19880516	46	4.13	--	10.0	--
19880520	32	4.58	--	--	--
19880601	96	3.91	--	--	--
19880608	34	4.75	--	20.0	--
19880616	19	3.50	--	--	--
19880717	56	4.24	--	1.8	--
19880917	66	6.50	--	--	--
19880924	14	4.96	--	.9	--
19881002	18	5.91	2.0	12.0	--
19881018	31	6.33	--	3.6	--
19881021	11	4.80	--	--	--
19881101	--	5.42	--	--	--
19881105	16	4.90	--	1.5	--
19881113	40	4.77	--	1.5	--
19881221	22	4.80	--	1.4	--
19890114	30	4.35	--	2.0	--
19890130	38	4.20	--	1.2	--
19890220	39	4.21	--	3.0	--

Appendix G.—Measurements of specific conductance, pH, alkalinity, chloride, and dissolved oxygen in samples collected at the Greenmount site—Continued

Date	Specific conductance	pH	Alkalinity	Chloride	Dissolved oxygen
			Storm runoff		
19860520	265	6.70	30.0	8.8	--
19861026	325	7.34	131	--	--
19861102	330	7.44	--	--	--
19861105	88	7.45	--	--	--
19871029	2,240	7.13	76.5	601	--
19870328	510	6.92	95.2	72.3	--
19870402	219	7.41	50.7	18.7	--
19870416	158	7.60	56.0	7.0	--
19870512	155	7.45	42.7	8.1	--
19870604	125	7.33	25.0	12.0	--
19870622	364	6.76	86.0	22.1	--
19870626	372	7.08	83.0	--	--
19870630	134	6.82	34.8	2.3	--
19870701	240	6.58	34.5	11.5	--
19870714	172	7.00	46.5	.2	--
19870819	368	6.51	49.8	--	--
19870829	108	6.66	26.5	4.4	--
19870910	320	6.59	66.0	16.0	--
19870930	97	6.90	--	3.9	--
19871127	6,750	7.01	89.0	--	--
19871204	198	6.85	35.0	18.0	--
19871215	404	7.04	87.0	25.9	--
19880219	--	7.24	68.0	--	--
19880324	280	6.68	21.0	19.0	--
19880326	189	7.38	64.0	27.0	7.96
19880404	375	6.90	74.9	--	--
19880415	180	7.60	42.5	18.3	--
19880418	210	7.11	41.0	25.0	--
19880423	385	7.79	102	23.0	--
19880506	160	7.30	28.5	4.2	--
19880601	575	7.50	60.5	115	--
19880608	785	7.17	64.0	135	--
19880616	1,310	7.17	--	440	--
19880717	1,420	6.97	74.0	360	--
19880829	--	7.69	50.0	1.2	--
19881018	118	6.75	--	8.0	--
19890305	365	7.80	96.0	22.0	--
			Impoundment (pond) water		
19870601	216	7.41	99.3	6.5	--
19870605	175	7.34	65.0	6.0	--
19880323	1,030	9.74	84.0	300	14.80
19880331	655	9.87	53.0	160	14.70
19880602	197	7.73	--	17.9	6.73
19880714	255	7.52	87.0	20.7	6.02
19880928	106	9.80	45.0	2.3	10.80
19881020	93	9.84	--	3.9	--
19881130	--	10.24	34.5	--	--
19881208	85	10.09	35.0	2.2	15.53
19890127	390	7.81	49.5	86.0	12.50
19890330	303	8.68	44.0	58.0	8.70
			Water from the unsaturated zone CL Bf 201		
19870818	378	7.41	--	--	--
19870910	570	7.03	43.0	23.0	--
19870917	625	7.24	--	--	--
19870930	666	6.80	248	16.3	--
19871014	643	7.66	265	10.3	--

Appendix G.—Measurements of specific conductance, pH, alkalinity, chloride, and dissolved oxygen in samples collected at the Greenmount site—Continued

Date	Specific conductance	pH	Alkalinity	Chloride	Dissolved oxygen
		Water from the unsaturated zone--Continued			
		CL Bf 201--Continued			
19871020	630	6.80	256	15.9	--
19871027	615	6.94	253	3.8	--
19871104	589	6.85	255	5.1	--
19871110	600	7.13	242	18.5	--
19871117	598	7.09	245	--	--
19871127	579	7.68	240	11.3	--
19871210	560	7.50	222	14.0	--
19871224	590	7.01	243	12.8	--
19871220	561	6.92	223	10.9	--
19880117	590	7.15	114	15.5	--
19880125	240	7.69	167	74.0	--
19880211	1,140	7.31	155	25.3	--
19880211	1,025	7.79	155	26.0	--
19880303	1,222	6.93	144	27.7	--
19880323	987	7.50	116	230	--
19880331	905	7.38	108	210	--
19880404	828	6.77	125	17.6	--
19880427	780	7.71	134	152	--
19880504	1,001	6.90	199	166	--
19880510	1,024	7.04	213	163	--
19880520	1,075	6.68	212	177	--
19880601	1,150	6.89	233	178	--
19880608	1,180	7.38	229	200	--
19880616	1,260	6.65	--	227	--
19880630	1,225	6.76	--	232	--
19880707	1,302	6.83	--	--	--
19880709	1,320	7.01	210	--	--
19880718	1,400	6.75	--	276	--
19880721	--	6.73	--	277	--
19880818	1,500	6.48	241	322	--
19880829	1,480	6.67	--	--	--
19880929	1,410	7.70	229	310	--
19881013	1,350	7.87	--	--	--
19881020	1,380	6.71	--	--	--
19881110	--	7.98	--	--	--
19881221	9,107	7.36	--	--	--
19890216	--	7.32	--	--	--
19890302	500	7.01	124	82.0	--
19890330	366	7.60	81.0	60.0	--
19890424	1,420	6.95	111	645	--
		Ground water			
		CL Bf 198 (upgradient/control well)			
19860617	135	5.68	10.0	22.0	6.80
19860625	147	5.68	12.5	10.0	6.00
19861217	190	5.41	9.5	22.0	--
19870602	178	5.80	12.7	17.0	--
19870604	181	5.63	13.5	14.0	--
19871007	181	5.35	7.5	11.1	--
19871210	201	5.53	10.0	24.0	--
19880324	188	5.33	5.4	17.0	6.87
19880602	333	5.36	--	30.0	--
19880714	235	5.35	8.8	15.4	--
19880929	242	5.30	6.0	20.0	6.00
19881020	156	5.36	--	17.9	--
19881202	250	5.25	6.5	19.7	--
19890127	340	5.29	6.0	34.0	--
19890330	290	5.25	7.5	54.0	--
19890804	154	5.45	6.0	18.0	--

Appendix G.—Measurements of specific conductance, pH, alkalinity, chloride, and dissolved oxygen in samples collected at the Greenmount site—Continued

Date	Specific conductance	pH	Alkalinity	Chloride	Dissolved oxygen
		Ground water--Continued			
		CL Bf 194 (Deep beneath-impoundment well)			
19860625	190	5.86	15.0	18.0	5.70
19861217	230	5.52	20.5	29.0	--
19871202	246	5.37	--	--	--
19871210	211	5.60	12.0	26.0	1.93
19880928	255	5.29	15.0	28.0	3.92
19881208	235	5.57	11.0	--	3.22
19890127	230	5.65	10.0	32.0	3.80
19890330	269	5.32	13.0	35.0	.64
19890804	220	--	10.5	35.0	--
		CL Bf 195 (Shallow beneath-impoundment well)			
19860619	270	5.45	10.0	33.0	3.80
19870601	246	5.23	11.0	30.0	--
19870604	239	5.32	9.0	28.0	0.00
19870605	250	5.15	10.0	30.0	--
19870910	245	5.08	9.5	28.0	3.18
19871007	225	5.12	7.7	27.1	--
19871015	220	5.27	7.5	27.8	2.96
19871202	206	5.02	--	--	--
19871210	194	5.40	8.5	23.0	2.23
19880323	210	5.32	8.7	27.0	.78
19880326	210	5.37	8.8	16.0	.69
19880331	230	5.25	8.6	29.0	.68
19880602	323	5.17	--	68.0	.25
19880714	350	5.25	9.1	74.6	.50
19880928	335	5.07	8.0	61.0	.28
19881020	340	5.33	--	71.4	.24
19881103	--	5.31	8.5	--	--
19881208	325	5.40	8.5	66.5	3.22
19890127	320	5.40	9.5	70.0	.25
19890330	289	5.28	8.4	24.0	.18
19890804	290	--	11.0	62.0	--
		CL Bf 199 (shallow downgradient well)			
19860617	245	5.25	--	--	--
19860619	270	5.62	--	--	--
19860620	250	5.43	11.5	38.0	5.20
19861217	230	5.08	7.5	39.0	--
19870602	275	5.32	9.2	43.0	--
19870604	276	5.25	8.6	35.0	--
19870605	285	5.23	10.0	50.0	--
19870910	360	5.05	7.0	74.0	3.81
19871007	415	4.92	--	--	--
19871015	390	4.99	5.8	88.1	4.26
19871202	256	5.40	--	--	--
19871210	400	5.61	19.0	79.0	5.33
19880323	322	5.35	9.1	64.0	5.10
19880326	300	5.67	13.1	53.0	2.00
19880331	319	5.27	6.5	72.0	2.50
19880602	400	5.40	--	74.0	4.16
19880714	315	4.90	--	74.2	3.92
19880929	320	5.55	14.0	60.0	6.51
19881020	350	5.08	--	87.1	3.09
19881103	--	5.26	8.5	--	--
19881208	365	5.20	7.5	85.7	4.27
19890127	370	5.49	15.0	78.0	5.29
19890330	260	5.72	16.2	48.0	4.05
19890804	250	5.51	13.0	32.0	--

Appendix G.—Measurements of specific conductance, pH, alkalinity, chloride, and dissolved oxygen in samples collected at the Greenmount site—Continued

Date	Specific conductance	pH	Alkalinity	Chloride	Dissolved oxygen
		Ground water--Continued			
		CL Bf 200 (deep downgradient well)			
19860618	195	5.35	--	--	--
19860620	196	5.64	12.0	26.2	4.30
19870602	145	5.39	6.3	14.0	--
19870604	147	5.28	5.5	15.0	--
19870605	150	5.28	7.0	19.0	--
19871007	153	5.37	--	--	--
19871015	150	5.38	--	--	5.41
19870910	144	5.32	5.5	21.0	5.67
19871210	159	5.45	6.5	20.0	4.57
19871202	229	4.93	--	--	--
19880323	170	5.59	8.8	23.1	2.01
19880929	170	5.79	4.6	19.0	1.59
19881208	155	6.31	7.5	21.4	--
19890127	151	6.08	6.5	22.0	--
19890330	206	5.44	9.5	28.0	--

Appendix H.—Measurements of specific conductance, pH, alkalinity, chloride, and dissolved oxygen in samples collected at the Prince Frederick site

[Specific conductance in microsiemens per centimeter at 25 degrees Celsius; pH in standard units; alkalinity in milligrams per liter as calcium carbonate; chloride and dissolved oxygen in milligrams per liter; --, no data; >, greater than; <, less than]

Date	Specific conductance	pH	Alkalinity	Chloride	Dissolved oxygen
			Rainfall		
19861025	89	3.78	--	--	--
19861105	99	3.94	--	--	--
19861118	77	6.17	--	--	--
19861120	35	4.39	--	--	--
19861126	31	4.54	--	--	--
19861209	18	4.25	--	--	--
19861218	8	4.63	--	--	--
19861224	12	4.15	--	--	--
19870110	40	3.30	--	--	--
19870115	33	3.96	--	--	--
19870309	42	3.61	--	--	--
19870315	77	3.81	--	--	--
19870328	24	3.92	--	--	--
19870415	31	4.41	--	--	--
19870512	108	4.06	--	--	--
19870519	54	4.08	--	--	--
19870613	85	3.89	--	--	--
19870725	61	4.61	--	--	--
19870822	70	3.61	--	--	--
19870827	65	3.92	--	--	--
19870908	31	4.57	--	--	--
19870909	9	4.80	--	0.4	--
19870912	23	4.34	--	1.5	--
19870919	29	4.27	--	--	--
19870930	20	4.56	--	--	--
19871027	16	5.06	--	--	--
19871110	30	4.43	--	--	--
19871128	34	4.56	--	--	--
19871204	44	4.08	--	--	--
19871211	25	4.77	--	.32	--
19871224	36	4.11	--	--	--
19880111	29	4.32	--	--	--
19880112	40	4.26	--	--	--
19880119	13	4.41	--	--	--
19880202	28	4.51	--	--	--
19880211	19	4.56	--	--	--
19880219	27	4.36	--	--	--
19880223	74	4.00	--	--	--
19880304	40	4.21	--	--	--
19880309	50	4.26	--	--	--
19880326	18	4.67	--	--	--
19880404	18	4.96	1.5	--	--
19880406	25	4.17	--	--	--
19880418	36	4.19	--	--	--
19880427	65	4.02	--	--	--
19880504	26	4.30	--	--	--
19880510	38	4.17	--	--	--
19880518	45	4.04	--	--	--
19880525	41	4.01	--	--	--
19880602	32	4.82	--	--	--
19880609	48	4.02	--	--	--
19880711	102	3.81	--	--	--
19880717	45	4.03	--	--	--
19880721	31	4.20	--	2.0	--
19880815	--	4.01	--	--	--
19880820	82	6.37	--	--	--
19880829	24	5.08	--	2.8	--
19880909	17	4.60	--	--	--
19881002	38	4.24	--	2.3	--
19881021	15	4.94	--	--	--

Appendix H.—Measurements of specific conductance, pH, alkalinity, chloride, and dissolved oxygen in samples collected at the Prince Frederick site—Continued

Date	Specific conductance	pH	Alkalinity	Chloride	Dissolved oxygen
		Rainfall--Continued			
19881105	--	4.58	--	--	--
19881113	--	4.28	--	--	--
19881117	19	4.72	--	1.0	--
19881127	22	4.92	--	1.4	--
19881214	34	5.62	--	--	--
19881223	35	4.67	--	--	--
19881228	21	4.83	--	1.5	--
19890106	51	3.63	--	1.3	--
19890112	34	4.34	--	2.5	--
19890130	57	4.25	--	--	--
19890203	48	4.17	--	2.0	--
19890207	56	4.05	--	--	--
19890216	33	4.27	--	1.5	--
19890304	37	3.97	--	2.0	--
19890315	39	4.24	--	--	--
		Storm discharge ("runout")			
19860828	198	8.28	86.0	3.7	--
19861105	420	8.64	184	9.8	--
19861118	360	8.44	--	10.0	--
19861120	375	8.88	--	--	--
19861126	410	8.78	--	8.8	--
19870110	244	8.08	97.4	24.1	--
19870115	314	8.20	144	5.7	--
19870309	7,100	8.71	195	2,060	--
19870315	6,000	8.85	214	2,240	--
19870328	2,800	7.49	177	752	--
19870512	1,003	8.22	180	205	--
19870519	1,400	8.87	--	--	--
19870613	644	8.28	131	95.0	--
19870626	378	8.13	86.0	47.6	--
19870725	825	8.82	168	85.8	--
19870805	394	7.57	88.0	40.8	--
19870816	625	8.39	159	64.3	--
19870822	412	8.09	111	39.0	--
19870827	595	8.44	169	67.9	--
19870908	395	7.92	117	--	--
19870912	275	7.61	85.5	25.0	--
19870919	395	8.46	135	29.3	--
19870930	258	8.15	85.0	14.6	--
19871009	382	7.92	117	38.0	--
19871012	435	8.22	149	33.8	--
19871027	334	8.72	121	13.3	--
19871110	320	7.58	114	18.0	--
19871128	2,600	8.11	175	675	--
19871204	930	8.54	129	190	--
19871211	814	8.00	125	160	--
19871224	770	8.10	160	126	--
19880104	--	8.74	236	--	--
19880202	6,200	7.73	176	1,933	--
19880223	--	8.46	160	--	--
19880326	1,010	8.36	122	230	--
19880406	972	8.46	154	205	--
19880418	698	8.27	125	143	--
19880420	694	8.14	125	130	--
19880427	860	8.31	179	174	--
19880509	823	8.19	166	150	--
19880510	700	8.67	177	108	--
19880602	800	8.31	160	98.0	--
19880609	450	8.12	112	55.0	--
19880701	700	7.75	108	132	--
19880712	396	7.43	94.0	46.0	--

Appendix H.—Measurements of specific conductance, pH, alkalinity, chloride, and dissolved oxygen in samples collected at the Prince Frederick site—Continued

Date	Specific conductance	pH	Alkalinity	Chloride	Dissolved oxygen
		Storm discharge ("runout")--Continued			
19880717	328	7.44	86.3	36.7	--
19880823	244	7.28	73.8	15.0	--
19880829	152	7.48	91.0	23.0	--
19880909	350	8.05	129	42.0	--
19880917	400	8.48	--	--	--
19881002	270	7.31	81.0	23.5	--
19881021	158	7.46	79.0	12.5	--
19881117	420	8.23	200	26.0	--
19881209	305	7.82	122	15.0	--
19881214	100	7.93	148	15.0	--
19881228	250	7.76	112	11.0	--
19890101	9,025	8.79	--	--	--
19890201	1,220	8.74	139	290	--
19890203	2,050	8.83	--	--	--
19890207	950	8.85	162	--	--
19890224	--	8.59	175	--	--
19890304	60,000	8.79	261	>8,000	--
19890315	2,600	8.73	114	775	--
19890323	178	8.25	63.0	100	--
		Impoundment storm water (porous-pavement reservoir) CA Db 85			
19870512	520	8.44	195	23.0	--
19870729	451	8.26	153	3.0	--
19870819	602	8.29	239	15.0	--
19870822	473	8.47	205	9.2	--
19870902	571	8.50	269	15.0	7.19
19870909	330	8.41	203	13.0	--
19870912	330	8.51	155	8.0	--
19870919	475	8.95	--	--	--
19870930	438	9.01	217	3.0	--
19871012	593	8.61	295	3.4	--
19871105	620	8.32	322	--	--
19871110	--	7.20	99.0	--	--
19871128	--	8.57	256	--	--
19871204	498	8.55	268	80.0	9.09
19871214	395	8.64	199	8.2	--
19880117	--	8.50	123	--	--
19880119	--	7.65	55.2	--	--
19880125	--	8.46	315	--	--
19880202	--	8.46	315	--	--
19880211	5,100	7.89	321	1,380	--
19880219	--	8.14	342	--	--
19880223	--	8.31	372	--	--
19880304	1,570	8.25	348	265	--
19880309	1,290	8.65	328	198	--
19880326	780	8.50	246	80.0	--
19880404	880	8.27	264	96.0	--
19880406	880	8.03	264	96.0	--
19880407	639	8.49	224	--	--
19880418	670	8.56	229	70.0	10.65
19880420	540	8.44	192	38.0	--
19880427	680	8.26	235	45.0	--
19880504	582	8.46	221	38.0	--
19880510	410	8.56	166	230	--
19880524	340	8.45	141	24.0	--
19880602	560	8.40	231	32.0	--
19880609	510	8.06	205	32.1	--
19880711	381	8.12	128	--	--
19880717	338	8.55	139	15.2	--
19880721	320	8.17	--	17.0	--
19880823	430	8.60	190	16.0	6.94

Appendix H.—Measurements of specific conductance, pH, alkalinity, chloride, and dissolved oxygen in samples collected at the Prince Frederick site—Continued

Date	Specific conductance	pH	Alkalinity	Chloride	Dissolved oxygen
Impoundment storm water (porous-pavement reservoir)--Continued					
CA Db 85--Continued					
19880829	13,380	8.59	176	13.4	--
19880917	520	8.56	243	24.0	--
19880923	420	8.39	--	10.6	--
19881002	430	8.51	216	13.0	--
19881019	510	8.87	271	15.8	--
19881105	490	8.78	--	--	--
19881116	555	8.88	--	1.0	--
19881122	450	8.64	229	2.5	--
19881129	310	8.45	174	1.5	--
19881207	370	8.23	183	4.0	10.78
19881222	600	7.92	319	2.0	--
19881223	635	8.23	--	2.0	--
19890101	850	8.64	333	2.0	--
19890103	--	8.23	297	9.0	--
19890130	610	8.88	--	11.0	--
19890203	560	8.83	--	--	--
19890207	520	8.94	--	--	--
19890224	--	7.95	320	--	--
19890301	970	8.50	241	330	10.08
19890315	2,600	8.28	223	712	--
19890322	1,700	8.00	--	--	--
Water from the unsaturated zone					
CA Db 84					
19870805	659	7.48	170	--	--
19870902	640	7.88	193	67.6	--
19870911	480	7.70	164	73.0	--
19870912	480	8.15	--	47.0	--
19870919	459	8.19	165	--	--
19870930	550	8.05	180	43.0	--
19871012	420	8.07	154	45.0	--
19871022	473	8.29	180	--	--
19871105	460	7.60	175	--	--
19871128	3,500	8.26	217	910	--
19871204	1,870	7.97	--	--	--
19871211	1,460	8.00	145	360	--
19871220	680	8.09	131	125	--
19871224	700	8.06	136	130	--
19880104	1,200	8.24	132	243	--
19880117	--	8.27	215	--	--
19880119	--	8.47	208	--	--
19880129	--	8.10	152	--	--
19880202	4,400	8.61	221	1,560	--
19880219	5,930	8.34	123	--	--
19880223	2,820	8.53	182	751	--
19880304	2,850	8.48	189	--	--
19880309	1,589	8.74	--	--	--
19880322	1,700	8.40	181	--	--
19880404	930	8.15	152	195	--
19880407	1,003	8.23	163	190	--
19880420	661	7.80	136	120	--
19880427	870	7.80	188	--	--
19880504	840	8.11	--	--	--
19880510	570	8.17	156	76.0	--
19880524	475	7.77	146	--	--
19880525	475	7.92	--	--	--
19880602	768	8.01	--	--	--
19880609	760	8.01	--	108	--
19880711	675	8.08	80.0	95.0	--

Appendix H.—Measurements of specific conductance, pH, alkalinity, chloride, and dissolved oxygen in samples collected at the Prince Frederick site—Continued

Date	Specific conductance	pH	Alkalinity	Chloride	Dissolved oxygen
		Water from the unsaturated zone--Continued			
		CA Db 84--Continued			
19880717	779	7.72	--	62.0	--
19880721	380	7.74	142	40.5	--
19880823	456	7.77	167	27.0	--
19880829	560	7.73	184	42.0	--
19880917	410	7.64	167	29.0	--
19880923	510	7.58	--	40.3	--
19881005	428	7.98	164	30.9	--
19881012	410	7.71	169	--	--
19881101	580	7.77	--	--	--
19881105	325	8.21	--	--	--
19881122	390	8.08	--	--	--
19881127	335	8.39	--	13.0	--
19881207	270	7.80	--	--	--
19881223	350	8.18	--	--	--
19890101	--	8.08	--	--	--
19890103	420	8.24	196	19.0	--
19890110	1,115	8.06	--	225	--
19890120	3,810	8.20	228	1,050	--
19890201	2,000	8.53	--	485	--
19890203	1,550	8.33	--	390	--
19890208	2,400	8.51	183	715	--
19890224	--	8.05	162	--	--
19890301	3,580	8.20	161	1,030	--
19890303	4,400	8.63	--	1,283	--
19890315	4,200	8.56	--	1,335	--
19890322	20,000	8.67	264	>4,500	--
19890412	3,500	8.07	--	--	--
		Ground water			
		CA Db 66 (deep upgradient (control) well)			
19860827	421	6.86	213	3.0	--
19861205	364	7.05	--	--	--
19861215	351	6.53	138	2.5	--
19870518	235	6.58	--	--	--
19870902	224	6.54	78.0	--	0.18
19870909	275	6.63	--	4.0	.07
19871211	260	6.94	124	4.3	3.92
19871214	246	6.82	107	2.6	3.13
19880421	242	6.70	101	2.7	2.62
19880601	284	6.69	--	3.4	2.68
19880713	243	6.65	98.0	5.0	.71
19880823	235	6.71	--	--	1.56
19880824	263	6.72	116	3.3	4.15
19881005	298	6.80	123	3.5	2.48
19881019	320	--	156	2.0	--
19881116	285	7.22	--	4.1	.34
19881207	335	--	149	3.5	.36
19890120	345	7.08	148	2.4	.66
19890301	340	7.20	155	2.5	.60
19890803	102	6.47	36.5	4.0	--
		CA Db 67 (shallow upgradient (control) well)			
19860825	275	6.45	--	--	--
19860827	269	6.35	94.0	3.9	--
19861205	184	6.52	--	--	--
19861215	175	5.95	64.0	2.8	--
19870518	163	6.32	58.0	5.5	--
19870521	165	6.52	--	--	--
19870613	164	6.48	52.5	9.3	--
19870902	189	6.53	75.8	--	1.30
19871211	189	6.22	67.0	6.0	2.12
19871214	145	6.53	53.0	4.7	3.93
19881005	142	6.42	50.0	3.9	2.43

Appendix H.—Measurements of specific conductance, pH, alkalinity, chloride, and dissolved oxygen in samples collected at the Prince Frederick site—Continued

Date	Specific conductance	pH	Alkalinity	Chloride	Dissolved oxygen
		Ground water--Continued			
		CA Db 69 (deep downgradient well)			
19860826	3,000	5.52	--	--	--
19860828	418	4.90	--	93.0	--
19861203	1,090	4.88	--	--	--
19861205	1,080	4.73	--	--	--
19861216	980	4.39	5.0	310	--
19870514	162	5.48	--	--	--
19870521	195	5.52	--	--	--
19870902	213	4.91	--	--	--
19870909	240	4.90	10.3	60.0	0.23
19871209	880	4.40	--	--	--
19871211	763	4.73	1.0	200	.10
19871214	650	4.76	--	170	.13
19880420	392	4.94	7.0	85.0	.20
19880601	273	4.75	--	55.0	.34
19880712	502	4.58	--	109	.32
19880823	887	4.44	--	260	.93
19881005	800	4.51	2.5	295	.80
19881019	630	4.95	3.5	183	--
19881116	650	4.58	--	220	.32
19881207	620	4.92	--	175	.39
19890120	830	4.48	--	250	.30
19890301	820	4.66	--	240	.22
		CA Db 70 (shallow downgradient well)			
19860828	310	5.36	--	--	--
19861203	412	5.46	--	--	--
19861216	347	5.33	27.0	83.0	--
19870625	193	5.53	38.5	9.9	--
19870902	182	5.15	21.0	--	--
19871209	493	4.88	--	--	--
19871211	457	5.19	10.4	120	2.64
19871214	415	5.19	11.0	110	.96
19880601	200	5.13	--	36.0	.64
19880712	254	5.08	18.0	--	.62
19880720	--	--	--	57.0	--
19881005	1,400	4.48	--	308	.78
19881116	1,020	4.59	--	289	1.58
19881207	1,000	4.54	--	270	.40
19890301	650	4.53	--	190	.24
		CA Db 72 (deep beneath-impoundment well)			
19860827	954	6.20	142	200	--
19861203	890	--	--	--	--
19861216	874	5.63	75.5	220	--
19870518	620	5.69	--	--	--
19870521	680	6.03	--	--	--
19871209	765	5.45	--	--	--
19871211	784	5.70	42.0	190	1.01
19871214	742	5.67	25.0	190	.81
19880421	787	5.50	27.0	200	.22
19880823	682	4.99	25.0	186	.32
19880824	700	5.35	19.0	190	2.07
19881005	670	5.70	22.5	170	1.07
19881207	570	5.62	23.5	135	1.79
19890120	630	5.61	24.0	160	1.48
19890301	761	5.59	22.5	200	2.51
19890803	670	5.04	8.5	190	--

Appendix H.—Measurements of specific conductance, pH, alkalinity, chloride, and dissolved oxygen in samples collected at the Prince Frederick site—Continued

Date	Specific conductance	pH	Alkalinity	Chloride	Dissolved oxygen
		Ground water--Continued			
		CA Db 73 (shallow beneath-impoundment well)			
19861215	686	5.88	78.0	160	--
19870518	734	5.64	52.0	170	--
19870613	896	5.52	46.0	230	--
19870902	895	5.40	37.0	--	0.31
19870909	869	5.43	39.0	220	1.58
19870911	853	5.42	38.0	220	1.04
19871209	765	5.61	--	--	--
19871211	753	5.85	44.5	180	.09
19871214	731	5.92	45.0	180	.12
19880421	669	6.05	75.0	140	1.47
19880601	683	5.80	--	143	1.85
19880712	600	5.62	46.0	126	.84
19880823	559	5.86	56.5	120	1.02
19881005	600	6.07	48.5	140	1.24
19881019	630	--	30.5	166	--
19881116	610	5.68	--	180	1.66
19881121	685	5.92	67.0	160	1.47
19881207	730	5.75	40.5	180	1.48
19890120	776	5.67	30.0	200	1.21
19890301	3,390	5.79	31.0	1,400	1.94

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