UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

RECONNAISSANCE OF SIX SOLID-WASTE DISPOSAL SITES IN PUERTO RICO AND EFFECTS ON WATER QUALITY

By Fernando Gómez-Gómez

U.S. GEOLOGICAL SURVEY

OPEN-FILE REPORT 79-1338

Prepared in cooperation with the
Environmental Quality Board,
Commonwealth of Puerto Rico

San Juan, Puerto Rico
1980

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS--Continued

Figure — Page

TABLES

4-6 Physical, chemical, and bacteriological data of Arecibo landfill at:

7-10 Physical, chemical, and bacteriological data of Caguas landfill at:

TABLES--Continued

Conversion Factors

Multiply SI unit	by	to obtain inch-pound equivalent
Length		
centimeter (cm)	0.0328	feet (ft)
centimeter (cm)	0.3937	inch (in)
kilometer (km)	0.6214	mile (mi)
meter (m)	3.2808	feet (ft)
millimeter (mm)	0.0394	inch (in)
Area		
hectare (ha)	2.471	acre (ac)
hectare (ha)	10.765×10^4	square feet (ft^2)
square meter (m^2)	1.1961	square yards (yd^2)
square meter (m^2)	10.765	square feet (ft^2)
Mass		
kilograms (kg)	2.2026	pounds (lb)
Flow		
cubic meters/second (m^3/s)	35.311	cubic feet/second (ft^3/s)

GLOSSARY

Arsenic (As) Arsenic occurs in nature mostly as arsenides or pyrites, found occasionally in elemental form. Used in manufacture of glass, pigments, textiles, paper, metal adhesives, ceramics, linoleum and mirrors. Its compounds are used in pesticides, wood preservatives, paints, and electrical semiconductors. Arsenic is a cumulative poison and has long-term chronic effects on both aquatic organisms and on mammalian species. Thus, a succession of small doses may add up to a final lethal dose. The possibility of biological methylation in increasing the txicity of arsenic has suggested added caution. Therefore, an upper limit of 0.2 mg/L is recommended in natural waters by the National Academy of Science and National Academy of Engineering (NAS, NAE, 1974).

Bicarbonate (HCO_3-) Carbon dioxide which is dissolved in waters usually appears in chemical analyses as bicarbonate. Carbon dioxide released from biological oxidation is capable of producing low pH if minerals that act as proton acceptors are scarce. Due to the presence of calcite in almost all natural water and soils, equilibrium conditions control pH to about 6. At such value the main species of dissolved carbon dioxide is HCO_3-.

Biochemical-oxygen demand (BOD 5-day) The BOD value represents the amount of oxygen utilized by microorganisms to decompose an amount of organic matter within a 5-day period. The value is obtained from the difference between the initial and final oxygen concentrations in the 5-day incubated sample. A high BOD value indicates high organic loading in the system. The test is entirely empirical and may be affected by toxic substances and lack of adaptiability of microorganisms to the test conditions. Natural unpolluted waters have BOD's of less than 5 mg/L (NAS, NAE, 1974).

Cadmium (Cd) A rare element in the environment, cadmium is normally found in natural water at concentrations below 10 ug/L. A major source for its presence is electroplating plants or zinc galvanized iron in which cadmium is a contaminant. Effects of its ingestion by humans has been associated with renal arterial hypertension, cardiovascular disorders, and the Itai-itai disease syndrome (with ingestion of as little as 600 ug/d). On the basis of information available it is recommended that concentrations in public water supplies not exceed 10 ug/L and 50 ug/L in water consumed by livestock (NAS, NAE, 1974).

Calcium (Ca) In most natural waters calcium is the principal cation. It is an essential constituent of igneous-rock minerals. Some calcium is to be expected in waters which have been in contact with igneous or metamorphic rocks, but in low concentrations. It is more commonly present in sedimentary rock, especially the carbonates. Its solubility in water is essentially controlled by the carbon dioxide partial pressure. Calcium and magnesium are the major contributors to hardness in natural waters.

Chemical oxygen demand (COD) Chemical oxygen demand is a measure of oxygen equivalent to that portion of the organic matter in a sample that is susceptible to oxidation by a strong chemical oxidant. It is determined by the dichromate reflux method in the presence of silver sulfate which is added as a catalyst. Sample preservation requires acidification with sulfuric acid which may cause the loss of light-weight organics. Unpolluted streams have COD values of about 10-30 mg/L.

Chloride (Cl^-) Chloride is present in most surface streams but its concentration is usually less than sulfate or bicarbonate. Chloride ions do not significantly enter into oxidation or reduction reactions, form no important solute complexes, do not form salts of low solubility, are not significantly adsorbed on mineral surfaces and play few vital biochemical roles. The circulation of chloride ions in the hydrologic cycle is largely through physical processes. Investigations have shown that chloride ions moved with water through most soils tested with less retardation or loss than any of the other tracers tested including tritium. However, the behavior should not be expected where movement is through compacted clay or shale. Human activities might be a major factor in chloride circulation.

Chromium (Cr) Chromium is a relatively common element, but the chromate $(CrO_4)^{-2}$ and dichromate $(Cr_2H_7)^{-2}$ forms probably are not found except in polluted waters. Both of these species are apparently relatively stable in ground-water environments. Recommended concentrations in public water supplies should not exceed 50 ug/L of total chromium (NAS, NAE, 1974). It has been found in shales at concentrations between 15-700 ug/kg and in limestone and dolomite at concentrations from less than 1 ug/kg to 150 ug/kg (Connor and Shacklette, 1975).

Coliform bacteria, fecal Fecal coliform bacteria are present in the intestine or feces of warmblooded animals. They are often used as indicators of the sanitary quality of the water. In the laboratory they are defined as all organisms which produce blue colonies within 24 hours when incubated at 44.5°± 0.2°C on M-FC medium (nutrient medium for bacterial growth). Their concentrations are expressed as number of colonies per 100 mL of sample. The nonfecal members of the coliform group survive longer than the fecal components. Therefore, the confirmation of members of the fecal coliform group may be used as an indicator of recent pollution. The NAS, NAE (1974) has recommended that the geometric mean of the fecal coliform densities should not exceed 2,000/100 mL of sample in raw surface waters.

Coliform bacteria, total Coliform bacteria are a particular group of bacteria that are used as indicators of possible sewage pollution. They are characterized as aerobic or facultative anaerobic, gram-negative, nonspore-forming, rod-shaped bacteria which ferment lactose with gas formation within 48 hours at 35°C. In the laboratory these bacteria are defined as all the organisms which produce colonies with a golden-green metallic sheen within 24 hours when incubated at 35°C ± 0°C on M-Endo medium (nutrient medium for bacterial growth). Their concentrations are expressed as number of colonies per 100 mL of sample. These groups of bacteria are also found in soils, thus reducing their significance as indicators of sewage pollution. In raw surface waters, it has been recommended that the geometrical mean of total coliform densities should not exceed 20,000/100 mL of sample (NAS, NAE, 1974).

Color A numerical value determined by comparison of the color of waters to an arbitrary standard of appropriate tint. The U.S. Geological Survey reports hues by comparison with that of colored disks which have been calibrated to correspond to the platinum-cobalt scale of Hazen (1892). Samples with turbidity are first centrifuged to remove suspended particulates. Color is expressed in units which go from one to several hundred. Waters with values below 10 are practically transparent; waters which drain from swamps or bogs have values of about 300.

Contaminant A contaminant is that which on coming into contact with something (water) will make it impure or unfit for use.

Cyanide (CN^-) Cyanide is a constituent of many compounds or complex ions that may be present in industrial wastes. Inorganic cyanide compounds, such as potassium cyanide (KCN) and sodium cyanide (NaCN) are used extensively in metal plating operations. The organic compounds are known as nitrides. Toxicity of cyanides varies widely with pH, temperature and dissolved oxygen concentrations. It is recommended that the concentration for cyanide should not exceed 5 ug/L at any time in order to protect aquatic life (NAS, NAW, 1974).

Dissolved oxygen (DO) Dissolved oxygen is the concentration of oxygen present in water in its uncombined gaseous form, O_2. Oxygen is essential for the higher forms of aquatic life and the oxidation of organic matter in water. Low DO values are indicative of stressed systems subject to high organic loading or respiration. It is recommended that the minimum DO concentration should not be lower than the seasonal natural minimum (NAS, NAE, 1974).

Iron (Fe) Iron is among the most abundant and widespread constituents of rocks and soils and is commonly responsible for their red or yellow color. A flowing stream at or near neutral pH even when grossly polluted, cannot contain at equilibrium a significant amount of uncomplexed ferrous (Fe^{+2}) iron. It is normally present as particulate ferric hydroxide (Fe_2OH_3) or as some form of organic complex. Water that is naturally colored often is rather high in iron. Ground waters with pH between 6 and 8 may be sufficiently reducing to carry as much as 50 mg/L ferrous iron at equilibrium where HCO_3- activity does not exceed 61 mg/L. This type of water is clear when drawn from the well but becomes cloudy and then brown from precipitated ferric hydroxide. Generally, ground waters high in dissolved iron can be associated with oxidation of reduced iron minerals at a regional or local contact between oxidizing and reducing conditions.

Landfill A landfill is the area in which garbage or rubbish is disposed of by burying it under a shallow layer of earth.

Landfill, sanitary An area for the disposing of refuse on land without creating a nuisance or hazard to public health or safety, utilizing the principles of engineering to confine the refuse to the smallest practical area, to reduce it to the smallest practical volume, and to cover it with a layer of earth at the conclusion of each day's operation, or at such more frequent intervals as may be necessary (American Society of Civil Engineers, 1959).

Leachate Leachate is water which has percolated through solid waste, carrying with it soluble and suspended substances.

Lead (Pb) Its main form in natural waters is lead found in the carbonate or sulfate forms, both of which have very limited solubilities, probably about 2 ug/L. Surface-water samples from 130 sites in the United States of America had a mean concentration of 23 ug/L. The main lead input into the environment may be from leaded gasoline. In surface soils it has been found in concentration from less than 7 ug/kg to 700 ug/kg (Connor and Shacklette, 1975). Recommended concentration in public water supplies should not exceed 50 ug/L, and 100 ug/L in natural waters consumed by livestock (NAS, NAE, 1974).

Loam Soil composed of clay, sand and some organic matter is loam.

Magnesium (Mg) In most natural waters magnesium is present in concentrations much lower than calcium. Its abundance in rocks is substantially below that of calcium. It is typically a constituent in mineral species such as montmorillonite and serpentine. In carbonates such as dolomite it is present in equal amounts with calcium and in the solution process equal amounts of the two ions will dissolve. Water that is near or above saturation may lose some calcite by precipitation, so that the water attains a concentration of Mg greater than that of Ca.

Manganese (Mn) Among the most common elements, manganese is widely distributed in rocks and soils. Reduction by organic material and bacteria may bring into solution considerable amounts of manganese from oxides present in soil and rock. Soluble Mn, present as manganous ion (Mn II) will appear prior to iron, present as ferrous ion (Fe II) upon progressive lowering of the oxidation potential in the water of an aquifer. Extensively used in steel production. Salts of manganese are used in inks and dyes, glass and ceramics, matches and fireworks, dry cell batteries, paints and varnishes. In contact with air, soluble manganese is precipitated as manganic oxide (MnO), which makes it improbable for it to be found at toxic levels in surface waters.

Mercury (Hg) Mercury is widespread in the environment as a result of wide industrial and agricultural uses. A recent survey showed that 93 percent of U.S. streams and rivers contained less than 0.5 ug/L of dissolved mercury. Concentration in soils has been reported as high as 4.6 ug/kg (Connor and Shacklette, 1975). Alkyl compounds of mercury are the most toxic to man. It is recommended that concentration of total mercury in public water supplies should not exceed 2 ug/L (NAS, NAE, 1974).

Nickel (Ni) Nickel is present as a constituent in many ores, minerals, and soils, particularly in serpentine-rock-derived soils. Used in corrosion resistant materials, long-lived batteries, electrical contacts, spark plugs, and electrodes. Salts of nickel are used for dyes, in ceramic, fabric, and ink manufacture. Nickel ions are toxic particularly to plants, and may exhibit synergism when present with other metallic ions.

Nitrogen forms Nitrogenous compounds are found throughout the aquatic environment principally in four different forms: organic, ammonia, nitrite, and nitrate nitrogen.

The organic nitrogen is one of the main components of living tissues, in amino acids and proteins. Its presence in water is indicative of pollution. In domestic wastewaters up to 80 percent of the total nitrogen may be organic.

Ammonia nitrogen (NH_4) is produced from the breakdown of organic nitrogen by bacteria and enzymes. More than 0.1 mg/L of NH_4-N usually indicates pollution (Brown and others, 1970). Its presence in water may be physiologically significant to man or livestock. Ammonia is noxious to most aquatic organisms even in low concentrations. In solution, its toxicity is dependent on the pH of water. The NAS, NAE (1974) has recommended that NH_4-N concentrations should not exceed 0.02 mg/L at any time or place.

Nitrite nitrogen (NO_2-) is an intermediate stage in the nitrogen cycle. NO_2- is very unstable, oxidizing into nitrate. The principal source of NO_2- in raw waters is from partially treated wastes from water treatment plants. Trace amounts of NO_2- may indicate organic pollution. No_2- is very toxic, producing fatal poisoning when at high concentrations. In drinking water supplies, NO_2-N concentrations should not exceed 0.30 mg/L.

Nitrate nitrogen (NO_3-) is the highest oxidation state in the nitrogen cycle. High nitrate concentrations occur in ground waters in farm areas. Upon ingestion in high concentrations, NO_3- is converted in the blood into NO_2^-, reducing the capacity of hemoglobin to transport oxygen. The illness (methemoglobinemia) is restricted to infants, and fatalities by oxygen suffocation have occurred. In public water supplies, NO_3-N concentrations should not exceed 2.3 mg/L (NAS, NAE, 1974).

pH The pH is a measure of the hydrogen-ion concentration, or more precisely, its activity (α). Most waters in Puerto Rico are slightly basic (pH greater than 7.0) ranging from 6.8 to 8.6. Toxic pH values depend on the specific conditions. It is recommended (NAS, NAE, 1974) that the normal range in pH value for a given freshwater environment should not vary by more than 0.5 units.

Phenols Hydroxy derivatives of benzene and its condensed nucleus are known as phenols. Concentrations of phenolic compounds are expressed as ug/L of phenol, C_6H_5OH. Phenolic compounds may exist with a bonded carboxyl, halogen, methoxyl or sulfonic acid group or with an alkyl, aryl, nitro, benzoyl, nitroso or aldehyde group. The sensitivity of the analytical test varies with the different phenolic groups present in a sample. For such reason the concentration found by analyses and expressed as phenol represents the minimum concentration present in a sample. It is recommended that public water supplies contain no more than 1 ug/L phenolic compounds (NAS, NAE, 1974).

Phosphorus forms Phosphorus is present in the environment both as organic and inorganic forms. In waters, orthophosphate (PO_4-P) is the most common ionized form. Together with nitrogen, phosphorus is one of the essential macronutrients for plant growth. The enrichment of natural waters with N and P induces rapid aquatic plant growth and nuisance algal blooms.

Pollutant A harmful chemical or waste material discharged into the water or atmosphere is a pollutant.

Potassium (K) Potassium is present in silicate rocks, minerals such as the feldspars, the micas, and the feldspathoid leucite. The potassium feldspars are very resistant to attack by water, but presumably are altered to silica, clay, and K^+ ions by the same process as other feldspars but only more slowly. Potassium exhibits a strong tendency to be reincorporated into solid weathering products, especially certain clay minerals. Concentrations of potassium more than a few tens of milligram per liter are decidedly unusual except in water with very high dissolved solids concentrations or in water from hot springs.

Selenium (Se) Selenium has been regarded as one of the dangerous chemicals reaching the aquatic environment. Used in photoelectric cells and other photometry uses. It occurs naturally in certain soils; in Puerto Rico it has been found in concentrations as high as 10 mg/kg in Yunes soils (Roberts, 1942).

Shale Shale is a fissile rock that is formed by the consolidation of clay, mud, or silt, has a fine stratified or laminated structure parallel to the bedding, and is composed of minerals that have been essentially unaltered since deposition.

Silt Silt is sediment particles having a size between 0.004-0.062 millimeters. Such particles are intermediate in size between sand and clay.

Sodium (Na) Sodium is the most common member of the alkali-metals. In igneous rock it is slightly more abundant than potassium, but in sediments sodium is much less abundant. There are no important precipitation reactions that can maintain low sodium concentrations in water in the way that carbonates precipitate calcium. Sodium is retained by adsorption on mineral surfaces when a high proportion of sodium to divalent cations exists, especially by those minerals with high cation exchange capacities such as clays.

Specific conductance A measurement of the ability of a solution to conduct an electric current is specific conductance. Its value increases with increasing concentration of ions in solution. Thus its value may be related to the concentration of dissolved solids. Unpolluted streams in Puerto Rico seldom exceed a specific conductance value of 400 umho/cm at 25°C.

Sulfate (SO_4^{-2}) Sulfate is not a major constituent of the earth's outer crust, but is widely distributed in reduced form in both igneous and sedimentary rocks as metallic sulfides. During weathering processes sulfide in contact with aerated waters yields the sulfate ion which is carried off. Sulfur is one of the main building blocks of proteins. During anoxic decomposition sulfide is produced but may be bonded with metallic ions, which are very insoluble.

Total organic carbon (TOC) TOC is a direct measure of the organic carbon constituents in water. Empirical relationships may be established between TOC, BOD and chemical oxygen demand (COD). TOC is usually lower than the BOD or COD. The TOC analysis is a convenient way of estimating other parameters that express the degree of organic pollution.

RECONNAISSANCE OF SIX SOLID-WASTE DISPOSAL SITES IN PUERTO RICO AND EFFECTS ON WATER QUALITY

by Fernando Gómez-Gómez

ABSTRACT

Five solid-waste landfills and an open burning dump were studied in Puerto Rico to obtain physical, chemical and biological data on leachates, give an overview of their pollution potential, and determine the adequacy of monitoring at these or similar sites. These sites are operated by the municipal governments of Arecibo, Caguas, Cayey, Humacao, Mayaguez and Guayama. The bulk of waste is of domestic origin but wastes from local industries and institutions are also handled. Data were collected between February and July 1976.

Parameters measured included temperature, specific conductance, pH, color, common ions, cyanide, macronutrients (nitrogen and phosphorus species), total organic carbon, dissolved oxygen, BOD_5 (biochemical oxygen demand), COD (chemical oxygen demand), total and fecal coliform, trace metals, and phenols.

The results obtained indicated that leachate from most sites is enriched in common ions, macronutrients, and trace metals. A sample obtained from runoff at the Cayey landfill was the only one with an acidic pH (5.8). It had a common ion concentration of 10,750 mg/L (milligrams per liter), or twice that found in leachate contained within the buried refuse. The leachate from the Caguas site had the highest common ion concentration (12,520 mg/L).

Maximum values for other parameters were as follows: Temperature, 33°C (or about 10°C above ambient ground-water temperature); specific conductance, 19,200 micromhos per centimeter; color, 2,200 units; cyanide, 30 ug/L (micrograms per liter); total nitrogen, 600 mg/L; total phosphorus, 4.3 mg/L; total organic carbon, 500 mg/L; 5-day biochemical oxygen demand, 5,540 mg/L; chemical oxygen demand, 3,000 mg/L; total coliform bacteria, 410,000 colonies per 100 milliliters; fecal coliform bacteria, 14,000 colonies per 100 milliliters; total arsenic, 54 ug/L; total cadmium, 15 ug/L; total chromium, 1,600 ug/L; total lead, 1,100 ug/L; total mercury, 2.6 ug/L; total nickel, 1,300 ug/L; and total phenols, 1,100 ug/L.

Pollution of water resources is limited to the periphery of the sites. A major problem throughout seems to be related to operating methods. Under the conditions found, large quantities of rainwater and runoff could be available for leachate production. Generation of leachate may not be significant at present probably because of the recent establishment of the landfills (less than 5 years).

Monitoring at these or similar sites in Puerto Rico can be limited to defining present baseline water-quality conditions and implementation of a sampling program. Baseline data could be limited to specific conductance, pH, color, common ions, and dissolved oxygen. A scheduled sampling program could be limited to specific conductance readings and measurement of concentration of bicarbonate, chloride, and dissolved oxygen.

RECONOCIMIENTO DE SEIS VERTEDEROS DE DESPERDICIOS SOLIDOS EN PUERTO RICO Y EFECTOS EN LA CALIDAD DE AGUAS

RESUMEN

Se estudiaron cinco rellenos sanitarios y un vertedero con quemado al aire libre en Puerto Rico de febrero a julio de 1976 para obtener datos sobre la composición física, química y biológica de jugos de lixiviación, hacer una evaluación somera del potencial de contaminación de aguas que éstos representan y ver la factibilidad de monitoría en estas operaciones y otras parecidas en la isla. Se incluyeron en el estudio los vertederos operados por los municipios de Arecibo, Caguas, Cayey, Humacao, Mayaguez y Guayama. Los desperdicios recibidos en estos son principalmente de origen doméstico, aunque también provienen algunos de industrias e instituciones locales.

Los datos obtenidos incluyen temperatura, conductividad específica, pH, color, iones comunes, cianuro, macronutrientes (nitrógeno y fósforo), carbón orgánico total, oxígeno disuelto, demanda bioquímica de oxígeno (BOD5), demanda química de oxígeno (COD), bacterias coliformes totales y fecales, metales pesados y fenoles.

Se encontró que los jugos de lexiviación tienden a tener un pH neutro. En Cayey una muestra de escorrentía del relleno sanitario fue el único caso con pH ácido (5.8). La muestra tenía una concentración de iones comunes de 10,750 miligramos por litro (mg/L). La concentración de iones comunes más alta se halló en aguas percoladas del relleno sanitario de Caguas, 12,520 mg/L.

Los valores máximos de otros parámetros fueron los siguientes: temperatura 33°C (esto representa aproximadamente 10°C sobre la temperatura de aguas suberráneas del ambiente); conductividad específica, 19,200 micromhos por centímetro; color, 2,200 Pt-Co (unidades de platino-cobalto); cianuro, 30 ug/L (microgramos por litro); nitógeno total, 600 mg/L; fósforo total, 4.3 mg/L; carbón orgánico total, 500 mg/L; BOD_5, 5,540 mg/L; COD, 3,000 mg/L; coliformes totales, 410,000 colonias por 100 mililitros; coliformes fecales, 14,000 colonias por 100 mililitros; coliformes fecales, 14,000 colonias por 100 mililitros; arsénico total, 54 ug/L; cadmio total,15 ug/L; cromio total, 1,600 ug/L; plomo total, 1,100 ug/L; mercurio total, 2.6 ug/L; niquel total, 1,300 ug/L; fenoles totales, 1,100 ug/L.

La contaminación de los recursos de aguas por estos vertederos al presente es mínima. Esto puede deberse al hecho de que no llevan más de cinco años de existencia dichos rellenos sanitarios. No obstante bajo las condiciones actuales, apreciables cantidades de lluvia y escorrentía podrían estar disponibles para la producción de jugos de lixiviación.

La monitoría de estos vertederos u otros parecidos en la isla podría limitarse a: (1) definir las condiciones actuales de la calidad de aguas adyacentes al predio e (2) implementar un programa de tomar muestras. En la primera los datos necesarios podrían limitarse a conductividad específica, pH, color, iones comunes y oxígeno disuelto. En la segunda, los datos adquiridos podrían limitarse a lecturas de conductividad específica y medidas de la concentración de bicarbonato, cloruros y oxígeno disuelto.

INTRODUCTION

Solid-waste disposal by landfill procedures will lead to deterioration of surface and ground water if not properly managed. Various reports (Hughes and others, 1971, Funagaroli, 1971, and Kimmel and Braids, 1975) have demonstrated the increase of inorganic constituents in ground water affected by landfills. In another investigation the presence of industrial chemicals (as many as 40) was detected within a landfill in which industrial wastes were basically absent (Robertson and others, 1974). This indicated that their origin was probably the leaching of finished commercial and domestic products which were part of the refuse loads.

Purpose and Scope

The U.S. Geological Survey in cooperation with the Puerto Rico Environmental Quality Board conducted an investigation of six solid-waste disposal sites between February 1 and June 30, 1976. The objective was to make a reconnaissance for a group of chemicals which may be leached from solid-waste disposal sites and analyze the adequacy of monitoring for these sites. Table 1 lists the parameters monitored during the investigation.

Five active landfill sites and one open burning dump were investigated. These are the municipal refuse disposal sites of Arecibo, Caguas, Cayey, Humacao, Mayaguez and Guayama (open burning dump). Observation wells were installed at Arecibo, Cayey, Humaco, Mayaguez and Guayama.

Leachates and Ground-Water Flow

The migration of pollutants is determined by the physical and chemical properties of the substance and the local hydrogeologic conditions. At many sites underlain by silts and clay, the diffusion of chemicals is retarded by fixation, complexation, filtration, adsorption and the ion exchange capacity of such formations. Unfortunately, such subsurface soil conditions are not found at many sites or are interlaced by bands of more permeable soils. Such isolated more permeable strata or solution channels in relatively impermeable limestone formations may cause leachate to be detected at a site farther from a landfill than at sites near it. The range of permeability which may be expected within different soil classes is shown in table 2.

An understanding of ground-water movement is necessary in evaluating the water-flow system which may be affected by a landfill. For many areas the general flow direction may be determined from the regional or local topography. If the aquifer is shallow, ground-water movement essentially follows a line perpendicular to the topographic contours. At other areas where a permeable material extends relatively deep below the water table, a third flow component, the vertical axis must be considered. A hypothetical ground-water flow system (fig. 1), which may exist in the mountainous interior of Puerto Rico, is a good representation of such conditions.

Table 1.--Parameters tested for at sampling sites.

I. Physical characteristics

    1. Temperature
    2. Ground-water level and (or) surface flow
    3. Specific conductance
    4. Color
    5. pH

II. Common ions

    1. Cations

        a. Calcium, magnesium, sodium, potassium, iron, and manganese

    2. Anions

        a. Chloride, sulfate, and bicarbonate

III. Cyanide

IV. Nutrients

    1. Nitrogen series

        a. Organic nitrogen, ammonia, nitrate, and nitrite

    2. Phosphorus series

        a. Orthophosphorus and total phosphorus

V. Organic carbon

VI. Oxygen series

    1. Dissolved oxygen
    2. Biochemical oxygen demand (5-day BOD)
    3. Chemical oxygen demand

VII. Sanitary quality

    1. Total and fecal coliform bacteria (membrane filter technique)

VIII. Trace metals

    1. Arsenic, cadmium, chromium, lead, mercury, nickel, and selenium

IX. Phenols

Table 2.--Comparison of permeability and representative aquifer materials.

PERMEABILITY

Centimeters per day

10^6	10^5	10^4	10^3	10^2	10	1	10^{-1}	10^{-2}	10^{-3}

RELATIVE PERMEABILITY

Very high	High	Moderate	Low	Very low
Representative materials				
Clean gravel	Clean sand and sand and gravel	Fine sand	Silt, clay and mixtures of sand, silt and clay	Massive clay
Vesicular and scorioceous basalt and cavernous limestone and dolomite		Clean sandstone and fractured igneous and metamorphic rocks	Laminated sandstone shale, mudstone	Massive igneous and metamorphic rocks

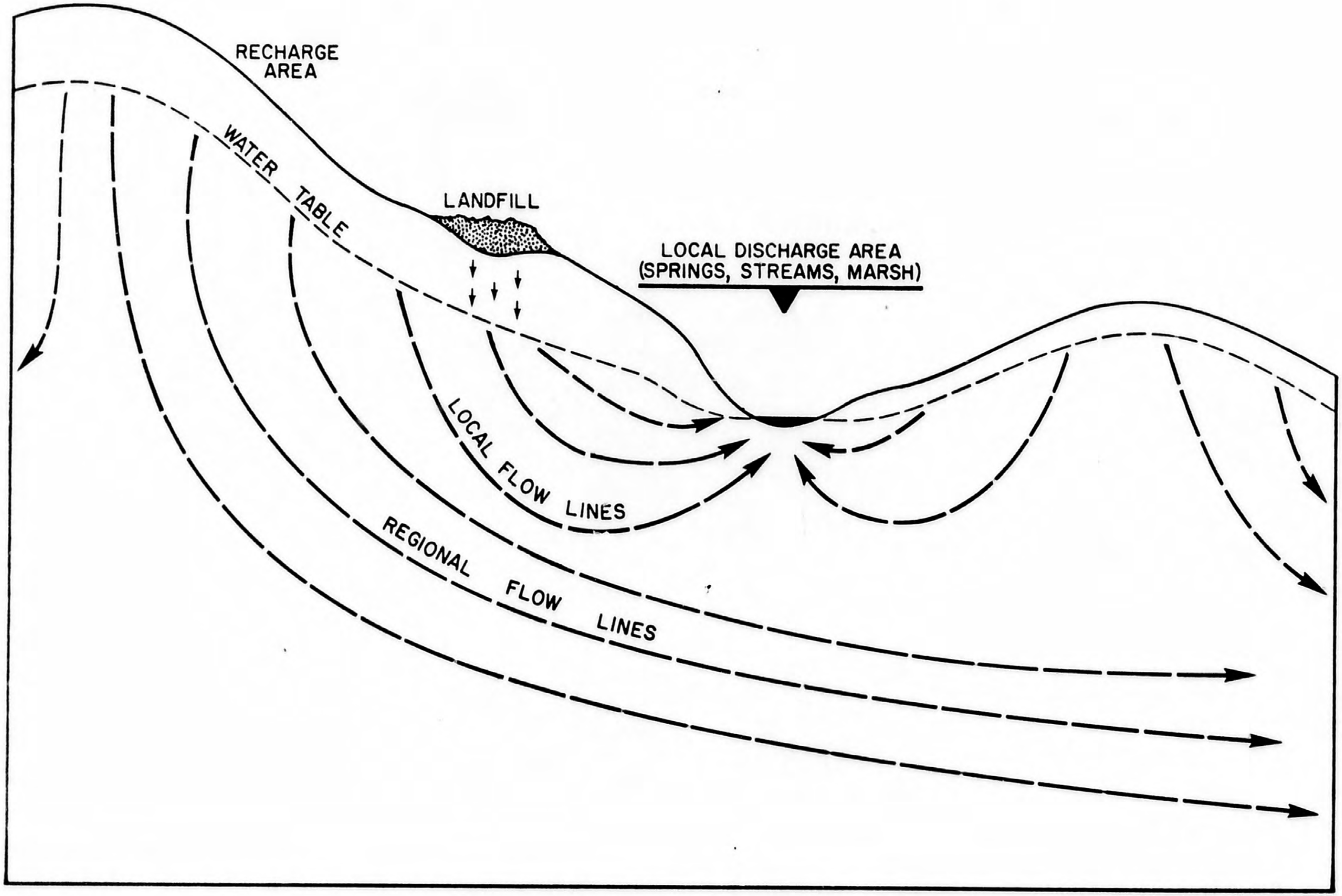


Figure 1.--Hypothetical ground-water flow system.

If a landfill is located within a local recharge area on hilly terrain, pollutants may not be detected at a monitoring well installed near the base of the site if flow lines emerging from the landfill are not intercepted by the well. Therefore, local surface features may give an insight into the probable flow direction of leached substances, but a detailed hydrologic study is necessary to define the distribution of ground-water flow lines. For most landfills such detailed studies may not be economically feasible. In its place a monitoring of water quality at streams, springs, marsh, or water-supply wells downgradient from the disposal site can often indicate leachate movement and flow direction.

METHODS AND TECHNIQUES

Construction of Observation Wells

Wells were drilled with a motorized auger, using 7.62-cm diameter drill bits. Casing consisting of 5.18-cm plastic pipe was installed the full depth of the well. An infiltration section of the pipe for the collection of liquid consisted of drilled 0.63-cm holes along a given segment of the casing. Due to the low permeability material expected at most sites (silt and loam), a plugged collection section was left below the infiltration segment of the casing to collect sufficient liquid for analyses within the short study period. A typical well design is shown in figure 2, and details of each observation well installed are shown in table 3.

Observation wells were bailed with a bailer after construction. This procedure was not very effective in removing the loose sediments which accumulated within the plastic casing, and most samples had considerable turbidity. Thus the analytical results may be interpreted as maximum available concentrations of a given constituent at the observation well site. For surface sampling points, the problem of turbidity by disturbed sediments was not significant.

An attempt was made to classify the soil series encountered at each site. Roberts' (1942) soil survey maps were used in identifying these. A description of the soil for each waste-disposal site follows. Details of the location of each observation well are given in other sections of the text.

Arecibo

Material at the three well sites consists of a sandy clay loam (tuffaceous, brown, plastic) possibly of the Martín Peña series. A dark reddish soil was encountered below the 1-m depth only at well No. 3; this soil is possibly of the Vega Alta series.

Cayey

Material consists of buried refuse; a cement-colored saturated mixture was encountered below the 2.5-m depth. This may possibly be a water-table mound. The original soil cover in the area is a light olive-brown clay loam,

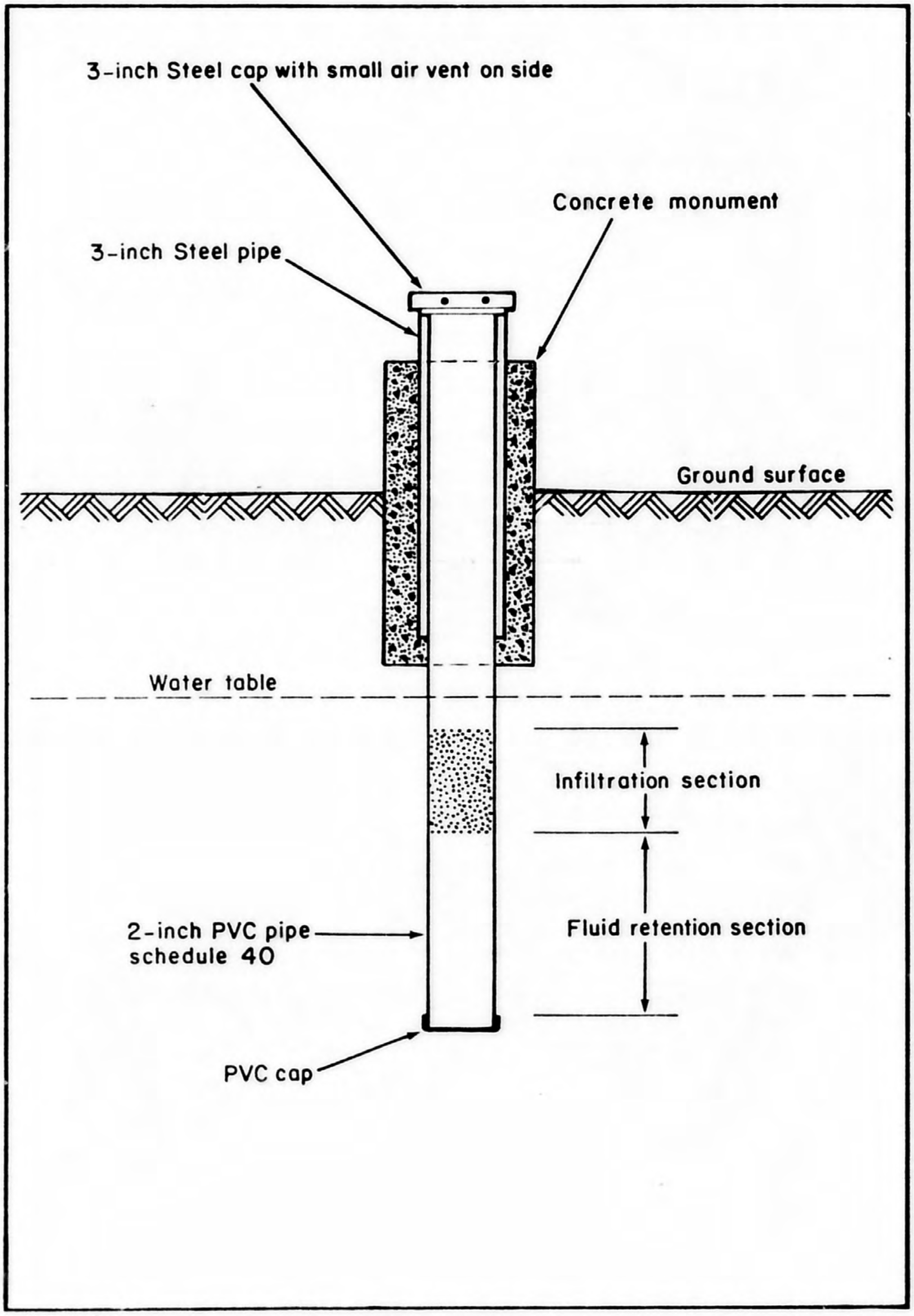


Figure 2.--Section showing typical observation well construction design.

Table 3.--Design characteristics for each observation well installed during the reconnaissance.

Site	Date installed	Depth of casing	Uncased zone	Depth to water table
		Meters below land surface		
Arecibo W1	2-19-76	5.0	0.46-1.98	0.5
Arecibo W2	2-20-76	5.1	.31-1.83	.3
Arecibo W3	2-20-76	4.5	.15-1.22	.2
Cayey W1	3-2-76	7.6(2)	2.13-3.65	2.4(1)
Humacao W1	3-19-76	5.6	1.22-2.44	.5
Humacao W2	3-19-76	3.2	.61-1.22	.5
Mayaguez W1	2-27-76	10.7(2)	6.86-9.91	4.7
Mayaguez W2	2-26-76	9.0	--	30 (3)
Guayama W1	3-25-76	10.8	9.14-10.05	9.0

(1) Water-table mound within fill

(2) Open bottom

(3) Estimated; test drilling abandoned

slightly sticky, possibly of the Naranjito series. The soil used for continuous cover of refuse is an olive-colored friable shale which is slightly plastic when wet.

Humacao

Material in the upper 1.0 m of both wells consists of a gray plastic clay soil, possibly of the Palmas Altas series. Below this layer, a light brown subsoil, with fragments of igneous rock, was encountered. Igneous rock (possibly the bedrock) was found at the bottom of site W2 and at a test hole about 5 m east of W2.

Mayaguez

Material at W1 consists of a reddish friable soil to a depth of about 5 m; below this layer was a pale yellow, clayey and slightly sandy soil contained within the water table. At W2 the entire bore material (9.0 m) consists of the same reddish friable soil, possibly of the Catalina clay series. The water table was not reached and may lie at about 30 m below ground surface. This estimated depth exceeds the auger capability; therefore, drilling was not continued.

Guayama

Material consists of a dry loose soil, coarse sand, gravel and cobbles. The surface soil at this site is classified as San Antón loam shallow phase, which are moderately fine-textured sediments over coarse sand and gravel derived from volcanic rocks. Igneous bedrock was encountered at the bottom the hole.

Sampling and Analytical Procedures

Measurements of temperature and specific conductance were made in the well or stream at each sampling point. It was found that in observation wells with a sealed lower catchment section as shown in figure 2, the specific-conductance value was slightly higher in the top of the water column than in the lower section. In wells with open bottom ends, specific-conductance values were higher at the lower section of the water column. For complete chemical analyses at each point about 8 liters of sample had to be collected. In observation wells the bailed volume was first homogenized in a plastic bucket and from this the specific conductance, pH, and alkalinity measurements (reported for the sample) were obtained.

Dissolved oxygen readings were made with a probe at wells and in highly colored leachate samples. The modified (Standard Methods) Winkler technique was used for surface samples in which organic coloring or turbidity were low.

AREA DESCRIPTION

Climate

Puerto Rico is within 17°53'N and 18°30'N latitudes, thus lying within the tropics. In general the temperature and relative humidity are high throughout the year. The annual mean island temperature is about 76°F, being somewhat cooler in the mountainous areas and hotter on the coasts. Relative humidity may vary considerably on a given day between the north and south coasts, but in general lies within 75 percent for the major part of the island.

The greatest climatological difference exists in the precipitation distribution and frequency. Annual rainfall on the island ranges from a high of 5,000 mm in the peaks of El Yunque rain forest (rain gage operated by the National Weather Service at 1,067 m elevation) to less than 750 mm in the semiarid southwest corner. Figure 3 shows the long-term annual mean precipitation distribution. This figure was prepared from data tabulated by the National Weather Service (Climatolography of the U.S., Bulletin No. 81, by State) using 30-year data covering the period 1941-1970, at 41 stations.

Rainfall may be the principal external factor affecting leachate production and translocation at landfills. Its magnitude and frequency are important parameters since an area may infiltrate much more rainfall if it falls in intensive showers throughout the year than in a distributed pattern. Figures 4 and 5 show the percent of days in a year a given area receives rainfall amounts of 2.54 mm or more, and 12.7 mm or more. Thus, from these figures it can be seen that although the Arecibo, Caguas, Cayey, Humacao and Mayaguez landfills receive on the average between 1,500-2,000 mm of rainfall per year, a significant difference exists when comparing rainfall intensities. These diagrams may also be helpful on an islandwide basis because even though refuse may be buried within the unsaturated zone, sufficient moisture may be maintained for extended periods to leach substances into the water table.

Geology

The central core of Puerto Rico consists largely of volcanic and intrusive rocks of late Cretaceous and early Tertiary age. The volcanic rocks are predominately ashy shale, agglomerate and tuff, and most of them are thoroughly indurated. These rocks are interbedded with thick dense lava flows of marine origin and relatively thin beds of limestone which have been partly recrystalized in many places. The volcanic rocks and interbedded limestones have been complexly faulted, folded, metamorphosed and intruded by dioritic rocks. The massive, dense dioritic intrusions are exposed by erosion in two large areas and many small areas in the island. Massive, dense serpentinite and associated silicified rocks, reported to be the oldest rocks in Puerto Rico (Mattson, 1960, p. 324), underlie large areas in the southwestern part of the island.

The complex central core of Puerto Rico is flanked on the north and south by clastic sediments and limestones of Oligocene and Miocene age. The older

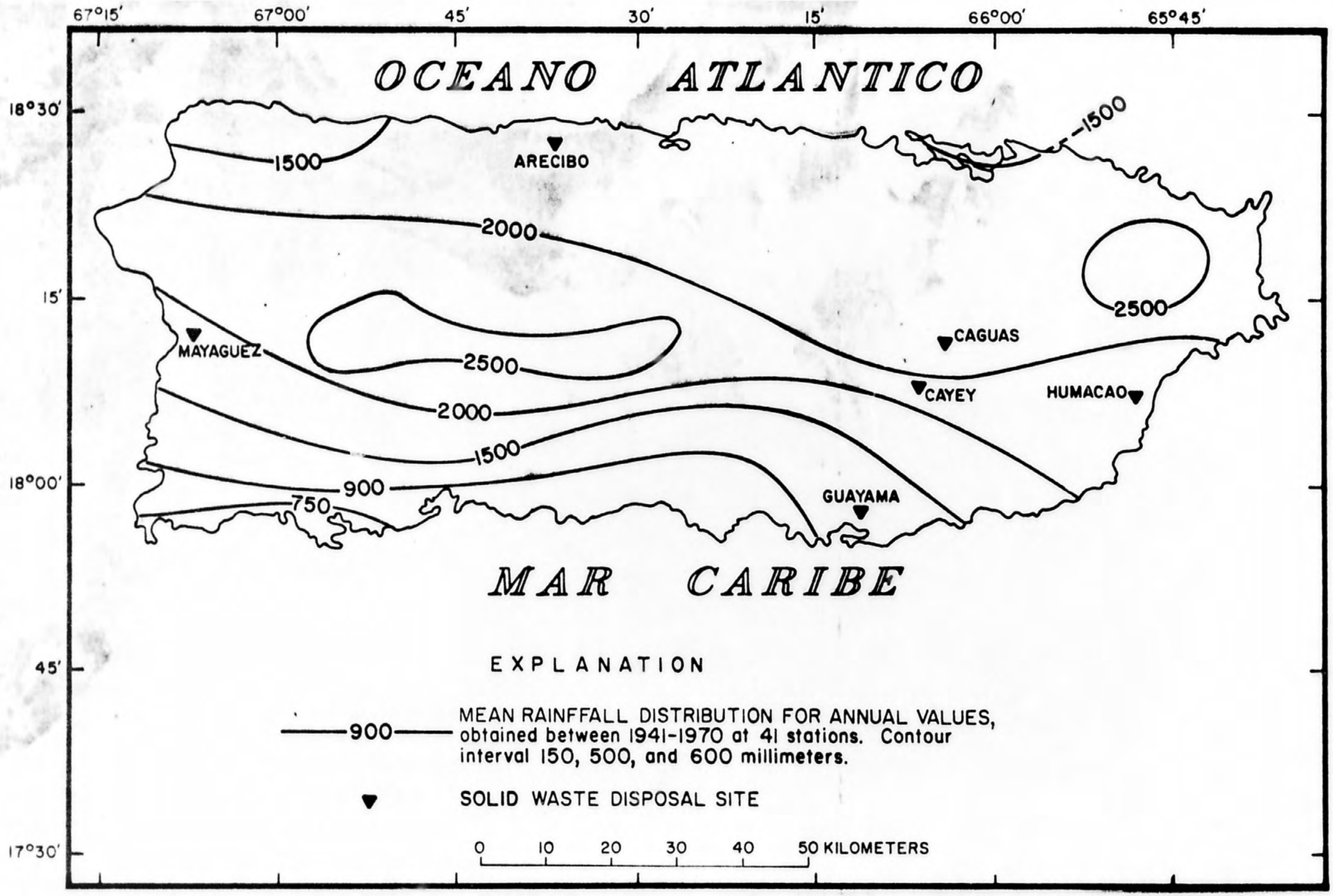


Figure 3.--Mean annual rainfall distribution and solid waste disposal site locations.

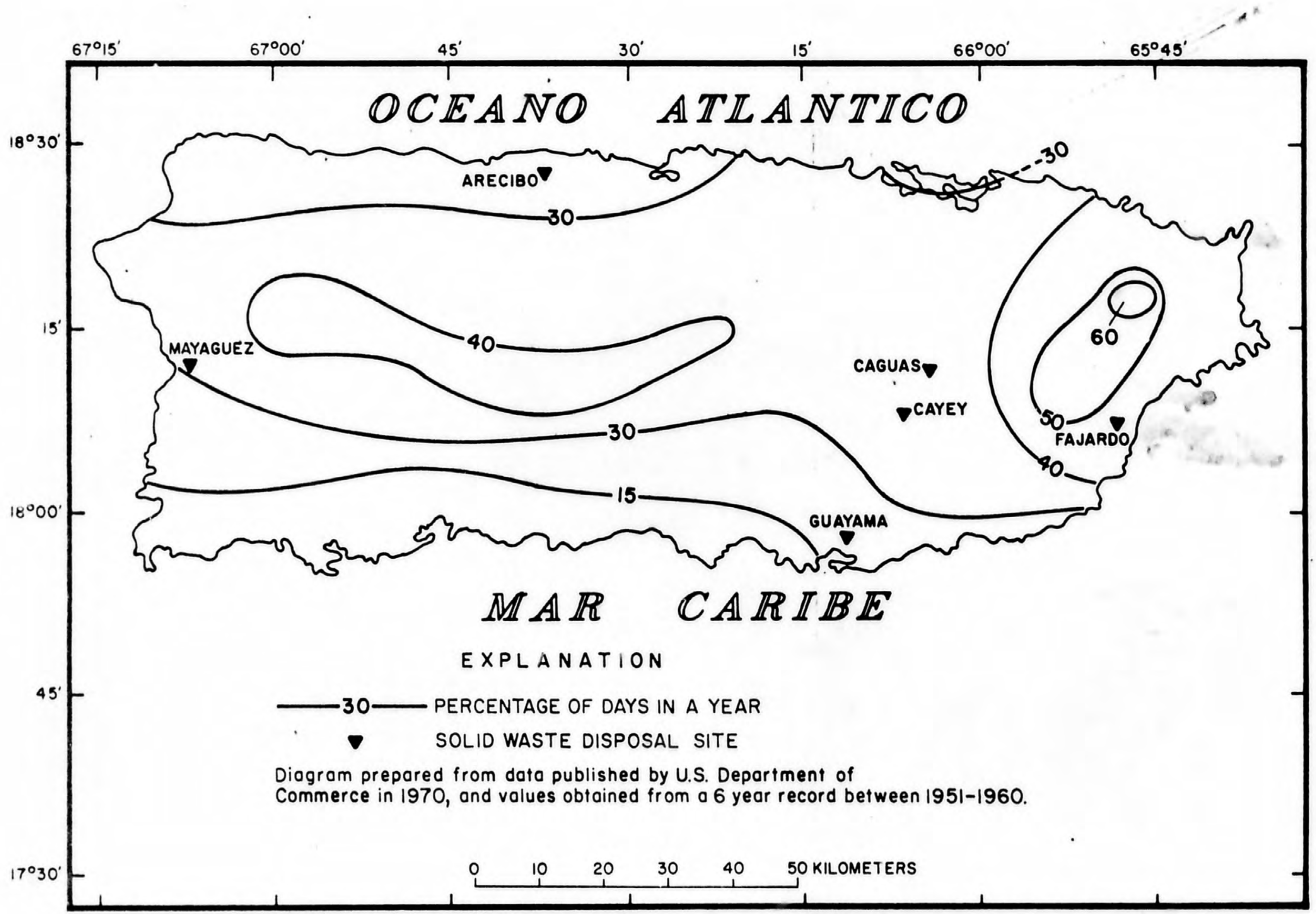


Diagram prepared from data published by U.S. Department of Commerce in 1970, and values obtained from a 6 year record between 1951-1960.

Figure 4.--Percentage of days in a year with rainfall amounts equal to or greater than 2.54 millimeters.

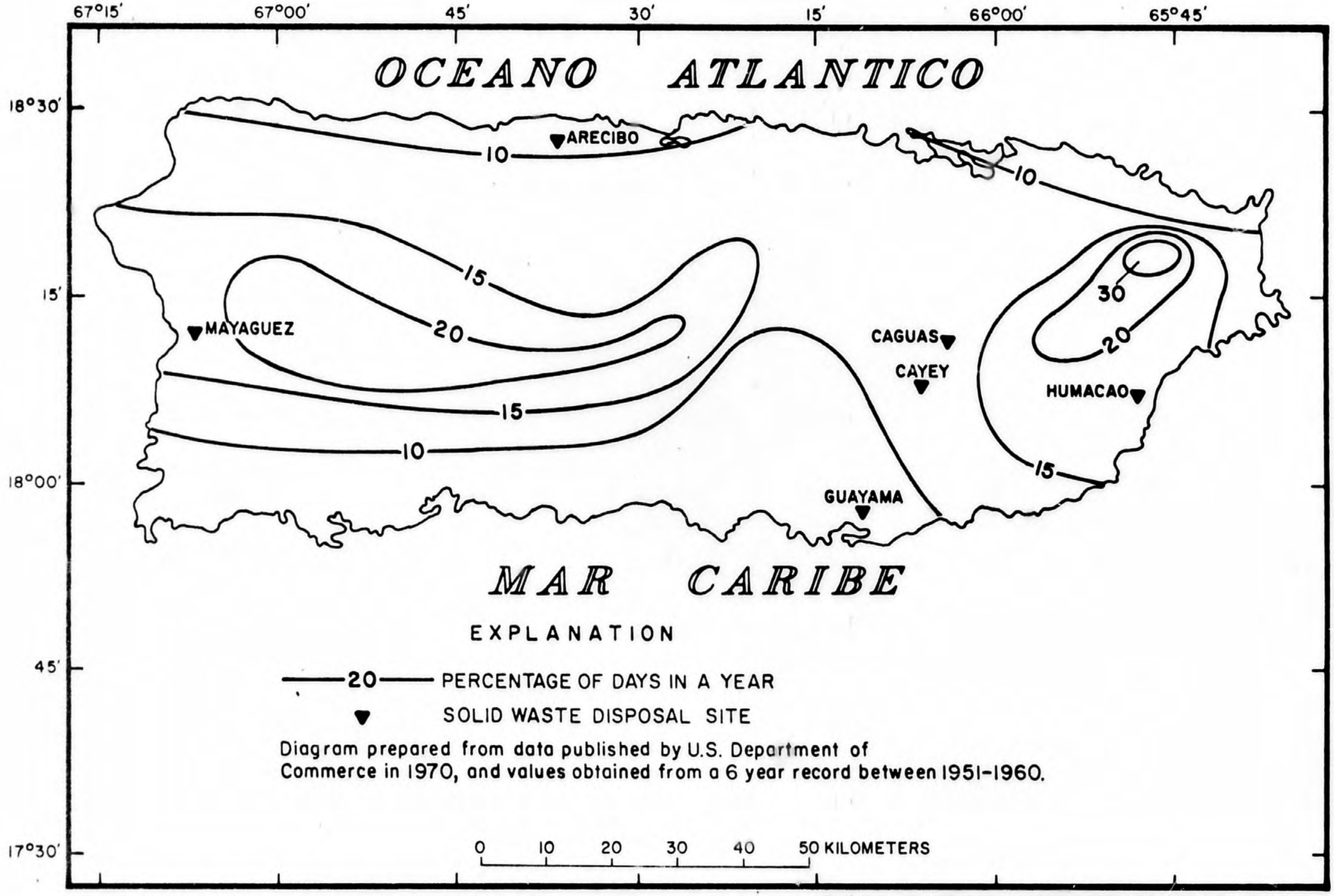


Diagram prepared from data published by U.S. Department of Commerce in 1970, and values obtained from a 6 year record between 1951-1960.

Figure 5.--Percentage of days in a year with rainfall amounts equal to or greater than 12.7 millimeters.

clastic sediments are predominately poorly sorted mixtures of gravel, sand, and finer materials. They grade upward, however, into thick beds of relatively pure limestone. The limestones have been subjected to extensive solutional activity which, on the north coast, has resulted in the formation of a mature karst topography.

Many of the river valleys, particularly on the north and west coasts, contain thick deposits of alluvium. In addition, an extensive blanket of alluvium along the south coast forms a plain which averages 3 to 4 miles wide and is about 40 miles long. Figure 6 shows the distribution of the main geologic formations in Puerto Rico (Meyerhoff, H. S., 1933).

Study Sites

Arecibo

Figure 7 shows the Arecibo landfill, sample sites and general features. This landfill was established in 1974 and lies near the southern boundary of a former marine slough, Caño Tiburones. As of completion of this investigation (June 1976), approximately 11 were in active use. Wastes are disposed of by excavation of trenches with a bulldozer. After trenches have been filled, the area method is used. These procedures are described in detail by Brunner and Keller (1972). Trench excavation is limited to a depth not greater than 2 meters, because of the shallow water table which lies at most places within the 2-meter depth. No weight scales exist at the site, but it is estimated by the P.R. Environmental Quality Board that 167,200 kg/d of solid wastes are generated within the municipality. During the study it was observed that indescriminate zones within the lot were being used for refuse burial with no well defined pattern of site development.

Levels were run along a north-south axis traversing point A shown in figure 7 and connecting the water-surface elevations at Canal Sur, the three wells and the lateral drainage ditch. The results of these levels are shown in figure 8. The datum used is arbitrary, but point A was set as being at a 3-m elevation which may be near the real value.

This landfill lies within a ground-water discharge zone. The natural water-table depth may have been at or near the surface, but after the construction of the drainage network under the direction of the Puerto Rico Land Authority which began in 1907 (Díaz, 1973), it may have obtained a new equilibrium position equivalent to the water level in the lateral drainage ditch. Thus, it is highly improbable that pollution from the landfill will penetrate into the subsurface waters much deeper than the burial depth. Leached substances from the landfill will travel with the water-table gradient. As can be observed from the levels presented in figure 8, there is a mounding of the water table away from the lateral ditch near the observation wells. Also it can be observed that the water level in Canal Sur is about 1.5 m higher than at the lateral ditch, but the land surface at the southern boundary of the landfill is above such elevation. Thus, if considerable increase of the water

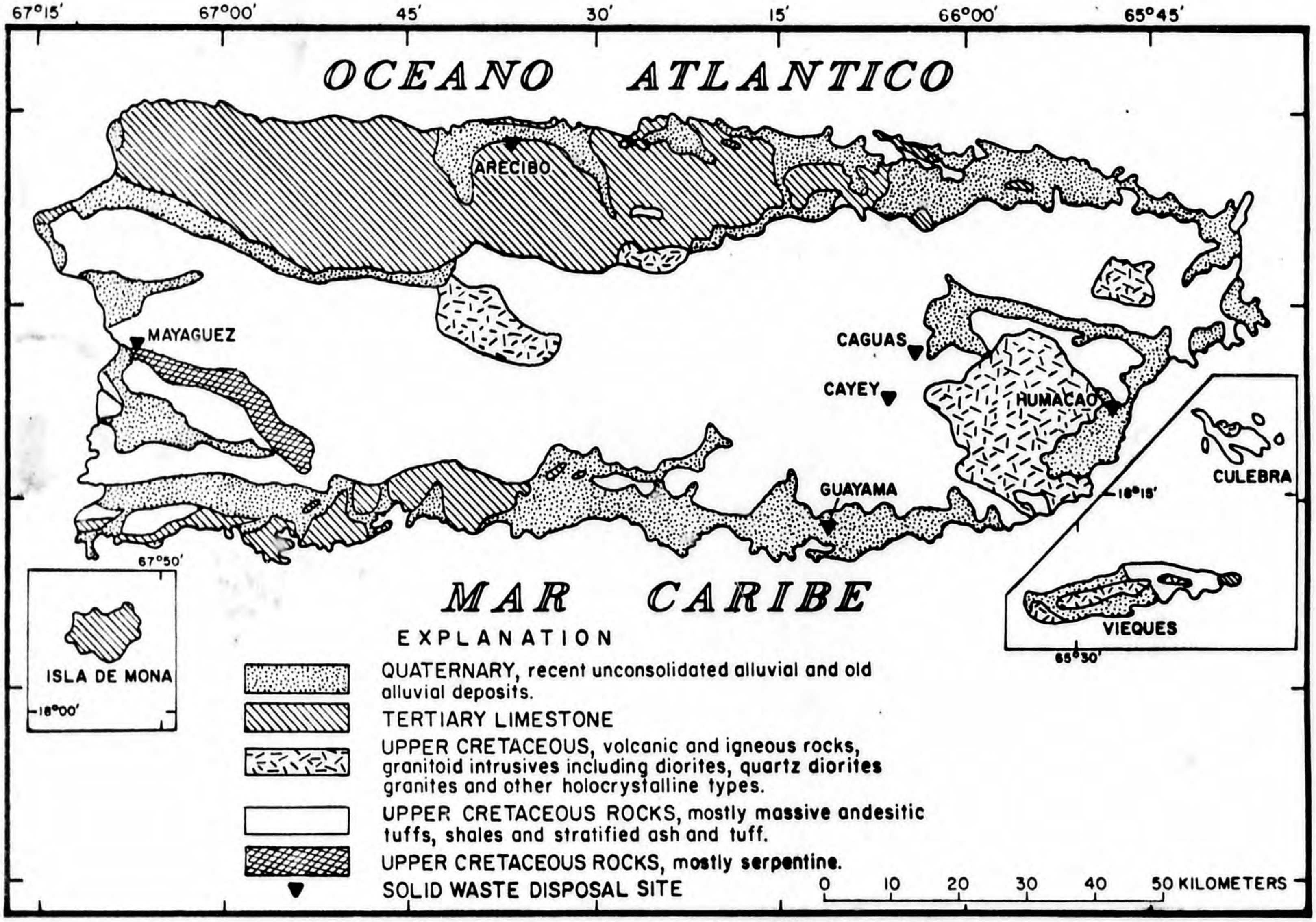


Figure 6.--Simplified geologic map of Puerto Rico and offshore islands.

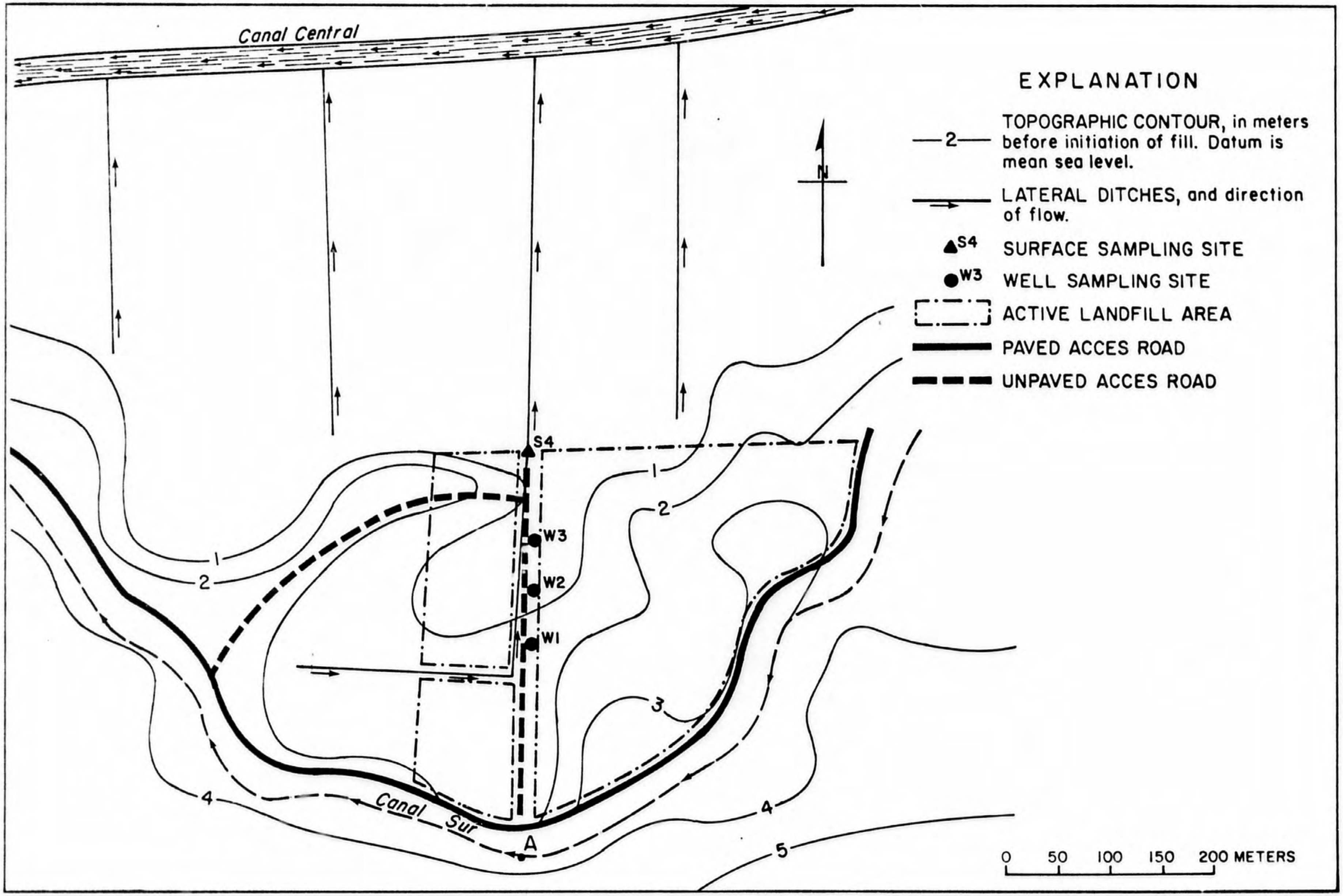


Figure 7.--Arecibo landfill, sampling sites, and general features.

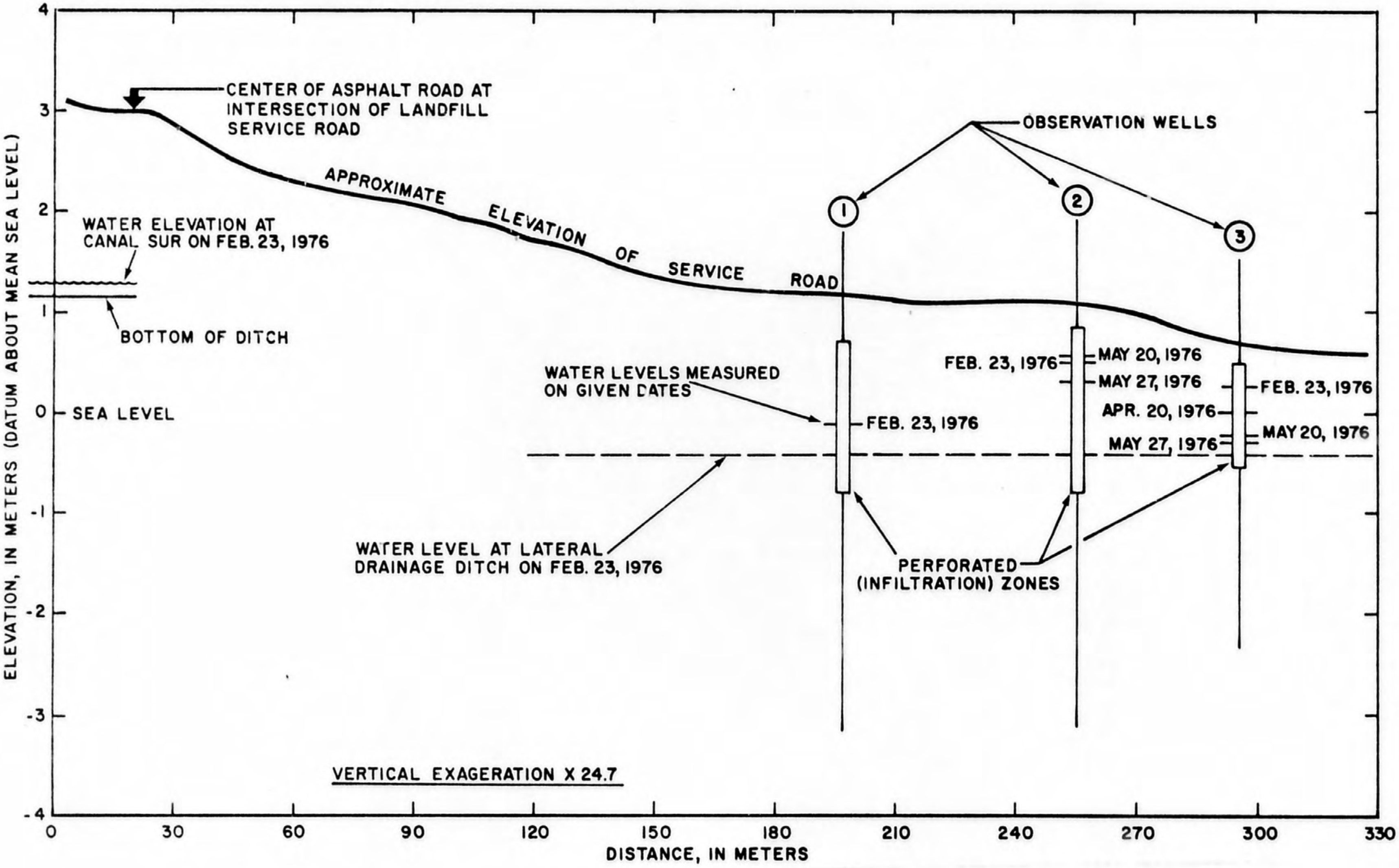


Figure 8.--Water levels at Arecibo landfill obtained February 23, 1976 and later dates.

table within the fill occurs, it may leach substances not only in the direction of the lateral ditch but also to Canal Sur. This canal serves to intercept storm runoff from land south of the Caño Tiburones area. During most of the year the water in the canal is intercepted ground-water flow.

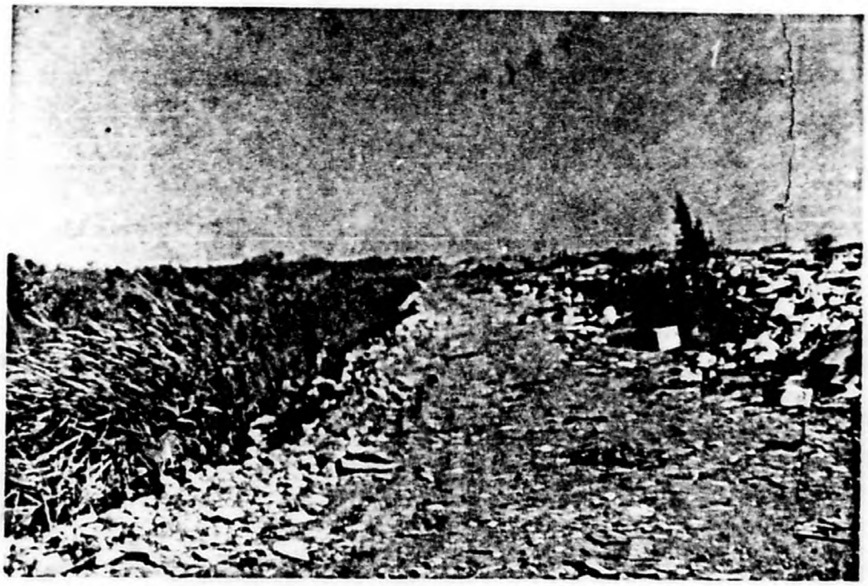
The absence of a drainage ditch along the entire perimeter of the landfill will enable subsurface flows to migrate in any direction instead of a south to north pattern, once the water table rises in the fill. Fortunately, rain in this area seems to fall in quantities below 2.54 mm in any given day as can be seen from figures 4 and 5. Potential evapotranspiration for this area is about 2,000 mm per year; thus, a major portion of the 1,500 mm mean annual precipitation in this area may be evaporated instead of being infiltrated through the buried wastes. Maintaining sufficient slope on the fill area will enhance runoff and reduce seepage of rainwater into the buried refuse.

Chemical data were obtained at observation wells W1 and W3 and at the north boundary limit of the landfill drainage ditch, site S4. The observation wells were installed along the edge of the active refuse-burial area. The following photographs (fig. 9) show the service road along which the wells were installed and a completed well. No water-quality data were obtained at observation well W1, for it was destroyed sometime previous to March 12, 1976. The data acquired are shown in tables 4, 5, and 6.

The significance of the data is rather limited because of lack of water-quality information at the specific site previous to waste disposal. In the reconnaissance study carried out by Díaz in 1967, the Caño Tiburones area was divided into four zones according to chloride concentration of waters at springs and surface flows (Díaz, 1973). By this classification the landfill is over a zone which until recently had waters containing less than 500 mg/L chlorides, but its northern boundary is within 350 m of a zone delineated by Díaz to contain waters with chlorides as much as 10,000 mg/L.

In essence, the water-quality data obtained at this landfill site reflect the history and present changes of the water environment. The relative abundance of anions reflects the fact that at W2 the water was previously fresh ($HCO_3>Cl_4>SO_4$) but is being enriched in chlorides, possibly from leachates or saltwater intrusion. Site W3 shows that it was previously in contact with seawater but has recently been affected by freshwater with the relative abundance of anions being SO4>Cl>HCO3. The chloride concentration is less than that of sulfate probably due to the higher solubility constant of chloride. At site S4 water is diluted seawater, as shown by its relative abundance of anions ($Cl>SO_4>HCO_3$).

The high concentrations of chromium at most sites deserve further investigation. Its source may be the soils and not the refuse. Possibly it is concentrated in organic substances with chelating capacities. At site W2 a filtered sample was tested for chromium showing a significant change from 110 ug/L unfiltered to 5 ug/L in the filtered sample. Samples were filtered at the laboratory, which may have permitted complexation of the chromate into a



Service road at Arecibo landfill, looking north, prior to installation of observation wells. Wells were installed along right edge of raod. Drainage canal, along left side, is covered with cattails (January 1976).

View of observation well W3 at Arecibo landfill (May 1976).

Figure 9.--Photographs of a well installation area (top), and completed observation well (bottom).

Table 4.--Physical, chemical, and bacteriological data of Arecibo landfill at site W2.

PARAMETER		DATE (month, day, year)		
		3-12-76	5-20-76	5-27-76
Time, hours		1200	1300	1200
Temperature, in degrees Celsius		--	29.0	27.5
Water depth, meters		0.5	0.5	0.7
Specific conductance, micromhos/cm at 25°C		1200	1200	1300
pH, units		6.9	7.0	7.2
Color, platinum-cobalt		--	--	20
Calcium	Cations, milligrams per liter (mg/L)	--	--	150
Magnesium		--	--	10
Sodium		--	--	83
Potassium*		--	--	3.3
Iron, micrograms per liter (ug/L)		--	--	34,000
Manganese (ug/L)		--	--	440
Chloride*	Anions (ug/L)	--	170	190
Sulfate*		--	81	91
Bicarbonate		--	299	311
Cyanide (mg/L)		--	--	.00
Organic nitrogen	Nitrogen species as nitrogen (mg/L)	--	--	1.0
Ammonia nitrogen		--	--	.19
Nitrate		--	--	.08
Nitrite				
Orthophosphate	As phosphorus (mg/L)	--	--	.01
Total phosphorus		--	--	.05
Total organic carbon (mg/L)		--	--	1.0
Dissolved oxygen (mg/L)		--	--	.0
Biochemical oxygen demand, 5-day (mg/L)		43	30	30
Chemical oxygen demand (mg/L)		--	--	110
Total coliform	Colonies/100 milliliters	--	--	170,000
Fecal coliform		--	--	30,000
Arsenic	Trace metals (ug/L)	--	--	7
Cadmium		--	--	2
Chromium		--	--	110
Lead		--	--	20
Mercury		--	--	1.5
Nickel		--	--	26
Selenium		--	--	0
Phenols (ug/L)		--	--	9
Chromium* (ug/L)		--	--	5
Manganese* (ug/L)		--	--	70
Iron* (ug/L)		--	--	10
Selenium* (ug/L)		--	--	0

---

* Denotes concentrations for samples filtered through a 0.45-micron inert filter.

Table 5.--Physical, chemical, and bacteriological data of Arecibo landfill at site W3.

PARAMETER		DATE (month, day, year)		
		4-20-76	5-20-76	5-27-76
Time, hours		1100	1200	1300
Temperature, in degrees Celsius		26.0	25.0	27.0
Water depth, meters		.7	.9	1.0
Specific conductance, micromhos/cm at 25°C		2,250	2,280	2,500
pH, units		6.8	6.4	6.4
Color, platinum-cobalt		20	40	--
Calcium	Cations, milligrams per liter (mg/L)	230	210	--
Magnesium		61	55	--
Sodium		280	280	--
Potassium*		6.0	4.0	--
Iron, micrograms per liter (ug/L)		400,000	100,000	--
Manganese (ug/L)		4,500	3,200	--
Chloride*	Anions (ug/L)	380	400	370
Sulfate*		720	630	700
Bicarbonate		366	204	128
Cyanide (mg/L)		.00	.00	--
Organic nitrogen	Nitrogen species as nitrogen (mg/L)	1.4	1.3	--
Ammonia nitrogen		.38	.36	--
Nitrate		.02	.15	--
Nitrite		.01		--
Orthophosphate	As phosphorus (mg/L)	.01	.01	--
Total phosphorus		.58	.20	--
Total organic carbon (mg/L)		120	4.0	--
Dissolved oxygen (mg/L)		.0	.6	.0
Biochemical oxygen demand, 5-day (mg/L)		6.0	12	16
Chemical oxygen demand (mg/L)		77	37	--
Total coliform	Colonies/100 milliliters	10,000	30,000	140,000
Fecal coliform		290	600	14,000
Arsenic	Trace metals (ug/L)	48	54	--
Cadmium		0	0	--
Chromium		1,200	270	--
Lead		56	20	--
Mercury		.0	.1	--
Nickel		58	27	--
Selenium		--	--	0
Phenols (ug/L)		5	8	--
Chromium* (ug/L)		--	--	5
Manganese* (ug/L)		--	--	2,000
Iron* (ug/L)		--	--	3,300
Selenium* (ug/L)		--	--	0

* Denotes concentrations for samples filtered through a 0.45-micron inert filter.

Table 6.--Physical, chemical, and bacteriological data of Arecibo landfill at site S4.

PARAMETER		DATE (month, day, year)	
		5-20-76	5-27-76
Time, hours		1030	1330
Temperature, in degrees Celsius		30.0	30.0
Water depth, meters		0	0
Specific conductance, micromhos/cm at 25°C		3,500	4,800
pH, units		7.1	7.7
Color, platinum-cobalt		70	50
Calcium	Cations, milligrams per liter (mg/L)	190	190
Magnesium		60	86
Sodium		430	670
Potassium*		15	23
Iron, micrograms per liter (ug/L)		1,900	1,500
Manganese (ug/L)		1,700	1,000
Chloride*	Anions (ug/L)	590	1,300
Sulfate*		330	350
Bicarbonate		288	287
Cyanide (mg/L)		.00	.00
Organic nitrogen	Nitrogen species as nitrogen (mg/L)	.54	.71
Ammonia nitrogen		.05	.04
Nitrate		.08	.00
Nitrite			
Orthophosphate	As phosphorus (mg/L)	.01	.01
Total phosphorus		.02	.02
Total organic carbon (mg/L)		6.4	1.6
Dissolved oxygen (mg/L)		6.2	9.4
Biochemical oxygen demand, 5-day (mg/L)		4.5	12.0
Chemical oxygen demand (mg/L)		64	50
Total coliform	Colonies/100 milliliters	2,100	130,000
Fecal coliform		2,000	3,100
Arsenic	Trace metals (ug/L)	2	2
Cadmium		0	0
Chromium		<10	60
Lead		3	0
Mercury		.2	.5
Nickel		7	0
Selenium		--	0
Phenols (ug/L)		9	7
Chromium* (ug/L)		--	--
Manganese* (ug/L)		--	--
Iron* (ug/L)		--	--
Selenium* (ug/L)		--	--

* Denotes concentrations for samples filtered through a 0.45-micron inert filter.

precipitate. The chromium may also be retained in particulates larger than the filter 0.45 micron-pore diameter. Nevertheless, its presence in any form may make it available for translocation either physically, chemically or by biological actions. Concentrations averaging about 50 ug/L of arsenic at site W3 may be related to the peculiar substratum encountered at this site or an external input to the landfill.

The presence of coliform bacteria in observation well samples in such high numbers indicates pollution at these points. The presence of fecal forms also at the ditch may indicate migration of these from the landfill, or contribution by stray dogs and cows, or the hundreds of snowy egrets which were observed scavenging the exposed refuse.

Leachate production at this site is presently not significant as observed in samples. Production rate of leachate might be diminished by avoiding the formation of a water-table mound within the buried wastes. This could be achieved by giving the fill area sufficient slope to enhance runoff and by building a drainage ditch along the entire perimeter of the area.

Caguas

Figure 10 shows the Caguas landfill, sample points and general features of the area. A view of the landfill is shown in figure 11. This disposal site was established as an open burning dump in the late 1950's and was converted to a landfill about 1973. Presently it covers an area of about 2.9 ha and at places the covered refuse may be about 9 m deep. Wastes are disposed of by the area method. Soil cover is obtained from the site and consists of an olive-yellow friable shale. The rate of loading or soil cover used is not being recorded. Solid wastes generated in the municipality of Caguas have been estimated at 213,300 kg/day by the Puerto Rico Environmental Quality Board.

This landfill rests on a geologic formation consisting of Upper Cretaceous rocks; andesitic tuffs, shales, stratified ash and tuff (fig. 6). From the cuts made in the sides of the mountain to obtain fill, it appears that the substratum is very homogeneous. Hydrologically, the landfill lies within a ground-water recharge area. Rainwater may be able to percolate through the fill, penetrate the shale and be discharged at the creek. This seems to be occurring as the creek gains in specific conductance values beginning at a point approximately 500 m from road 7784. The natural base-line specific conductance at this creek seems to be about 400 umho/cm but when the water reaches road 7784 the specific conductance is about 1,200 umho/cm. The results of this specific conductance survey at the creek is shown in figure 12. The continuous gain in specific conductance indicates that ions enter the creek essentially from a nonpoint source. The only surface leachate flows found are at sampling sites S2 and S4.

An estimate can be made of the local ground-water flow system affected by the landfill. By drawing smoothed topographic contours of the region as shown

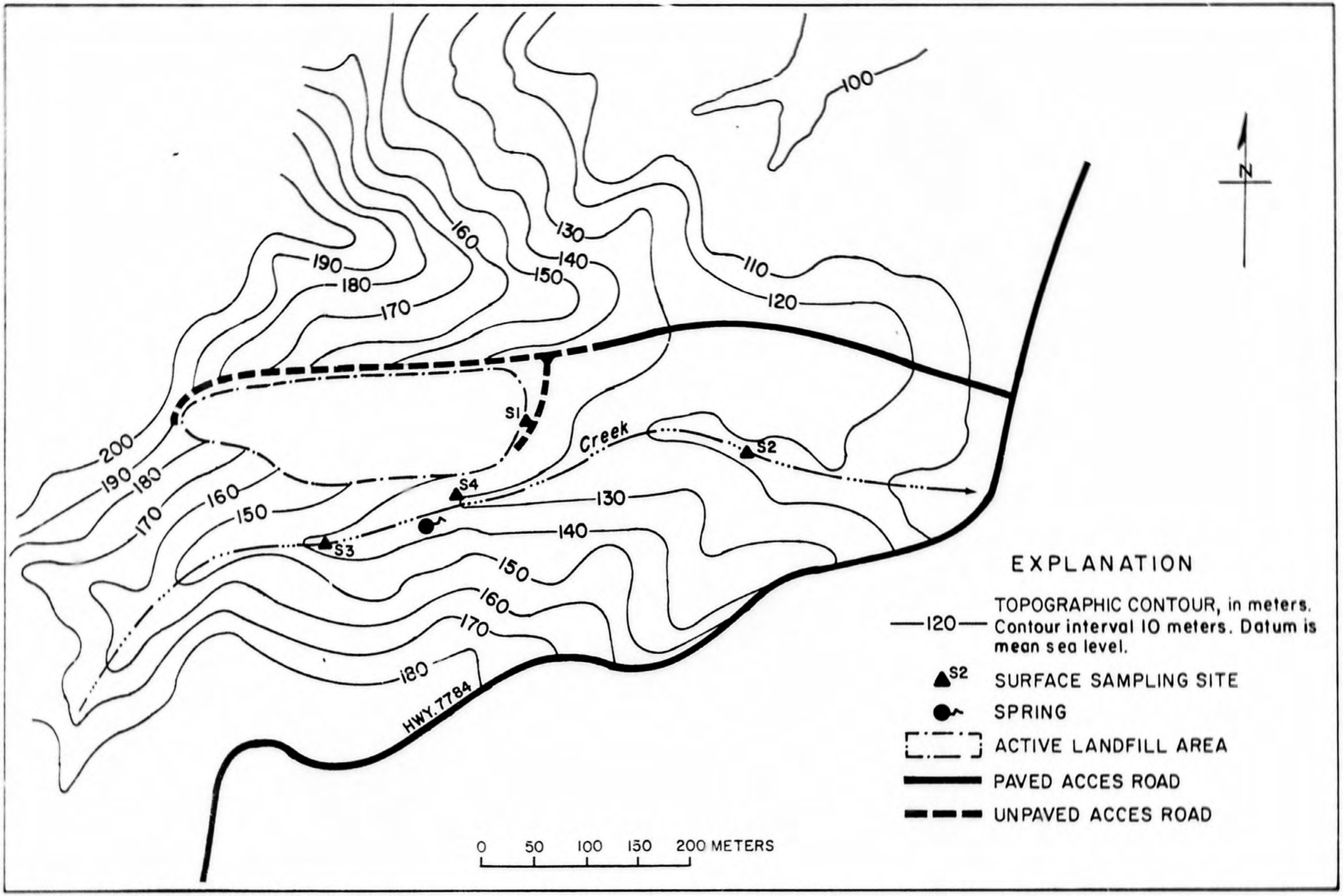


Figure 10.--Caguas landfill, sample sites, and general features.

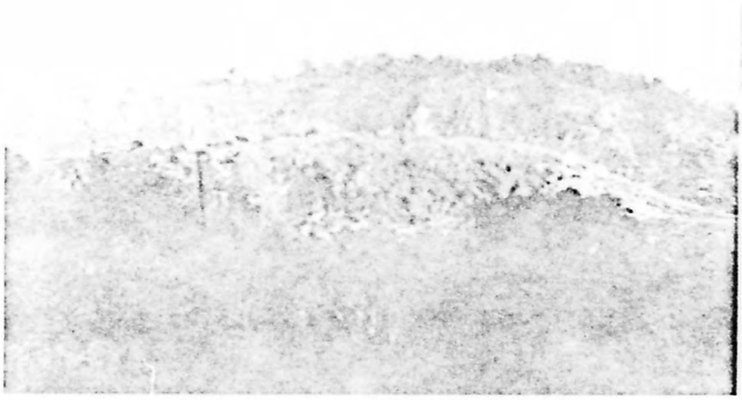


Figure 11.---Caguas landfill as seen from road 7784 (January 1976).

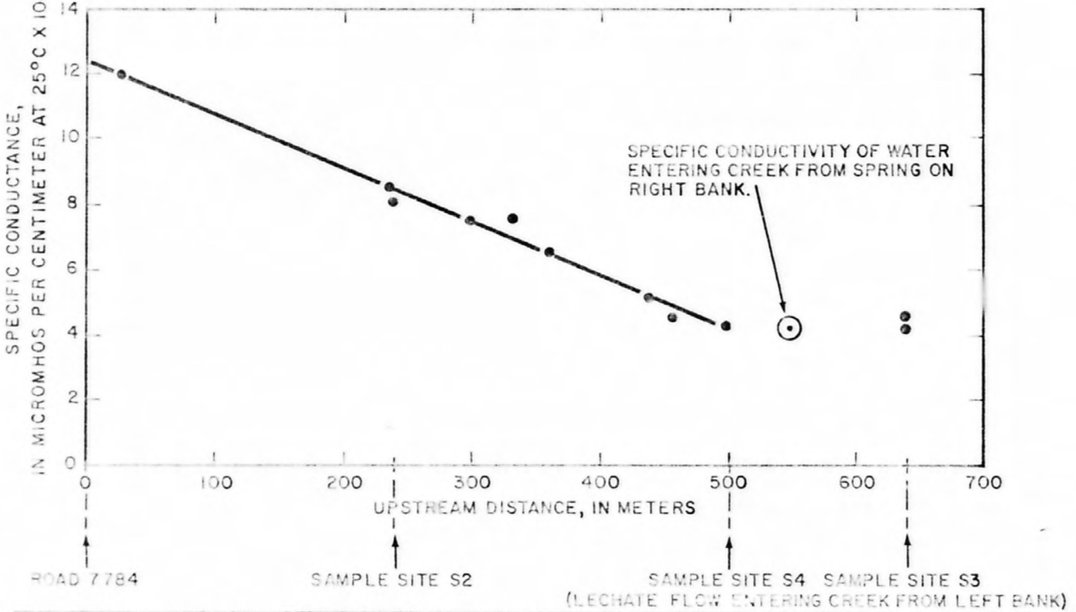


Figure 12.--Specific conductance readings along creek adjacent to Caguas landfill.

in figure 13, the horizontal ground-water movement direction can be estimated. The potential affected zone may also be obtained by drawing flow lines perpendicular to the smoothed topographic contours. To confirm if such pollution is occurring and its extent, observation wells would be needed to determine the ground-water depth and gradient, and also to obtain samples.

Data obtained during this investigation of the Caguas landfill are summarized in tables 7, 8, 9, and 10.

Samples from S4 may be representative of the leachate contained within the landfill. The samples are rich in almost all the chemical parameters tested and in effect are highly toxic. By far the greatest ion concentrations are sodium and chloride. Such excessive concentrations are not typical of domestic landfill leachates. The Cl:Na ratio of 1:2 at sites S2 and S4 indicate the source is well distributed and not a local concentration near S1.

Though the nitrogen concentrations at the creek leachate flow (site S2) were not determined, these should be within the same magnitude as at S4. The steady value of 13.7 mg/L NO_3 (3.1 mg/L as N) at the creek in site S1 indicates ammonia conversion to nitrate is occurring. This site also shows presence of phenolic compounds. Both contaminants are health hazards in drinking water. At present (1978) water from this creek is not a source of public supply, but is the source of water for livestock to adjacent farmers.

As with the Arecibo landfill, chromium in the filtered samples had a considerably lower concentration than the unfiltered ones. Nevertheless, their presence within the samples and especially in the leachates indicates that these may be bonded by organic compounds with chelating properties which make their translocations faster than if they existed in inorganic forms.

The high total and fecal coliform counts at all sites may originate from various sources. Within the creek the source may be stray dogs, rats, or livestock in the area.

Leachate production from this landfill possibly may be diminished by giving the fill area sufficient slope to enhance runoff during strong showers. At Caguas, potential evapotranspiration is about 1,600 mm per year. In practice, actual evapotranspiration within watersheds may be about 0.70 its potential. Assuming the same rate of evapotranspiration at the landfill site, then a maximum of about 780 mm of rainwater may infiltrate through the buried refuse during the year, or approximately 22,600 m^3. Based on visual observations during this study such estimates seem reasonable. This flow may be discharged as toe leachate or into the local ground water.

Actual quantitative analysis would involve measurements of the water table within the fill itself, collection of precipitation data, and construction of monitoring wells to obtain hydraulic data and ground-water samples, both upgradient and downgradient from the fill.

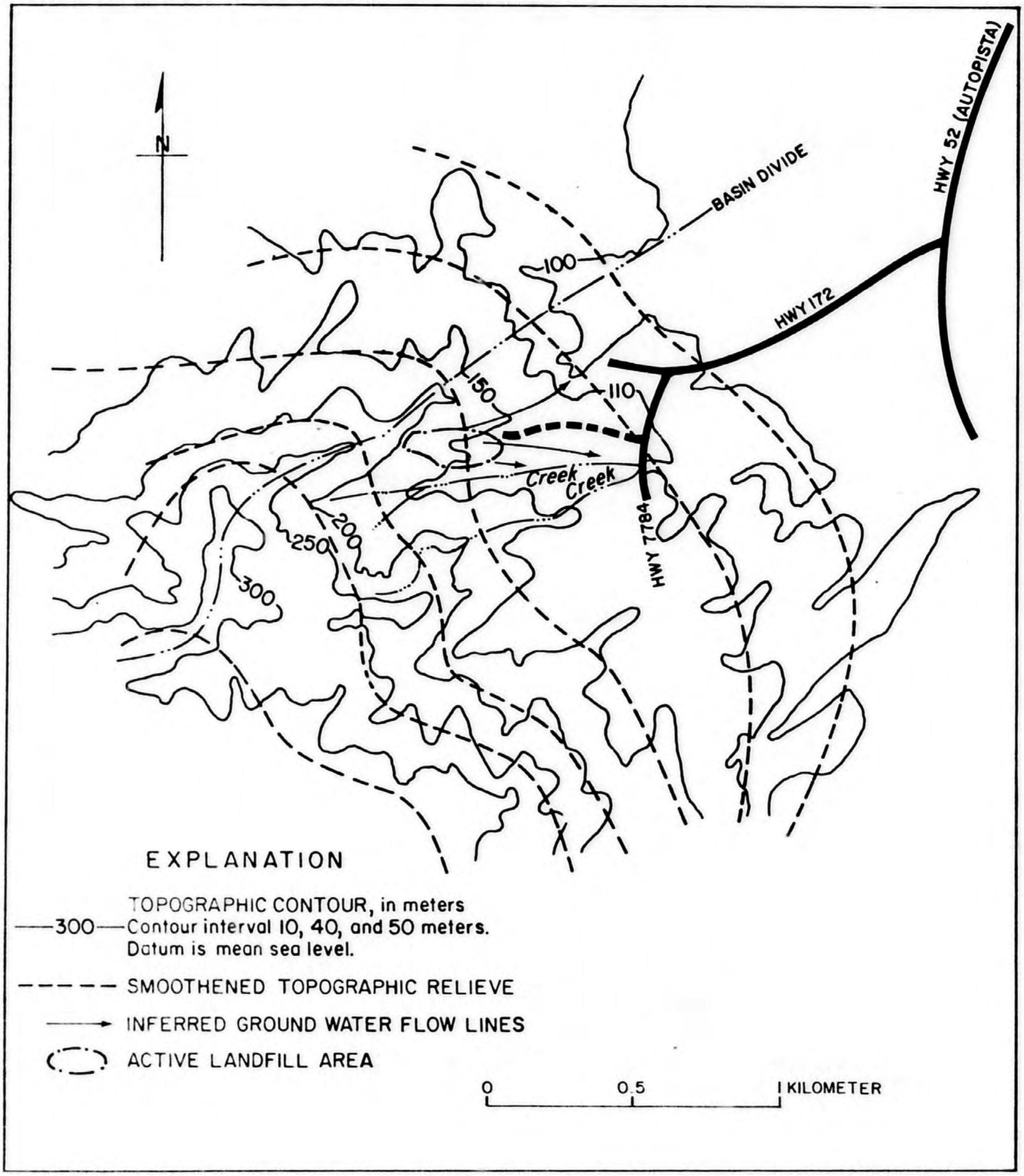


Figure 13.--General topographic contours in the vicinity of the Caguas landfill, and estimated ground-water flow lines.

Table 7.--Physical, chemical, and bacteriological data of Caguas landfill at site S1.

PARAMETER		DATE (month, day, year)	
		5-24-76	5-29-76
Time, hours		1430	1230
Temperature, in degrees Celsius		26.0	26.0
Water depth, meters		.03	.04
Specific conductance, micromhos/cm at 25°C		850	800
pH, units		7.7	7.7
Color, platinum-cobalt		40	30
Calcium	Cations, milligrams per liter (mg/L)	43	51
Magnesium		30	29
Sodium		67	67
Potassium*		6.5	6.0
Iron, micrograms per liter (ug/L)		470	250
Manganese (ug/L)		10	<10
Chloride*	Anions (ug/L)	130	130
Sulfate*		44	41
Bicarbonate		207	195
Cyanide (mg/L)		.00	.00
Organic nitrogen	Nitrogen species as nitrogen (mg/L)	1.16	.94
Ammonia nitrogen		.04	.00
Nitrate		3.1	3.1
Nitrite			
Orthophosphate	As phosphorus (mg/L)	.15	.09
Total phosphorus		.17	.10
Total organic carbon (mg/L)		9.6	2.5
Dissolved oxygen (mg/L)		6.8	7.6
Biochemical oxygen demand, 5-day (mg/L)		3.9	3.6
Chemical oxygen demand (mg/L)		30	25
Total coliform	Colonies/100 milliliters	32,000	8,500
Fecal coliform		1,250	900
Arsenic	Trace metals (ug/L)	0	0
Cadmium		0	0
Chromium		20	60
Lead		.0	.0
Mercury		.6	.4
Nickel		5	0
Selenium		--	0
Phenols (ug/L)		2	4
Chromium* (ug/L)		--	--
Manganese* (ug/L)		--	--
Iron* (ug/L)		--	--
Selenium* (ug/L)		--	--

* Denotes concentrations for samples filtered through a 0.45-micron inert filter.

Table 8.--Physical, chemical, and bacteriological data of Caguas landfill at site S2.

PARAMETER		DATE (month, day, year) 5-29-76
Time, hours		1215
Temperature, in degrees Celsius		31.0
Water depth, meters		.003
Specific conductance, micromhos/cm at 25°C		13,000
pH, units		7.8
Color, platinum-cobalt		--
Calcium	Cations, milligrams per liter (mg/L)	150
Magnesium		200
Sodium		2,000
Potassium*		370
Iron, micrograms per liter (ug/L)		1,700
Manganese (ug/L)		3,400
Chloride*	Anions (ug/L)	4,000
Sulfate*		46
Bicarbonate		756
Cyanide (mg/L)		--
Organic nitrogen	Nitrogen species as nitrogen (mg/L)	--
Ammonia nitrogen		--
Nitrate		--
Nitrite		--
Orthophosphate	As phosphorus (mg/L)	--
Total phosphorus		--
Total organic carbon (mg/L)		--
Dissolved oxygen (mg/L)		.0
Biochemical oxygen demand, 5-day (mg/L)		98
Chemical oxygen demand (mg/L)		1,200
Total coliform	Colonies/100 milliliters	300,000
Fecal coliform		6,000
Arsenic	Trace metals (ug/L)	--
Cadmium		2
Chromium		220
Lead		50
Mercury		.0
Nickel		260
Selenium		0
Phenols (ug/L)		--
Chromium* (ug/L)		--
Manganese* (ug/L)		--
Iron* (ug/L)		--
Selenium* (ug/L)		--

---

* Denotes concentrations for samples filtered through a 0.45-micron inert filter.

Table 9.--Physical, chemical, and bacteriological data of Caguas landfill at site S3.

PARAMETER		DATE (month, day, year)	
		5-24-76	5-29-76
Time, hours		1330	1100
Temperature, in degrees Celsius		25.0	23.0
Water depth, meters		.03	.05
Specific conductance, micromhos/cm at 25°C		430	410
pH, units		7.0	7.2
Color, platinum-cobalt		40	--
Calcium	Cations, milligrams per liter (mg/L)	32	36
Magnesium		24	22
Sodium		24	25
Potassium*		2.2	1.6
Iron, micrograms per liter (ug/L)		7,500	820
Manganese (ug/L)		230	50
Chloride*	Anions (ug/L)	35	38
Sulfate*		24	25
Bicarbonate		207	183
Cyanide (mg/L)		.00	--
Organic nitrogen	Nitrogen species as nitrogen (mg/L)	.94	--
Ammonia nitrogen		.06	--
Nitrate		.47	--
Nitrite			
Orthophosphate	As phosphorus (mg/L)	.11	--
Total phosphorus		.18	--
Total organic carbon (mg/L)		10	--
Dissolved oxygen (mg/L)		5.0	5.6
Biochemical oxygen demand, 5-day (mg/L)		4.4	4.2
Chemical oxygen demand (mg/L)		14	--
Total coliform	Colonies/100 milliliters	56,000	3,900
Fecal coliform		1,800	3,400
Arsenic	Trace metals (ug/L)	0	0
Cadmium		0	0
Chromium		10	60
Lead		5	0
Mercury		.1	.3
Nickel		12	0
Selenium		0	0
Phenols (ug/L)		4	--
Chromium* (ug/L)		--	--
Manganese* (ug/L)		--	--
Iron* (ug/L)		--	--
Selenium* (ug/L)		--	--

* Denotes concentrations for samples filtered through a 0.45-micron inert filter.

Table 10.--Physical, chemical, and bacteriological data of Caguas landfill at site S4.

PARAMETER		DATE (month, day, year)	
		5-24-76	5-29-76
Time, hours		1200	1400
Temperature, in degrres Celsius		31.5	32.0
Water depth, meters		.01	.02
Specific conductance, micromhos/cm at 25°C		19,200	17,000
pH, units		7.6	7.5
Color, platinum-cobalt		2,200	--
Calcium	Cations, milligrams per liter (mg/L)	150	280
Magnesium		290	380
Sodium		3,100	2,800
Potassium*		520	350
Iron, micrograms per liter (ug/L)		29,000	37,000
Manganese (ug/L)		2,200	28,000
Chloride*	Anions (ug/L)	6,000	5,900
Sulfate*		40	62
Bicarbonate		2,390	2,340
Cyanide (mg/L)		.01	.03
Organic nitrogen	Nitrogen species as nitrogen (mg/L)	110	--
Ammonia nitrogen		490	--
Nitrate		.16	--
Nitrite			--
Orthophosphate	As phosphorus (mg/L)	.30	.21
Total phosphorus		.46	.84
Total organic carbon (mg/L)		500	60
Dissolved oxygen (mg/L)		.0	.0
Biochemical oxygen demand, 5-day (mg/L)		80	150
Chemical oxygen demand (mg/L)		2,500	3,000
Total coliform	Colonies/100 milliliters	250,000	--
Fecal coliform		1,200	--
Arsenic	Trace metals (ug/L)	8	16
Cadmium		1	1
Chromium		110	210
Lead		180	170
Mercury		.0	.7
Nickel		110	280
Selenium		--	0
Phenols (ug/L)		150	130
Chromium* (ug/L)		--	1
Manganese* (ug/L)		--	2,100
Iron* (ug/L)		--	2,600
Selenium* (ug/L)		--	--

* Denotes concentrations for samples filtered through a 0.45-micron inert filter.

Cayey

Figure 14 shows the Cayey landfill, sample points and general features. This landfill has an area of about 0.8 ha. It has been in operation from about 1971. No records are kept on refuse loading or amount of fill used. Puerto Rico Environmental Quality Board estimates indicate this municipality to be generating about 83,700 kg/day of refuse. Solid wastes are disposed of by the area method as seen in figure 15. Soil cover used consists of an olive-yellow friable shale similar to that at the Caguas landfill.

This landfill lies in the same geologic formation as is found at Caguas. The basic difference is that this site rests directly in a ravine where maximum depth of fill may be as much as 20 m.

It appears that water filtering through the fill has created a groundwater mound within the buried wastes. Water-table data from observation well W1, drilled within the fill, shows the water level to lie between 2.5 and 3.5 m deep. During this reconnaissonce there was a continuous decline of the water level within the water-table mound until late May (fig. 16). The water table within the landfill dropped about 1 m, yet no toe leaching existed at the site. This may indicate the discharge zone could be the marsh area south of Highway 52.

Chemical quality data obtained at a spring, shown as S2 in figure 14, tends to confirm a ground-water system at this site somewhat similar to that shown in figure 1. A general view of the local ground-water flow direction could be obtained by drawing smoothed topographic contours as was done for the Caguas landfill. The estimated ground-water flow pattern is shown in figure 17. The regional discharge zone is Quebrada Beatriz. Because the Cayey landfill lies near the discharge zone, future ground-water contamination may be limited to a small area.

Data obtained during this investigation at the Cayey landfill are shown in tables 11, 12 and 13. A large portion of the soluble solids (anions and cations) seem to be washed away in surface runoff at Cayey as can be observed from a surface leachate sample at site S3. Unfortunately, no sample was obtained at site S3 when this flow was higher, following a local intensive shower on March 4.

Chemical parameters that were higher in the Cayey leachate at W1, in comparison with the Caguas toe leachate samples were the BOD_5 results, although the COD values were lower. This is probably an indication that the Cayey W1 samples represent wastes with a higher content of light-weight organics. These were probably volatized from the COD run sample on acidification. Within the fill the anaerobic decomposition of wastes seems to be highly active as temperatures were about 33°C, or 12°C above the mean ambient temperature. Samples from W1 were also relatively high in Fe and Mn, but filtered samples were lower in concentration by two orders of magnitude. It is probable that these are retained in organic compounds unable to filter through the 0.45-micron membrane

Table 11.--Physical, chemical, and bacteriological data of Cayey landfill at site W1.

PARAMETER		DATE (month, day, year)		
		4-14-76	4-29-76	5-28-76
Time, hours		1200	1200	1100
Temperature, in degrees Celsius		--	32.5	33.0
Water depth, meters		3.2	3.	3.3
Specific conductance, micromhos/cm at 25°C		3,700	4,700	5,000
pH, units		7.4	7.0	7.0
Color, platinum-cobalt		--	1,200	1,500
Calcium	Cations, milligrams per liter (mg/L)	--	390	400
Magnesium		--	260	330
Sodium		--	390	380
Potassium*		--	190	270
Iron, micrograms per liter (ug/L)		--	66,000	390,000
Manganese (ug/L)		--	13,000	10,000
Chloride*	Anions (ug/L)	1,000	610	540
Sulfate*		260	13	8.3
Bicarbonate		--	2,730	3,030
Cyanide (mg/L)		--	.00	.02
Organic nitrogen	Nitrogen species as nitrogen (mg/L)	--	100	71
Ammonia nitrogen		--	7.3	69
Nitrate		--	.14	.10
Nitrite		--	.01	
Orthophosphate	As phosphorus (mg/L)	--	.15	1.0
Total phosphorus		--	3.2	3.3
Total organic carbon (mg/L)		--	450	22
Dissolved oxygen (mg/L)		.0	.0	.0
Biochemical oxygen demand, 5-day (mg/L)		600	5,540	250
Chemical oxygen demand (mg/L)		--	786	890
Total coliform	Colonies/100 milliliters	--	--	85,000
Fecal coliform		--	--	--
Arsenic	Trace metals (ug/L)	--	9	--
Cadmium		--	7	15
Chromium		--	60	260
Lead		--	130	1,100
Mercury		--	.9	--
Nickel		--	56	290
Selenium		--	--	--
Phenols (ug/L)		--	1,100	140
Chromium* (ug/L)		--	--	10
Manganese* (ug/L)		--	--	110
Iron* (ug/L)		--	--	1,400
Selenium* (ug/L)		--	--	--

* Denotes concentrations for samples filtered through a 0.45-micron inert filter.

Table 12.--Physical, chemical, and bacteriological data of Cayey landfill at site S2.

PARAMETER		DATE (month, day, year)
		5-28-76
Time, hours		1430
Temperature, in degrees Celsius		22.0
Water depth, meters		--
Specific conductance, micromhos/cm at 25°C		700
pH, units		7.0
Color, platinum-cobalt		300
Calcium	Cations, milligrams per liter (mg/L)	33
Magnesium		30
Sodium		57
Potassium*		17
Iron, micrograms per liter (ug/L)		13,000
Manganese (ug/L)		2,800
Chloride*	Anions (ug/L)	86
Sulfate*		5.1
Bicarbonate		317
Cyanide (mg/L)		.00
Organic nitrogen	Nitrogen species as nitrogen (mg/L)	2.2
Ammonia nitrogen		2.9
Nitrate		.02
Nitrite		
Orthophosphate	As phosphorus (mg/L)	.27
Total phosphorus		.47
Total organic carbon (mg/L)		4.4
Dissolved oxygen (mg/L)		.0
Biochemical oxygen demand, 5-day (mg/L)		18
Chemical oxygen demand (mg/L)		66
Total coliform	Colonies/100 milliliters	5,000
Fecal coliform		--
Arsenic	Trace metals (ug/L)	2
Cadmium		0
Chromium		90
Lead		0
Mercury		.8
Nickel		9
Selenium		0
Phenols (ug/L)		0
Chromium* (ug/L)		0
Manganese* (ug/L)		1,900
Iron* (ug/L)		>10
Selenium* (ug/L)		0

* Denotes concentrations for samples filtered through a 0.45-micron inert filter.

Table 13.--Physical, chemical, and bacteriological data of Cayey landfill at site S3.

PARAMETER		DATE (month, day, year)
		3-16-76
Time, hours		1300
Temperature, in degrees Celsius		--
Water depth, meters		>.03
Specific conductance, micromhos/cm at 25°C		10,500
pH, units		5.8
Color, platinum-cobalt		--
Calcium	Cations, milligrams per liter (mg/L)	840
Magnesium		430
Sodium		830
Potassium*		450
Iron, micrograms per liter (ug/L)		240,000
Manganese (ug/L)		21,000
Chloride*	Anions (ug/L)	620
Sulfate*		19
Bicarbonate		7,300
Cyanide (mg/L)		--
Organic nitrogen	Nitrogen species as nitrogen (mg/L)	--
Ammonia nitrogen		--
Nitrate		--
Nitrite		--
Orthophosphate	As phosphorus (mg/L)	--
Total phosphorus		--
Total organic carbon (mg/L)		--
Dissolved oxygen (mg/L)		.0
Biochemical oxygen demand, 5-day (mg/L)		>4,000
Chemical oxygen demand (mg/L)		--
Total coliform	Colonies/100 milliliters	--
Fecal coliform		--
Arsenic	Trace metals (ug/L)	--
Cadmium		--
Chromium		--
Lead		--
Mercury		--
Nickel		--
Selenium		--
Phenols (ug/L)		--
Chromium* (ug/L)		--
Manganese* (ug/L)		--
Iron* (ug/L)		--
Selenium* (ug/L)		--

---

* Denotes concentrations for samples filtered through a 0.45-micron inert filter.

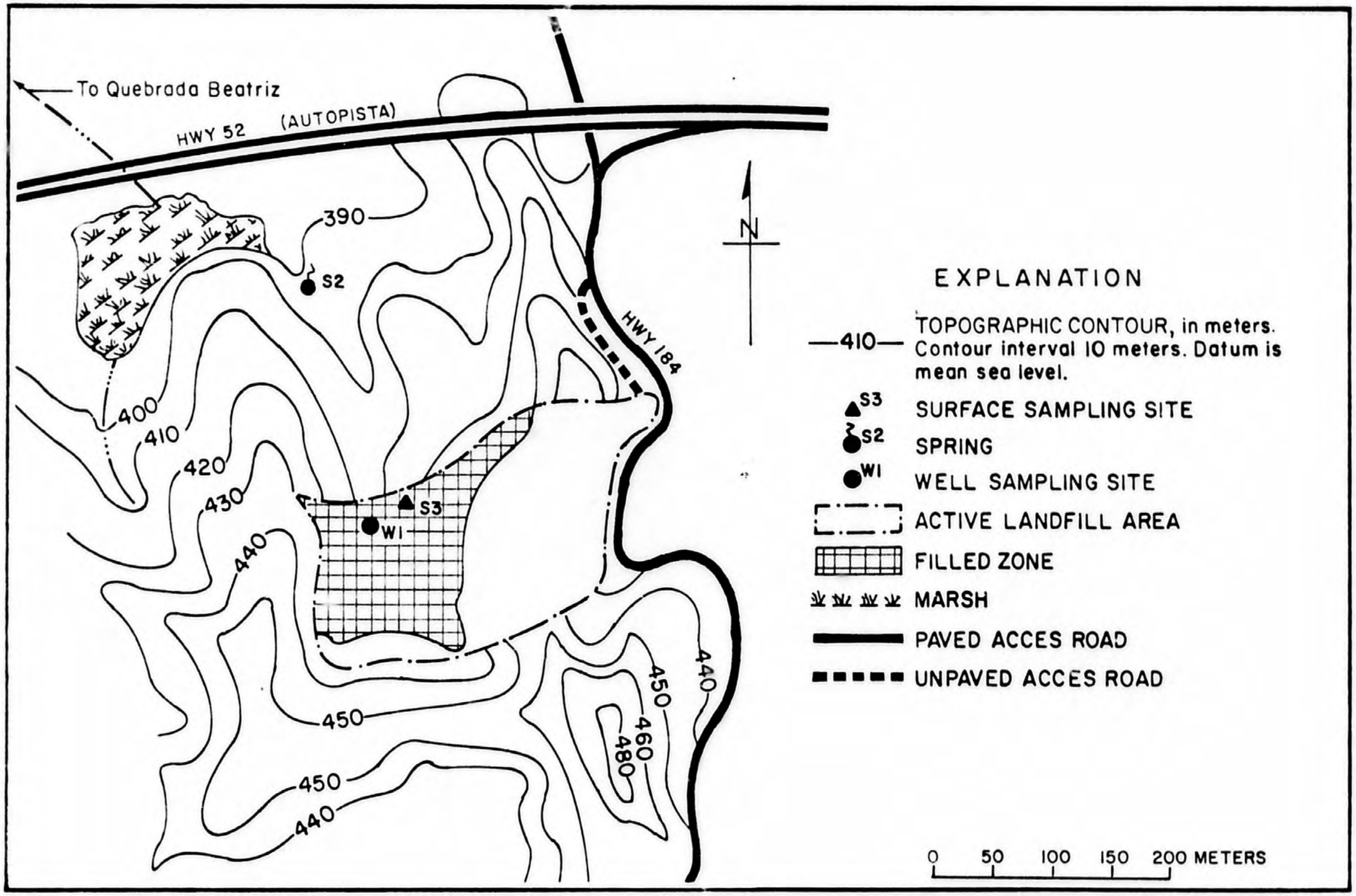


Figure 14.--Cayey landfill, sample sites, and general features.

Figure 15.--Bulldozer compacting refuse by area method along northern edge of Cayey landfill.

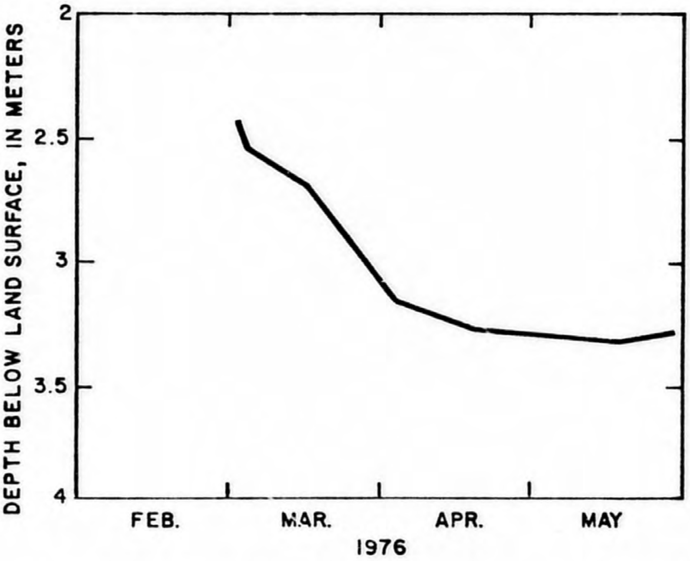


Figure 16.--Water levels in observation well W1, Cayey landfill.

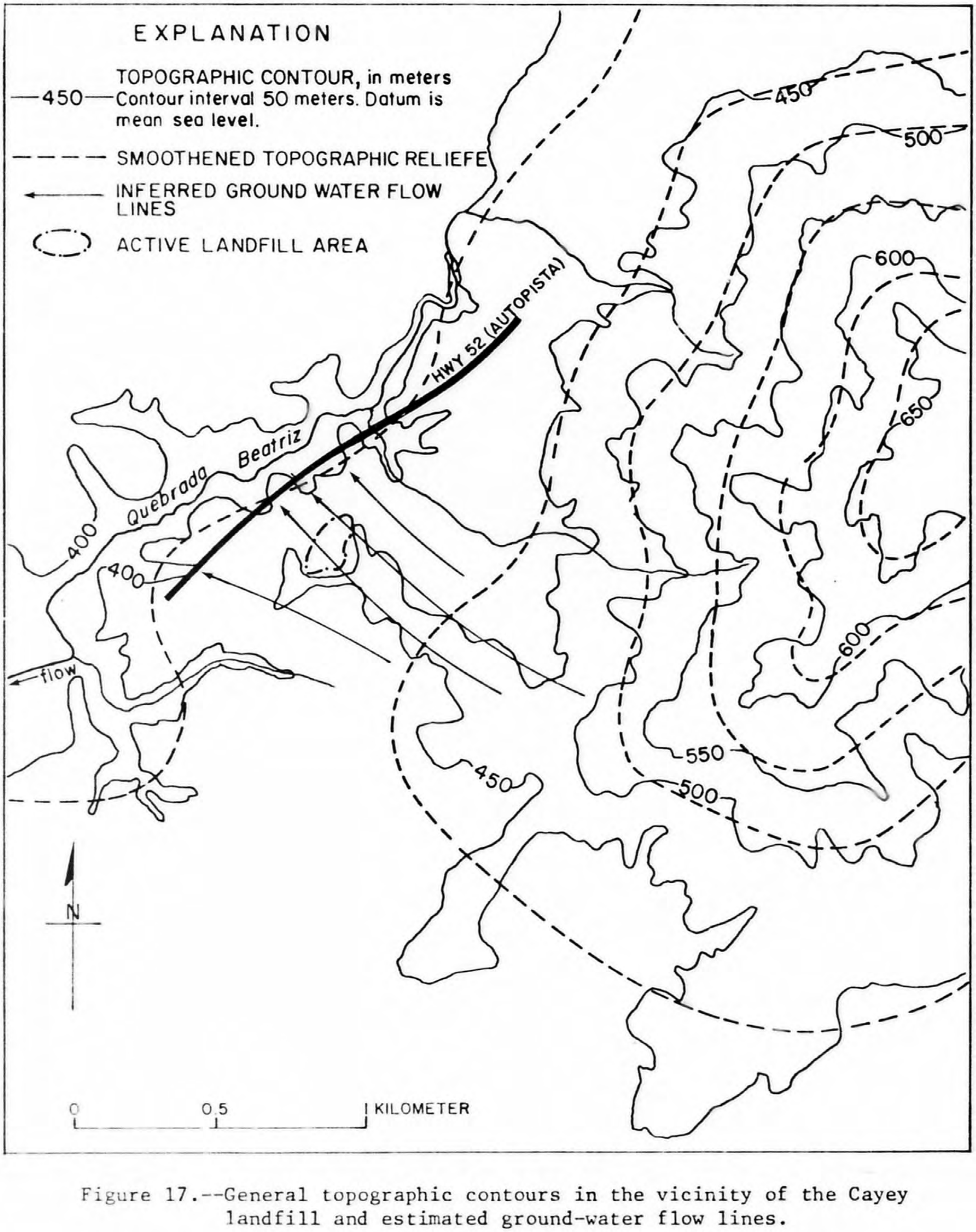


Figure 17.--General topographic contours in the vicinity of the Cayey landfill and estimated ground-water flow lines.

or were precipitated before filtration when in contact with atmospheric oxygen. The same results were obtained in a filtered sample for chromium analysis.

Leachate from this landfill probably is migrating through the subsurface in addition to that which may be washed by rainfall runoff from the surface. A sample at site S2, a spring, was anaerobic. This may indicate oxygen depletion by bacteriological decomposition of organic wastes. The reducing conditions created increase the solubility of iron and manganese, which may be liberated from soil. Although no background water-quality information at the spring is available, its specific conductance is higher than that of the creek which drains into the marsh to the west of the spring. The specific conductance of this stream was 250 umho/cm. The difference in conductivity is caused by the high bicarbonate concentration found at the spring, which may be a product of organic decomposition. Other indexes of a contaminated flow at S2 are the high organic nitrogen, ammonia, phosphorus, COD (to a lesser degree the above average BOD_5 value), and high total coliform count. Toxic metals analyzed show that mercury seems to have a baseline value near 0.8 ug/L, but a greater number of samples are necessary for confirmation.

At this site annual potential evapotranspiration may be about 1,300 mm. The mean annual rainfall is about 2,000 mm. Assuming actual evapotranspiration is 0.70 the total value, a total of about 1,100 mm of rainfall may be available for infiltration into the soil. This represents a maximum of about 5,800 m^3 of rainwater available to percolate through the buried refuse and be discharged as leachate during the year. Although a significant amount of this rainfall may leave the area as runoff, it may be compensated for by runoff into the area from the adjacent hills as no provisions exist to divert flow away from the operation site.

To make a quantitative evaluation of leachate discharge would require monitoring of the water level within the fill and obtaining actual data of the water-retainment capacity of the soil-refuse mixture. This may be estimated by correlating water-level fluctuations with rainfall and runoff observations.

The local surface features at the area indicate that the ground-water discharge from this fill will be at the spring and marsh area. Therefore, sampling may be conducted at the spring to indicate future changes in ground-water quality caused by the landfill.

Efforts should be made at this site to divert runoff from the adjacent hills from the fill zone. Also a sufficient slope maintained over the filled area can enhance runoff and diminish the infiltration potential. The present conditions at this landfill (a thick saturated mixture) may be a safety hazard in this terrain because of landslide potential.

Humacao

Figure 18 shows the Humacao landfill, sample points and general features of the area. This landfill covers an area of about 2.4 ha and has been in operation since about 1973. Though the area method of landfilling is used, open burning was observed on most visits during the investigation as seen in the photograph (fig. 19). No records are kept on waste loading or rate of fill used. Estimates by the Puerto Rico Environmental Quality Board indicate the municipality of Humacao to be generating 80,700 kg/day of solid wastes. Soil cover consists of a friable shale with igneous rock fragments obtained from the bordering hills. Presently the depth of waste and fill averages about 6 m.

Two observation wells were installed at the foot of the landfill and are shown in figure 20. A clay substratum less than 1 m deep (from about land surface to 1 m below) was encountered at the observation well sites. This clay horizon does not seem to be homogeneous below the fill. If such clay barrier extended homogeneously below the fill, it would be an effective shield for downward migration of leachate. Analyses at the observation wells, which have the percolation segment of the casing below this clay layer, indicate the subsurface waters are affected by leachate. Therefore, it is possible that the entire ground-water body below the fill has been polluted. Across the northern perimiter, the bedrock seems to lie less than 10 m and probably not much deeper than 6 m below land surface as shown in figure 21 from well construction data.

The base of the landfill lies at about 160 m from Quebrada Cataño. From exposed soil sections eroded by Quebrada Cataño, the soil horizon along the creek consists of alluvium rich in fine sand. Ground-water flow through such tight media may move at a rate of 0.1 cm/d to 100 cm/d as shown in table 1. It seems the true velocity favors the lower rate, judging by a specific conductance survey made at Quebrada Cataño during July 15, 1976. The flow at the creek was about 0.01 m^3/s and no increase in specific conductance was detected from point A to B, shown in figure 18. A value of 410 umho/cm at 25°C was obtained. If the ground-water velocity were near the 100-cm/d range, the effect of leachates would already be felt at the creek.

The water table within the fill may rise to within 2 m of the fill surface, if the Cayey landfill data can be extrapolated to this site. It is probable that a water-table mound exists within the fill as the water level in the observation wells is near ground surface and may at times reach ground surface as was found at well W1 on March 28, 1976. During the sampling runs Quebrada Cataño was at base flow; under such condition the water surface at the creek is equivalent to the water-table depth. Therefore, the water table presently drops about 2 m from the base of the fill to the creek. This gradient aids in increasing the flow rates of pollutants from the landfill to the creek.

Data collected during the investigation period at the Humacao landfill are shown in tables 14 and 15. Leachate migration to the observation wells is evident from the high specific conductance values in the 10^3-umho/cm range and

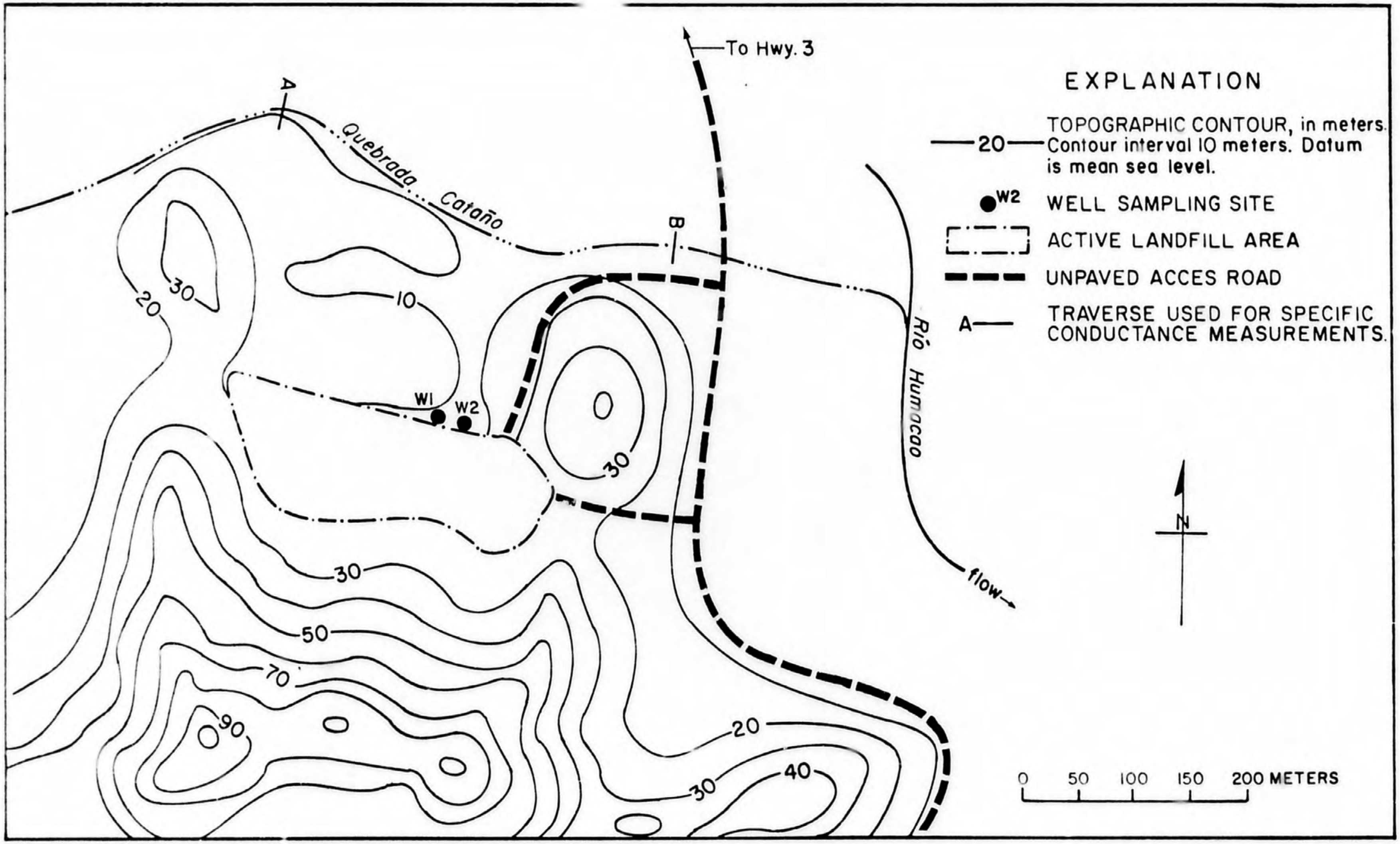


Figure 18.--Humacao landfill, sample sites, and general features.

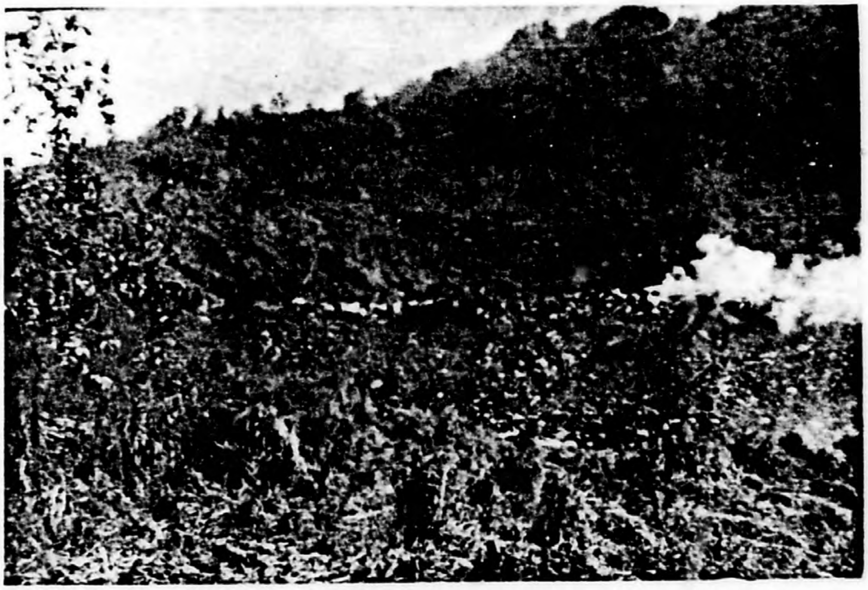


Figure 19.--Humacao landfill as seen from the north (May 1976).

Figure 20.--Observation wells at foot of Humacao landfill. Concrete monument is well W2. Observation well W1 is farther back and on other side of fence (May 1976).

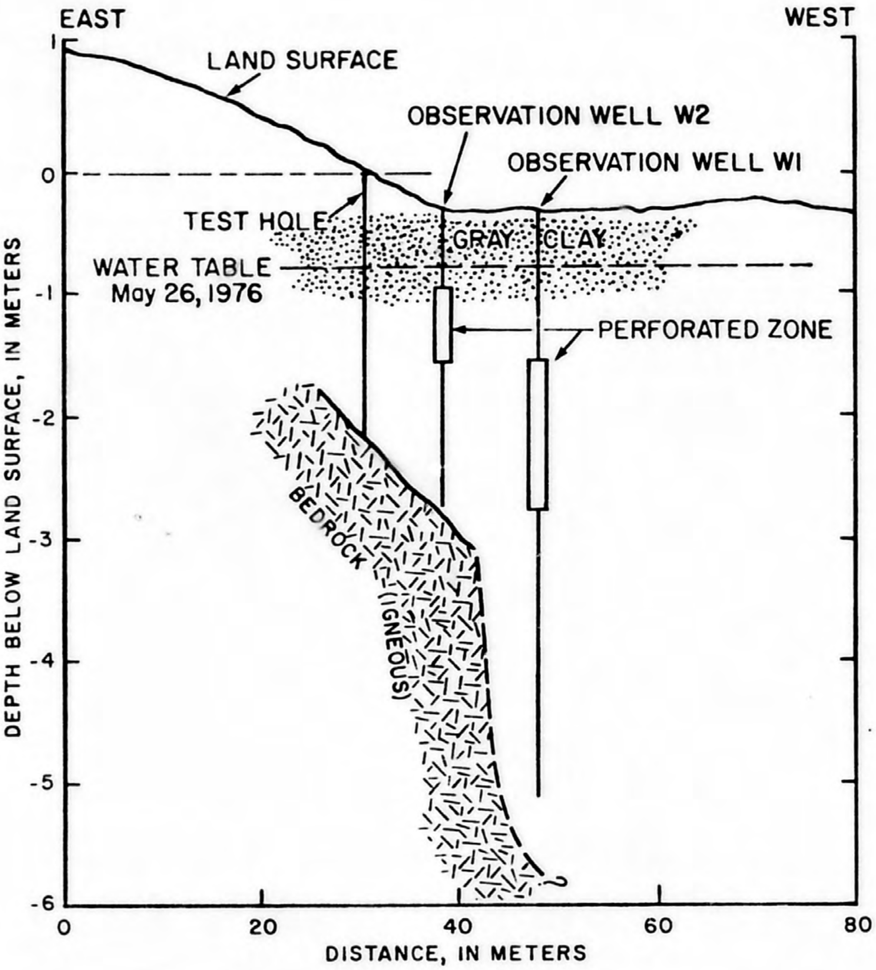


Figure 21.--Approximate profile view along foot of Humacao landfill at observation wells.

Table 14.--Physical, chemical, and bacteriological data of Humacao landfill at site W1.

PARAMETER		DATE (month, day, year)	
		4-28-76	5-26-76
Time, hours		1300	1200
Temperature, degrees Celsius		27.0	27.0
Water depth, meters		.0	.5
Specific conductance, micromhos/cm at 25°C		4,100	2,160
pH, units		7.3	6.9
Color, platinum-cobalt		30	160
Calcium	Cations, milligrams per liter (mg/L)	270	260
Magnesium		120	160
Sodium		530	190
Potassium*		14	3.3
Iron, micrograms per liter (ug/L)		120,000	190,000
Manganese (ug/L)		6,100	9,000
Chloride*	Anions (ug/L)	1,200	470
Sulfate*		280	100
Bicarbonate		439	634
Cyanide (mg/L)		.00	.00
Organic nitrogen	Nitrogen species as nitrogen (mg/L)	4.7	4.6
Ammonia nitrogen		1.2	.30
Nitrate		.06	.11
Nitrite		.02	
Orthophosphate	As phosphorus (mg/L)	.11	.02
Total phosphorus		.40	.27
Total organic carbon (mg/L)		52	3.6
Dissolved oxygen (mg/L)		.0	.0
Biochemical oxygen demand, 5-day (mg/L)		10	3.9
Chemical oxygen demand (mg/L)		120	78
Total coliform	Colonies/100 milliliters	--	200
Fecal coliform		--	10
Arsenic	Trace metals (ug/L)	1	0
Cadmium		1	0
Chromium		150	270
Lead		22	35
Mercury		.6	1.2
Nickel		110	280
Selenium		--	0
Phenols (ug/L)		24	2
Chromium* (ug/L)		--	10
Manganese* (ug/L)		--	6,000
Iron* (ug/L)		--	150
Selenium* (ug/L)		--	0

* Denotes concentrations for samples filtered through a 0.45-micron inert filter.

Table 15.--Physical, chemical, and bacteriological data of Humacao landfill at site W2.

PARAMETER		DATE (month, day, year)	
		4-28-76	5-26-76
Time, hours		1200	1300
Temperature, in degrees Celsius		27.0	27.0
Water depth, meters		.4	.5
Specific conductance, micromhos/cm at 25°C		1,300	2,980
pH, units		6.9	6.9
Color, platinum-cobalt		--	50
Calcium	Cations, milligrams per liter (mg/L)	370	270
Magnesium		380	210
Sodium		82	200
Potassium*		9.5	16
Iron, micrograms per liter (ug/L)		740,000	450,000
Manganese (ug/L)		59,000	13,000
Chloride*	Anions (ug/L)	300	760
Sulfate*		38	78
Bicarbonate		622	659
Cyanide (mg/L)		.00	.00
Organic nitrogen	Nitrogen species as nitrogen (mg/L)	6.3	2.1
Ammonia nitrogen		.18	.62
Nitrate		.04	.03
Nitrite		.03	
Orthophosphate	As phosphorus (mg/L)	.05	.01
Total phosphorus		1.1	.09
Total organic carbon (mg/L)		280	4.8
Dissolved oxygen (mg/L)		.0	.0
Biochemical oxygen demand, 5-day (mg/L)		110	42
Chemical oxygen demand (mg/L)		390	95
Total coliform	Colonies/100 milliliters	280	4.8
Fecal coliform		--	5,900
Arsenic	Trace metals (ug/L)	0	1
Cadmium		1	0
Chromium		1,600	800
Lead		500	52
Mercury		.8	2.6
Nickel		1,300	400
Selenium		--	0
Phenols (ug/L)		11	5
Chromium* (ug/L)		--	6
Manganese* (ug/L)		--	6,200
Iron* (ug/L)		--	210
Selenium* (ug/L)		--	0

---

* Denotes concentrations for samples filtered through a 0.45-micron inert filter.

high alkalinity values which had an average concentration of about 600 mg/L as HCO_3. The concentration of other ions is typical of leachate flows at other sites considered in this report. The concentration of nutrients obtained is typical of young wastes as most of the nitrogen is in the organic form and phosphorus in the complexed form. Most parameters analyzed showed a considerable reduction in concentration between both visits. The reason for such change could not be determined.

Fecal contamination does not seem to be a problem with leached flows at the observation well sites. The apparent high density at W2 may be caused by leakage from the soil cover since the water table is located at only 0.60 m from the land surface. Fecal coliform, which are more indicative of pollution were not present in significant counts in relation to the coliform population.

The presence of significant concentrations of chromium, lead, mercury and nickel seem to be related to wastes. Near observation well W2 a large stain, probably waste oil, was observed along the bottom edge of the landfill which may be the cause for such high values. Mercury concentrations are excessive, averaging 1.3 ug/L. This is the highest average found at any of the investigation sites on the island.

At this site the mean annual potential evapotranspiration may be about 1,800 mm. Assuming the actual evapotranspiration as 0.70 the potential amount, then a maximum of 740 mm of rainfall may percolate into the buried refuse. This represents a total water volume of almost 18,000 m^3 per year. In reality, the amount of leachate which may be produced could be greater as runoff from the adjacent hills is not diverted from the operation site and may flow to the fill area. This site receives rainfall in excess of 2.54 mm/d on an average of 160 days in a year and amounts in excess of 12.7 mm/d an average of 60 days in a year. Therefore, to reduce the rainfall infiltration potential requires effective site planning to increase rainfall runoff away from the fill.

Mayaguez

Figure 22 shows the Mayaguez landfill, sample sites, and general features. This site has been in operation since about 1973 and is used as a provisional waste-disposal site by the municipality of Mayaguez. The plot of land belongs to the Puerto Rico Industrial Development Company (PRIDCO) and is on a short-term lease to the municipal government (Eng. C. Manzano, oral commun., 1976). Domestic wastes compose the bulk of refuse being buried at the site. A view of the domestic waste burial area is shown in figure 23. Records are kept at the site of the waste loading brought in by municipal trucks. The average input rate of domestic wastes is about 125,300 kg/day. Other disposal zones are reserved for wastes from the tuna canning industry located in Mayaguez, and from a computer components factory at San Germân. Loading from these sources is not recorded. The tuna canning wastes are deposited in trenches which are operated by the individual factories. The amount of land under active use for all wastes totals about 6.5 ha.

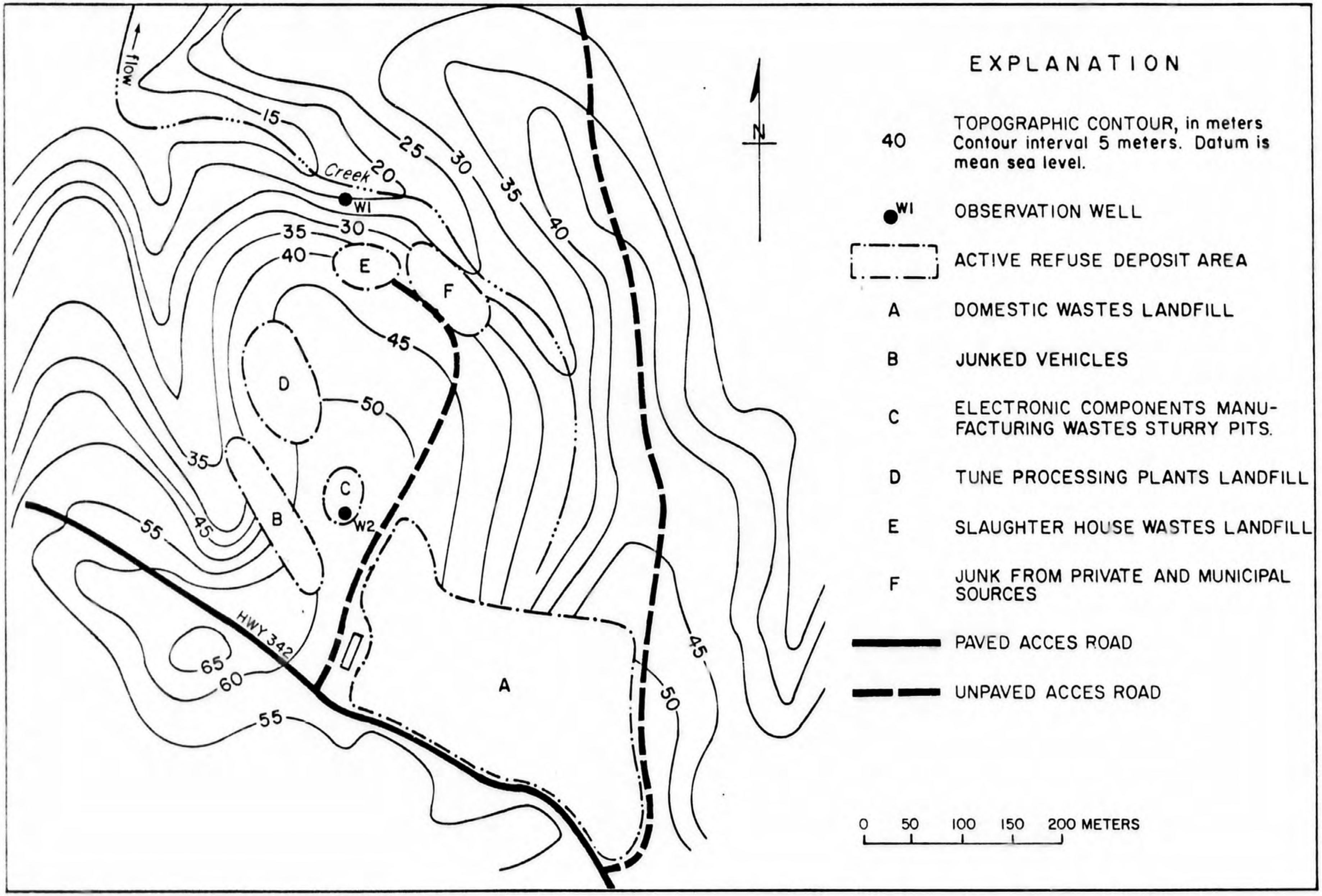


Figure 22.--Mayaguez landfill, sampling sites, and general features.

Figure 23.--Domestic waste burial site at Mayaguez landfill (January 1976).

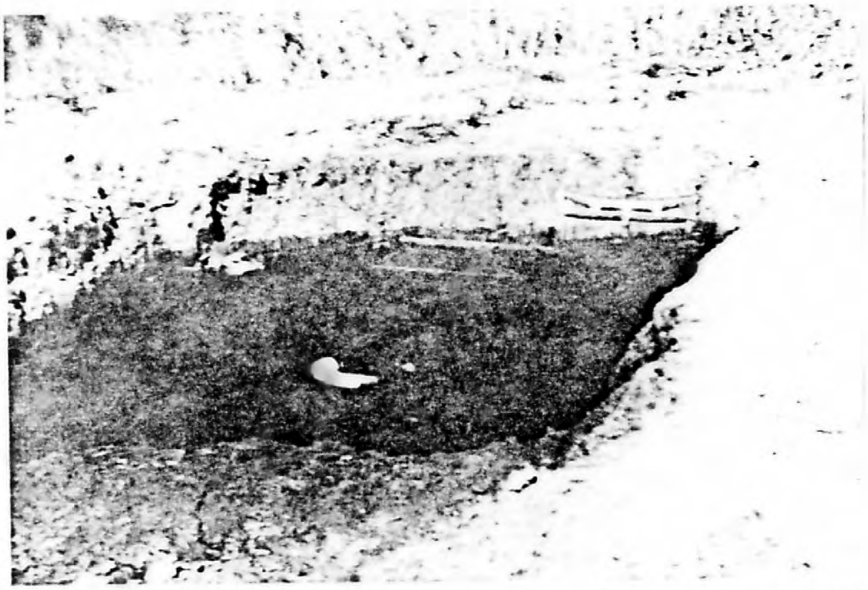


Figure 24.--Filled slurry pit at hilltop in Mayaguez landfill. This pit was filled prior to May 1975 and very little settling has occurred (January 1976).

Wastes from the electronics plant consist of metal oxides (Puerto Rico Environmental Quality Board, oral commun.). Judging from the visual appearance and odor, the wastes are probably mixed with organic solvents. These are dumped in pits similar to that shown in the photograph (fig. 24). Presently, two pits have been filled and a third dug. These new pits measure approximately 3x3x3 m. If the depths of the other pits are similar to the latest then about 45,000 L of these wastes has been deposited. One pit (shown in fig. 24) was already filled when the site was first visited in May 1975. The wastes contained in this pit have, in appearance, a viscosity similar to liquid tar and very little settling has occurred.

These pits lie in highly weathered soils which have the same geologic origin as the Caguas and Cayey landfills. An observation well (W2 in fig. 22) constructed adjacent to the first filled pit revealed the soil horizon was similar from the surface to at least a depth of 9.0 m. The water table at this point was not encountered and may lie at a depth of about 30 m. Nevertheless, the deeper soil tailings from the drill bit were slightly humid and had the pungent odor of the wastes contained in the pit.

At observation well W1, the water table was encountered at about 4.15 m within a soil layer rich in sand. It fluctuated within 1 m during the study period. Water-depth observations are shown in figure 25. At this site, the soil horizon found below the red soil layer is rich in sand and in the saturated zone. It is similar in appearance to the outcrop existing in the southeastern edge of the landfill site. By hand-bailing this well, the static water level could not be lowered more than 0.5 m. This may indicate a relatively high transmissivity value of the aquifer in the immediate area.

The ground-water flow pattern could probably be in the direction shown in figure 26. This is assuming the ground-water gradient may be described by drawing a smoothed topographic contour map of the highly eroded topography which typifies this region. The domestic wastes are buried near the top of a local hill (figs. 22 and 26). The depth to the water table in this area may be slightly less than 20 m. Such depth to the water table and the local slope will likely retard the effect of leachates in reaching site W1.

Data collected at observation well W1 are given in table 16. The specific conductance values show stratification within the approximately 3 m of standing water. Values increase from about 210 umho/cm near the surface of the water column to about 380 umho/cm at the bottom of the well casing. Lack of ground-water data at this site previous to the establishment of the landfill limits the evaluation of these analyses. The only signs of some slight contamination are given by the low oxygen content, presence of ammonia nitrogen and presence of fecal organisms. These may be entering the ground-water system either from the slaughter house waste burial area or the domestic waste zone, based on the flow lines shown in figure 26. The low oxygen concentrations result from bacterial activity. This will cause increases in manganese and iron, which can leach from the soils under anoxic conditions. Future indications of leachate pollution can be detected by higher concentrations of bicarbonate, which at the moment seem to be within normal concentrations.

Table 16.--Physical, chemical, and bacteriological data of Mayaguez landfill at site W1.

PARAMETER		DATE (month, day, year)		
		3-15-76	4-19-76	5-25-76
Time, hours		1300	1430	1430
Temperature, in degrees Celsius		--	25.0	25.0
Water depth, meters		4.9	5.6	5.2
Specific conductance, micromhos/cm at 25°C		320	270	230
pH, units		6.4	6.6	6.9
Color, platinum-cobalt		--	10	160
Calcium	Cations, milligrams per liter (mg/L)	--	18	16
Magnesium		--	19	16
Sodium		--	13	11
Potassium*		--	5.4	2.5
Iron, micrograms per liter (ug/L)		--	22,000	16,000
Manganese (ug/L)		--	4,200	3,500
Chloride*	Anions (ug/L)	--	17	23
Sulfate*		--	7.7	6.1
Bicarbonate		--	152	116
Cyanide (mg/L)		--	.00	.00
Organic nitrogen	Nitrogen species as nitrogen (mg/L)	--	2.1	.51
Ammonia nitrogen		--	.55	.28
Nitrate		--	.00	.04
Nitrite		--	.01	
Orthophosphate	As phosphorus (mg/L)	--	.03	.02
Total phosphorus		--	.17	.08
Total organic carbon (mg/L)		--	18	2.0
Dissolved oxygen (mg/L)		--	1.6	1.8
Biochemical oxygen demand, 5-day (mg/L)		35	9.3	9.0
Chemical oxygen demand (mg/L)		--	24	29
Total coliform	Colonies/100 milliliters	--	--	18,000
Fecal coliform		--	32,000	1,500
Arsenic	Trace metals (ug/L)	--	2	1
Cadmium		--	6	1
Chromium		--	120	110
Lead		--	34	24
Mercury		--	.7	1.0
Nickel		--	25	31
Selenium		--	--	0
Phenols (ug/L)		--	0	3
Chromium* (ug/L)		--	--	10
Manganese* (ug/L)		--	--	1,700
Iron* (ug/L)		--	--	<10
Selenium* (ug/L)		--	--	0

* Denotes concentrations for samples filtered through a 0.45-micron inert filter.

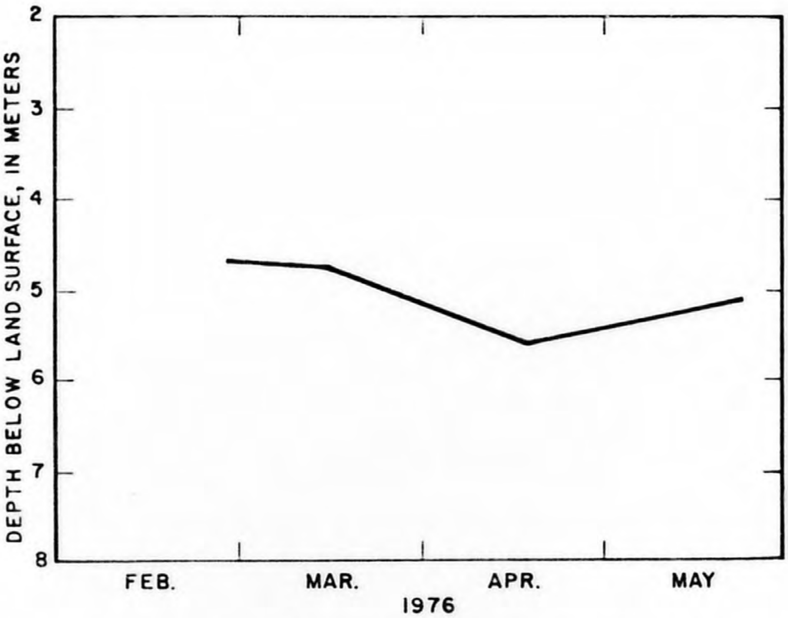


Figure 25.--Water levels at observation well W1, Mayaguez landfill.

Other chemical constituents which are present in significant concentrations were chromium, lead and mercury. The limited data are insufficient for pinpointing the source of these toxic metals.

Future efforts should include drilling observation wells to determine the ground-water gradient within the landfill area. Once this is determined observation wells can be installed across the flow zone to monitor the advancement of leachate from this area.

The amount of rainfall which may infiltrate through the wastes during the year would involve detailed monitoring of rainfall, runoff and evapotranspiration at the site. Mean annual rainfall at this site is about 2,000 mm and potential evapotranspiration may be about 1,900 mm. This indicates that 100 mm may be available for infiltration through the soil layer.

In practice, actual evapotranspiration is about 0.70 potential evapotranspiration values. Considering the high incidence of days with more than 12.7 mm of rainfall in this area (between 55 and 73 days per year), a potential infiltration of 670 mm may be a better estimate. Using this infiltration value about 28,600 m^3 of rainfall may percolate through the buried domestic wastes alone in an average year and enter the water table.

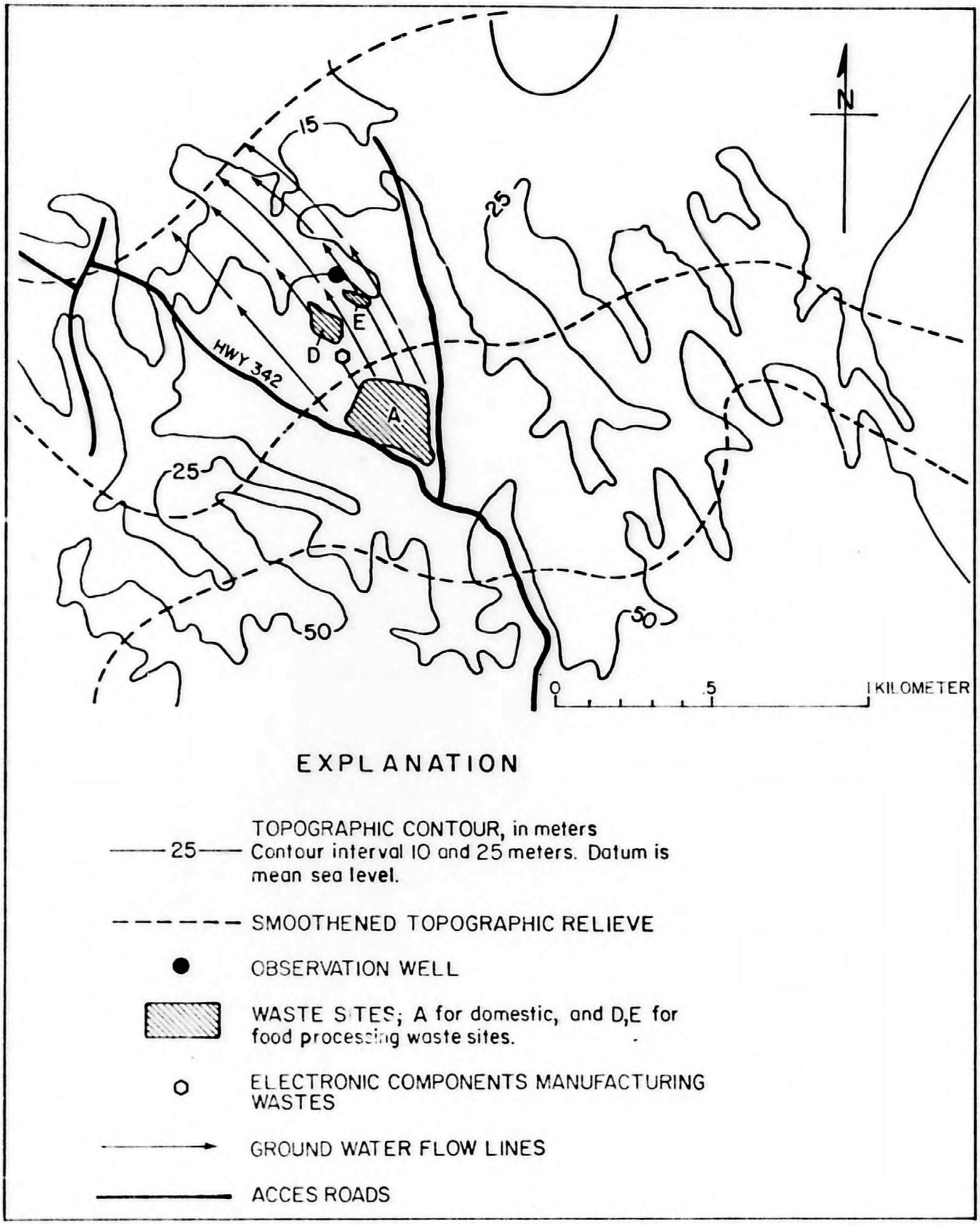


Figure 26.--Probable ground-water flow lines at the Mayaguez landfill area.

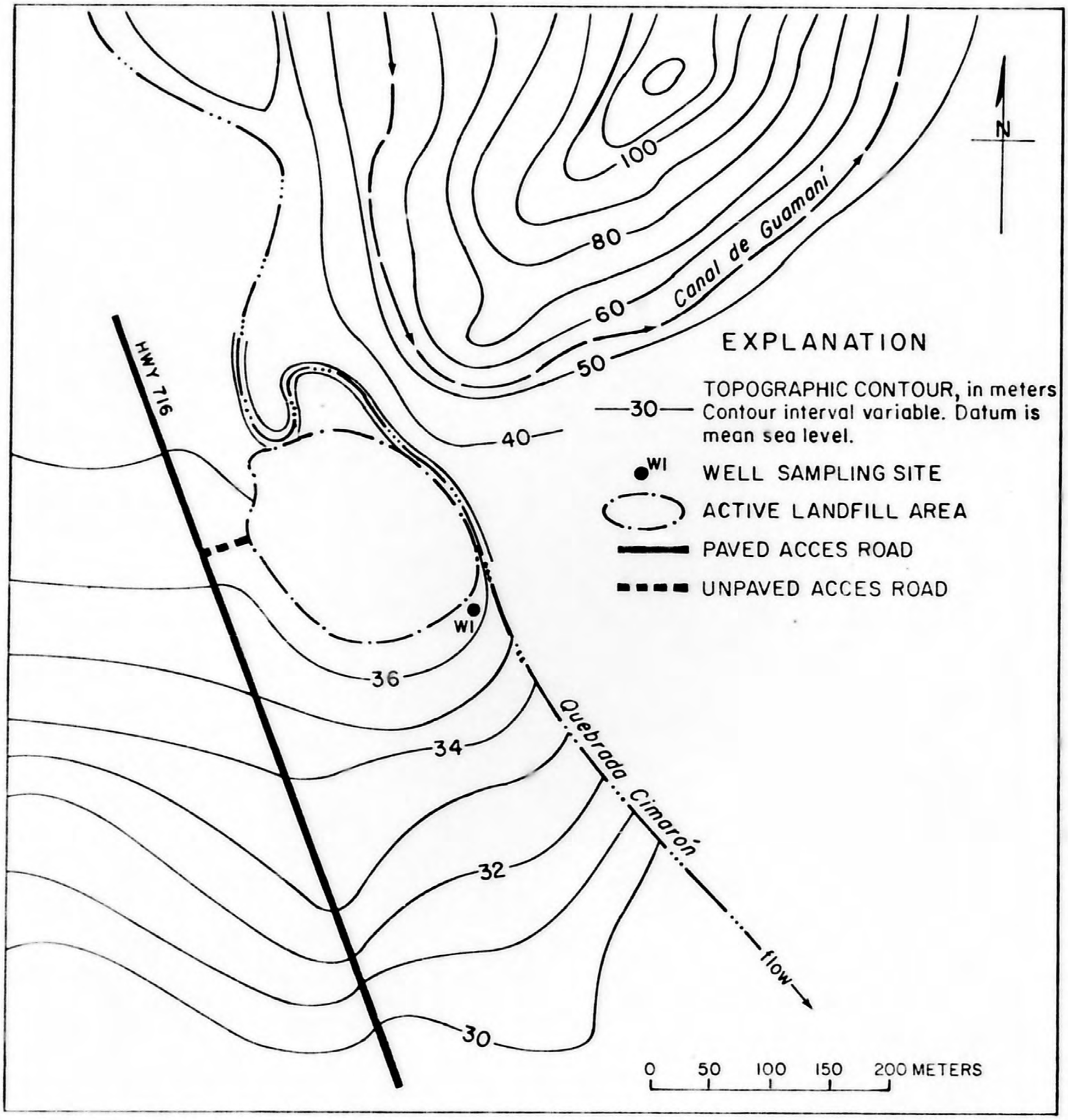


Figure 27.--Guayama open burning dump, observation well location, and general features.

Guayama

An attempt to evaluate the effect of an open burning dump on subsurface waters was made at the Guayama site. This open dump has been in operation for about 10 years. An observation well was installed near its southeastern boundary, but could not be developed for sampling within the study's time constraint. The location of the well and general features of the area are shown in figure 27.

According to McClymonds and Díaz (1972) the water table at this site is very near the bedrock surface. At the observation well site, bedrock was encountered at 10.8 m. Mud filled the lower 1.5 m of the pipe which indicates the presence of a saturated zone. Future efforts should be made to develop this, or a similar well, and determine if any significant ground-water deterioration has taken place. In the lack of baseline information, areal data compiled by McClymonds and Díaz (1972) could be utilized. Such effort may aid in assessing the pollution potential of abandoned burning dumps.

SUMMARY AND CONCLUSIONS

Five landfills were investigated in Puerto Rico between February and June 1976. The landfills are operated by the municipal governments of Arecibo, Caguas, Cayey, Humacao and Mayaguez. An open burning dump operated by the municipality of Guayama was included in the study. This open dump was included in an effort to obtain water-quality data on ground water affected by this type of waste-disposal procedure. Most landfills were established recently. The oldest located at Cayey had been in use for about 5 years. Other sites had been in use for about 3 years, except the Caguas site which was operated as an open burning dump between the late 1950's and 1973. The Guayama open burning dump is about 10 years old.

Pollution potential of these sites on water resources may be estimated by conducting a field survey of the local hydrologic and soil conditions. Such a procedure was used in selection of surface and ground-water sampling sites. When possible, observation wells and sampling points were located adjacent to active waste-disposal sites to determine the maximum concentrations of contaminants. At Cayey an observation well was installed in the landfill proper because toe leaching was not present. At Mayaguez it was not possible to obtain samples adjacent to the industrial wastes slurry pits or domestic waste area. The water table seems to be about 30 m from ground surface at the slurry pits and 20 m at the domestic waste site. Active surface leaching (toe seepage) and specific conductance anomalies at a creek adjacent to the Caguas fill did not make drilling of wells necessary at this site. A well was constructed at Guayama in order to differentiate the quality of landfill leachates and substances leached from open burning dumps. Unfortunately, the Guayama site observation well could not be developed within the study period and samples were not obtained.

Findings obtained during this investigation for the individual sites follow:

Arecibo.--This landfill lies on a ground-water discharge zone which makes it improbable for leached substances to migrate much deeper than the water table. Instead, lateral migration downgradient from a mounded water table in the fill may occur. Lack of drainage ditches along the north, east and southern perimeter will permit travel of the mounded ground water in any of these directions. The chemical data reflect the past conditions of this former marine slough. This history makes it difficult to differentiate between substances leached from the fill and those which were present before establishment of the waste disposal site. The text should be consulted for physical and chemical data collected (tables 4, 5, and 6). All values, with the exception of chromium, mercury, and arsenic were nevertheless within tolerable concentrations when compared with leachate contained within the Caguas and Cayey landfills. This may be due to the young age of the fill. At observation well W2, chromium was present in a concentration of 110 ug/L and mercury of 1.5 ug/L. At well W3, chromium concentrations were as high as 1,200 ug/L and arsenic as high as 54 ug/L. The origin of these elements may possibly be the soil, but additional sample sites and a greater number of samples would be necessary to confirm this.

Caguas.--This landfill lies on a ground-water recharge zone. Though it rests on a steep-sided hill, rainfall may infiltrate in significant quantities through the leveled fill. Water-quality data at the adjacent creek appear to indicate ground water discharging into the creek has been contaminated by the landfill. Leachate from site S4 (toe seepage) is very rich in all the chemical constituents analyzed except cyanide, cadmium and selenium which do not seem to be present in significant amounts at any of the sampled sites. Another surface seepage was found at site S2, entering the creek, and although only a partial analysis was made, the concentration of constituents was very similar to the analysis at S4. By far the greatest concentration was found for sodium and chloride ions. These were present in a ratio of 1 to 2, respectively, in leachate samples taken both at S2 and S4. The toe seepage samples had concentrations of 3,000 mg/L for Na and 6,000 mg/L for Cl; such values are not typical of landfill leachates. It is not known if the past history of this site as an open burning dump is the cause for such high concentrations or if these are caused by some particular wastes disposed of at the site. Data for this site are presented in tables 7, 8, 9, and 10.

Cayey.--This landfill rests on what was originally a ravine and presently may have a maximum fill depth of about 20 m. An observation well drilled within the fill to a depth of 7.6 m from the ground surface revealed a water table at only 2.5-m depth. Between March 1 and May 31 it dropped about 0.75 m, but there was no toe leaching present during this entire period. This may indicate infiltration of rainfall through the fill and into the local ground-water system which may discharge into Quebrada Beatriz at only 400 m from the edge of the fill. Local surface features favor this flow path and chemical data from a spring (site S2) 175 m away seem to confirm that such is the case at this site. Leachate samples from within the fill were high in total dissolved solids (5,860 mg/L) and other constituents. Significant concentrations of trace metals were detected within leachate samples, except for selenium. Physical and chemical data are shown in the text in tables 11, 12, and 13. Though the landfill is 5 years old it is biologically active as can be deduced from the low ammonia nitrogen, high BOD5 values, and a temperature of 12°C above the average ambient temperature. A surface sample taken about 12 days after a strong rainfall was richer in dissolved solids than the leachate within the fill. This may indicate that runoff may scavenge a significant loading during rainfall periods.

Humacao.--This landfill has a fill depth of about 6 m and may lie above a soil layer composed of silt and loam with some isolated clay horizons. The base of the landfill lies at about 160 m from Quebrada Cataño. Erosion along this creek reveals an alluvial soil rich in fine sand. Observation wells were installed at the base of the fill and revealed a high water table which at times reaches the land surface. Bedrock appears to lie at less than 10 m from the ground level at the edge of the fill.

Chemical data at the wells indicate leachate migration. The ground water at these points is enriched in all constituents analyzed except cyanide, cadmium and selenium. Excessive concentrations of chromium, lead, mercury and nickel may be related to wastes deposited at this site. Tables 14 and 15 list the physical and chemical data obtained at this site.

A specific conductance survey was conducted along a 350-m reach of Quebrada Cataño but values remained constant. This may indicate that leachate discharge into the creek is not occurring or is negligible.

Mayaguez.--It was not possible to install an observation well and reach the water table at sites adjacent to the slurry pits and the domestic wastes area. An observation well was installed at site W1 where the water table lies at about 5-m depth. This site may reveal pollution from the domestic wastes zone or slaughter-house wastes for it apparently lies within the ground-water flow path traversing these zones. During construction of this well a soil layer rich in sand was encountered within the water table. By hand-bailing this well, the static water level could not be lowered more than 0.5 m, which indicates that a high transmissivity value may exist.

Analyses shown in the text in table 16 indicate there is some pollution at this site. The origin may be either the slaughter-house wastes or the domestic wastes zone. These data show pollution at this site is only beginning as the cation and anion concentrations are low. Low dissolved oxygen values which could be caused by bacterial activity on wastes have solubilized iron and manganese from soils. As with other landfill sites, chromium concentrations were high, averaging 115 ug/L. Mercury concentrations averaged 0.8 ug/L.

Guayama.--This open dump lies above an alluvial soil underlain by coarse sands and cobbles. It has been in existence for about 10 years. Installation of an observation well at the southeastern edge of the disposal area revealed bedrock (igneous rock) at 10.8 m from the surface. This agrees well with an appraisal study of the ground-water resources in this region conducted in 1962 (McClymonds and Díaz, 1972). The saturated zone may be less than 1.5-m thick, as this is the mud level presently contained in the well casing. Unfortunately, this well could not be developed during the study period. Future efforts should be made to obtain water samples at this point. Such data would be beneficial in comparing leached solutes from abandoned open burning dumps and those from landfills. The soil below this disposal site indicates rainfall percolation may be rapid. Thus, sampling at this well should be conducted during an intensive rainstorm or immediately after.

General conclusions.--The results obtained in this investigation show that leachates from landfills in Puerto Rico may be enriched in almost all chemical constituents. Table 17 lists the concentration range of "undiluted" leachates from the Caguas and Cayey landfills.

The results at these two sites show the great range which may be expected for most parameters. This is an indication that a greater number of sites within a given area as well as samples are actually necessary to define these constituents in a quantitative form. The data obtained in this study also indicate that in addition to water-quality analyses, future site evaluation should include geochemical analyses. It seems Puerto Rico soils have high concentrations of heavy metals which can be chelated by organic compounds leached from buried wastes.

As a check on pollution from landfills, once a sampling network is established and baseline data obtained, routine analyses may be limited to specific conductance readings and concentration measurements of bicarbonate, dissolved oxygen and chloride. If significant changes are found in these parameters, pollution at the point is likely and a larger group of parameters may be checked and compared to baseline data.

At the sites studied in this investigation the ground-water flow pattern may be estimated by local surface features. This may be sufficient information to establish water-quality sampling points for routine surveillance.

If a quantitative analysis of leachate flow is required, then a detailed study of ground-water flow rates and the distribution of flow lines is needed. Such detailed analyses may be necessary at landfills located upgradient from ground-water users, valuable ground-water reserves, or for protection of surface waters.

Table 17.--Range of leachate composition from the Caguas and Cayey landfills.

Constituent	Concentration range, mg/L	Constituent	Milligrams per liter
Ca	150-840	DO	0.0-0.0
Mg	200-430	BOD_5	80-5, 540
Na	380-3,100	COD	786-3,000
K	190-520	Cd	.001-.015
Fe	1.7-390	Cr	.060-.260
Mn	2.2-28	Pb	.050-1,100
Cl	540-6,000	Hg	$0.0\text{x}10^{-3}$-$0.9\text{x}10^{-3}$
SO_4	8.3-260	Ni	.056-0.290
HCO_3^-	756-7,300	As	.008-016
CN^-	0.00-0.03	Se	0.000
org-N	71-110	Phenols	0.130-1.100
NH_4-N	7.3-490	Total coliforms	85,000-300,000 col/100 mL
NO_3+NO_2-N	0.10-0.16	Fecal coliforms	1,200-6,000 col/100 mL
o-P-P	0.15-1.0	Sp. conductance at 25°C, umho/cm	3,700-19,200
total P	0.46-313		
TOC	22-500	pH	5.8-7.8
Temperature, °C		Color, platinum-cobalt units	1,200-2,200

REFERENCES

American Public Health Association, American Water Works Association and Water Pollution Control Federation, 1976, Standard methods for the examination of water and wastewater, 14th edition: American Public Health Association, Washington, D.C., 1,193 p.

American Society of Civil Engineers, 1959, Sanitary landfill: Manuals of Engineering Practice, No. 39, New York, 61 p.

Berkey, C. P., 1915, Geological reconnaissance of Porto Rico: New York Academy of Science, v. 26, p. 1-70.

Brown, Eugene, Skougstad, M. W., and Fishman, M. J., 1970, Methods for collection and analysis of water samples for dissolved minerals and gases: U.S. Geological Survey Techniques of Water Resources Investigations, book 5, chapter A1, 160 p.

Brunner, D. R., and Keller, D. J., 1972, Sanitary landfill design and operation: U.S. Environmental Protection Agency (SW-65ts), 59 p.

Connor, J. J., and Shacklette, H. T., 1975, Background geochemistry of some rocks, soils, plants, and vegetables in the conterminous United States: U.S. Geological Survey Professional Paper 574-F, 168 p.

Díaz, J. R., 1973, Chemical quality of water in Caño Tiburones, Puerto Rico: U.S. Geological Survey open-file report, San Juan, Puerto Rico.

Fungaroli, A. A., 1971, Pollution of subsurface water by sanitary landfills, v. I: U.S. Environmental Protection Agency (SW-1212rg), 132 p.

Goerlitz, D. F., and Brown, Eugene, 1972, Methods for analysis of organic substances in water: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chapter A3, 40 p.

Hazen, A., 1892, A new color standard for natural waters: American Chemical Journal, 14:300-310.413.

Hughes, G. M., Landon, R. A., and Farvolden, R. M., 1971, Hydrogeology of solid waste disposal sites in northeastern Illinois: U.S. Environmental Protection Agency (SW-12d), 154 p.

Kimmel, G. E., and Braids, O. C., 1975, Preliminary findings of a leachate study of two landfills in Suffolk County, New York: U.S. Geological Survey Journal of Research, v. 3, no. 3, p. 273-280.

Mattson, P. H., 1960, Geology of the Mayaguez area, Puerto Rico: Geological Society of America Bulletin, v. 71, no. 3, p. 319-362.

REFERENCES--Continued

McClymonds, N. E., and Díaz, J. R., 1972, Water resources of the Jobos area, Puerto Rico: U.S. Geological Survey Water Resources Bulletin 13, San Juan, Puerto Rico, 32 p.

Meyerhoff, H. A., 1933, Geology of Puerto Rico: University of Puerto Rico, Monograph Series B, Physical and Biological Science no. 1, 306 p. and geologic map.

National Academy of Science and National Academy of Engineering, 1974, Water quality criteria, 1972: U.S. Government Printing Office, Washington, D.C., 594 p.

National Weather Service, (1) Annual mean precipitation 41-1970, Bulletin no. 81 by station (Climate of the United States); (2) Bulletin no. 86-44 rain intensity (3) Pan evaporation values.

Roberts, R. C., 1942, Soil survey, Puerto Rico: U.S. Department of Agriculture Bureau of Plant Industry, 503 p.

Robertson, J. M., Toussaint, C. R., and Jorque, M. A., 1974, Organic compounds entering ground water from a landfill: U.S. Environmental Protection Agency, EPA 660/2-74-077, 47 p.