Waste Reduction and Management Institute
School of Marine and Atmospheric Sciences

Geology

in the Vicinity of the

Town of Brookhaven

(Suffolk County, NY)

Landfill

Prepared by:

Omkar Aphale

Department of Technology and Society

David J. Tonjes

Department of Technology and Society
Waste Reduction and Management Institute
Long Island Groundwater Research Institute

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Stony Brook University
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Abstract

A key requirement for a sound groundwater flow and contaminant transport simulation model is a reasonably accurate depiction of the litho-stratigraphic profile and the water bearing characteristics of the sediment mass that underlies the study area. The available literature and extant records have been reviewed to develop such a geologic profile. The profile includes the stratigraphic, lithologic, and hydrologic characteristics of geologic units in the study area – bedrock, sand and clay members of the Raritan Formation, Matawan Group-Magothy Formation, Monmouth Greensand, Gardiners Clay, Upper Glacial, and Holocene deposits.

Gardiners Clay separates the Upper Glacial aquifer and the Magothy aquifer, the two uppermost elements of the aquifer system, and key to contamination extent, transport, and fate. Gardiners Clay is a potential natural barrier to the downward flow of the contaminating leachate into the Magothy aquifer and may affect water movement between the two key aquifers. Gardiners Clay therefore is an important stratigraphic element. The title “Gardiners Clay” is not to be taken literally: although the name connotes that the unit is composed of solid clay, the geologic evidence suggests that the composition of this stratigraphic layer is variable, from sandy to silty to solid clay.

The investigation intended to determine the physical extent of Gardiners Clay by reviewing geologic data such as drilling and geophysical logs. However, the position, thickness, and extent of a sediment mass matching the conventional description of Gardiners Clay in the vicinity of the landfill cannot be made. The lithologic descriptions from numerous boring logs were not consistent with Gardiners Clay. However, the logs showed the presence of low-permeability material at many locations, which can be interpolated as a consistent layer. This layer is named here as the “potentially semi-confining unit” (PSU). The PSU is not an unclassified geologic feature, but is a hypothetical unit comprised of an ensemble of various low permeability units found across the study area, including some called Gardiners Clay and some that match the classic description of Gardiners Clay. This unit, where present, provides semi-confining to confining conditions between the Upper Glacial and the Magothy aquifer in the study area. The confirmed northern extent of the PSU was the north perimeter of the landfill site. The thickness and clay content of the PSU increases to the south. The confining ability of the PSU varies based on the composition and thickness of the unit.

The quality of the information used to develop this description varied, and the natural phenomena that are sampled by borings are not uniform. The techniques used to interpret samples and to interpolate among our defined data sets all cause certain amounts of uncertainty associated with the descriptions of the hydrogeologic characteristics of the sedimentary units. These factors have been discussed here, as they can be important to the development of and analysis of results from the ensuing flow and transport model.
1. Introduction

The Town of Brookhaven Waste Management Facility is located in the hamlet of Brookhaven, Suffolk County, New York. The landfill, constructed in 1972, was one of the first artificially lined landfills in the country. However, by 1980 it was determined that the liner system failed some time after installation causing widespread groundwater contamination (Dvirka and Bartilucci, 2010). The impact is on the Upper Glacial aquifer which is the water table aquifer and the leachate contamination appears to be flowing in a southeasterly direction, the direction of advective flow of groundwater in the study area. The US Geological Survey (USGS) entered into a cooperative agreement to investigate the groundwater contamination. Its lead researcher, E.J. Wexler, created a 2-D, steady-state groundwater flow and contaminant transport model of the Upper Glacial aquifer (Wexler, 1988a; Wexler 1988b; Wexler and Maus, 1988). In addition, a water budget was generated, and the effects of several remedial designs on the plume (as defined by chloride concentrations) were modeled (Wexler, 1988b).

Today we are reconstructing and enhancing the groundwater flow and contaminant transport simulation model over 25 years after the earlier USGS work. Since 1988, a number of investigators have studied the regional and site-specific hydrogeologic properties of this area. More data are available pertaining to quantity, quality, and flow of water. Modeling practices have also improved due to advances in computational power and graphic abilities of computers.
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2. Objective

The objective of this report is to depict the geology of the Brookhaven landfill site and its vicinity using available data describing the stratigraphy, lithology, and water bearing properties of the sedimentary units underlying Long Island in general and the Brookhaven landfill site and vicinity in particular.

Reasonably accurate interpretation of the geology of an area is important for defining a conceptually sound model domain that is an acceptable representation of the real world conditions (Anderson and Woessner, 1992; Buxton and Reilly, 1985). Not only is the domain important for model processes, but the features of the domain can influence its boundary conditions, a key element in creating an accurate depiction of the hydrologic system. Therefore model representations of the physical features of the real world system should be as realistic as possible (Reilly and Harbaugh, 2004).

Review of available geologic information such as geologic maps, cross sections, and geophysical/ geotechnical boring and well logs helps to define this geologic framework (Buxton and Smolensky, 1999). Researchers and organizations (private and public) have conducted regional or site-specific hydrogeological studies on Long Island in the past. The range of methods utilized includes:

(i) Geophysical investigation: use of gamma ray logs, soil samples (Dvirka and Bartilucci, 1994b, 1996c, 2001, 2010, 2011; Scorca et al., 1996), palynography, mineralogic and chemical analyses, and microscopic examination of the sediments excavated during drilling to characterize the sub-surface geology (Sirkin, 1986).

(ii) Hydrological investigation: installation of groundwater monitoring and piezometer well networks and observing fluctuations in groundwater levels to characterize groundwater flow regimes (Koszalka, 1984; Voorhis, 1986), slug tests and pumping tests to characterize the properties of the aquifer units (Franke and McClymonds, 1972; Veatch et al., 1906).


This report presents a comprehensive review of the relevant literature. Section 3 presents necessary background information about the landfill site and vicinity. Section 4 lists relevant hydrogeological investigations that were carried out at the landfill and elsewhere on Long Island. Sections 5 to 8 summarize the findings: the surficial features of Long Island (Section 5); regional geology (Section 6); the geologic history of Long Island (Section 7); and, a detailed discussion of
the stratigraphy and water bearing properties of the major geologic units identified on Long Island and at the landfill site – bedrock, the Lloyd member of the Raritan Formation, the clay member of the Raritan Formation, the Matawan Group-Magothy Formation, Monmouth Greensand, Gardiners Clay, the Upper Glacial deposits, and Holocene deposits (Section 8). Section 9 depicts (i) the geologic profile of the study area in the form of 2-dimensional interpolated regional and local geologic cross sections, and (ii) a 3-dimensional extrapolated geologic layer indicating the physical extent of the Gardiners Clay underneath the study area developed using interpolation tools available in Visual MODFLOW v.4.2. Section 10 discusses our findings, followed by conclusions in Section 11.
3. Description of the Study Area

The Town of Brookhaven Waste Management Facility is located in south-central Town of Brookhaven, Suffolk County, New York (Figure 1). It is bounded by Horseblock Road to the north, Sunrise Highway to the south, the Horizon Village residential community to the west, and Yaphank Avenue to the east (Figure 2).

Bellport Bay, part of the south shore estuary system, is located about 2.5 miles south of the landfill. Fresh water streams near the landfill site are Beaverdam Creek, Yaphank Creek, Little Neck Run, and Carmans River. The Beaverdam Creek is closest; its headwaters rise south of Sunrise Highway, southeast of the landfill. Carmans River is the largest stream near the landfill, located approximately 1¾ miles to the east of the landfill. Yaphank Creek and Little Neck Run are tributaries to Carmans River and are located approximately ¾ miles southeast of the landfill. The Station Road well-field, a public water supply source operated by the Suffolk County Water Authority (SCWA), is located about a mile west of the site, along Station Road.

Vegetation surrounding the landfill consists of a typical eastern Long Island forest mix of oaks, American Beech, and Pitch Pine. The undergrowth is typically Lowbush Blueberry and Scrub Oak. A more deciduous mix is found along Montauk Highway, composed of Red Maple, Highbush Blueberry, Red Cedar, and Black Willow. The tidal and freshwater marshes along the Beaverdam Creek south of Beaverdam Road, at Fireplace Neck, and along the Carmans River south of Sunrise Highway are comprised of Phragmites, Salt Marsh Hay, Spike Grass, American Beach Grass, and sedges (LIRPB, 1990).

Beaverdam Creek is a “Significant Fish and Wildlife Habitat” (New York State Department of State, 1987). It harbors birds such as the Short-eared Owl, Marsh Hawk, and Rough-legged Hawk, and waterfowl such as the Mallard, Black Duck, Mute Swan, Canvasback, and Canadian Goose. The Great South Bay is productive habitat for fish species such as Winter Flounder, Bluefish, Blue Claw Crab, Atlantic Silverside, Striped Killfish, Mummichog, Northern Pipefish, and Sticklebacks (LIRPB, 1990).

Certain threatened species including Osprey, Northern Harrier, and Mud Turtle are found in the vicinity of the landfill. Commonly found fauna around the landfill site includes the Muskrats, Woodchuck, moles, rabbits, White-tailed Deer, Hognose Snake, stray cats, and dogs. (LIPRB, 1990). Abundant gulls are found at the site, especially at the transfer station. Turkeys have also colonized the landfill area.
Figure 1: Approximate location of the study area (indicated by red box)

Figure 2: Aerial view of the Brookhaven landfill site and its vicinity
The landfill occupies about 180 acres of the 536 acre Town of Brookhaven Waste Management Facility. Other facilities at the site include a Material Recycling Facility (MRF), a landfill gas-to-energy recovery system, a waste transfer station, a Stop-Throwing-Out-Pollutants (STOP) facility, a residential drop-off center, an area for wood chipping, four leachate storage tanks, a machine shop, the scale-house and several of the landfill administrative buildings. Four recharge basins are located on the facility - two to the south of the landfill, one to the east, and one to the north (Dvirka and Bartilucci, 2001).

The former two-mound topography of the landfill is being altered by new construction. The mound to the east is composed of older sections or “Cells” of the landfill – Cells 1, 2, 3 and 4 (Figure 3). The mound to the west is Cell 5. The two mounds were separated from each other by a valley. Cell 6 has been constructed in the valley and will extend along the northern edge of Cell 5 and the Cells 1-4 massif. All of the landfill cells are lined, with the liner being of varying composition and design. The older cells of the landfill, Cells 1, 2 and 3, received municipal solid waste (MSW). Cell 4 received a combination of MSW, construction and demolition (C&D) debris, and incinerator ash. Waste inputs to Cell 5 and Cell 6 are restricted to incinerator ash, C&D, and other inert material. The current fill rate is approximately 2,700 tons/d or about 1 million tons/yr.
Figure 3: Brookhaven landfill site plan (Dvirka and Bartilucci, 2011)
The operating history of the landfill, along with liner composition and footprint sizes, is summarized in Table 1.

A topographic map of Bellport developed by the USGS in 1967, prior to construction of landfill, indicates that the landfill area was a vacant, wooded area. The landfill modules were excavated into the vadose zone sediments, which are predominantly Pleistocene glacial outwash. The bottom elevation of Cell 1 appears to be about 32 ft mean sea level (msl), judging from the elevation of the gravity feed leachate pipe at its egress from the landfill into a manhole collection chamber. The basal depth of Cell 2 is unknown, but is assumed to be approximately the same. The bottom elevations of Cell 3 and Cell 4 are about 31.5 ft msl and 39.5 ft msl respectively (Dan Johnson, personal communication, April 6, 2012). Cell 1 strikes to the west, Cell 3 and Cell 4 to the south. The low point of Cell 2 is a little north of its center point, and Cell 2 drained to a central low center line.

All phases of Cell 5 were designed to drain west. The bottom elevation of Cell 5 ranges from about 54 ft msl to about 37 ft msl (Dan Johnson, personal communication, April 6, 2012). Phase 1 of Cell 6 drains south, Cell 6- Phase 2 drains north, and Cell 6- Phase 3 drains west. The leachate systems are designed to have automated pumpage activated by level indicators. The pumps in the leachate collection systems for Cell 5 and 6 are designed to maintain less than 1 foot of head on the liner system. The landfilled ash has caused operational problems due to clogging and fouling, and the harsh chemical atmosphere in the manhole is tough on equipment. In 2011, about 30 million gallons of leachate was pumped from the liner systems (Greene and Tonjes, 2012). The leachate is temporarily stored in tanks onsite, and then shipped by tanker trucks to the Suffolk County Bergen Point sewage treatment plant in Babylon, treated, and discharged into the Atlantic Ocean.
<table>
<thead>
<tr>
<th>Cell - Phase</th>
<th>Year Opened</th>
<th>Year Capped</th>
<th>Baseliner (Acres)</th>
<th>Type of waste received</th>
<th>Liner System</th>
<th>Evidence of Liner Leak</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell 1</td>
<td>1974</td>
<td>1993</td>
<td>45</td>
<td>Municipal Solid Waste (MSW)</td>
<td>Single liner - 20 mil PVC</td>
<td>Yes</td>
</tr>
<tr>
<td>Cell 2</td>
<td>1980</td>
<td>1993</td>
<td>36</td>
<td>Double liner - 20 mil PVC overlain with 20 mil Chlorinated Polyethylene</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Cell 3</td>
<td>1989</td>
<td>1993</td>
<td>4</td>
<td>Double liner – 80 mil HDPE overlain with 60 mil PVC</td>
<td>Unknown</td>
<td></td>
</tr>
<tr>
<td>Cell 4</td>
<td>1991</td>
<td>1997</td>
<td>4.5</td>
<td>MSW + Incinerator Ash</td>
<td>Triple liner – One 60 mil PVC + Two 80 mil HDPE over liners</td>
<td>No</td>
</tr>
<tr>
<td>Cell 5</td>
<td>1996</td>
<td>Partially capped in 2002, 2005</td>
<td>56</td>
<td>Construction and Demolition Debris (C&amp;D) + Incinerator Ash</td>
<td>Double composite liner</td>
<td>No</td>
</tr>
<tr>
<td>Cell 6- Phase 1</td>
<td>2003</td>
<td>--</td>
<td>13.2</td>
<td>C&amp;D + Incinerator Ash</td>
<td>Double composite liner</td>
<td>No</td>
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<td>Cell 6- Phase 2</td>
<td>2003</td>
<td>--</td>
<td>10.5</td>
<td>C&amp;D + Incinerator Ash</td>
<td>Double composite liner</td>
<td>No</td>
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<td>Cell 6- Phase 3</td>
<td>2006</td>
<td>--</td>
<td>13.7</td>
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<td>Double composite liner</td>
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<td>Cell 6- Phase 4</td>
<td>2011</td>
<td>--</td>
<td>8.4</td>
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<td>Cell 6- Phase 5</td>
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<td>--</td>
<td>12.3</td>
<td>--</td>
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<tr>
<td>Cell 6- Unbuilt Phases</td>
<td>--</td>
<td>--</td>
<td>70</td>
<td>--</td>
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</tr>
</tbody>
</table>

Table 1: Operational history and liner properties of the Brookhaven landfill (Dvirka and Bartilucci, 2010; 2011); 1 mil = 0.001 inch
4. Previous investigations

The hydrogeology of Long Island has been studied by researchers for over a century. Fifty-seven publications relevant to this study are listed in Table 2.
<table>
<thead>
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<th>Year of Publication</th>
<th>Author(s)</th>
<th>Title</th>
<th>Agency</th>
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<tr>
<td>1906</td>
<td>Veatch, A., Slichter, C., Bowman, I., Crosby, W., Horton, R.</td>
<td>Underground Water Resources of Long Island, NY</td>
<td>USGS¹</td>
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<tr>
<td>1914</td>
<td>Fuller, M.L.</td>
<td>The Geology of Long Island, NY</td>
<td>USGS</td>
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<td>1949</td>
<td>Suter, R., DeLaguna, W., Perlmutter, G.</td>
<td>Mapping of Geologic Formations and Aquifers of Long Island, NY</td>
<td>NYSWPCC²</td>
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<td>1963</td>
<td>DeLaguna, W.</td>
<td>Geology of Brookhaven National Laboratory and Vicinity, Suffolk County, NY</td>
<td>USGS</td>
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<tr>
<td>1963</td>
<td>Perlmutter, N., Gerathy, J.</td>
<td>Geohydrology and Groundwater Conditions in Southern Nassau and Southeastern Queens Counties, Long Island, NY</td>
<td>USGS</td>
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<tr>
<td>1963</td>
<td>Swarzenski, W.</td>
<td>Hydrogeology of Northwestern Nassau and Northeastern Queens County, Long Island, NY</td>
<td>USGS</td>
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<tr>
<td>1964</td>
<td>Pluhowski, E.J., Kantrowitz, I.</td>
<td>Hydrology of the Babylon-Islip Area, Suffolk County, Long Island, NY</td>
<td>USGS</td>
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<tr>
<td>1966</td>
<td>Isbister, J.</td>
<td>Geology and Hydrology of Northeastern Nassau County, Long Island, NY</td>
<td>USGS</td>
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<td>1968</td>
<td>Warren, M., DeLaguna, W., Lusczynski, N.</td>
<td>Hydrology of Brookhaven National Laboratory and Vicinity, Suffolk County, NY</td>
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<td>1971</td>
<td>Jensen, H., Soren, J.</td>
<td>Hydrogeologic Data from Selected Wells And Test Holes in Suffolk County, Long Island, NY</td>
<td>SCDEC⁴</td>
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<td>1971</td>
<td>Soren, J.</td>
<td>Results of Subsurface Exploration in the Mid-Island Area of Western Suffolk County, Long Island, New York</td>
<td>SCWA⁵</td>
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<td>1976</td>
<td>Fetter, C.</td>
<td>Hydrogeology of the South Fork of Long Island, NY, in March 1975</td>
<td>USGS</td>
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<td>1976</td>
<td>Prince, K.</td>
<td>Potentiometric Surface of the Magoty Aquifer on Long Island, NY, in March 1975</td>
<td>USGS</td>
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<td>1982</td>
<td>Sirkin, L.A.</td>
<td>Wisconsinan Glaciation of Long Island, NY to Block Island, Rhode Island</td>
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<td>1983</td>
<td>Aronson, D.A., Lindner, J.B., Katz, B.G.</td>
<td>Geohydrology of the Meadowbrook Artificial Recharge Site at East Meadow, Nassau County, NY</td>
<td>USGS</td>
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<td>1984</td>
<td>Koszalka, E.J.</td>
<td>Geohydrology of the Northern Part of the Town of Brookhaven, Suffolk County, NY</td>
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<td>1987</td>
<td>Peterson, D.</td>
<td>Ground Water Recharge Rates in Nassau and Suffolk counties, NY</td>
<td>USGS</td>
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<td>1987</td>
<td>Kilburn, C., Krulikas, R.K.</td>
<td>Hydrogeology and Water Quality of the Northern Part of the Town of Oyster Bay, Nassau County, NY, in 1980</td>
<td>USGS</td>
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<td>1990</td>
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<td>Evaluation of Land Use Impacts on Environmental Quality in Urban and Semi-rural Streams Tributary to Great South Bay, Long Island, New York, Long Island</td>
<td>LIRPB</td>
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<td>1993</td>
<td>Tonjes, D.J., Black, J.</td>
<td>Town of Brookhaven Landfill Groundwater Assessment 1992 Update</td>
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<td>1994</td>
<td>Tonjes, D.J., Black, J.</td>
<td>Town of Brookhaven Landfill Groundwater Assessment 1993 Update</td>
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<td>1997</td>
<td>Cartwright, R.A.</td>
<td>Hydrogeologic-Setting Classification for Suffolk County, Long Island, NY</td>
<td>USGS</td>
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<td>2001</td>
<td>--</td>
<td>Part 360 Hydrogeologic Investigation Report Brookhaven Landfill Cell-6 Expansion</td>
<td>D&amp;B</td>
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<td>2001</td>
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<td>Town of Brookhaven 2001 Post-Closure Monitoring Report Cells 1-4</td>
<td>CA</td>
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<td>2002</td>
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<td>Carmans River Environmental assessment, Suffolk County, NY</td>
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<td>2003</td>
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<td>Town of Brookhaven Cells 1-4 2002 Groundwater and Leachate Monitoring Report</td>
<td>CA</td>
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<td>2004</td>
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<td>2008</td>
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<td>Beaverdam Creek, Brookhaven, NY, Status and Trends in Water Quality</td>
<td>SCDHS</td>
</tr>
<tr>
<td>2010</td>
<td>--</td>
<td>Leachate Plume Characterization Report for the Town of Brookhaven Landfill, Suffolk County, NY</td>
<td>D&amp;B</td>
</tr>
<tr>
<td>2011</td>
<td>--</td>
<td>Data Summary Report and Leachate Plume Monitoring Plan, Town of Brookhaven Landfill, Suffolk County, NY</td>
<td>D&amp;B</td>
</tr>
</tbody>
</table>

1 U.S. Geological Survey, 2 New York State Water and Power Control Commission, 3 New York State Water Resources Commission, 4 Suffolk County Department of Environmental Control, 5 Suffolk County Water Authority, 6 Long Island Regional Planning Board, 7 Town of Brookhaven, 8 Divrka and Bartilucci, Inc., 9 Cashin Associates, 10 Suffolk County Department of Health Services

Table 2: Selected relevant hydrogeological investigations
5. **Regional and local physiography**

Long Island extends approximately from 72ºW to 74ºW and from 40º30’N to 41º15’N (Figure 4) and is located at the farthest end of the North Atlantic Coastal Plain physiographic province (Aronson et al., 1983). It extends east from the southeastern part of New York and is separated from mainland New York by the East River. Long Island is about 120 miles long and about 20 miles wide at most places. It is bounded to the north by the Long Island Sound, to the south and east by the Atlantic Ocean, and by New York Bay and the East River to the towards west. Long Island is divided into four administrative units – Kings, Queens, Nassau and Suffolk Counties. Kings and Queens Counties are part of new York City. Islands such as Fire Island, Gardiners Island, Shelter Island, Fishers Island, and Plum Island are included in the administrative boundaries of Suffolk County.

The major surficial features of Long Island are two east-west trending lines of hills, the Harbor Hill and Ronkonkoma moraines. The generally accepted tenet is that the moraines mark the southernmost extent of Woodfordian ice sheet advance during the Wisconsinan Glaciation at the Last Glacial Maximum 18,000 years ago. The two moraines are joined in Nassau County but bifurcate eastward. The Harbor Hill moraine is located along the north shore of Long Island and extends from Kings County from west to north fork of Long Island to east. The Ronkonkoma moraine forms a chain of hills that extends from northwestern Nassau County to south fork of Long Island via central Suffolk County. At certain locations, north-south trending inter-lobate moraines were formed in the gaps between different sub-lobes of the moraines (Sirkin, 1982).

The moraines have a general altitude of about 200 to 300 ft msl (Figure 5). The outwash plains along the north shore have been severely eroded due to wave action and form vertical bluffs that may reach an elevation of up to 100 ft msl. The south shore outwash plains slope gently towards the shore at the rate of about 20 ft/mile (McClymonds and Franke, 1972).
Figure 4: Long Island counties and topographical features (McClymonds and Franke, 1972)

Figure 5: Digital Elevation Model (DEM) showing the land surface altitude of Long Island topographic features (Modified from Bennington, J.B., 2005, Available at http://people.hofstra.edu/J_B_Bennington/research/long_island/li.html#DEM)
The moraines are flanked to the north and south by a thick blanket of outwash plains (Sirkin, 1982). Sources of these outwash deposits can be traced back to central Connecticut and Rhode Island, indicating transport of the sediments south by the Woodfordian glacial advance (Sirkin, 1982). The meltwaters deposited abundant quantity of sand along the south shore outwash plains. This, along with reworking due to wave action, low topographical gradient and longshore drift resulted in formation of a series of disconnected barrier beaches such as the Long Beach, Jones Beach and Fire Island (Scorca et al., 1995). The space between the barrier beaches and the outwash plains along the south shore is occupied by saltwater bodies such as South Oyster Bay, Great South Bay, Moriches Bay, and Shinnecock Bay. The Peconic estuary system splits eastern part of Long Island into two peninsulas – the North Fork and South Fork (McClymonds and Franke, 1972). Harbors on the north shore such as Flushing Bay, Little Neck Bay, Manhasset Bay, Oyster Bay, Cold Spring Harbor, Northport – Huntington Bay, Port Jefferson Harbor, Port Washington, Port Jefferson, and Hempstead Harbor are generally deep enough to serve as useful ports.

The composition of the moraines and the outwash plains is primarily sand and gravel with occasional silt and clay (Wexler, 1988a; Garber, 1986). The outwash plains appear to have blended in with the morainal deposits with no apparent contact due to lithological resemblance (Koszalka, 1984). The sediments in the moraines are reworked due to the Woodfordian glacial advance and deposition of glacial till (Sirkin, 1982). The sand is mostly quartzose with traces of alkali feldspar, mica, muscovite, pyroxene, amphibole, and other minerals (DeLaguna, 1963).

The landfill site is south of the Ronkonkoma moraine on a relatively flat, featureless, and southward sloping outwash plain with gently rolling topography. The topography at the landfill site strikes in the northwest direction and dips in southeast direction. The land surface elevation at the landfill site varies from 70-80 ft msl to the northwest to about 35-50 ft msl to the southeast. Elevations in the landfill vicinity range from a high of 80 ft to the northwest of the site to near sea level to the southeast, near to Great South Bay. Maximum actual elevation in the area of the landfill is about 250 ft msl - the elevation of the landfill mounds (as of 2009) (Figure 6a).

The topographical elevation dips on the western boundary of the landfill site due to presence of a valley that is approximately 2 ½ miles wide. All four major water bodies near the landfill site lie in this valley: Beaverdam Creek lies on the eastern edge and Carmans River on the western edge of the valley, while Yaphank Creek and Little Neck Run traverse through the valley in a southeastern direction. The elevation of the valley is noticeably lower than the surrounding area: 20-25 ft msl on the edges while in the center of the valley it is less, about 15-20 ft msl (Figure 6b-c). The elevation of the valley gently dips towards the Great South Bay where it approaches sea level.
Figure 6: (a) Digital Elevation Model (DEM) of the Brookhaven landfill site and its vicinity, (b) elevation profile transect (yellow line), and (c) elevation profile.
6. Regional and Local Geology

The Long Island sub-surface is composed of unconsolidated sediments of Cretaceous and Pleistocene age (DeLaguna, 1963). These sediments rest on a bedrock surface that dips in the southeasterly direction. The thickness of the sedimentary deposits vary across Long Island with about 0 ft in northwestern Queens County to about 2,000 ft underneath the barrier islands located in the southeastern Suffolk County (Smolensky et al., 1989). The sedimentary units that overlie the bedrock are (from bottom to top) (i) the Lloyd sand member of the Raritan Formation, (ii) the clay member of the Raritan Formation (Raritan Clay), (iii) the Matawan Group-Magothy Formation, (iv) Gardiners Clay, (v) the Upper Glacial aquifer, and (vi) Holocene or recent deposits. The members of the Raritan Formation and the Matawan Group-Magothy Formation are Cretaceous in origin; Gardiners Clay and the Upper Glacial deposits are of Pleistocene age, while the recent deposits belong to the Holocene age (McClymonds and Franke, 1972). The Upper Glacial deposits, the Matawan Group-Magothy Formation, and the Lloyd sand member of the Raritan Formation act as aquifers while Gardiners Clay and the clay member of the Raritan Formation act as confining units that confine the Magothy aquifer and the Lloyd aquifer respectively. Along with these major hydrogeologic units, certain units such as Jameco Gravel and Monmouth Greensand have localized presence and therefore influence the hydrogeologic conditions in certain areas of Long Island. The sedimentary deposits along the south shore of Long Island extend beyond the mainland and barrier beaches out under the Atlantic Ocean (Scorca et al., 1995).

The general geology of Long Island near the landfill is summarized in Table 3.
<table>
<thead>
<tr>
<th>System</th>
<th>Series</th>
<th>Hydrogeologic Unit</th>
<th>Geologic Unit</th>
<th>Approximate thickness (ft)</th>
<th>Approximate upper surface elevation (ft below MSL)</th>
<th>Description and water-bearing character</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quaternary</td>
<td>Holocene</td>
<td>Recent deposits</td>
<td>Recent deposits</td>
<td>0-10</td>
<td>--</td>
<td>Recent shore, beach, and salt marsh deposits and artificial fill</td>
</tr>
<tr>
<td>Pleistocene</td>
<td>Upper Glacial</td>
<td>Upper Pleistocene</td>
<td>Upper Pleistocene deposits</td>
<td>150-200</td>
<td>--</td>
<td>Mainly brown, gray sand and gravel of moderate to high hydraulic conductivity; may also include deposits of clayey till and lacustrine clay of low hydraulic conductivity. A major aquifer.</td>
</tr>
<tr>
<td></td>
<td>Aquifer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gardiners Clay</td>
<td>Gardiners Clay</td>
<td></td>
<td>10-20</td>
<td>90-150</td>
<td>Green and grey clay, silt, clayey and silty sand, and some interbedded clayey and silty gravel. Unit has low hydraulic conductivity and tends to confine underlying aquifer.</td>
</tr>
<tr>
<td>Cretaceous</td>
<td>Cretaceous</td>
<td>Monmouth Greensand</td>
<td>Monmouth Group, undifferentiated</td>
<td>10-20</td>
<td>70-165</td>
<td>Interbedded marine deposits of dark gray, olive-green, dark greenish-gray and greenish-black glauconitic and lignitic clay, silt, and clayey and silty sand. Unit has low hydraulic conductivity and tends to confine water in underlying aquifer.</td>
</tr>
<tr>
<td></td>
<td>Magothy Aquifer</td>
<td>Matwan Group -</td>
<td>Matwan Group - Magothy Formation,</td>
<td>900-1100</td>
<td>110</td>
<td>Gray and white fine to coarse sand of moderate hydraulic conductivity. Generally contains sand and gravel beds of low to high hydraulic conductivity in basal 100 to 200 ft. Contains much interstitial clay and silt, and beds and lenses of clay of low hydraulic conductivity. A major aquifer; partially developed in study area.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Raritan Clay</td>
<td>Clay member of Raritan Formation</td>
<td>200</td>
<td>1100</td>
<td>Gray, black, and multicolored clay and some silt and fine sand. Unit has low hydraulic conductivity and tends to confine water in underlying aquifer.</td>
</tr>
<tr>
<td></td>
<td>Llloyd Aquifer</td>
<td>Lloyd Sand Member</td>
<td>Lloyd Sand Member of the Raritan Formation</td>
<td>300-500</td>
<td>1300</td>
<td>White and gray fine-to-coarse sand and gravel of moderate hydraulic conductivity and some clayey beds of low hydraulic conductivity.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paleozoic /</td>
<td></td>
<td>Bedrock</td>
<td>Undifferentiated crystalline rocks</td>
<td>--</td>
<td>1600</td>
<td>Mainly metamorphic rocks of low hydraulic conductivity; surface generally weathered; considered to be the bottom of the groundwater reservoir.</td>
</tr>
<tr>
<td>Precambrian</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Table 3: Generalized Long Island hydrogeologic units around the Brookhaven landfill site (modified from Jensen and Soren, 1971)
7. Depositional History of Long Island Sediments

The deposition of sedimentary units and topographical features on Long Island is a result of movement and structuring of the sedimentary mass brought first by the erosion of northeastern highlands during the upper Cretaceous and thereafter by glacial advances during the late Pleistocene epoch (about 100,000 to 18,000 yrs before present (BP)) (Sirkin, 1982).

The bedrock in the region is of late-Precambrian to early Paleozoic era (about 575 million yrs BP). This crystalline bedrock was eroded sub-aerially into a fall zone peneplain during the late Triassic and Jurassic times (about 250 million to 150 million yrs BP). It was then raised in the northwestern direction due to uplifting of the earth’s crust along eastern parts of North America. This resulted in the present northeasterly strike and southeasterly dip of the bedrock. This tilting provided a southeasterly topographical gradient that facilitated erosion of the sediments from bedrock in New York and New England (Sirkin, 1982).

Erosion of the northwesterly highlands and the deposition of sediments continued during the Cretaceous age (138 million to 63 million yrs BP) and resulted in the formation of the Raritan and Magothy Formations. During the Tertiary period (from 63 million to 2 million yrs BP), the deposition of sediments either came to halt, or was subsequently followed by erosion that washed away the sediment deposition (Koszalka, 1984). A “cuesta” shaped valley found in Kings Point and Sand Point implies severe erosion of the Raritan Formation during the Tertiary period (Swarzenski, 1963; Koszalka, 1984). The origin of high relief of Cretaceous deposits on the north shore has been attributed to erosion from the post-Cretaceous streams flowing east-west into the strike valley (the present Long Island Sound) draining into the Atlantic Ocean (Swazensky, 1963). These streams may also have eroded the Cretaceous surface along the present north shore of Long Island to form the adjacent bays along the north shore (Swarzenski, 1963; Lewis and DiGiacomo-Cohen, 2000). The Tertiary period was followed by the Pleistocene epoch (from about 2 million to 10,000 yrs BP), when upper sedimentary units - Jameco Gravel, Gardiners Clay, and the Upper Pleistocene deposits - were laid down in cycles of glacial deposition and inter-glacial restructuring to give Long Island its present form.

Glacial/ interglacial events that occurred during the late Pleistocene epoch are of particular interest with regard to formation of the present topography and upper geology of Long Island. The late Pleistocene epoch is comprised of two stages – the Sangamonian Interglacial stage (> 43,000 yrs BP) and the Wisconsinan Glacial stage (43,000 to 18,000 yrs BP). The Wisconsinan stage is further classified into three glacial substages and two interglacial substages: the Altonian Glacial substage followed by the Nassauan Glacial substage (43,000 to 33,000 yrs BP), the Portwashingtonian Interglacial substage (33,000 to 28,000 yrs BP), the Farmadalian Interglacial substage (28,000 to 21,000 yrs BP), and the Woodfordian Glacial substage (21,000 to 18,000 yrs BP). After the Woodfordian, the glaciers began receding and had completely retreated from Long Island about 18,000 years ago (Sirkin, 1982).
Sirkin (1982) posits that the ice front of the Woodfordian advance was formed by three lobes – the Hudson lobe that deposited sediments in the western section of Long Island and in New Jersey, the Connecticut lobe that formed the morainal and outwash deposits on eastern Long Island, and the Eastern Connecticut-Rhode Island lobe that deposited sediments to southeastern Long Island extending up to Block Island. Each glacial lobe had a number of individual extensions or sub-lobes the extent of whom varied. The lobate ice margins are distinctly reflected in the horse-shoe shaped arrangement of the moraine deposits on Long Island.

At the beginning of the Wisconsinan glacial advance, the ice pushed outwash and till that it came into contact with as the glaciers moved south. This southerly movement of glaciers and the sediments is termed the “Ronkonkoma drift.” The farthest extension of the drift along the north shore is marked by the Ronkonkoma moraine in west-central Long Island. During interglacial period, the glacier retreated and re-advanced assuming a new position and thereby forming the Harbor Hill moraine (Swarzenski, 1963). Therefore, these moraines are considered a terminal moraine (representing the farthest extent of the glacial advance) and a recessional moraine (representing the subsequent position of the receding ice) respectively (Sirkin, 1982).

Hanson (2012) proposes that the glaciers extended further south of the Ronkonkoma moraine; thus the Ronkonkoma moraine is not a terminal moraine but a push moraine; the terminal moraine had been created further south, and is now submerged and/or eroded in the Atlantic Ocean. Hansons’s theory is based partially on observations of till south of the Ronkonkoma moraine, which could only have been deposited if the glacier passed over the Ronkonkoma moraine and deposited coarse sediments and unsorted material to the south. King et al. (2003) found till at shoreline locations such as Westhampton and Amityville, south of the Ronkonkoma moraine. Till was also observed at the Cell 5 excavation in 1993.

According to Sirkin (1982), ancient channels that existed prior to the glacial advance were further eroded and deepened as they carried the meltwater from the glaciers. Post-glacial outwash deposition buried some of these channels while meltwater in the channels that persisted carved through the morainal deposits to the seashore. This erosion of the moraines formed stream valleys adjoined by high to medium relief hills or “cols”, such as the valley that harbors the Carmans River and its tributaries (Bennington, 2003). In addition, melting of buried ice formed localized kettle holes that were later transformed into kettle lakes in places where the water table levels exceeded the ground elevation. Lake Ronkonkoma in central Suffolk County (Sirkin, 1982) and the scuttle hole ponds near Bridgehampton (Sen and Hanson, 2007) are believed to be examples of kettle lakes. Similarly, low lying areas where proglacial lakes formed filled with finer sediments (such as the Smithtown Clay) which later created localized perched water, which when expressed above the ground surface creates isolated perched ponds (Koszalka, 1984).
8. Hydrogeologic Units of Long Island

The sub-surface geology of Long Island represents an unconformable arrangement of the member geological units. Some geologic units have pan-Long Island presence while others are localized. The major hydrogeologic units present at the study area are as follows (along with the hydrologic unit they represent) (from bottom to top) (Figure 7):

a. bedrock
b. Lloyd sand member of the Raritan Formation (Lloyd aquifer)
c. Clay member of Raritan Formation
d. Matawan Group-Magothy Formation (Magothy aquifer)
e. Monmouth Greensand
f. Gardiners Clay
g. Upper Pleistocene deposits (Upper Glacial aquifer)

The description of the hydrologic units matches with the description of the lithostratigraphic units on Long Island and therefore these units are combined as “hydrogeologic units” of Long Island (Garber, 1986). The following discussion describes the regional and local extents and composition of each of the hydrogeologic units along with their water bearing properties.
Figure 7: Generalized cross section of Long Island geology near the study area (modified from McClymonds and Franke, 1972)
8.1. **Bedrock**

The bedrock on Long Island forms the foundation on which the unconsolidated sedimentary units rest. Long Island bedrock elements can be observed in mainland New York and Connecticut (DeLaguna, 1963). The bedrock is composed of crystalline rocks such as schist and gneiss (Perlmutter and Gerathy, 1963). Its surface is a relatively flat, gently sloping, undulating surface (a peneplain) (Suter et al., 1949). Outcrops can be observed in the northwestern Queens County. The bedrock strikes in northeasterly direction and dips in southeasterly-easterly direction at a rate of 65 ft to 100 ft/mile (Garber, 1986; Soren, 1971). It is found at a depth of -2,000 ft msl along the south shore of the southeastern Suffolk County (Suter et al., 1949) (Figure 8). The bedrock is of Precambrian age (Sirkin, 1982).

The upper surface elevation of the bedrock underneath the landfill is about -1,600 ft msl. The material composition, geologic gradient, and overall strike direction of the local observations concur with that of the regional pattern. A lack of fracture zones, fissures, and openings resists substantial infiltration and subsequent storage of groundwater and therefore the bedrock is not considered to be a hydrologic unit on Long Island (DeLaguna, 1963).

8.2. **Raritan Formation**

The members of the Raritan Formation are unconsolidated sedimentary deposits formed during the Cretaceous period (DeLaguna, 1963). The Raritan Formation was named owing to its resemblance to riverbed outcrops observed along the Raritan River in New Jersey (DeLaguna, 1963; Garber, 1986). The Raritan Formation consists of two members - the Lloyd sand member that directly overlies the bedrock (unconformably), and the capping clay member of the Raritan Formation – the Raritan Clay (Koszalka, 1984).

8.2.1. **Lloyd Sand Member**

The Lloyd sand member of the Raritan Formation extends from New Jersey out onto the continental shelf south of the south shore of Long Island (Veatch et al., 1906; Garber, 1986). It overlies the Precambrian bedrock under most parts of Long Island. It is absent in Kings and Queens Counties and northern Nassau County where extensive erosion of the Cretaceous deposits occurred. In these places, the eroded surface has been filled by glacial deposits of Pleistocene age (Aronson et al., 1983; Soren, 1971).
Figure 8: Bedrock elevation contours (in ft msl) (modified from Smolensky et al., 1989)
The Lloyd member of the Raritan Formation is hypothesized to continue beneath the Long Island Sound (DeLaguna, 1963); however, Chu (2006) sets a northern limit of the unit in northern Kings, northwest Queens and Nassau, and northeast Suffolk Counties. The thickness of the sand member averages about 300 ft, but varies from being entirely absent or very thin in northwestern Queens to about 350 ft in southeastern Suffolk County. The Lloyd sand member is generally thickest along the south shore and tapers to the north (Chu, 2006).

The Lloyd sand member is composed of white-gray, fine to coarse grained sand and gravel, and interstitial clay with occasional lenses of sandy to pure clay and pebbles (Aronson et al., 1983; DeLaguna, 1963). The sand is mostly quartz while the clay is mostly kaolinite. The abundance of kaolinite indicates a non-marine origin (DeLaguna, 1963). Traces of lignite, iron oxide, and some other heavy minerals can also be found (Garber, 1986). The mineralogical composition of the Lloyd sand member, dominated by material that withstood extended periods of weathering and abrasion, suggests that its deposition occurred during a warm, possibly interglacial period (DeLaguna, 1963).

The Lloyd aquifer is the deepest aquifer unit on Long Island. Direct recharge to the Lloyd occurs only at the center of Long Island, at the major hydrologic divide. Groundwater from overlying aquifer units can percolate into the Lloyd aquifer but the rate and quantity is controlled by the Raritan clay and other overlying confining units. Groundwater withdrawal from the Lloyd aquifer is restricted mostly to Queens and Nassau Counties where the Lloyd sand member is shallower (Garber, 1986; Busciolano, 2002).

The upper elevation of the Lloyd sand member ranges from sea level in northwestern Long Island to an estimated -1,700 ft msl south of south shore of Long Island. Underneath the landfill site, the elevation of the Lloyd sand member ranges from -1,300 to -1,400 ft msl (Figure 9).

Compared to Long Island other hydrogeologic units, the Lloyd sand member has the lowest average hydraulic conductivity, ranging from 40 ft/d to 67 ft/d. The average transmissivity for the unit, assuming an average thickness of 240 ft and an average horizontal hydraulic conductivity of 48 ft/d, is estimated to be about 90,000 gpd/ft (gallons per day per ft) (McClymonds and Franke, 1972). Pumping tests conducted at the Brookhaven National Laboratory (BNL) site found a hydraulic conductivity estimate of 26 ft/d and a transmissivity value of 12,500 gpd/ft (Warren et al., 1968). A hydraulic conductivity value of 67 ft/d was estimated near Lake Ronkonkoma in central Suffolk County (Soren, 1971). Transmissivity estimates range from 35,000 gpd/ft (Kings County) to 60,000 gpd/ft (Queens County) to 90,000 gpd/ft (northern Nassau County) to 120,000 gpd/ft (southern Nassau County), with values of 75,000 gpd/ft to 90,000 gpd/ft for Suffolk County (McClymonds and Franke, 1972). The average anisotropy ratio of the Lloyd aquifer is 10:1 (Smolensky et al., 1989).
Figure 9: Lloyd sand member elevation contours (in ft msl) (modified from Smolensky et al., 1989)
8.2.2. Clay Member of the Raritan Formation

The clay member of the Raritan Formation conformably overlies the Lloyd sand member except in places where the Raritan Formation members have been eroded. No formal name has been designated to the clay member, although it is commonly known as the Raritan Clay (Perlmutter and Gerathy, 1963).

Similar to the Lloyd sand member, the Raritan Clay is present at a shallower depth in northwestern Long Island; it outcrops in areas in northern Queens and then dips in a southeasterly direction. The gradient of the dip has been estimated to be about 42 ft/mile. Its elevation ranges from about 30 ft msl in northern Kings County to about -300 ft msl along the south shore. The average thickness of the Raritan Clay is about 200 ft (Aronson et al., 1983). Raritan Clay extends underneath the Long Island Sound to the north and underneath the barrier islands to the south (Soren, 1971).

Raritan Clay is about 200 ft thick and is present at an approximate elevation of -1,150 ft below msl underneath the landfill site (Dvirka and Bartilucci, 1994a) (Figure 10). Raritan Clay is composed of silty to dense lignitic pure clay, interstitial, localized fine sand, and pyrite. Perlmutter and Gerathy (1963) suggest the clay was deposited as fine particles by slow moving streams in broad flood plains, as they found no marine fossils in the Raritan Clay samples. Similarly, Lonnie (1982) proposes a non-marine origin based on the presence of resistant material such as kaolinite, and the absence of chlorite and lesser amounts of illite than found in most marine clays.

The Raritan Clay is nearly impermeable and therefore acts as a confining unit that separates Lloyd aquifer from the overlying aquifer units. The horizontal hydraulic conductivity of the Raritan Clay is about 0.01 ft/d and the vertical hydraulic conductivity is approximately 0.001 ft/day (Franke and Cohen, 1972).
Figure 10: Raritan Clay elevation contours (in ft msl) (modified from Smolensky et al., 1989)
8.3. Matawan Group - Magothy Formation

The uppermost (youngest) sedimentary deposit of the Cretaceous period that underlies Long Island is the Matawan Group-Magothy Formation, undifferentiated. DeLaguna (1963) suggests that the Matawan Group-Magothy Formation on Long Island is an easterly extension of the Magothy Formation of New Jersey and that it resembles its type area found along the Magothy River in Maryland. The Matawan Group-Magothy Formation unconformably overlies the Raritan Clay and is overlain unconformably for most part by the Monmouth Greensand or by the transitional deposits of Pleistocene age (Aronson et al., 1983). This unit is absent in northern and western Kings, northern and central Queens, and the northern margins of Nassau and Suffolk Counties (Garber, 1986; DeLaguna, 1963). Its surface is irregular as it is severely eroded by advancing-retreating glaciers and glaciofluvial channels (Sirkin, 1982).

The elevation of the Matawan Group-Magothy Formation ranges from about 200 ft msl to -500 ft msl; its thickness ranges from about 400 ft at the north shore to about 900 ft under the south shore, and from less than 500 ft to the west to about 800 ft to the east (Soren, 1971; Doriski and Wilde-Katz, 1983; Lindner and Reilly, 1983). Geophysical investigations suggest that the upper surface of the Matawan Group-Magothy Formation at the landfill site begins between -110 to -130 ft msl while its thickness is about 900 ft (Dvirka and Bartilucci, 1994a) (Figure 11).

The Matawan Group-Magothy Formation is composed of fine to medium quartzose sand interbedded with silt, gray clay with abundant amounts of lignite, pyrite, marcasite, organic matter, and clay (Aronson et al., 1983; Lindner and Reilly, 1983; Dvirka and Bartilucci, 1994a). Geologic borings indicate the presence of localized clay lenses (discontinuous zones of solid clay of variable thickness) (Smolensky and Feldman, 1992). These clay lenses can be as much as 50 ft thick, generally proportionate with the overall thickness of the surrounding Matawan Group-Magothy Formation. Such localized clay lenses obstruct recharge pathways, lower the hydraulic conductivity, and can generate semi-confining conditions within the aquifer. The degree of confinement increases with depth.

Suter et al. (1949) links the non-fossiliferous nature of the Matawan Group-Magothy Formation on Long Island and the lack of glauconite indicate deposition to non-marine, continental deltaic origins. Also, Lonnie (1982) observes a southerly increase in marine fossils and decreases in sand content in the deposition, and so postulates that the source of the continental deposits was northeast of Long Island.
Figure 11: Matawan Group-Magothy Formation elevation contours (in ft msl) (Modified from Smolensky et al., 1989)
In the absence of overlying Pleistocene transitional deposits, the Matawan Group-Magothy Formation is directly overlain by Monmouth Greensand in south-central Suffolk County, Jameco Gravel in southwestern Kings and Queens Counties, and the Upper Glacial aquifer unit elsewhere on Long Island. The Matawan Group-Magothy Formation can be distinguished from other deposits by differences in the composition and texture of sand and clay. For example, the sand in Jameco Gravel is coarser with brown texture and commonly contains biotite, feldspar, and hornblende which are usually scarce or absent in the sands in the Magothy deposits (Perlmutter and Gerathy, 1963). Also, the clay in the Magothy Formation is light to dark gray, occasionally tan or black and it is composed of clay minerals along with muscovite, lignite, and quartz. Pollen grains and spores are commonly found in the clay although there is absence of any marine fossils. Conversely, clay in Pleistocene deposits is generally grayish green and is composed of biotite, chlorite, and glauconite with marine fossils (Perlmutter and Gerathy, 1963).

The Magothy aquifer, the hydrologic name of the Matawan Group-Magothy Formation, is considered a principal aquifer on Long Island (Aronson et al., 1983; DeLaguna, 1963). The shallower sections of the Magothy aquifer are comprised of fine sand and therefore have very low hydraulic conductivity values, and the least aquifer potential. The basal portion of the Magothy Formation contains coarse sand and gravel mixed with pebbles for about 100 to 150 ft from the base; the highest conductivity values for the Magothy, ranging from 160 ft/d to 210 ft/d, are assigned to this basal portion (Dvirka and Bartilucci, 2001).

Conductivity values decrease from west to east. This trend correlates with increases in thickness and fine material content of the aquifer (Gerathy and Miller, 1985). Groundwater from this aquifer is widely used in Nassau and Suffolk Counties (Busciolano, 2002). McClymonds and Franke (1972) calculate the average horizontal hydraulic conductivity of the aquifer to be 54 ft/d with a range of 27 ft/d to 134 ft/d. Soren (1971) measures conductivity at 67 ft/d for Nassau and Queens Counties while Isbister (1962) finds 268 ft/d for the same area. Franke and Cohen (1972) infer a value of 50 ft/d.

The mean horizontal hydraulic conductivity calculated by Dvirka and Bartilucci based on their hydrogeologic investigation at a shallow Magothy well MW-11M (220 ft below grade or about -150 ft msl) is 1 ft/d (Bouwer-Rice rising head test) and 0.033 ft/d (Hazen method). Based on the average horizontal hydraulic conductivity value of 1 ft/day, the average groundwater velocity for the upper portion of the Magothy aquifer is calculated to be about 0.0043 ft/d (Dvirka and Bartilucci, 1994a). Also, vertical hydraulic conductivity based on the same test is estimated to be 0.03 ft/d (Dvirka and Bartilucci, 1994a, 1996a).
Estimates of anisotropy range from 30:1 to 100:1 (Lindner and Reilly, 1983; Smolensky et al., 1989; Franke and Cohen, 1972). The large range is attributed to the gradational deposition of sands in the Magothy aquifer, coarser basal units, and the presence of localized lenticular clay lenses (Franke and Cohen, 1972). Dvirka and Bartilucci calculated 33:1 anisotropy at the landfill site (Dvirka and Bartilucci, 1994a).
8.4. Monmouth Greensand

Monmouth Greensand is found along the south shore of Long Island from southeastern Nassau County to the southern edge of the Shinnecock Bay (Figure 12). Monmouth Greensand directly overlies the Matawan Group-Magothy Formation and is itself overlain by Gardiners Clay (in the vicinity of landfill site). Monmouth Greensand thickness increases from less than a foot at its northern limit to about 200 ft at the barrier beaches (Perlmutter and Todd, 1965). Its upper surface elevation ranges from -70 to -165 ft msl (Doriski and Wilde-Katz, 1983; Perlmutter and Todd, 1965). Wexler and Maus (1988) interpret Monmouth Greensand to be present south of the landfill site, from south of Montauk Highway to the west and to the south of Beaverdam Road to the east. They estimate it to be about 80 to 100 ft thick.

Due to the presence of glauconite and foraminifera, the Monmouth Greensand is generally thought to be marine deposits from the Late Cretaceous period (Perlmutter Todd, 1965). The lithology of the unit primarily consists glauconitic and lignitic clay of dark green to gray to black color interbedded with silty sand (Scorca et al., 1995).

The Monmouth Greensand has poor permeability. McCloymonds and Franke (1972) estimate vertical hydraulic conductivity to be about 0.0001 ft/day. Since the Monmouth Greensand is overlain by another confining unit, the Gardiners Clay, these units combine to serve as a confining layer generating discontinuous hydraulic connectivity between the Upper Glacial aquifer and the Magothy aquifer.
Figure 12: Monmouth Greensand elevation contours (in ft msl) (Modified from Smolensky et al., 1989)
8.5. Gardiners Clay

Gardiner Clay represents the uppermost confining unit of the Long Island hydrogeologic system, and is believed to have been deposited during the Pleistocene age. It lies unconformably under the Upper Glacial deposits that form the water table aquifer (DeLaguna, 1963). For the most part the Gardiners Clay overlies Monmouth Greensand, or the Matawan Group-Magothy Formation where the Monmouth Greensand is absent (Doriski and Wilde-Katz, 1983). Gardiners Clay extends over the whole south shore of Long Island to Southampton (Figure 13).

Gardiners Clay ranges from essentially no thickness at all at its northern limit to about 90 ft thick beneath the barrier islands (Doriski and Wilde-Katz, 1983). It may extend beyond the south shore beaches with an elevation ranging from -100 to -150 ft msl to -200 ft msl (Smolensky et al., 1989; DeLaguna, 1963). The vertical and horizontal extent of Gardiners Clay varies locally as a result of restructuring of sediments from glacial meltwater stream erosion (Doriski and Wilde-Katz, 1983) and its deposition on an irregular Cretaceous surface (Perlmutter and Gerathy, 1963).

A biostratigraphic investigation (Stone and Borns, 1986) indicates the age of the clay unit to be about Sangamon interglaciation period (~38,000 years BP), which is supported by others (Soren, 1971; Pluhowski and Kantrowitz, 1964; Doriski and Wilde-Katz, 1983; Koszalka, 1984; Sirkin, 1982).

Gardiners Clay is generally believed to be marine in origin, although it has also been described as a brackish, lagoonal, non-marine cold water (pro-glacial) deposit (Sirkin, 1986). Weiss (1954) found foraminifera in the samples of the Gardiners Clay collected from south central Long Island and therefore concludes that the clay was deposited in a shallow, brackish setting. Similarly, Lonnie (1982) analyzed clay samples from a boring on Fire Island and found traces of illite, traced back to its parent sediment in north-northeastern Long Island. He hypothesizes the material was transported by the glaciofluvial streams and deposited in a brackish bay environment. The general pattern Gardiners Clay elevations matches estimates of glacial era sea level (approximately -120 ft msl). Sirkin (1982) concludes that Gardiners Clay was ocean origina sediments that were reworked. Dvirka and Bartilucci (1994a) interprets sediment samples and a gamma ray log from a boring at the landfill site as corroborating marine origins. The presence of organic matter and fossiliferous sediments are said to support a marine deposit affected by wave action (Swarzenski, 1963; Sirkin, 1982).
Figure 13: Gardiners Clay elevation contours (in ft msl) (Modified from Smolensky et al., 1989)
There is little consensus regarding the local elevation and thickness of the Gardiners Clay underneath the landfill site and its vicinity. Gerathy and Miller (1985) and Fanning, Phillips and Molnar (1986) find no Gardiners Clay unit beneath a previously proposed ashfill site that was located across Horseblock Road north of the Town landfill. On the other hand, Voorhis (1986) reports the presence of (i) discontiguous thin bands of brown clay with sandy facies at Patchogue-Yaphank Road, north of the landfill site, at an elevation of -137 ft msl; (ii) a 15 foot layer of sandy clay at an elevation of -89 ft msl on Bellport Station Road, west of the landfill site; and, (iii) a 28 ft thick layer of Gardiners Clay at the Head of the Neck Road well site south of the landfill site at an elevation of -118 ft msl. The clay found at this site was interbedded with thin bands of Upper Glacial deposits. Buxton and Modica (1992) interpolate that Gardiners Clay is not present underneath the site. Dvirka and Bartilucci (1994a) suggests that Gardiners Clay extends north of the Long Island Expressway north of the landfill site. DeLaguna (1963) and Weiss (1954) studied the hydrogeology of Brookhaven National Laboratory (BNL) and vicinity and find Gardiners Clay is present at the northern boundary of the BNL site and is contiguous with the south shore facies of the Gardiners Clay at an elevation of -90 to -130 ft msl. Conversely, Smolensky et al. (1989) restrict the extent of the Gardiners Clay to just slightly north of Sunrise Highway near BNL.

Gardiners Clay is composed of greenish-gray to gray clay, with medium to coarse quartzose sand and is interbedded with silt, mixed layer clays, and fine gravel (Wexler, 1988a; Wexler and Maus, 1988; Voorhis, 1986). The unit may occasionally contain lenses of gravel. Fossil contents vary from completely absent to a few diatoms and foraminifera (Koszalka, 1984). Minerals present are glauconite, quartz, muscovite, biotite, pyroxene, amphibole, illite, chlorite, and minor kaolinite (Lonnie, 1982). Glauconite, a green iron silicate mineral of the mica group, is responsible for the greenish appearance of the clay unit (Koszalka, 1984). Gardiners Clay can be distinguished from the underlying Matawan Group-Magothy Formation based on the presence of biotite, chlorite, and hornblende, as well as plant material, pollen grains and spores, shell fragments, and foraminifera (Perlmutter and Gerathy, 1963; Pluhowski and Kantrowitz, 1964). Samples from clay in the boring for well MW-11M at the landfill found mica and lignite, and traces of sand.

Gardiners Clay is a shallow confining unit that disconnects the Upper Glacial aquifer from the underlying Magothy aquifer and thus retards the vertical flow of recharge (Jensen and Soren, 1974). The average vertical hydraulic conductivity of the Gardiners Clay unit is estimated to be 0.001 ft/d by Franke and Cohen (1972). During the hydrogeologic investigation for Cell 5, Dvirka and Bartilucci (1994a) calculated the horizontal hydraulic conductivity of Gardiners Clay using a slug test and the Hazen method. The slug test found the horizontal hydraulic conductivity to be 6.5 ft/ d. The vertical hydraulic conductivities calculated from the slug test range from 0.0081 to 1.22 ft/d, with a mean of 0.01 ft/d. Vertical permeability, based on laboratory testing, ranges from 0.03 ft/d to 1.56 ft/d with a geometric mean of 0.23 ft/d (Dvirka and Bartilucci,
Generally, in southwestern Suffolk and southeastern Nassau County the vertical hydraulic conductivity value ranges from 0.0184 ft/d to 0.0000221 ft/d (Wexler and Maus, 1988). The variation in values of horizontal and vertical hydraulic conductivity result from values derived at different locations and depths using differing procedures.

It is difficult to consider the unit described as “Gardiners Clay” as a single solid clay. Evidence suggests that the composition of this unit is highly variable, ranging from clays containing sand and silt to more solid areas. The thickness and continuity of the clays determine the effectiveness of confinement of the Magothy aquifer by Gardiners Clay (Doriski and Wilde-Katz, 1983). The degree of aquifer confinement is enhanced if Gardiners Clay is underlain by the Monmouth Greensand (Gerathy and Miller, 1985). The presence or absence of Gardiners Clay beneath the landfill site is an important element to determine whether landfill leachate releases will be, are, or have been transported from the Upper Glacial aquifer into the Magothy aquifer. The presence and absence of Gardiners Clay, and, if present, its composition and thickness, are discussed extensively in Section 9 (beginning page 47), based on interpretations of well logs from the vicinity of the landfill.
8.6. **Upper Glacial Deposits**

The uppermost geologic unit is the Upper Glacial deposit of the Upper Pleistocene age. The upper surface of these deposits forms the topography of Long Island that comprises surficial features such as the moraines, and outwash deposits, etc. (discussed in sections 5, 6, and 7 above). These deposits extend across Long Island with variable surface elevation and growing thickness southeasterly. The Upper Glacial deposit is overlain by a thin layer of Holocene deposits and it overlies Gardiners Clay, or the Matawan Group-Magothy Formation in absence of Gardiners Clay.

Upper Glacial deposits are composed of stratified, tan to brown, coarse to fine grained sand and gravel with small amounts of clay and silt (Perlmutter and Gerathy, 1963). The sand is mostly quartzose and contains alkali feldspar, mica, amphibole, biotite, chlorite, and hornblende (DeLaguna, 1963; Perlmutter and Gerathy, 1963). Generally, the coarseness of the sand increases from the bottom to the top; however, the basic lithology of the unit remains the same (Dvirka and Bartilucci, 2001). The bottom 15 ft to 20 ft of the deposit is made up of reddish brown to brown, fine, micaceous, silty sand near the landfill (Wexler, 1988a).

Upper Glacial deposits represent the uppermost aquifer unit on Long Island. The saturated portion of the Upper Glacial deposits as well as the Holocene sediments represent the Upper Glacial aquifer (Koszalka, 1984). It is the water table aquifer because it receives recharge directly from precipitation and is in pressure equilibrium with the atmosphere. The thickness of the saturated portion of the aquifer generally ranges from approximately 30 ft to 120 ft (Perlmutter and Gerathy, 1963); the range is 90-135 ft around the landfill (Dvirka and Bartilucci, 1994a). The porous sand deposits are highly permeable and readily absorb, store, and yield large quantities of water. Therefore, the Upper Glacial aquifer is the main source of potable water for Suffolk County (Busciolano, 2002).

Hydraulic conductivity values vary with depth and grain size (McClymonds and Franke, 1972). The deposits in the upper sections are generally coarse and readily yield water, while the deeper sections of the Upper Glacial aquifer have better sorted sands with lower permeability. Table 4 shows the horizontal hydraulic conductivity values calculated by Dvirka and Bartilucci (1994a) for the Upper Glacial aquifer at several groundwater wells in the vicinity of the landfill. The values range between 607 ft/d (Bouwer-Rice Rising Head Test) and 30 ft/d (Bouwer-Rice Rising Head Test) for the shallower section, between 208 ft/d (Hazen method) to 58 ft/d (Bouwer-Rice Rising Head Test) for the intermediate section, and from 363 ft/d (Bouwer-Rice Rising Head Test) to 17 ft/d (Bouwer-Rice Rising Head Test) for the deeper Upper Glacial aquifer. In general, the typical horizontal hydraulic conductivity of the Upper Glacial aquifer is estimated to be 200 ft/d to 300 ft/d (Lindner and Reilly, 1983).
<table>
<thead>
<tr>
<th>Zone</th>
<th>Monitoring well/ Piezometer</th>
<th>Screened Interval Depth (ft below grade)</th>
<th>Hazen method geometric mean K (ft/d)</th>
<th>Bouwer-Rice Rising Head Test K (ft/d)</th>
<th>Bouwer-Rice Falling Head Test K (ft/d)</th>
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<td>MW-8S</td>
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(– Monitoring well was screened partially in the unsaturated zone; therefore the falling head test was not conducted due to expected non-representative results.)

Table 4: Horizontal hydraulic conductivity values for the Upper Glacial aquifer
(Dvirka and Bartilucci, 1994a)
Anisotropy ranges from 2:1 to 24:1 with an average ratio of 10:1 (Lindner and Reilly, 1983; Gerathy and Miller, 1985; Smolensky et al., 1989; Reilly et al., 1983). Assuming an anisotropy ratio of 10:1 and using a horizontal hydraulic conductivity value of 270 ft/d, the vertical hydraulic conductivity in the vicinity of the landfill calculates to be 27 ft/d. The porosity of the Upper Glacial aquifer averages about 0.33 (McClymonds and Franke, 1972), while the effective porosity values range from 0.25 to 0.30 (Kimmel and Braids, 1980; Gureghian et al., 1981). The horizontal hydraulic gradient for the Upper Glacial aquifer near the landfill is estimated to be 0.0012 to 0.0013 ft/ft (Dvirka and Bartilucci, 1996a). The mean transmissivity value and the mean specific yield for the Upper Glacial aquifer at the landfill border is estimated to be 310,000 gpd/ft and 0.22 respectively (Lockwood, Kessler and Bartlett (LKB), 1994).

A number of estimates of horizontal flow velocity have been made. Dvirka and Bartilucci (1996a) finds the average flow velocity to range from 0.3 ft/d (110 ft/yr) to 1.1 ft/d (409 ft/yr) for the shallow Upper Glacial aquifer. Wexler (1988b) calculates a range of 0.8 to 1.8 ft/d (292 ft/yr to 657 ft/yr). Groundwater flow velocity was calculated for on-site well MW-121 using the falling head slug test and Hazen method and was found to be within the range of 0.09 to 1.4 ft/d (32.85 ft/yr to 511 ft/yr) (Dvirka and Bartilucci, 1996a). LKB (1994) estimates a velocity value of 2.05 ft/d (749 ft/yr), based on its groundwater flow model developed from a pump test. Using a vertical hydraulic gradient of 0.0001 ft/ft and porosity of 0.30, a vertical velocity was calculated to be 0.09 ft/d (Dvirka and Bartilucci, 1994a). The values of hydraulic attributes for the Upper Glacial aquifer are approximations and/or are values averaged over the entire aquifer that may vary with location of the sampling/test well, depth of the sample collection or with the screen interval of the well. If the horizontal hydraulic conductivity is 270 ft/d (K), the porosity is 0.30 (n), and the horizontal hydraulic gradient for the shallow Upper Glacial aquifer (i) is 0.001 ft/ft, Darcy’s law (v = K*i/n, where v = groundwater velocity (L/T), K = hydraulic conductivity (L/T), i = hydraulic gradient (L/L), n = effective porosity (dimensionless)) (Fetter 2001) computes a horizontal groundwater velocity of about 1 ft/d (365 ft/yr), which is the common value assigned to the Upper Glacial aquifer. The choices of input values are reasonable according to the reports cited above.
8.7. **Holocene Deposits**

Holocene deposits represent the youngest sediments on Long Island. Holocene deposits unconformably overlie the Upper Glacial deposits and are deposited and reworked by wind, waves, tides, floods and rains, frost, ice, or by human activity. Holocene deposits occur along the shores of Long Island, on barrier beaches, in marshlands, along the riverbanks, and on streambeds of present streams (Perlmutter and Gerathy, 1963). Holocene deposits also constitute the soil layers found across Long Island.

There are six different soil associations on Long Island, the classification of which that highlights the suitability of these deposits for human activities such as farming or housing development. The soil association around the landfill site is of Riverhead-Plymouth-Carver type, considered more suitable for urban development than farming owing to its coarse nature. The soil near the banks of Beaverdam Creek and the Carmans River, as well as along the ditched region near the mouth of the Carmans River has been classified as tidal marsh (Warner et al., 1975). These recent deposits are composed of fine to coarse quartzose sand, mainly containing minerals such as feldspar, garnet, ilmenite, and biotite (Perlmutter and Gerathy, 1963). They also comprise of deposits developed as a result of artificial (man-made) restructuring, such as the fill material deposited during construction of landfill cells and access roads that consists of medium to coarse sand with small amounts of silt, gravel, and inert shredded material such as plastic.

These deposits are discontinuous and are not thick enough to be considered separate from the underlying Upper Glacial deposits (DeLaguna, 1963). Holocene deposits are not considered hydrologically important due to their thinness and localized, limited deposition (DeLaguna, 1963).
9. Geologic Cross Sections

Since the presence of Gardiners Clay under the study area is important with regard to containment of leachate flow from the landfill (see Section 8.5), the presence and extent of Gardiners Clay were developed using geologic drilling logs. The following section depicts the drilling logs at boring locations in the vicinity of the Brookhaven landfill. These locations were arranged along transects to reveal patterns in the sediments that underlie the landfill.

These transects were classified either as “regional” or “local”. Regional transects are longer (average length of transect was approximately 30,000 ft) than local transects (average length of transect was approximately 600 ft). Local transects are mostly comprised of borings that were drilled during hydrogeologic investigations conducted by the Town’s consultant (Dvirka and Bartilucci) at the landfill from 1994 to 2010 as part of the regulatory requirements for permitting or closing landfill cells. Seven local geologic cross sections were included in this class. The regional geologic cross sections were created primarily using drilling logs obtained from the New York State Department of Environmental Conservation (NYSDEC), from records associated with public supply wells. There were also seven transects in this class.

Gamma ray logs are available for some of the wells at the study location. Typically, the radiation levels for sand (sandy material) are relatively lower than clay minerals. Therefore, the amount of radiation observed correlates with the amount of clay in the sediments (Keys, 1990). Gamma ray logs thus provide supplementary information about the stratigraphy and lithology of the sediment units. Two gamma ray transects have been depicted here.

The range of elevation at which presence of Gardiners Clay could be observed was estimated to be -50 ft to -150 ft msl (Jensen and Soren, 1971; see Table 3; Figure 13). Thus, particular attention was given to observations of clay within this range. All local depths below ground surface were converted into “feet in relation to mean sea level” (ft msl), using measured or approximated boring elevations.
9.1. Regional Geologic Cross Sections

Table 5 lists the regional geologic cross sections (transects).

<table>
<thead>
<tr>
<th>Cross section</th>
<th>Included borings*</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-A’</td>
<td>S29492 / S52944 / S47438 / S56039</td>
</tr>
<tr>
<td>B-B’</td>
<td>S47035 / S62022 / S49018 / S71882 / S33920</td>
</tr>
<tr>
<td>C-C’</td>
<td>S28408 / S69364 / S129174 / S52493 / S46713 / S65905</td>
</tr>
<tr>
<td>D-D’</td>
<td>S18846 / S9349 / S47024</td>
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<td>E-E’</td>
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<tr>
<td>F-F’</td>
<td>S52944 / S49018 / S69364</td>
</tr>
<tr>
<td>G-G’</td>
<td>S29492 / S49018 / S129174 / S52493 / S47024</td>
</tr>
</tbody>
</table>

(* alphanumeric combinations are well numbers; “S” indicates a Suffolk County location)

Table 5: Regional geologic cross sections
9.1.1. Transect A-A’ (S29492 / S52944 / S47438 / S56039)

The regional geologic cross section A-A’ is located north of the landfill, and runs approximately parallel to the Long Island Expressway (Figure 14). The borings that form this transect consist of (with depths) - S29492 (234 ft), S52944 (203 ft), S47438 (269 ft), and S56039 (163 ft).

![Figure 14: Location of geologic cross section A-A’](image)

Figure 14 shows the stratigraphic profile at the individual wells. One foot thick, fine, brown sand with a streak of gray clay was observed at 29242 at about -75 ft msl. Also, a foot of thick, solid, brown, clay was observed at well S52944 at about -100 feet msl. No clay was observed at well S56039 throughout the boring. At well S47438, a 2 ft band of solid, brown clay was observed at -75 ft msl followed by 8 ft of solid, sandy clay at about -100 ft msl, then 9 ft of solid, gray, sandy clay at about -140 ft msl (Figure 15).

Except at S47438, the clay that was found was sandy. The depth of clay observations is consistent throughout the transect except at S56039 where no clay was found. The depth of observations was between -50 and -150 ft msl; the range of depth and thickness was similar to that of Gardiners Clay as defined by Jensen and Soren (1971) (see Table 3; p. 22). The gray / brown clay units observed in this cross section are uncharacteristic of the greenish-grayish appearance of Gardiners Clay.
The described clays are a foot thick, except at S47438 where the cumulative thickness of the clay bands totaled 19 feet. One foot may not be thick enough to generate confining conditions, but 19 feet is more substantial. Therefore, the presence and extent of the Gardiners Clay could not be confirmed across this cross section.
9.1.2. **Transect B-B’ (S47035 / S62022 / S49018 / S71882 / S33920)**

The regional geologic cross section B-B’ runs east-west, parallel to Sunrise Highway, and traverses the landfill site (Figure 16). The borings in this transect (with depths) consist of S47035 (503 ft), S62022 (313 ft), S49018 (527 ft), S71882 (318 ft) and S33920 (630 ft).

![Figure 16: Location of geologic cross section B-B’](image)

Clay was found several times at well S47035, as 4 ft of solid black clay at -100 ft msl followed by another 6 ft of solid gray clay at -104 ft msl, and then two solid gray clay layers, each about 9 ft thick, that were observed at -150 ft msl and -170 ft msl (Figure 17). Occasional clay was found at boring S62022 and 160 ft of fine to coarse sand hardpan with clay was recorded from -110 ft msl until the well termination at -275 ft msl; the sand hardpan may have a lower permeability than the overlying material. In S49018, coarse to fine brown sand was found until about -135 msl. The first occurrence of clay was observed at -135 ft msl in the form of 24 ft of fine gray sand with strips of clay, followed by a 10 ft of solid dark gray clay at -175 ft msl. Two more clay bands were found deeper in the boring: 20 ft of solid gray clay at about -340 ft msl and 4 ft of solid gray clay at about -475 ft msl. 32 ft of solid and silty gray clay was observed at well S71882 at -130 ft msl, overlain by mostly coarse to fine brown sand and followed by fine to coarse gray sand with pyrite, lignite and mica until termination. After coarse sand and gravel until about -275 ft msl, 30 ft of dark solid clay was observed at well S33920 at -275 ft msl; this was then followed by 72 feet of fine to coarse gray sand. 51 ft of dark solid gray clay was observed at about -400 ft msl; this clay might be a local clay lens in Magothy aquifer.
Figure 17: Cross section B-B' (inferred position of the potentially semi-confining unit is shown with dotted line)

The material composition of less permeable material varied across this transect from solid dark clay to sand hardpan. Nonetheless, the occurrence of solid clay units in this transect is frequent. The clay units observed at wells S47035, S49018, and S71882 seem to indicate the presence of a continuous unit of clay. Therefore, presence of a continuous layer of potentially semi-confining unit was determined for the transect, except at well S33920.
9.1.3. Transect C-C’ (S28408 / S69364 / S129174 / S52493 / S46713 / S65905)

The regional geologic cross section C-C’ is located south of the landfill site, parallel to Montauk Highway (Figure 18). The borings that form this transect (with depths) consist of S28208 (335 ft), S69364 (529 ft), S129174 (260 ft), S52493 (110 ft), S46713 (444 ft) and S65905 (161 ft).

![Figure 18: Location of geologic cross section C-C’](image)

The drilling log for well S28408 suggests possible presence of a 100 ft contiguous confining unit between -75 ft msl and -175 ft msl. The first 22 ft of this unit consists of black clay, followed by a 27 ft of green to black clay, 25 ft of silt, 9 ft of green clay, and 17 ft of gray sand with black clay. 9 ft solid green and gray clay was observed at well S69364 at -110 ft msl. At well S46713, 9 ft of clayey sand with green clay was observed at -105 ft msl, followed by 6 ft of solid green clay. In addition, 15 ft of solid gray clay was observed at -135 ft msl.

The drilling log at well S129174 indicated that the well penetrates through the Gardiners Clay unit. The drilling log noted the presence of the Gardiners Clay from -125 to -165 ft msl. No lithologic description of the clay unit is given. The remaining two wells of this transect - S52943 and S65905 – seem to have been terminated on hitting clayey material at the bottom. The depth of occurrence of clayey sand or clay at these well locations is near parallel to findings of clay at the other three wells of the transect (Figure 19).
The descriptions in the boring logs for cross-section C-C’ suggest the presence of a continuous Gardiners Clay unit with uniform depth. The depth of this unit ranges from about -80 ft msl to about -165 ft msl while the thickness varies from 6 ft to 40 ft. The clay unit is mostly green clay, either solid or sandy.

Figure 19: Cross section C-C’ showing Gardiners Clay (inferred position of the Gardiners Clay is shown with dotted line)
9.1.4. Transect D-D’ (S18846 / S9349 / S47024)

The regional geologic cross section D-D’ runs in a southwest to northeast direction along the Fire Island shoreline (Figure 20). The borings that form this transect (with depths) consist of S18846 (549 ft), S9349 (340 ft), and S47024 (378 ft).

![Location of geologic cross section D-D’](image)

24 ft of firm, dark brown clay was observed at well S18846 at -175 ft msl, followed by 250 ft of dark clay with lignite and iron pyrite. This massive clay unit is likely Monmouth Greensand, which has been found beneath the barrier beaches (Scorca et al., 1995). Clayey sand was observed at well S9349 from about -150 ft msl until its termination at -340 ft. At well S47024, 9 ft of hard, brown clay was observed at -80 ft msl. Another clay unit of about 20 ft thickness was observed at -200 ft msl at well S47024, consisting of black to gray clay with pyrites, shells and mica (Figure 21).

The continuity of the Gardiners Clay is difficult to interpret from this transect due to distance between each of the three points. Also, lithologic descriptions of the clay occurrences do not conform to the typical greenish-grayish appearance of the Gardiners Clay. Hence, the presence and extent of Gardiners Clay could not be ascertained at cross-section C-C’. However, the observation of clay across the cross-section indicates the likely presence of a contiguous low permeability and potentially semi-confining layer of material.
Figure 21: Cross section D-D’ (inferred position of the potentially semi-confining unit is shown with dotted line)
9.1.5. Transect E-E’ (S29492 / S66184 / S47035 / S28208 / S18846)

The regional geologic cross section E-E’ runs north-south approximately parallel to Nicolls Road (Figure 22). All wells except S18846 are on mainland Long Island. The borings (with depths) that form this transect consist of S29492 (234 ft), S66184 (383 ft), S47035 (313 ft), S28208 (335 ft), and S18846 (549 ft).

![Figure 22: Location of geologic cross section E-E’](image)

A foot thick, fine, brown sand with streaks of gray clay was observed at S29242 at about -75 ft msl. At well S66184, medium grained sand with streaks of clay was observed at -100 ft msl followed by a 38 ft thick unit of solid clay from -130 ft msl to -170 ft msl (Figure 23). Clay was found further south at well S47035 at three different depths - 10 ft of solid black and gray clay at -100 ft msl, 9 foot solid gray clay at -150 ft msl, and 12 ft of hard, solid, two-tone gray clay at -170 ft msl. The material between these clay units contained a mixture of small gravel, pyrite, medium to fine sand, and gray clay. From this, it was inferred that all three clay units are contiguous and represent Gardiners Clay (Figure 23). The drilling log for well S28408 suggests possible presence of a 100 ft contiguous confining unit between -75 ft msl and -175 ft msl. The first 22 ft of this unit consists of black clay, followed by a 27 ft of green to black clay, 25 ft of silt, 9 ft of green clay, and 17 ft of gray sand with black clay. S18846 is located on Fire Island and was shown to have approximately 275 ft thick clay between -175 ft msl and - 450 ft msl.
The 27 ft green clay and/or the subsequent 9 ft green clay found at S28408 can be referred to as the Gardiners Clay. No other clays were lithologically similar and therefore the continuity of the Gardiners Clay layer could not be confirmed. Therefore, it was concluded that a potentially semi-confining unit is continuous along the E-E’, except at S29492.
9.1.6. Transect F-F’ (S52944 / S49018 / S69364)

The regional geologic cross section F-F’ runs north-south, parallel to Station Road (not shown) (Figure 24). The borings (with depths) that form this transect consist of S52944 (203 ft), S49018 (527 ft), and S69364 (529 ft).

![Figure 24: Location of geologic cross section F-F’](image.png)

This transect includes wells that are closest to the landfill site. Well S52944 had 1 foot solid, brown clay at -100 ft msl. Clay was observed at well S49018 at -135 ft msl in the form of 24 ft of fine gray sand with strips of clay, followed by a 10 ft of solid dark gray clay at -175 ft msl. No apparent demarcation of the lower-most limit of the observed clay could be made at this borings, and hence, the clay was assumed to have terminated at -185 ft msl at S49018. 15 ft of solid gray to green clay was observed at well S69364 at -110 ft msl followed by 11 ft of sandy dark clay at -170 ft msl. Occurrence of clay, either in the form of streaks, clayey sand, bits of clay, or thin bands of solid dark clay was frequent at wells S49018 and S69364, at least 100 ft below the clay observance at S52944.

The presence of green clay at S69364 indicates Gardiners Clay while the gray clay units at other locations may represent clay in the upper Magothy aquifer. In combination, these clay units may give rise to potentially semi-confining conditions. Thus, rather than designating the
clays specifically as the Gardiners Clay, it was inferred that a continuous layer of potentially semi-confining unit is present along the transect F-F’ (Figure 25).

Figure 25: Cross section F-F’ (inferred position of the potentially semi-confining unit is shown with dotted line)
9.1.7. Transect G-G’ (S29492 /S49018 / S129174 / S52493 / S47024)

The regional geologic cross section G-G’ follows a northwest-southeast trending line. This transect runs parallel to the approximately southeasterly flow of groundwater in southeastern Suffolk County (Figure 26). The borings in this transect (with depths) consist of wells S29492 (234 ft), S49018 (527 ft), S129174 (250 ft), S52493 (110 ft), and S47024 (378 ft).

A foot thick, fine, brown sand with streak of gray clay was observed at S29492 at about -75 ft msl. Clay was observed at well S49018 at -135 ft msl as 24 ft of fine gray sand with strips of clay, followed by 10 ft of solid dark gray clay at -175 ft msl. S52943 was probably terminated upon hitting clayey material at -100 ft msl. Coarse, tan to gray sand with gravel was encountered at S129174 from grade to -140 ft msl; green clay was found at the bottom 20 ft. The drilling log noted Gardiners Clay from -140 ft to -180 ft msl. Lithologic description of the clay is absent. It was inferred that the Gardiners Clay was found at S52943 at a depth of -100 ft msl; however, because the well is shallow, the thickness of the clay unit is not available. 9 ft of hard brown clay was observed at -80 ft msl at S47024. Another clay unit of 20 ft thickness was observed at -200 ft msl at well S47024 that consisted of black to gray clay with pyrites, shells and mica. Although the upper brown clay is well within the stratigraphic range assumed for the Gardiners Clay (-50 to -150 ft), the brown coloration could not be equated with the typically green Gardiners Clay. Green clay (or Gardiners Clay) was found only in one well, at S129174. The rest of the cross-
section consisted of solid to sandy, gray to brown clays that may provide semi-confining conditions. Therefore, based on the boring descriptions, it was inferred that a continuous, potentially semi-confining unit is present across cross section G-G’, except at S29492 where it was assumed to be too thin to be correlated with the rest of the cross-section (Figure 26).

Figure 27: Cross section G-G’ (inferred position of the potentially semi-confining unit is shown with dotted line)
9.2. **Local Geologic Cross Sections**

Table 6 and Figure 28 shows the local transects. Two geotechnical cross sections (M-M' and N-N') are also depicted in this section and are shown in the inset.

<table>
<thead>
<tr>
<th>Cross section</th>
<th>Included borings*</th>
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</thead>
<tbody>
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<td>H-H'</td>
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</tr>
<tr>
<td>I-I'</td>
<td>MW12-D / B-18 / MW8-D / MW10-D</td>
</tr>
<tr>
<td>J-J'</td>
<td>MW11-M / MW4-D / 103142 / S72813M / PB-24</td>
</tr>
<tr>
<td>K-K'</td>
<td>MW5-D / B-18 / S72812M</td>
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<tr>
<td>L-L'</td>
<td>MW12-D / B-18 / MW11M / S72814M / MW102-D / S129174</td>
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<tr>
<td>M-M'</td>
<td>B-21 / MW11M / B-20 / S72813M / PB-24</td>
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<tr>
<td>N-N'</td>
<td>B-18 / B-20</td>
</tr>
</tbody>
</table>

(* alphanumeric combinations are well numbers where MW = monitoring well, M = Magothy well, B = boring, D = deep, PB = permanent boring, S = boring / well was registered with NYSDEC and is in Suffolk County)

Table 6: Geologic and geotechnical cross sections used to depict sub-surface geology at the Brookhaven landfill site and its vicinity
Figure 28: Local geologic cross sections and geotechnical cross sections (in inset)
9.2.1. Transect H – H’ (S72812M / PB-24 / S72814M / MW106-D)

Geologic cross section H-H’ trends north to south across the study area. All the wells in the section are east of the landfill and are drilled either into the upper Magothy aquifer or the potentially semi-confining unit between the Upper Glacial and Magothy aquifers. Well S72812M is located at the northeastern corner of the landfill site and represents the northern limit of the cross section. PB-24 was bored near the southeastern edge of landfill. S72814M is located along the Montauk Highway between Southaven Drive and Orient Avenue. Well MW106-D is the southernmost point of the cross section located on the northern portion of Bay Road. The depths of S72812M, PB-24, S72814M, and MW106-D are 210 ft, 150 ft, 221 ft, and 107 ft respectively.

S72812M: The suffix M indicates that this well was drilled into the Magothy aquifer. Sand was the predominant material for the first 123 ft, color ranging from light brown to brown. From -123 ft to -127 ft msl gray-brown, fine-grained, quartzose sand was found accompanied by small white clay lumps. From -127 ft to -175 ft msl, material was mostly clean, very fine to fine, light gray quartzose sand with occasional presence of muscovite mica and dark minerals.

PB-24: The first 100 ft of the boring contained tan, brown or red colored quartzose sand of mixed grain size containing traces of silt, gravel, dark minerals, and muscovite flakes. Olive green to gray colored, medium to fine sand with traces of gravel and green silt was encountered for another 20 ft. Compacted fine sand with reddish brown silt and traces of muscovite was found from -80 ft to -90 ft msl where the drilling ended. The compacted portion of the sand is considered to be Gardiners Clay (Dvirka and Bartilucci, 1996c). Alternatively, the distinct coloration of the overlying silty sand, an olive green to gray color similar to that of the glauconitic Gardiners Clay, could be considered to be the Gardiners Clay. Here, the latter interpretation is preferred and thus, it was inferred that about 20 feet of silty, sandy facies of Gardiners Clay is present at PB-24 between -60 ft to -80 ft msl.

S72814M: The top 112 ft of the boring consisted of light brown to brown, fine to coarse grained, quartzose sand with traces of gravel and feldspar. A similar pattern of sediments was continued from -57 ft to -78 ft msl with the addition of occasional clay lumps. Light brown, medium to coarse quartzose sand with rock fragments and pebbles was found between -78 and -102 ft msl. Orange to brown, medium to coarse silty sand was accompanied by olive gray clay was observed between -110 ft to -116 ft msl. Below this point, the sand was mostly light gray, very fine to fine, silty with traces of lignite and gravel. The occurrence of olive gray clay was interpreted by Doriski (Dvirka and Bartilucci, 1996c) as the presence of approximately six feet of Gardiners Clay.

MW106-D: The entire boring consists of mostly tan to brownish tan sand of increasing fineness containing occasional traces of silt. No clay was observed.
Due to shallow nature of MW106-D, no interpretation about the presence or thickness of a continuous clay unit could be made for this portion of the transect at the critical depth range. The location and texture of the white clay lumps found at well S72812M do not conform to the greenish or grayish coloration of Gardiners Clay. Thus, continuity of the Gardiners Clay could not be ascertained. It was therefore inferred that a potentially semi-confining unit is present across H-H’, except potentially at MW106-D (Figure 29).

Figure 29: Cross section H-H’ (inferred position of the potentially semi-confining unit is shown with dotted line)
9.2.2. Transect I-I’ (MW12-D / B-18 / MW8-D / MW10-D)

This north-south geologic cross section follows the western edge of the older cells of the landfill, and extends under Cell 6. MW12-D is at the northern perimeter of the landfill; boring B-18, MW8-D, and MW10-D are located in the “valley” area between Cells 1-4 and Cell 5. Wells MW12-D, MW8-D, MW10-D and boring B-18 have depths of 180 ft, 190 ft, 186 ft, and 192 ft respectively.

MW12-D: Light tan to brown, medium to fine, quartzose sand containing traces of fine gravel and silt was observed until 170 ft below grade. At -90 ft msl, the material changed to dark brown to red compact silt containing little fine sand. The coloration of the silt unit did not match with the distinct olive green to gray color of the Gardiners Clay. However, it was inferred that 10 feet of compacted silt could produce semi-confining conditions similar to sandy to silty facies of the Gardiners Clay (Dvirka and Bartilucci, 1994a).

B-18: The material in this boring mostly consisted of tan to brown, coarse to fine, quartzose sand with traces of silt, medium to fine gravel, and dark minerals. This pattern continued until 176 ft below grade. For about 10 ft below this point (-100 to -110 ft msl), material composition changed to compacted brown clayey silt with traces of fine sand and muscovite flakes. The rest of the boring consisted of gray colored fine sand with traces of black organic silt and muscovite.

MW8-D: Light-tan colored, fine to medium quartzose sand with traces of rock fragments, feldspar with pink, red or black colored minerals was observed until about 170 ft below grade. Below this point, the sand became very dense and changed color to reddish brown or brown. Traces of mica and clay were observed until -111 ft msl. Solid black clay with silvery gray medium sand and lignite was found from -111 ft to well termination at about -113 ft msl.

MW10-D: Similar to MW8-D, the upper 150 ft of the boring was light tan to brown, medium to fine, quartzose sand with a presence of rock fragments and traces of pink or black minerals and an occasional appearance of mica. Compact, brown sand was found between -80 ft msl and -105 ft msl. Solid brown colored clay with little medium to fine silvery sand was encountered from about -105 ft msl to -113 ft msl, where the boring terminated.

None of the clay observations in this transect match typical green or gray color attributes of Gardiners Clay. Nonetheless, the material composition across the transect at a similar depth varied from clayey silt and sand to solid clay. This description indicates potential semi-confining abilities, similar to that of Gardiners Clay, throughout the length of the transect. Figure 30 depicts the inferred semi-confining unit across the cross section I-I’.
Figure 30. Cross section I-I’ (inferred position of the potentially semi-confining unit is shown with dotted line)
9.2.3. Transect J–J’ (MW11M / MW4-D / 103142 / S72813M / PB-24)

This geologic cross-section runs from east to west, paralleling the southern boundary of the landfill. Well MW11M is located south of Cell 5; MW4-D, 103142, and S72813M are south of Cells 1-4. PB-24 is at the southern corner of the landfill. The depths of the wells are 220 ft (MW11M), 182 ft (MW4-D), 180 ft (103142), 248 ft (S72813M), and 151 ft (PB-24).

MW11M: The sand for the first 150 ft below grade was light tan to brown, coarse to very fine, and contained a little gravel and traces of round pebbles. From 150 to 160 ft below grade, the sand became silvery gray, fine grained and micaceous with traces of gravel. The composition of the material changed at -95 ft msl to black, micaceous, lignitic silt with some black clay and a little fine sand. This continued until -125 ft msl. Silvery gray, micaceous, medium, quartzose, lignitic sand with traces of silt was encountered below this point until termination.

MW4-D: After encountering tan to brown, quartzose sands for the first 107 ft of the boring, a dark gray to brown clay with orange staining was detected. Gray clay clasts interbedded in silty clay were observed at -40 ft msl. The description in the boring logs suggests the position of the Gardiners Clay between -100 ft to -104 ft msl where grayish brown silty clay with fine sand was found. Grayish brown medium sized gravelly sand was found thereafter.

103142: The well is entirely in the Upper Glacial aquifer unit. Thus, the material found in the boring was entirely comprised of light brown, medium to fine sand with traces of mica till about 140 feet below grade. The sand became finer thereafter until the end of the boring at about 180 feet below grade (-110 ft msl). No clay was observed.

S72813M: For about 160 ft below grade, the material at S72813M was mostly tan to brown, coarse to fine grained, quartzose sand with some muscovite mica, feldspar, silt and occasional gravel. From -106 ft to -112 ft msl, the material was reddish brown to brown and increasingly silty with presence of dark minerals and some clay. Lumps of dark gray clay were observed between -111 to -117 ft msl. Glaucocitic sand with dark gray clay lumps and lignite was observed for a further 15 ft (-117 to -132 ft msl). A drilling log note said that “the rig is drilling like clay” from -135 ft to-140 ft msl. Samples recovered between -140 and -160 ft msl showed medium to coarse grained sand, some muscovite mica and dark minerals. Lumps of yellow brown and black clay, along with silty, fine to medium grained sands were observed from -160 ft to -173 ft msl. Black, sandy clay was found from -173 ft to -183 ft msl where the drilling ended. Thomas Doriski of USGS (Wexler, 1988a) concluded that 7 feet thick layer of sandy facies of Gardiners Clay, with some clay and silt, was present at S72813M from about -115 ft msl to -122 ft.
Figure 31: Cross section J-J’ (inferred position of the Gardiners Clay is shown with dotted line)
PB-24: The first 100 ft of the boring contained tan, brown or red colored quartzose sand of mixed grain size containing traces of silt, gravel, dark minerals, and muscovite flakes. Olive green to gray colored, medium to fine sand with traces of gravel and green silt was encountered from the depth of 110 ft to 130 ft below grade. Compacted fine sand with reddish brown silt and traces of muscovite was found from -85 ft to -95 ft msl where the drilling ended. The compacted portion of the sand is considered to be the semi-confining unit described as the Gardiners Clay (Dvirka and Bartilucci, 1996b). Alternatively, the distinct coloration of the overlying silty sand, olive green to gray color similar to that of the glauconitic Gardiners Clay, could be considered to be Gardiners Clay. Here, the latter interpretation was preferred and thus, it was inferred that about 20 feet of silty, sandy facies of Gardiners Clay is present at PB-24 between -60 ft to -80 ft msl.

The composition of the material found in borings varied from compacted sand to solid clay. Borings of PB-24 and 72813M indicate the presence of Gardiners Clay; other borings suggest the presence of low permeability material. This variation in composition may give rise to semi-confining to confining conditions along the landfill perimeter. Figure 31 depicts the inferred position of the potentially semi-confining unit across the cross section J-J’.
Figure 32: Cross section K-K’ (inferred position of the Gardiners Clay is shown with dotted line)
9.2.4. Transect K-K’ (MW-5D / B-18 / S72812M)

This east-west cross section traverses the north side of the landfill. Well MW-5D is located on the northwestern corner of Cell 5 and marks the eastern limit of the cross section. Boring B-18 is located near the eastern edge of Cell 5 and it approximately bisects the cross section. Well S72812M represents the western limit of the cross section and is located at the northeastern edge of the landfill property. The depths of the boring are 188 ft for MW-5D, 192 ft for B18, and 211 ft for S72812M.

MW-5D: Sediment to about -100 ft msl are primarily sand. The color of the sand varied from tan to brown to tan again and the grain size gradually reduced from coarse to fine. Traces of minerals such as quartz and feldspar were observed. Clay was observed at -100 ft msl and continued until -105 ft msl. The clay was dense, silty, brown to gray in color and was mixed with fine, tan-colored sand, mica and quartz. Tan-colored fine sand was found thereafter until the end.

B18: The material from grade to about 176 ft below grade (-100 ft msl) consisted of tan to brown, coarse to fine, quartzose sand with traces of silt, medium to fine gravel, dark minerals. For about 10 ft below this point (until about -110 ft msl), the material composition changed to compacted brown clayey silt with traces of fine sand and muscovite flakes. For the rest of the boring, the material recovered consisted of gray colored fine sand with traces of black organic silt and muscovite.

S72812M: The suffix M indicates that this well was drilled into the Magogy aquifer. Sand was the predominant material until -123 ft msl, color ranging from light brown to brown. From -123 ft to -127 ft msl gray-brown, fine-grained, quartzose sand was found accompanied by small white clay lumps. From -127 ft to -175 ft msl, material was mostly clean, very fine to fine, light gray quartzose sand with occasional presence of muscovite mica and dark minerals. The drilling log indicates recovery of tannish gray, solid clay from bottom 12 inches of the boring.

None of the borings’ lithological descriptions hint at the presence of Gardiners Clay (no “greenish” clay). However, the presence of low permeability material such as silty, sandy clay, and clay lumps was inferred as a depicting a potentially semi-confining unit along the northern boundary of the landfill site (Figure 32).
Figure 33: Cross section L-L’ (inferred position of the Gardiners Clay is shown with dotted line)
9.2.5. Transect L-L’ (MW12-D / B-18 / MW11M / S72814M / MW102-D / S129174)

This cross section is from northwest to southeast, in direction of the groundwater flow. The depths of the wells are 180 ft (MW12-D), 220 ft (MW11M), 192 ft (B-18), 221 ft (S72814M), 100 ft (MW102-D), and 260 ft (S129174).

MW12-D: The geologic description of the boring indicate the presence of light tan to brown, medium to fine, quartzose sand that contains traces of fine gravel and silt until a depth of 170 ft from grade. At -95 ft msl, the material changes to dark brown to red compact silt containing little fine sand. This was designated as the presence of a potentially semi-confining unit (Dvirka and Bartilucci, 1996a).

B-18: The material from grade to about 176 ft below grade (-100 ft msl) consisted of tan to brown, coarse to fine, quartzose sand with traces of silt, medium to fine gravel, and dark minerals. For about 10 ft below this point (until about -110 ft msl), the material composition changed to compacted brown clayey silt with traces of fine sand and muscovite flakes. For the rest of the boring, the material recovered consisted of gray colored fine sand with traces of black organic silt and muscovite.

MW11M: The sand for the first 150 ft below grade was light tan to brown, coarse to very fine, and contained a little gravel and traces of round pebbles. From 150 to 160 ft below grade, the sand became silvery gray, fine grained and micaceous with traces of gravel. The composition of the material changed at -95 ft msl to black, micaceous, lignitic silt with some black clay and a little fine sand. This continued until -125 ft msl. Silvery gray, micaceous, medium, quartzose, lignitic sand with traces of silt was encountered below this point until termination. It was inferred that a 30 ft thick layer of silty, potentially semi-confining unit is present at this location from -95 to -125 ft msl (Dvirka and Bartilucci, 1994a).

S72814M: The top 112 ft of the boring consisted of light brown to brown, fine to coarse grained, quartzose sand with traces of gravel and feldspar. A similar pattern was continued from -57 ft to -78 ft msl with the addition of occasional clay lumps. Light brown, medium to coarse quartzose sand with rock fragments and pebbles was found between -78 and -102 ft msl. Orange to brown, medium to coarse, silty sand was accompanied by olive gray clay was observed between -110 ft to -116 ft msl. Below this point, sand was mostly light gray, very fine to fine, silty with traces of lignite and gravel. The occurrence of olive gray clay was interpreted as the presence of approximately 6 ft of Gardiners Clay (Wexler 1988a).

MW102-D: Brown to tan, coarse to medium to fine sand, with little gravel and silt was found throughout the boring. No clay was observed.

SS129174: tan, coarse to medium sand with gravel was observed for the first 120 ft below grade. From about -105 to -125 ft msl, green clay with sand and stones was observed. The sediments
from -125 to -165 ft msl were described as “gardiners clay” (sic) in the drilling log. The material description changed thereafter until the termination point to gray, coarse sand with bits of lignite.

It was concluded that a southeasterly slanting potentially semi-confining unit is present along the cross section. Its thickness and clay content increases southeasterly and the material composition varies from silty, clayey sand to solid clay, including Gardiners Clay at several boring locations.
9.2.6. **Transect M-M’ (B-21 / MW11M / B-20 / S72813M / PB-24)**

The geotechnical (gamma ray log) cross section M-M’ comprises of five borings that are located at the southern boundary of the landfill and are parallel to the Sunrise Highway (Figure 29). Boring B-21 marks the western limit while PB-24 is at the eastern terminus of the cross section. The boring depths are 186 ft, 220 ft, 192 ft, 180 ft and 152 ft for B-21, 11M, B-20, S72813M, and PB-24 respectively.

**B21:** The boring mostly consists of tan to brown, medium to fine, quartzose sand with occasional traces of dark minerals, silt, and gravel. This pattern continues until about -100 ft msl. The sand turns reddish to orange brown at about -113 ft msl. The sand color changes to silvery gray for the rest of the boring until termination.

**MW11M:** The sand for the first 150 ft below grade was light tan to brown, coarse to very fine, and contained little gravel and traces of round pebbles. From 150 to 160 ft below grade, the sand became silvery gray, fine grained and micaceous with traces of gravel. The composition of the material changed at -95 ft msl to black, micaceous, lignitic silt with some black clay and little fine sand. This continued until -125 ft msl. Silvery gray, micaceous, medium, quartzose, lignitic sand with traces of silt was encountered below this point until termination.

**B20:** The boring consists of brown to tan, medium to fine, quartzose sand for about 150 ft below grade (-80 ft msl). Silty, brown, fine sand is found thereafter until about -100 ft msl. Then the material changes to brown silt to brown, fine to medium quartzose sand for about -103 ft msl. Gray-colored, silty, clayey, fine sand is observed until about -113 ft msl. Dark gray fine quartzose sand with little silt is found thereafter until the termination point. A 0.25 inch layer of dark green glauconitic fine sand was observed at about -115 msl.

**S72813M:** For about 160 ft below grade, the material at S72813M remained mostly tan to brown, coarse to fine grained, quartzose sand with some muscovite mica, feldspar, silt and occasional gravel. From -106 ft to -112 ft msl, the material became reddish brown to brown and increasingly silty with presence of dark minerals and some clay. Lumps of dark gray clay were observed between -111 to -117 ft msl. Glauconitic sand with dark gray clay lumps and lignite was observed for a further 15 ft (-117 to -132 ft msl). A drilling log note said that “the rig is drilling like clay” from -135 ft to-140 ft msl. Samples recovered between -140 and -160 ft msl showed medium to coarse grained sand, some muscovite mica and dark minerals. Lumps of yellow brown and black clay, along with silty, fine to medium grained sands were observed from -160 ft to -173 ft msl. Black, sandy clay was found from -173 ft to -183 ft msl where the drilling ended. Thomas Doriski of USGS (Wexler, 1988a) inferred that 7 feet thick layer of sandy facies of Gardiners Clay, with some clay and silt, was present at S72813M from about -115 ft msl to -122 ft. A geophysical investigation at S72813M by USGS indicated a “clay kick” in the gamma ray log between -115 ft msl and -125 ft msl.
Figure 34: Cross section M-M’ (inferred position of the Gardiners Clay is shown with dotted line)
PB-24: The first 100 ft of the boring contained tan, brown or red colored quartzose sand of mixed grain size containing traces of silt, gravel, dark minerals, and muscovite flakes. Olive green to gray colored, medium to fine sand with traces of gravel and green silt was encountered from the depth of 110 ft to 130 ft below grade. Compacted fine sand with reddish brown silt and traces of muscovite was found from -85 ft to -95 ft msl where the drilling ended. The compacted portion of the sand is considered to be the semi-confining unit described as the Gardiners Clay (Dvirka and Bartilucci, 1996b). Alternatively, the distinct coloration of the overlying silty sand, olive green to gray color similar to that of the glauconitic Gardiners Clay, could be considered to be the Gardiners Clay. Here, the latter interpretation preferred and thus, it was inferred that about 20 feet of silty, sandy facies of Gardiners Clay is present at PB-24 between -60 ft to -80 ft msl.

Except for S72813M and PB24, and possibly of B20, the rest of the borings do not indicate the presence of material similar to Gardiners Clay. The pattern of gamma ray log suggest presence of some low-permeability material across the transect. The pattern matches well with the geologic boring descriptions (Figure 34). Therefore, it was inferred that Gardiners Clay is present across the eastern portion of the cross-section M-M’. The gamma ray response at wells B21 and 11M seem to indicate presence of finer, low-permeability material at stratigraphic positions conform to that of the inferred Gardiners Clay in rest of the section. Taken together, it was inferred that a potentially semi-confining unit, which includes the Gardiners Clay, is present across the cross-section M-M’.


Figure 35: Cross section N-N' (inferred position of the potentially semi-confining unit is shown with dotted line)
9.2.7. Transect N-N'(B-18 / B-20)

Cross section N-N’, the other geotechnical cross section, cuts across the landfill from north to south, between Cell 5 and Cells 1-4 (the present bottom of Cell 6 Phase 1 and 2) (Figure 29). The section joins two borings, B-18 and B-20, both about 190 ft deep.

B18: The material from grade to about 176 ft below grade (-100 ft msl) consists of tan to brown, coarse to fine, quartzose sand with traces of silt, medium to fine gravel, dark minerals. For about 10 ft below this point (until about -110 ft msl), the material composition changes to compacted brown clayey silt with traces of fine sand and muscovite flakes. For the rest of the boring, the material recovered consists of gray colored fine sand with traces of black organic silt and muscovite.

B20: The boring consists of brown to tan, medium to fine, quartzose sand for about 150 ft below grade (-80 ft msl). Silty, brown, fine sand is found thereafter until about -100 ft msl. Then the material changes to brown silt to brown, fine to medium quartzose sand for about -103 ft msl. Gray-colored, silty, clayey, fine sand is observed until about -113 ft msl. Dark gray fine quartzose sand with little silt is found thereafter until the termination point. A 0.25 inch layer of dark green glauconitic fine sand was observed at about -115 msl.

Presence of quarter inch thick green sand may indicate presence of sandy facies of Gardiners Clay at this location. No such material was found at B18 and therefore it could not be confirmed as to whether Gardiners Clay extends up to the northern boundary of the landfill. However, gamma kicks in the geophysical logs coincide well with the occurrence of clayey silt and therefore it was inferred that a potentially semi-confining unit containing low permeability material such as clayey silt and fine sand is present across this section. Figure 35 shows the inferred position of the potentially semi-confining unit.
10. Discussion

The standard model of Long Island geological stratigraphy south of the Ronkonkoma moraine is (from bottom to top): bedrock, the sand member of the Raritan Formation, Raritan Clay, the Matawan Group-Magothy Formation, Monmouth Greensand, Gardiners Clay, Upper Glacial deposits, and Holocene deposits (see Table 3, p. 22, and Figure 7, p.26). Here we explicitly define a stratigraphy for the vicinity of the Brookhaven landfill that generally accords with the standard model.

The Upper Glacial aquifer extends across the study area, slanting and thickening in a south to southeasterly direction. It is overlain by a thin veil of Holocene deposits, including anthropogenic materials of various kinds. The saturated and unsaturated sediments associated with this upper stratigraphic unit range from about 150 to 200 ft thick, with the water table aquifer being about 90 to 135 ft thick. The Upper Glacial aquifer is underlain by confining layer that for conventional purposes we call Gardiners Clay, or by the Magothy aquifer in absence of this confining unit. The major sediment type in the uppermost geologic unit is sand of variable texture and grain size. A downward fining of the sand in the Upper Glacial deposits was observed (see p. 43); consequently, and in keeping with groundwater monitoring practices at the site, the Upper Glacial aquifer has been considered to have three sections – shallow, intermediate, and deep. For purposes of the groundwater model, a different set of hydrologic properties has assigned to each sub-unit (Table 7, at the end of this section, p. 87).

The confining unit we are calling Gardiners Clay can act as a natural barrier to the downwardly leachate flow and its presence underneath the leaky landfill can prevent contaminated groundwater in the Upper Glacial aquifer from mixing with deeper waters. The title “Gardiners Clay” is not to be taken literally; i.e. although it connotes that the unit is composed of solid clay, the geologic evidence suggests that the composition of this unit is highly variable, from sandy to silty to solid clay. In addition, although the characteristic greenish clay appears at certain borings, other colors such as brown, white, black, and gray have been used to describe clay and silts at similar depths at other boring locations, including sand hardpan in one notable instance. Therefore, the position, thickness, and extent of classic Gardiners Clay in the vicinity of the landfill cannot be ascertained.

However, the evidence indicates the presence of low-permeability material. We prefer the term “potentially semi-confining unit” (PSU), to Gardiners Clay as a more accurate descriptor of this unit (or set of units). This is not an unclassified geologic unit, but rather to be taken as a hypothetical layer that is an ensemble of various low permeability materials found across most of the study area. The PSU includes some clay that matches the classic description of Gardiners Clay. The PSU, wherever present, provides semi-confining to confining conditions that may retard groundwater flow between the Upper Glacial and the Magothy aquifer in the study area. The confining conditions in the area are increased when the PSU is underlain by another low permeability unit, the Monmouth Greensand. Because it is difficult to separate the Monmouth
Greensand from PSU units where Monmouth Greensand is present, we prefer to treat them as a combined hydrogeologic unit.

Based on regional transects from the boring log analysis in Section 9.1, it was inferred that the PSU is not present north of the landfill site, across cross-section A-A', located about 2 miles north of the landfill site (see p. 49). Cross-section B-B', which crossed through the landfill site parallel to Sunrise Highway, showed the presence of the PSU (see p. 51). A Gardiners Clay-dominated PSU is clearly indicated across cross-section C-C', which is located about 1 mile south of the landfill, also parallel to Sunrise Highway (p. 53). The thickness and clay content of the PSU appears to increase to the south, with a massive 275 ft clay unit found at well S18846 on Fire Island in cross-section D-D'.

In Section 9.2, local cross-sections were created using boring logs. Cross section K-K', which runs along the northern boundary of the landfill site, had some indications of the PSU (see p. 73). Stronger evidence of the presence of the PSU was shown in transect J-J', across the southern boundary of the landfill. Combined geophysical and geological logs for cross-sections N-N' and M-M' further suggest the presence of the PSU underneath the landfill site (see pp. 77-81). North-south cross-sections such as the regional transects E-E' (p. 57) and F-F' (p. 59) and local transects H-H' (p. 65) and I-I' (p. 67) support the continuity of the overall PSU, although materials involved in it vary considerably. Overall the occurrence of low-permeability material from just north of the landfill across the study area is consistent. No borings have been made (and preserved) between the northern perimeter of the landfill and I-495 that could define the northernmost extent of the PSU. The thickness and clay content of the PSU increases irregularly from north to south; a 1 foot thick sandy facies is present near the landfill, while a 275 ft thick solid clay is found under Fire Island. It was assumed that the PSU extends beyond the barrier beaches into the Atlantic Ocean, congruent with theoretical extents of Gardiners Clay and Monmouth Greensand. The slope of the unit is inconsistent; the PSU undulates with the upper surface elevation ranging from about -50 ft msl to -120 ft msl.

The inferred position and thickness of the PSU, as developed from the boring log interpretations developed in Figures 14-35, were interpolated into a pair of two dimensional surfaces, depicting its top and bottom surface elevation (Figure 36). The layers were generated using ArcScene v. 10 (ESRI Inc.). The surfaces were populated using the “natural neighbor” interpolation scheme. The surfaces show the perceived physical extent of the PSU, but do not reflect varying hydrologic characteristics (such as differences in the sandy and clayey facies).
Figure 36: Interpolated surfaces of the PSU a) top surface b) bottom surface
Because of the PSU is only “potentially” “semi-confining,” the shallow portions of the Magothy aquifer may not be completely insulated from the overlying Upper Glacial aquifer. However, because flow in the Upper Glacial aquifer at the edge of the Deep Recharge Zone is almost entirely horizontal, groundwater in the Upper Glacial aquifer is unlikely to percolate deeper, into the Magothy aquifer. Further, the shallow Magothy is composed of lower permeability fine sand that can lead to generation of anisotropic conditions, which can retard downward movement of groundwater.

The upper surface elevation of the Magothy aquifer ranges from -50 ft to -150 ft msl. This upper surface is undulatory; most depictions of the Magothy aquifer, especially those presented in coarser resolution, regional contour maps (see p. 34) are smooth and lack erosional features found in finer resolution discussions. However, it is clear that the Magothy is not a even, flat surface near the Brookhaven landfill. We lack local information for deeper portions of the Magothy aquifer, and so the hydrologic properties for the aquifier given in Table 7 represent the average values assumed to apply to the entire aquifer underneath the study area. The hydraulic properties of the PSU were assumed to be those generally associated with Gardiners Clay.

<table>
<thead>
<tr>
<th>Hydrologic unit</th>
<th>Average Kh (ft/d)</th>
<th>Maximum Kh (ft/d)</th>
<th>Minimum Kh (ft/d)</th>
<th>Groundwater velocity (ft/d)</th>
<th>Anisotropy ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shallow UGA (0 to 70 ft below grade)</td>
<td>260&lt;sup&gt;a&lt;/sup&gt;</td>
<td>677&lt;sup&gt;a&lt;/sup&gt;</td>
<td>30&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1-1.8&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2:1–10:1–24:1&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Intermediate UGA (70 to 100 ft below grade)</td>
<td>130&lt;sup&gt;a&lt;/sup&gt;</td>
<td>208&lt;sup&gt;a&lt;/sup&gt;</td>
<td>58&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1-1.4&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Deep UGA (100 ft below grade to confining layer)</td>
<td>70&lt;sup&gt;a&lt;/sup&gt;</td>
<td>363&lt;sup&gt;a&lt;/sup&gt;</td>
<td>17&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.3-1&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Potentially semi-confining unit (PSU)</td>
<td>6.5&lt;sup&gt;a&lt;/sup&gt;</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>5:1–24:1&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>Magothy aquifer</td>
<td>50&lt;sup&gt;d&lt;/sup&gt;</td>
<td>268&lt;sup&gt;e&lt;/sup&gt;</td>
<td>1&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.0043&lt;sup&gt;a&lt;/sup&gt;</td>
<td>30:1 – 100:1&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

Table 7: Hydrologic characteristics of the hydrologic units at the study area (<sup>a</sup> Dvirka and Bartilucci, 1994; <sup>b</sup> Lindner and Reilly, 1983; <sup>c</sup> Eckhardt and Wexler, 1986; <sup>d</sup> Franke and Cohen, 1972; <sup>e</sup> Isbister, 1962; UGA = Upper Glacial aquifer)

All of the values presented here are qualified. These qualifications are attributed to three causes – natural causes, human interpretation, and mathematical inference techniques.
Table 8: Excerpts from drilling logs from borings along the transect C-C’ at the depths where presence of the Gardiners Clay was inferred

<table>
<thead>
<tr>
<th>Boring</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MW11M</td>
<td>160’-182’: Black to silvery black micaceous, lignitic SILT, some clay, little to some fine sand</td>
</tr>
<tr>
<td></td>
<td>185’-187’: No recovery-drilling indicates clay</td>
</tr>
<tr>
<td></td>
<td>190’-192’: Same as above</td>
</tr>
<tr>
<td></td>
<td>195’: Drilling change at approximately. 195’ indicating sand</td>
</tr>
<tr>
<td>MW4-D</td>
<td>172’-174’: 0-1.2’ → Br f S, a(+)$: no prt, mica, dense, wet</td>
</tr>
<tr>
<td></td>
<td>1.2-2.1’ → Gy br C l(+), fs, tr(-) c: ang qtz, faint br prt, damp, stiff, mica</td>
</tr>
<tr>
<td></td>
<td>2.1-2.2’ → Or br f(-) c S, l(-) $yc, tr (-)f(+)$cg; md, stiff, damp</td>
</tr>
<tr>
<td>103140</td>
<td>Medium to coarse dark brown sand-some gravel and mica</td>
</tr>
<tr>
<td>S72813M</td>
<td>180-187: Gardiners Clay (sandy facies, some clay and silt)</td>
</tr>
<tr>
<td>PB-24</td>
<td>Top of semi-confining unit encountered at 140 ft bg...End of drilling at 150.5 ft</td>
</tr>
</tbody>
</table>
10.1 Natural Variation in Geologic Settings

As discussed in Section 7, the sedimentary mass on Long Island was subjected to repeated periods of glacial deposition and intra- or inter-glacial restructuring. This restructuring may have resulted in a spatially uneven stratigraphy for a given geologic unit, especially when considered at local scales. For example, Figure 37 shows the variation in the physical extent of Gardiners Clay described by Smolensky et al. (1989). The terminal extent (0 ft thickness) is marked by the red line that indicates absence of the Gardiners Clay from the area approximately overlapping with the Forge River basin located to the east of the landfill. The pattern of elevation contours (the two -100 ft closed contours adjacent to the protruding Forge River basin terminal line) suggest local erosion of the layer. This example is indicative that natural processes are not uniform across the landscape, and they result in variations in local geology.

10.2 Variation Introduced due to Differing Human Interpretations

The quality of the observational data depends on factors such as the level of sophistication of the laboratory or field procedures used for exploration, adherence to procedural standards, and expertise of the analyst(s)/observer(s). Needless to say, the observational data do not speak for themselves and it is the human observers that process the data, define their context, and draw inferences from them. This review covered a range of studies; the following factors affect the interpretation of collected data.

10.2.1 Data Collection Methods

A lack of standardized methods for geologic observations limits the utility of the available data. Drilling logs in particular showed noticeable variability in reporting the observations of the core analyses. Dvirka and Bartilucci (1994b) consistently used a modified version of the Bermister soil classification system to describe the samples obtained during the drilling operations. However, other boring logs, such as for public supply wells (filed with NYSDEC) did not specify the type of methodology used for classifications. In addition, the descriptions were not consistent, varying from boring log to boring log. For example, Table 8 shows those sections of the drilling logs that were perceived to be indicating the presence of Gardiners Clay along transect C-C’ (see p. 54). Notice that the method of description was not consistent and varied from well to well. No complementary evidence such as preserved boring samples or photographic logs is available. Thus, we often interpreted different descriptions as applying to the same physical phenomenon.

10.2.2 Linearity Assumption

As discussed in Section 10.1, the subsurface geology of one area can be significantly different than that of the other. This variability may also hold true for comparatively smaller segments of the study area. Absence of any concrete geologic evidence generally forces the
interpreter to assume a certain pattern of stratigraphy is continued. For example, it was assumed that the interpolation of the geologic surface between two boring locations along a transect follows linear projections. This assumption was made because either there were no borings between the two adjacent data points (or if one was present, it was too shallow and therefore not useful for interpolation).

10.2.3 Discretization and Zoning

The continuous gradation of the geologic units (and their hydrogeologic properties) were simplified either by (i) segregating units with distinct properties (discretization), or by (ii) lumping hydrogeologically similar units together (zoning). Both processes have physical basis but also are a result of interpretations introduced by observers.

For example, the Upper Glacial aquifer is divided into three aquifer layers – shallow, intermediate, and deep (see p. 87). Evidence suggests that there is an downward fining of the sediments constituting the Upper Glacial aquifer - from coarse sand and gravel to medium to fine sand with silt and clay to fine sand. Horizontal hydraulic conductivity values decrease progressively from top to bottom. The gradation of sediment size and hydraulic conductivity is continuous; however, the aquifer unit was divided into discrete layers. Each layer has hydrologic properties and sediment types different than the other, although each layer is considered homogenous in distribution of grain size and conductivity within itself, despite evidence for continuous change, not discrete layers.

One can also merge two or more homogenous units into a single zone. The homogeneity may be facilitated by hydrologic similarity and geologic continuity. For example, both Gardiners Clay and the Monmouth Greensand were combined to represent a single aquitard because both units have similar hydrologic properties (both have low permeability) and they are physically connected (the former is underlain by the latter).
10.3 Variation due to Mathematical Inference Techniques

The use of mathematical algorithms to generate inferences based on observational data is supposed to minimize the effect of human judgment. However, variations among mathematical tools was found to influence outcomes. Other interpolation schemes other than natural neighbors (kriging and inverse distance interpolation) were used to populate the three-dimensional clay layer. A visual comparison of these different interpolations indicates that they define top of the Gardiners Clay differently from each other (Figure 38). The natural neighbor method was preferred because it was most consistent with the generalized understanding of a southeasterly dip of Gardiners Clay (see p. 26).

In addition, the interpolation methods calculated surface elevations for the area outside the area enclosed by the outermost set of boring locations. This extrapolation may change if additional set of boring data were to be included in the calculation. In addition, the spatial distribution of the available borings is non-uniform. More borings, represented by red dots in the Figure 39, are located inside the landfill property, and the borings outside of the landfill property are therefore relatively sparse in comparison. The boring locations are neither equidistant nor uniformly distributed across the interpolation surface. This introduces bias in the calculations which in turn affects the interpolation of the Gardiners Clay layer. Thus, the effectiveness of inferential techniques is also conditional on the availability and distribution of the input data points.
Figure 38: Upper surface of Gardiners Clay, extrapolated three ways: a) natural neighbors, b) inverse distance, and c) Kriging.
11 Conclusions

The Brookhaven landfill site is located on the Long Island south shore outwash plain, formed by post-Cretaceous glaciofluvial erosion and deposition. The topography in the landfill vicinity gently slopes in a southeasterly direction and is marked by features such as the Carmans River valley to the east and the Ronkonkoma terminal moraine to the north. This report defined a stratigraphy for the vicinity of the Brookhaven landfill that accords with the generalized model of Long Island geology. The stratigraphic profile of the landfill site and vicinity consists of Pre-Cambrian bedrock overlain by Cretaceous members of the Raritan Formation and the Matawan Group-Magothy Formation, and then by Monmouth Greensand. The Cretaceous members are disconformably overlain by upper Pleistocene deposits such as Gardiners Clay, and the Upper Glacial and Holocene deposits. The Upper Glacial unit and the Magothy Formation are the two major aquifers in the area. A range of hydrologic properties were assigned to the different aquifer units. The Upper Glacial aquifer has a higher average hydraulic conductivity than the Magothy aquifer.

Based on analysis of available geologic and geophysical boring logs, it was concluded that the position and extent of Gardiners Clay, that is, a classically-defined low permeability aquitard thought to separate the Upper Glacial and Magothy aquifers, could not be determined across the study area. Several low permeability materials were observed at many of the boring locations. These occurrences were mostly found within a depth range of -50 to -150 ft msl, the range at which Gardiners Clay is generally understood to be in the study area. However, the lithologic descriptions and in particular, the coloration of these materials, differed from the generalized lithology and the characteristic greenish appearance of Gardiners Clay.

Therefore, rather than defining the low permeability materials as Gardiners Clay, they were classified into a potentially semi-confining unit (PSU). The composition of the PSU is hardpan to sandy and silty clay to firm clay; overall, the PSU has low enough permeability that it is confining to semi-confining, where present. It was concluded that the northernmost extent of the PSU lies at the northern perimeter of the landfill site and the thickness and depth of the unit, as well as its confining capabilities, progressively increase from north to south. The PSU was assumed to have the same general hydrologic properties as that of the classic definition of Gardiners Clay.

This report presents a comprehensive review of the pre-existing established literature. This information is sufficient to support a sophisticated model of subsurface groundwater movement. It can be used to populate modern modeling platforms such as MODFLOW. Other preliminary steps required before constituting such a model will include (i) developing a hydrologic framework that explains phenomena such as interaction between surface water and ground water, quantification of groundwater recharge from precipitation and due to hydraulic connectivity between different aquifer units, and water balance of the study area; and (ii) developing the conceptual framework of the model, including identification of model...
boundaries, the pattern and chronologic evolution of the leachate source, and the leachate indicators and their physico-chemical and biological reaction rates.
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