HYDROGEOLOGY OF A RAPID INFILTRATION BASIN SYSTEM AT CAPE HENLOPEN STATE PARK, DELAWARE

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INTRODUCTION

Rapid Infiltration Basin Systems (RIBS) consist of several simple and relatively standard technologies employed for land-based disposal of wastewater. In Delaware, wastewater generated by parks, homes, and businesses is collected and conveyed to a treatment plant. Following chemical and physical processing and treatment of the wastewater, the effluent is discharged to an unlined excavated or constructed basin. By design, the effluent quickly infiltrates through the unsaturated or vadose zone to the water table. Once in the aquifer, much of the effluent flows and eventually discharges to a body of surface water. Depending on the location and design characteristics of an individual RIBS, effluent may be intercepted and pumped by water supply wells, or portions of effluent from an individual facility may slowly percolate deeper into the water aquifer or into underlying confined aquifers.

If all of the individual components of a RIBS are working properly, there is potential for the water to be safely reclaimed for other purposes such as maintaining surface water flow, sustaining important subaqueous and wetland habitat, and supplying water for non-potable or perhaps potable uses. However, nearly forty years of research by academia, state, and federal scientists have documented that the Columbia aquifer is highly susceptible to contamination from application of wastes onto and into the ground. Contaminants persist in the groundwater for decades where they commonly impact potable water supply wells, and the contaminants will eventually discharge into bodies of surface water leading to well documented eutrophication problems (Miller, 1972; Robertson, 1977; Ritter and Chirnside, 1982, 1984; Andres, 1991; Guitierrez-Magness and Raffensperger, 2003; Denver et al., 2004; Pellerito et al., 2006). Debrewer et al. (2005) and Ator (2008) found that the causes of Delaware's water quality problems are consistent with those observed throughout the Delmarva Peninsula and much of the mid-Atlantic Coastal Plain. In this context, it should be anticipated that when one or more of the components of a RIBS malfunction, or if unanticipated natural hydraulic and/or geochemical factors are present, there is substantial risk for the effluent to create conditions that will adversely impact sensitive public (water supply wells) and environmental (streams, wetlands) receptors.

Purpose and Scope

This report covers the physical hydrogeologic component of the second phase of a multi-year, multi-disciplinary project to systematically analyze the components and the risks associated with operation of RIBS in Delaware. During this work we have conducted a variety of field experiments designed to characterize the geology and hydrogeology of a RIBS facility located at Cape Henlopen State Park (CHSP, Figure 1) and the physical hydrogeologic affects on shallow groundwater caused by the addition of treated sewage effluent through rapid infiltration beds.

Acknowledgments

This work was funded by the Delaware Department of Natural Resources and Environmental Control (DNREC) and the Delaware Geological Survey (DGS). We thank Patrick Boetcher, Joshua Kasper, and Scott Strohmeier (DNREC), Steve McCreary, Thomas McKenna, and Jaime Tomlinson (DGS), and Janine Howard, Ashley Beers, Justin Wagner, Jennalee Ruftt, Curt Romanchock, Ian McCann, and Holly Michael (University of Delaware) for their participation in the field work. The Delaware Division of Air and Waste Management provided a Geoprobe rig equipped with a single barrel coring device and operator (Patrick Boettcher) for three days. We especially thank the DNREC Division of Parks and Recreation and the staff of CHSP for permission to access property and for their assistance with logistics.

METHODS

Subsurface materials were characterized by analysis of samples and measurements collected from test borings and direct push coring, downhole geophysical logging, monitoring wells, collection and analyses of samples, and collection and analyses of hydraulics data. Analyses of soils and sediments included visual description, grain size distribution, and water content. Testing of hydraulics included single-well aquifer tests (slug tests), ring infiltrometer tests, and groundwater-level measurements. Locations of

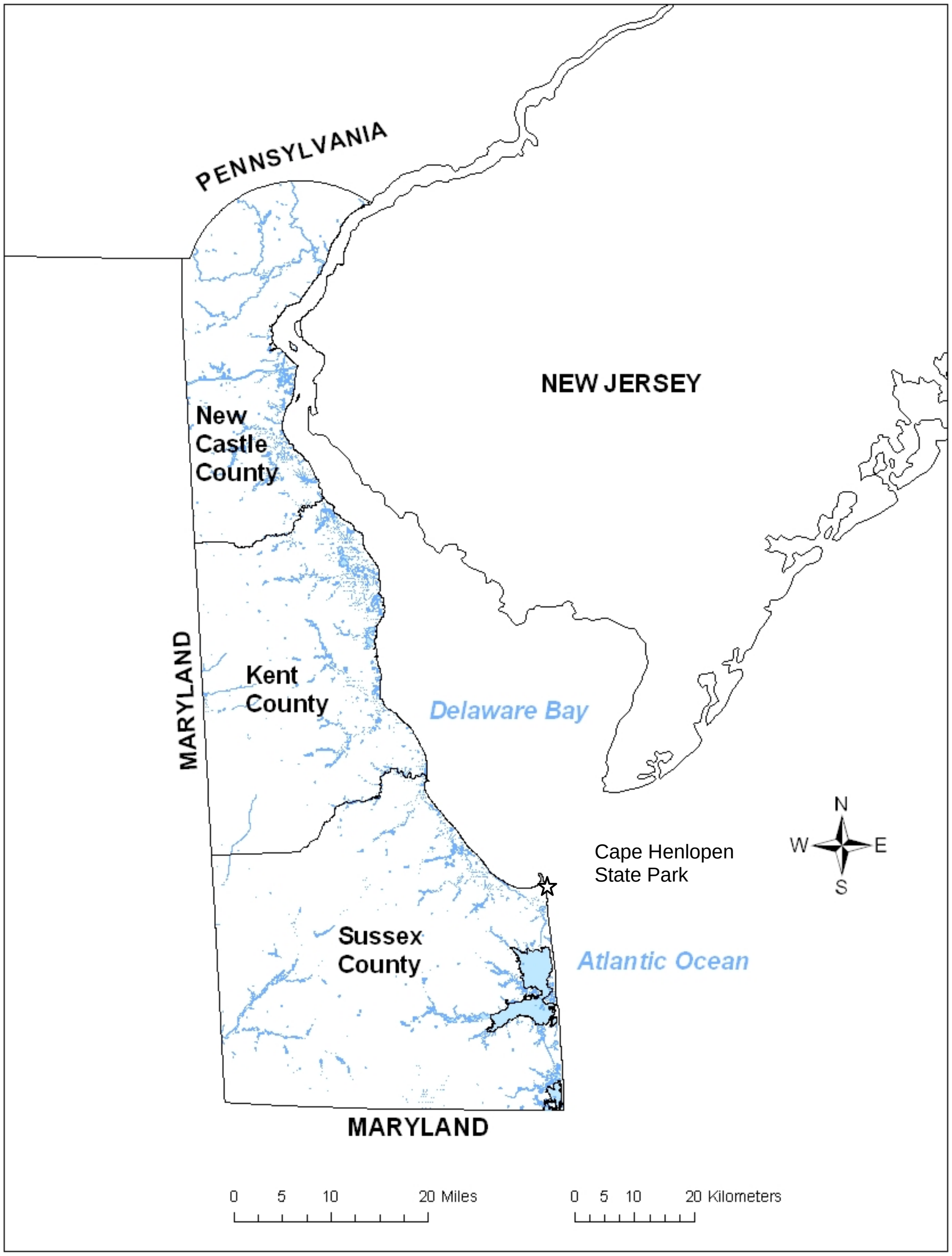

Figure 1. General location map.

observation points are shown on Figures 2a and 2b. Site identifiers shown on Figure 2a are indexed to wells listed in Appendix A.

Field Methods for Characterization of Soils, Sediments, and Water

Locations of observations made within the infiltration basins were determined using 2007-edition high resolution, georeferenced aerial photography (http://datamil.delaware.gov) in conjunction with the facility's engineering drawings. Locations of observations made outside of this area were determined using a real-time corrected global positioning system.

During February 2008, two 25-ft borings and eight 10-ft borings were completed using a Geoprobe rig equipped with a single barrel coring device (Figure 2a). Core samples were collected within standard acetate core barrel liners. The liners were opened in the field, visually inspected, and any material sloughed from the side of the hole was discarded. The core samples were cut into 2 foot lengths, photographed, placed in core boxes, and covered with polyethylene film and transported to the DGS laboratory. At the laboratory, samples were split with a mechanical splitter with one portion saved for particle size analysis and the other portion for chemical analysis.

In February and March 2008, two 2-ft deep hand auger borings were made in each of the eight infiltration beds (Figure 2b). Within each bed, one boring was completed in a vegetated area near a wastewater discharge head, and one boring was completed in a non-vegetated area. Separate samples were collected from 0 to 1 ft and 1 to 2 ft below surface. Samples were split with a mechanical splitter with one portion saved for particle size analysis and the other portion for chemical analysis.

Test borings were completed and monitoring wells were installed at nine locations using the DGS CME-55 drill rig and at five locations using a hand auger (Figure 2a). Split-spoon core samples and downhole natural gamma radiation logs were collected through the annulus of the 2-1/4 inch inside diameter (ID) augers at Ni45-33 and Ni45-35. The

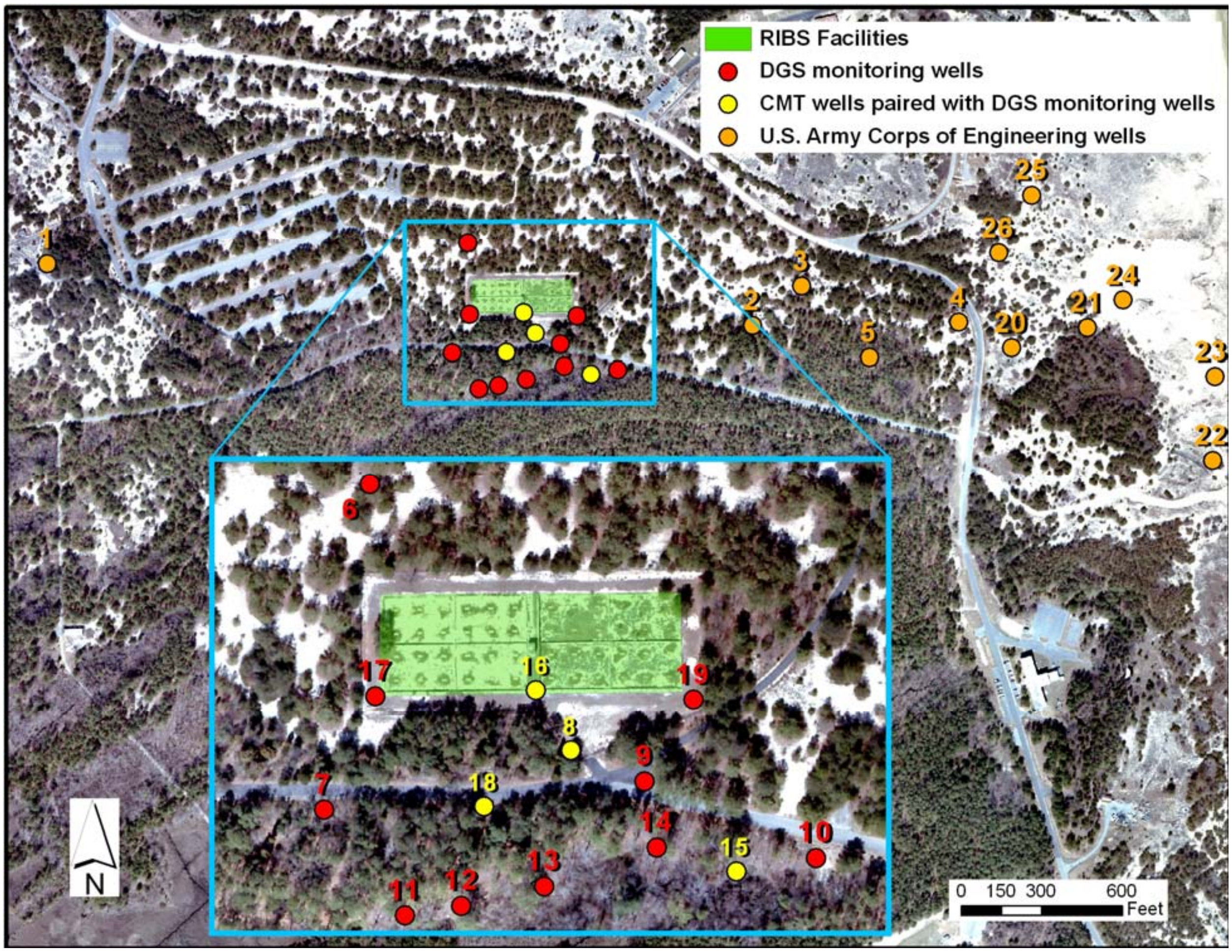

Figure 2a. Locations of monitoring wells. CMT refers to Solinst CMT multi-port monitoring device. Site identification numbers are indexed to wells listed in Appendix A.

core samples were described in detail on site and compared with the gamma logs to develop a model of site stratigraphy and hydrostratigraphy and to design well screen settings at all well sites. Several of the core samples were later subsampled for chemical testing.

Standard monitoring wells consisting of 2-inch ID threaded flush joint schedule 40 PVC pipe connected to machine slotted schedule 40 PVC well screen were installed. Wells installed in holes drilled by the truck-mounted equipment had 15 feet of well screen. Wells installed by hand augering had 3 ft of machine-slotted well screen. All wells were gravel packed and grouted with granular sodium bentonite. In all cases, the gravel pack extended at least one foot above the top of the screen interval. Grout was emplaced by tremie pipe in the machine drilled holes and by hand in the hand augered holes. Protective steel casings were placed over all wells located in easily accessible areas and sealed with concrete.

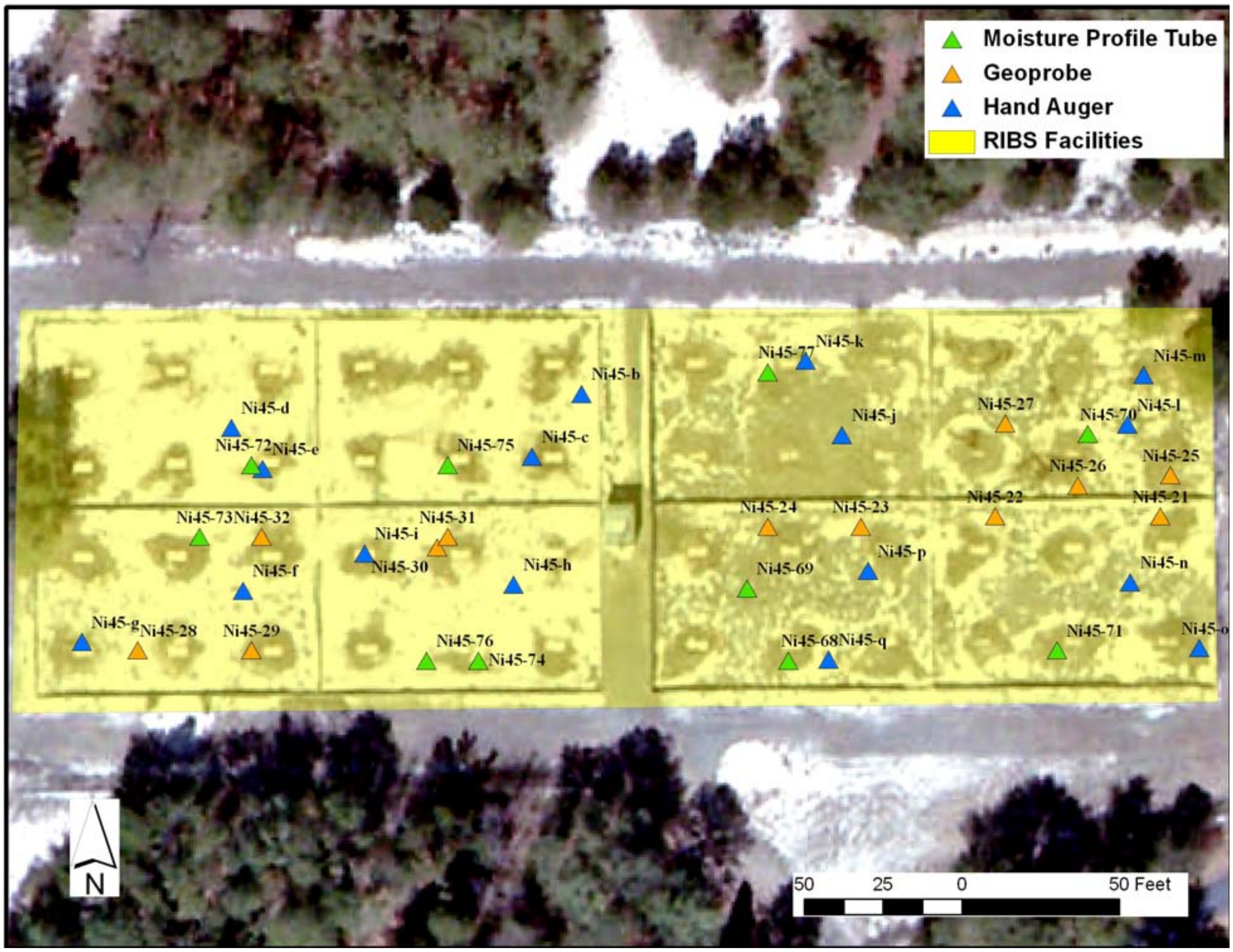

Figure 2b. Locations of test borings and moisture profiling tubes.

Consultants for the U.S. Army Corps of Engineers installed wells during multiple subsurface investigations, one in the 1990s (US Army Corps of Engineers, 1997), and another in November and December 2008 (James Stuby, written communication). Four wells from the 1990's investigation were monitored for this study (Figure 2a). Seven temporary 2-inch ID monitoring wells were installed in 2008 (Figure 2a), and water levels were measured in these wells during December 2008.

Natural gamma-induction electric logs were run in all of the wells installed with the CME rig. Geophysical logs and visual descriptions from samples of drill cuttings were used to refine interpretations of hydrostratigraphy developed from the cored-test-borings.

Four, seven-channel multi-level wells (CMT System - Solinst Canada) were installed next to standard wells at four locations (Figure 2a). The depths of individual sample ports were determined from analysis of the descriptive and geophysical logs collected at the same site. Gravel pack was emplaced to span the interval between 2 feet above the top sample port to the bottom of the CMT tube. Grout was emplaced with a tremie pipe from the top of the gravel pack to within a few feet of land surface. Protective casings were placed over all CMT wells and sealed with concrete or bentonite.

Moisture content of vadose zone

Ten additional split-spoon-test-borings were completed within the infiltration basins (Figure 2b) for determination of gravimetric (Wg) and volumetric water contents (Vw), and construction of time domain reflectometry (TDR) moisture profiling tubes (MPT). At each location a standard split spoon sampling device with acetate liner was driven with hand tools (slide hammer, tripod, and winch). In order to sample a known volume of material, the split spoon was advanced one foot and then removed from the hole. The cores were inspected on site and any portion of the core containing material sloughed from the side of the hole was discarded. The samples were then capped and transported back to the DGS building for determination of grain size distribution and gravimetric moisture content, and computation of volumetric moisture content (Vw) and porosity (n).

Each MPT constructed in the split spoon holes described in the preceding paragraph consists of a 2-inch ID schedule 40 PVC pipe with bottom end plug and top slip cap. Because the diameter of the MPTs is larger than the split spoon sampler, installation of the MPTs required that the holes be enlarged by inserting and removing a 2-inch ID schedule 40 galvanized steel pipe. This process allowed for close coupling of the MPTs and the surrounding material.

In-situ Vw was monitored with a Trime FM tube-type TDR in the MPT devices. The TDR probe was inserted into the MPT to a predetermined depth, the electronics were activated, and depth and Vw were recorded. Our instrument was factory calibrated in July 2008 and November 2008. Field calibration was conducted at the beginning of every field day and consisted of activating the instrument with the probe in free air to ensure that the instrument would return the expected 0 percent moisture value. Detailed description of the principles of TDR operations can be obtained from Robinson et al. (2003) and Laurent et al. (2005). These measurements were collected to estimate irreducible water content (Vw0), saturated water content (VWs), and effective porosity (ne). Bear (1979) defines irreducible Vw0 as the proportion of water (relative to total volume, Vt) that is immobile because it is held by capillary forces or in dead-end pores. Similarly, ne is the difference between n and Vw0, and VWs is equivalent to n.

Groundwater measurements

Groundwater levels were measured manually to the nearest 0.01 ft with Solinst electric water-level meters and automatically with In-Situ, Inc. transducer/data logger instruments. Barometric pressure data were collected on site with an In-Situ, Inc. barometer. For periods when this barometer was inoperable, barometric pressure data were collected at the nearby Delaware Environmental Observation System (DEOS) station located approximately 3 miles to the south in Rehoboth Beach, Delaware. Barometric corrections were computed with In-Situ Baromerge software or, in the case of the DEOS data, in an electronic spreadsheet. Quality assurance/quality control (QA/QC) procedures for the automated data were conducted following manufacturer’s guidance and internal DGS procedures. All data were archived in DGS internal databases.

Analysis of small changes in water level records required subtracting long-term trends (i.e., declines and increases) from the raw data (Figure 3). In these cases, the analysis consisted of linear regression analysis followed by calculation of residuals.

Hydraulics testing

Slug tests were conducted and analyzed using the guidelines established in Butler (1998). Because the well screens spanned the water table, water displacement was accomplished with a mechanical slug constructed of a sand-filled 0.75 inch ID capped, PVC pipe. Insertion and retrieval of the slug were controlled with a nylon cord. Within each 2-inch ID monitoring well, at least three rising head tests were conducted with an In-Situ, Inc. transducer/data logger used in conjunction with the manufacturer's software for instrument control and data capture. Data analysis was conducted using the Bouwer and Rice (Bouwer, 1989) method and Aquifer Test Pro software (Schlumberger Water Systems, 2008).

Several types of infiltration tests were conducted in the infiltration basins at the sites of the MPTs. Double ring infiltrometer experiments were conducted by a method that is functionally equivalent to ASTM D3385 (ASTM, 2003). The data from these tests provide an indication of apparent saturated vertical hydraulic conductivity. A more complete description of the various test methods used on the site is the subject of a UD Water Resources Center Undergraduate Internship project due to be submitted in April 2010.

For these tests, dataloggers in the inner and outer rings recorded head at 2-second intervals. Two 40-gallon tanks were used as reservoirs and water was delivered to the rings via valve controlled hoses. (Mariotte tubes could not deliver the amount of water needed because of the high permeability of the infiltration surface and the difficulty of moving large water reservoirs across the soft sandy surface of the basins.) The valves were adjusted to maintain head in the rings as close to one foot as possible. Flow rate to the inner ring was determined from the time series of height of water in a reservoir with a predetermined stage height – volume curve. Stage-height data were recorded by a datalogger mounted in the reservoir. Data from tests were processed in spreadsheets and infiltration rates were determined from periods for which flow rates and heads were held relatively constant.

Laboratory Measurements of Physical Properties

Methods described in Kramer (1987) were used to determine grain-size distribution on some samples (Appendix B). Gravimetric water contents were determined on selected core samples.

For all of these tests, weights were determined to the nearest 0.1 gram with an Ohaus E400 electronic scale. Total sample volume was estimated from the length of the sample and inside diameter of the core barrel liner. Density of the solid phase was assumed to be 2.65 g/cc (e.g., quartz). Porosity (n), volumetric water content (Vw), and bulk density were estimated for these samples using standard soil mechanics equations. Because of the loose nature of the samples, determination of sample length and computation of volumetric water content and bulk density proved to be problematic.

RESULTS AND DISCUSSION

Wastewater Treatment and Effluent Disposal

The wastewater treatment plant at the CHSP is a primary treatment system consisting of two Imhoff tanks constructed for the U.S. Army in 1941 (Lee McDaniel, personal communication). The plant treats water generated by a campground, a beach bath house, several administrative and maintenance buildings, a visitor center, several residences occupied by CHSP personnel, and several dormitories that include food preparation facilities. Dormitories at CHSP are used by school groups during the school year and by several sports camps during the summer.

The treatment plant is maintained by two CHSP employees who are State of Delaware licensed wastewater treatment plant operators. A detailed description of the plant is contained in Turkmen et al. (2008). Because the treatment plant has minimal storage capacity, effluent is discharged to the infiltration basins in frequent doses, with the frequency dependent on influent flow rates.

A mechanical valve system in a small building located in the middle of the array of eight infiltration basins, or beds, switches discharge of treated effluent between basins roughly every day following a clockwise pattern (Lee McDaniel, personal communication). CHSP personnel record cumulative flow on a paper form most weekdays along with the infiltration bed that was receiving effluent at the time of observation of flow. Our observations of effluent discharge location did not match records written by park personnel. We also observed that switching between beds does not happen at the same time every day. We estimated weekend flows as the difference between flows recorded on Fridays and Mondays.

In part, effluent disposal rates vary with the number of daily and overnight park visitors (Figure 4). The number of park visitors and generation of sewage vary by season and days of the week, with the greatest sewage flow usually occurring during summer months and weekends when the numbers of visitors using the beach and campground bath houses, visitor center, and dormitories are largest. Flow rates during summer weekends tend to be 10,000 to 15,000 gpd greater than those during summer week days, and more than 20,000 gpd greater than during the off season. During much of the year effluent disposal rate sometimes coincide with variation in the temperature of the effluent. Effluent temperatures measured at the infiltration site range from a low of about 12 degrees C in the winter to over 21 degrees C in the summer. The increased temperature appears to be correlated with increased use of warm water at the bath houses.

Effluent disposal rates also are affected by hydrologic conditions. Because portions of the sewage collection system consist of terra cotta pipe (Lee McDaniel, personal communication) there is substantial infiltration of groundwater when the water table is high enough or when sections of the collection system fail. A period of greater than normal effluent discharge was noted by park personnel in winter and spring of 2008 and this prompted repairs of the collection system (Lee McDaniel, personal communication). Differences between monthly effluent flow rates and monthly water purchase amounts in 2009 also indicate infiltration of groundwater to the sewage collection system.

Geologic Framework

Our understanding of the hydrogeology of the Cape Henlopen field site is derived from a synthesis of previous studies and our own observations made during drilling, water sampling, and other visual observations on the site. In this report we followed the stratigraphic names and mapping model presented by Ramsey (2003) to map and describe geologic units. Chadwick (2000) provided additional guidance for interpreting the sediments in the context of depositional environments. Leis (1974) conducted a hydrogeologic assessment of the general area including an investigation of aquifer hydraulics. In general, we found that these previous works provided reasonable interpretations of the geology and hydrogeology of the site.

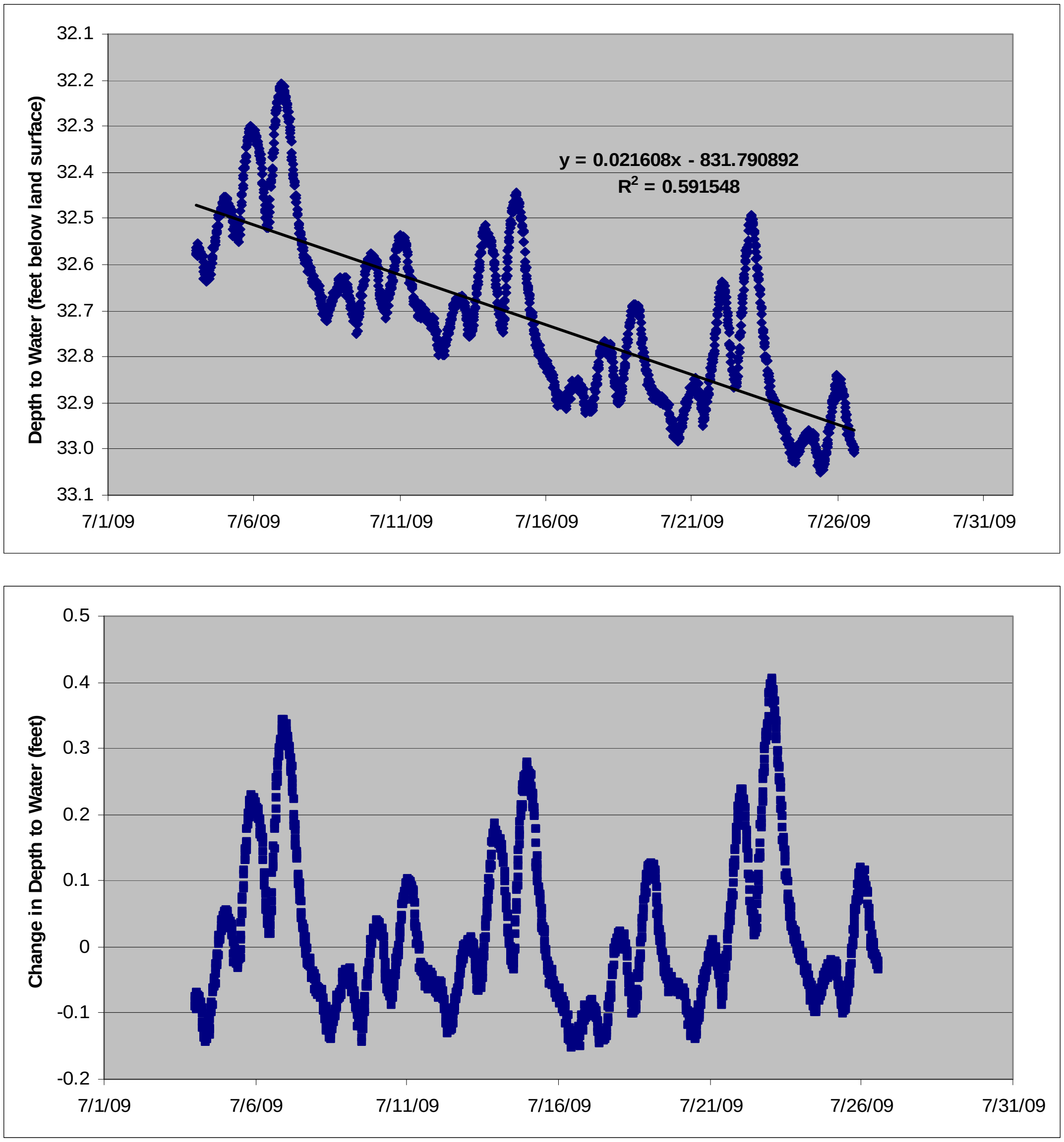

Figure 3. Illustration of raw (top) and detrended (bottom) water level records. Example is from well Ni45-43.

Geologic units encountered in the drilling program at CHSP are fill, unnamed Holocene dune deposits, unnamed Holocene swamp and marsh (herein named swamp/marsh) deposits, unnamed Holocene shoreline and spit deposits, and unnamed Holocene marine deposits (Figures 5 and 6, Appendix A). Chadwick (2000) found that non-fill materials deposited in these environments exhibit complex interfingering and gradational facies changes over short lateral and vertical distances. While drilling, we did not encounter any deposits that could be positively identified as older Quaternary units (e.g., Lynch Heights or Scotts Corners Formations) or Tertiary units (e.g., Beaverdam or Bethany Formations).

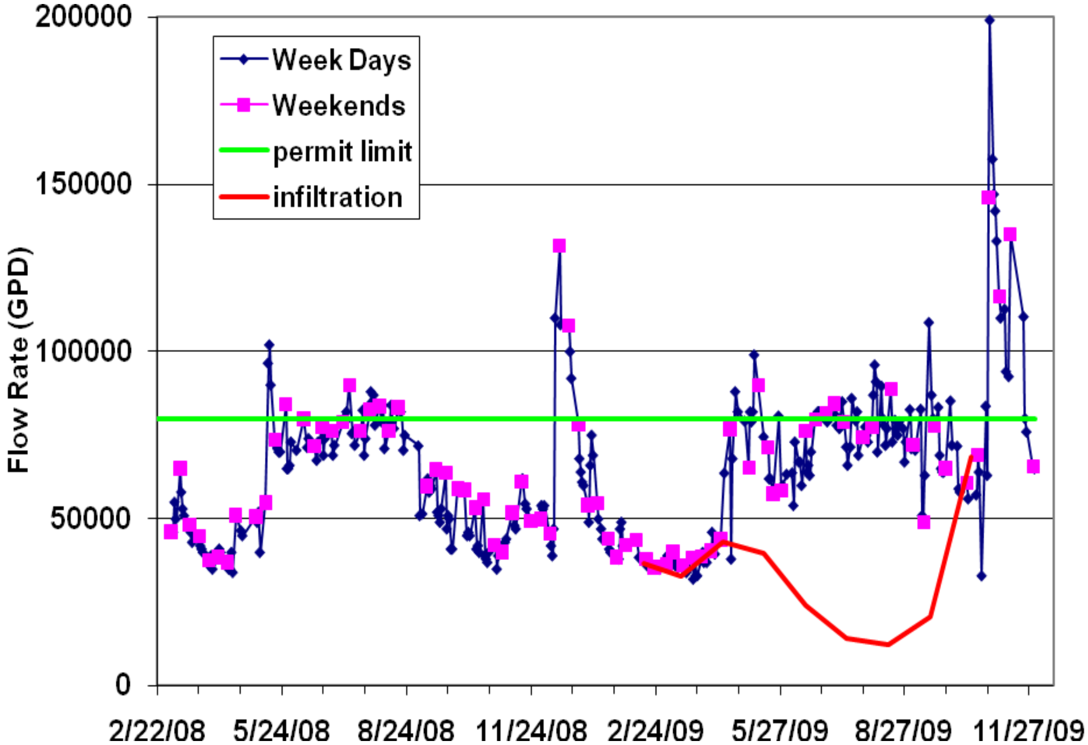

Figure 4. Reported daily effluent discharge from the park wastewater treatment plant in gallons per day (GPD). Infiltration calculated as the difference between monthly effluent flow and water purchase records. Flow reported in gallons per day (gpd). The permit limit of 80,000 GPD is an average monthly flow.

Fill

Military and subsequent park activities have moved large quantities of material for use in road fill and fortifications. Materials identified as fill are predominately sand derived from the site with variable amounts of concrete, rebar, crushed stone, and trace amounts of coal, paper, plastic, and metal foil. Exclusive of fortifications, the most significant accumulations of fill are located along the road (Figure 2a) and the south facing slip face of the Great Dune.

Dune deposits

Dune deposits are associated with the Great Dune and are predominately composed of sand with trace amounts of granules. These materials are generally shades of yellow and orange indicating oxidizing geochemical conditions. Dune deposits range in thickness from a featheredge at the toe of the dune to about 45 feet under the top of the dune.

Grain size testing of 95 samples of dune deposits show that the sands are relatively uniform, with a mean grain size of 1.2 mm (range 0.68 - 1.62 mm) and standard deviation of 0.57 (Appendix B). Samples collected from the infiltration beds at depths less than 2 feet tend to have finer grain sizes than samples from greater depths.

Porosities (n) estimated from core samples range between about 0.3 and 0.5 (Appendix B) and are consistent with maximum Vw determined by TDR. Although these values are reasonable for the materials, difficulties with collecting and handling of the cores indicate that accuracy of these estimates cannot be quantified. TDR-measured ambient Vw collected during the autumn and winter at depths greater than 3 feet range from about 8.5 to 12 percent. These values were consistently observed following periods of limited precipitation when no plants were growing indicating that they represent irreducible water content (Vw0). Effective porosity (ne) is the difference between n and Vw0 (Bear, 1979), and computed ne values range between 0.28 and 0.41. The term ne is used for computing flow velocity (Bear, 1979).

Soils developed on the dune deposits are identified as Acquango-Beaches complex, 0 to 10 percent slopes in the USDA Web Soil Survey (http://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx). In general, the uppermost one to two feet of this soil is composed of well-sorted, loose, medium to fine sands that are very pale yellow to very pale gray. Areas within the infiltration basins where effluent discharge has promoted plant growth have a different soil profile. These areas will be referred to as vegetated areas. The soil profile in vegetated areas contains more silt-sized material than in non-vegetated areas and in undisturbed areas outside of the disposal area. The upper one foot of the profile commonly contains visible organic debris that ranges up to 0.2 percent organic carbon as determined by loss on ignition.

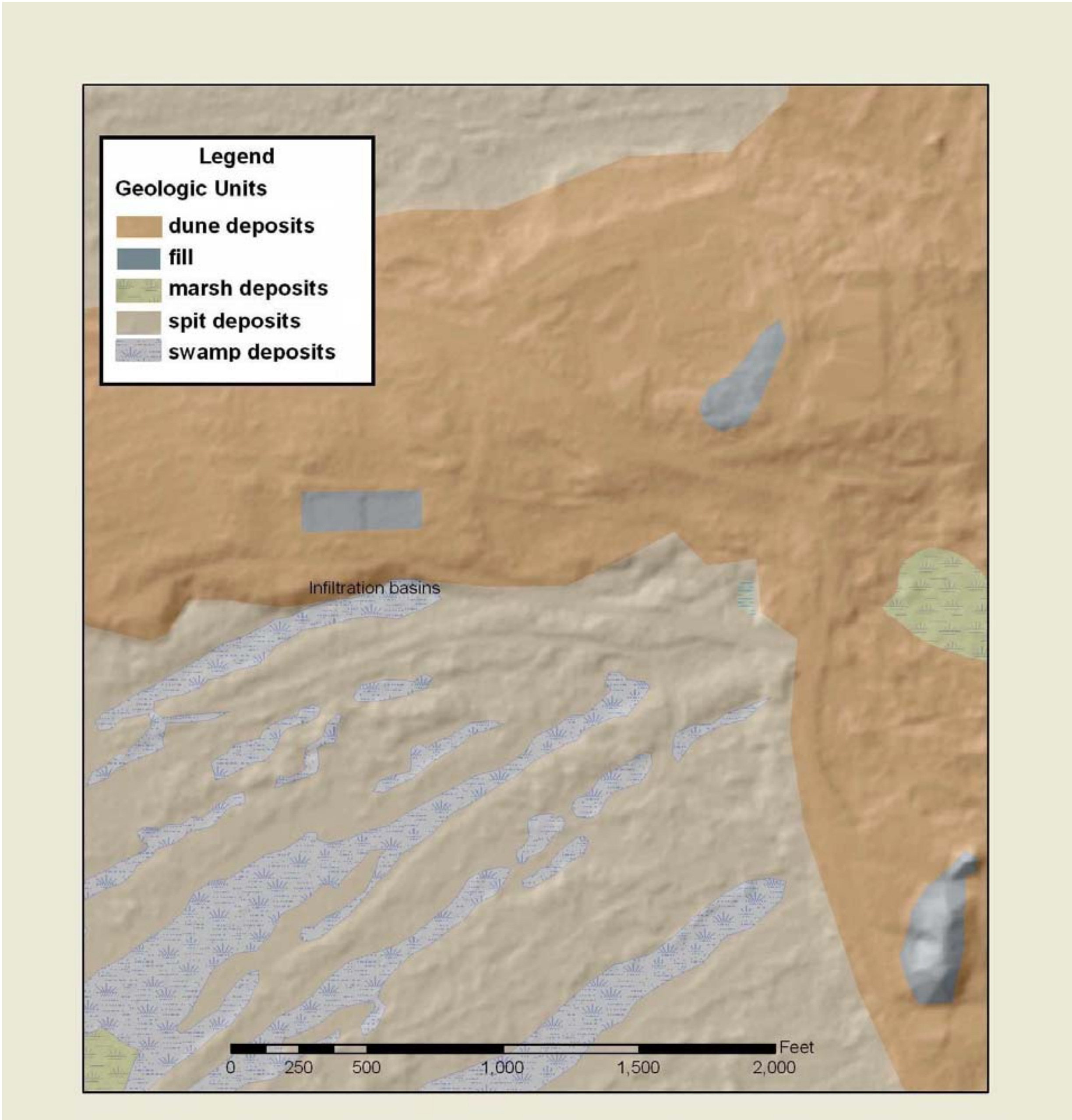

Figure 5. Surficial geologic map of CHSP study site. Geologic map of Ramsey (2003) modified from interpretation of field observations and LIDAR data. Shaded relief map created from LIDAR data.

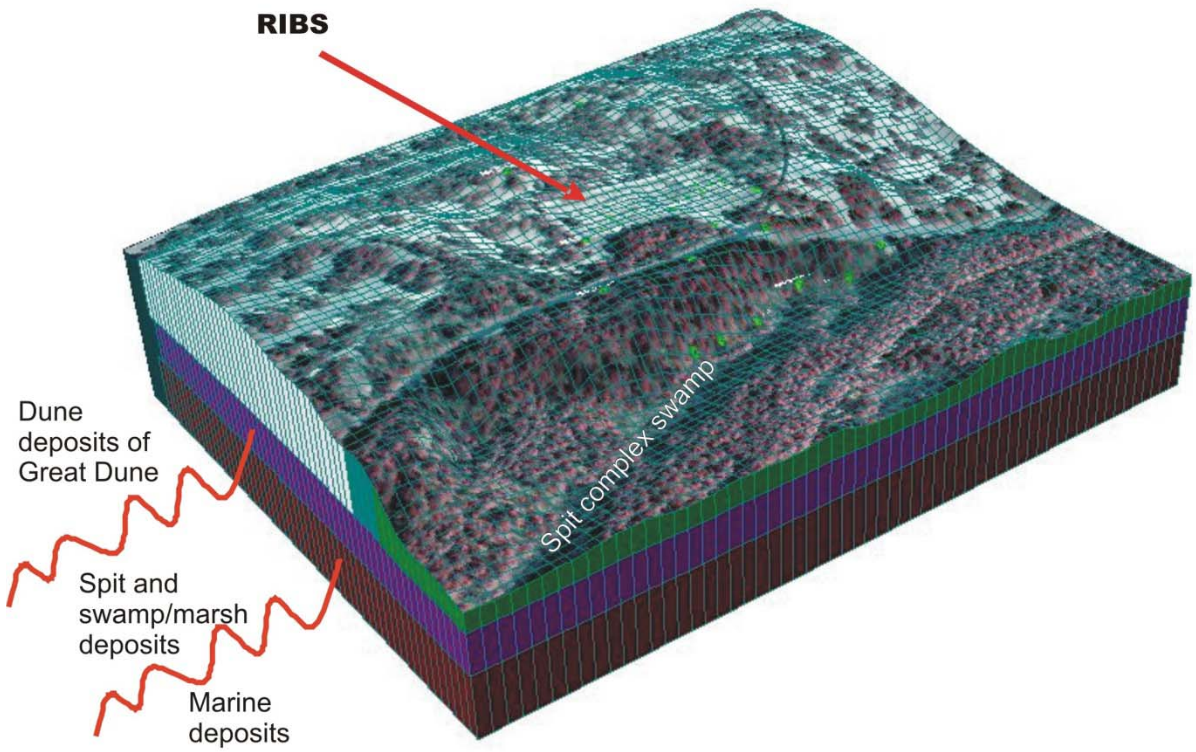

Figure 6. Block diagram showing surface and subsurface distribution of geologic units at CHSP study site. Base image is 2002 false color infrared aerial photograph draped on LIDAR-derived DEM.

Natural gamma radiation (gamma) logs show dune deposits typically emit relatively low amounts of radiation, which is consistent with the quartzose sand composition. Electromagnetic conductance (EM) logs show that dune deposits give very low conductance readings when dry and 2 to 5 times higher when wet.

Spit deposits

Spit deposits were formed during the northward migration of proto-Cape Henlopen (Chadwick, 2000). These deposits form the northeast-southwest trending arcuate ridges in the area located south of the Great Dune. Spit deposits are present beneath the swampy swales in the area south of the Great Dune, and also underlie the Great Dune. They are composed of medium to coarse sand with some beds of fine sand, gravelly sand, silty sand, sandy silt, and shelly sand. Above the water table these materials are generally shades of yellow and orange indicating oxidizing geochemical conditions. Below the water table, colors range from shades of yellow and orange to shades of gray, indicating a more reducing environment. Spit deposits range in thickness from about 12 to about 18 feet.

Gamma logs show spit deposits emit relatively low amounts of radiation, which is consistent with the quartzose sand composition. EM logs of wet spit deposits show relatively low conductance readings.

Swamp and Marsh deposits

Swamp/marsh deposits were encountered in two distinct settings. Hand auger borings and field observations indicate that freshwater swamp deposits occur at land surface in low lying swales located south of the Great Dune (Figures 5 and 6) in an area that was mapped as spit deposits by Ramsey (2003). Swamp deposits are distinct from the sandy spit deposits in that they are rich in organic material that contains recognizable leaves from trees, shrubs, and grass. Swamp/marsh deposits are also encountered in three boreholes (Ni45-35, -37, and -46, Figure 2a, Appendix A) that penetrated through the dune deposits. Ni45-35 contained peat (sample 104972, Beta 266551) indicating an age of 720 to 920 years before present at a depth of 35 ft below land surface (-7 ft NAVD88). Due to locations of the three samples beneath the Great Dune these deposits are older than both the Great Dune and the surficial swamp deposits described above. Consistent with the older age, plant remains in these boreholes are much more decomposed than those located in the freshwater swamps described above. As a result, we cannot identify the plant types and definitively state whether the organic-rich beds found at depth in Ni45-35, Ni45-37, and Ni45-46 are freshwater swamp or marsh deposits, or saltwater marsh deposits. Chadwick (2000) concluded that freshwater and salt-water environments and the associated swamp and marsh deposits were deposited within short lateral and vertical distances of each other and the adjacent spit deposits.

The swamp/marsh deposits are very heterogeneous. These deposits range from silty, peaty sands to sandy, silty, peats with scattered logs, partially carbonized wood fragments, possible charcoal, and pebbles. Organic matter ranges from relatively fresh, whole leaves and woody material at the surface to organic silt and small carbonized fragments at depths greater than 1 foot. These deposits are very gassy, and emit gas bubbles with strong hydrogen sulfide odors when disturbed. Swamp/marsh deposits occur as discontinuous beds ranging in thickness from a few tenths of a foot to about 5 feet thick. These materials range in color from moderate to dark shades of brown and gray. High organic content, colors, and presence of gas indicate a strongly reducing environment.

Gamma logs show swamp/marsh deposits emit relatively higher amounts of radiation than the sandier dune and spit deposits, which is consistent with the organic-rich composition. EM logs show that swamp/marsh deposits typically exhibit conductance readings that are greater than sandy, wet dune and spit deposits.

Marine deposits

Marine deposits are very heterogeneous and range from silty sands, to sandy, clayey, silts. These materials range from light yellow to dark brown and dark gray, with the brown and gray shades sometimes associated with hydrogen sulfide odors indicating reducing conditions. During this study, marine deposits were encountered in Ni45-33 and Ni45-35 (Figure 2a, Appendix A). It appears that marine deposits interfinger with spit deposits. The entire thickness of this unit was not penetrated during this study.

Gamma logs show marine deposits emit relatively higher amounts of radiation than dune and spit deposits, which is consistent with the silty and clayey composition. EM logs did not penetrate marine deposits.

A note on geophysical logs

Comparison of gamma logs run in the hollow stem auger with gamma logs run in the finished wells at the same locations shows different patterns. Higher radiation values are observed in the finished wells in intervals where bentonite pellets were used to seal the annular space between casing and borehole wall. EM logs run in the finished wells show higher conductance values in the same intervals. Much higher than ambient radiation values were observed when the gamma tool was placed in a bucket of bentonite pellets. This indicates that the bentonite pellets have significantly affected the response of the geophysical tool and masked the geophysical properties of the surrounding formation.

Conceptual Hydrogeologic Model and Water-Table Configuration

Where saturated, dune and spit deposits function as a water table aquifer. Within the framework of DGS hydrostratigraphic nomenclature, this would be the Columbia aquifer. Swamp/marsh and fine-grained marine deposits are much less permeable and likely function as leaky confining beds. Existing data are not sufficient to determine the locations and characteristics of hydraulic connections between the Columbia and underlying aquifers.

The conceptual hydrogeologic model for the study area is illustrated in Figure 7. Groundwater flows under water-table conditions from topographically high areas (e.g., Great Dune) to topographically low areas. The water table occurs nearly 45 feet below land surface (bls) beneath the topographically highest areas of the Great Dune. The water table also intersects and sometimes exceeds land surface in swampy areas located south of the Great Dune. Because these swampy areas occur within the proto-Cape Henlopen spit complex (Chadwick, 2000) it will be referred to as the spit complex swamp (SCS). The water table intersects and sometimes exceeds land surface in swampy areas located in some of the deeper depressions within the area of the Great Dune to the east of the infiltration basins.

Discharge of effluent to the infiltration basins has caused a water-table mound under the basins. The position and height of the mound change with time. These changes are thought to largely reflect rate and location of effluent discharge (Figures 8-10). The steepest hydraulic gradient is directed toward the SCS.

Within the SCS, the overall slope of the land surface is westward toward the Lewes and Rehoboth Canal. The 1:24,000-scale USGS topographic map (Figure 11) identifies blue line streams extending eastward from the canal into some portions of the SCS area. However, because topography is hummocky and vegetation is dense in this area, we were not able to positively identify a stream that extends from the canal eastward to the SCS area just south of the infiltration basins. Rather, during periods when the water-table elevation was high (e.g., spring 2009); we observed that this area contains many poorly drained depressions that hold standing water. Most if not all of these undrained depressions contain no standing water when the water table declines during drier periods (e.g., summer and autumn 2008). As such, it would be reasonable to consider these features to be ephemeral groundwater-fed ponds. Groundwater elevations within the SCS have not been measured and as a result the water-table configuration and groundwater flow paths are conceptual. Given the general westward slope of the land surface toward the canal and the water-table elevations observed in wells Ni45-38 through Ni45-42, we expect that flow within the SCS is also generally directed to the west. The conceptual model shows a secondary trend of northwestward and southeastward directed flow associated with the expected higher water-table elevations under the low ridges. Of particular interest is the source of water for the ephemeral ponds described above. It is possible that groundwater originating as recharge from the Great Dune and RIBS is flowing into this area and discharging to these ponds. We are waiting for the results of water quality analyses to test this hypothesis.

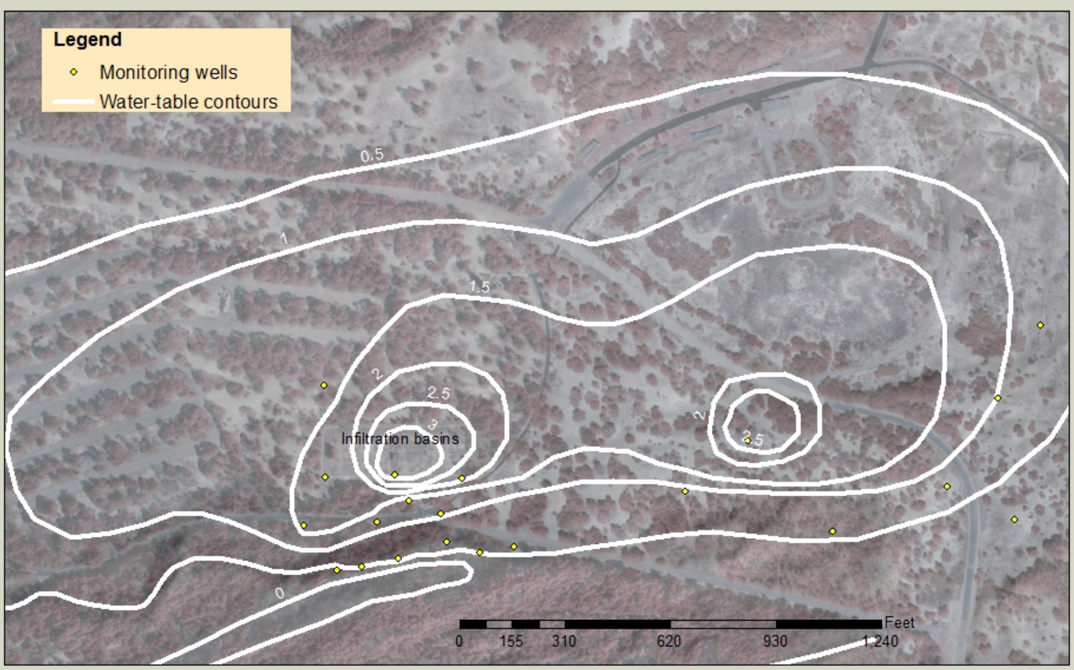

Figure xs. Water-table contours for August 12, 2008 plotted on 2002 false-color infrared aerial photograph. Elevations are in feet NAVD88.

Figure 8. Water-table contour map for August 2008. Elevations are in feet, NAVD 1988.

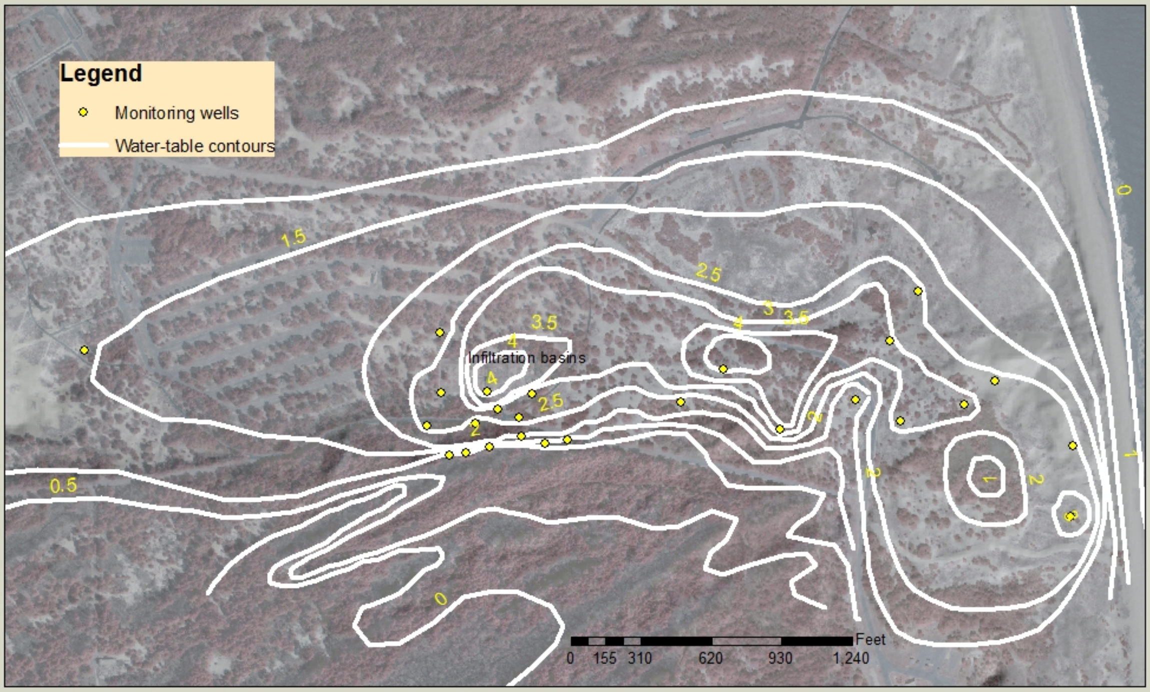

Figure x. Water-table elevation contours (in white) for December 17, 2008 plotted on 2002 false color infrared aerial photograph. Elevations are in feet NAVD 1988.

Figure 9. Water-table contour map for December 2008. Elevations are in feet, NAVD 1988.

In general, lesser gradients are directed from the infiltration basins towards the north, east, and west. Our understanding of water-table configuration and flow directions is limited because there are few monitoring wells in these areas. Water-table elevations from December 2008 (Figure 9) indicate complex flow patterns east of the infiltration basins in areas of complex topography. This complex topography includes several deep, closed depressions that sometimes contain standing water. The combination of standing water and limited groundwater-level data indicate that the deep closed depressions are sites of focused discharge.

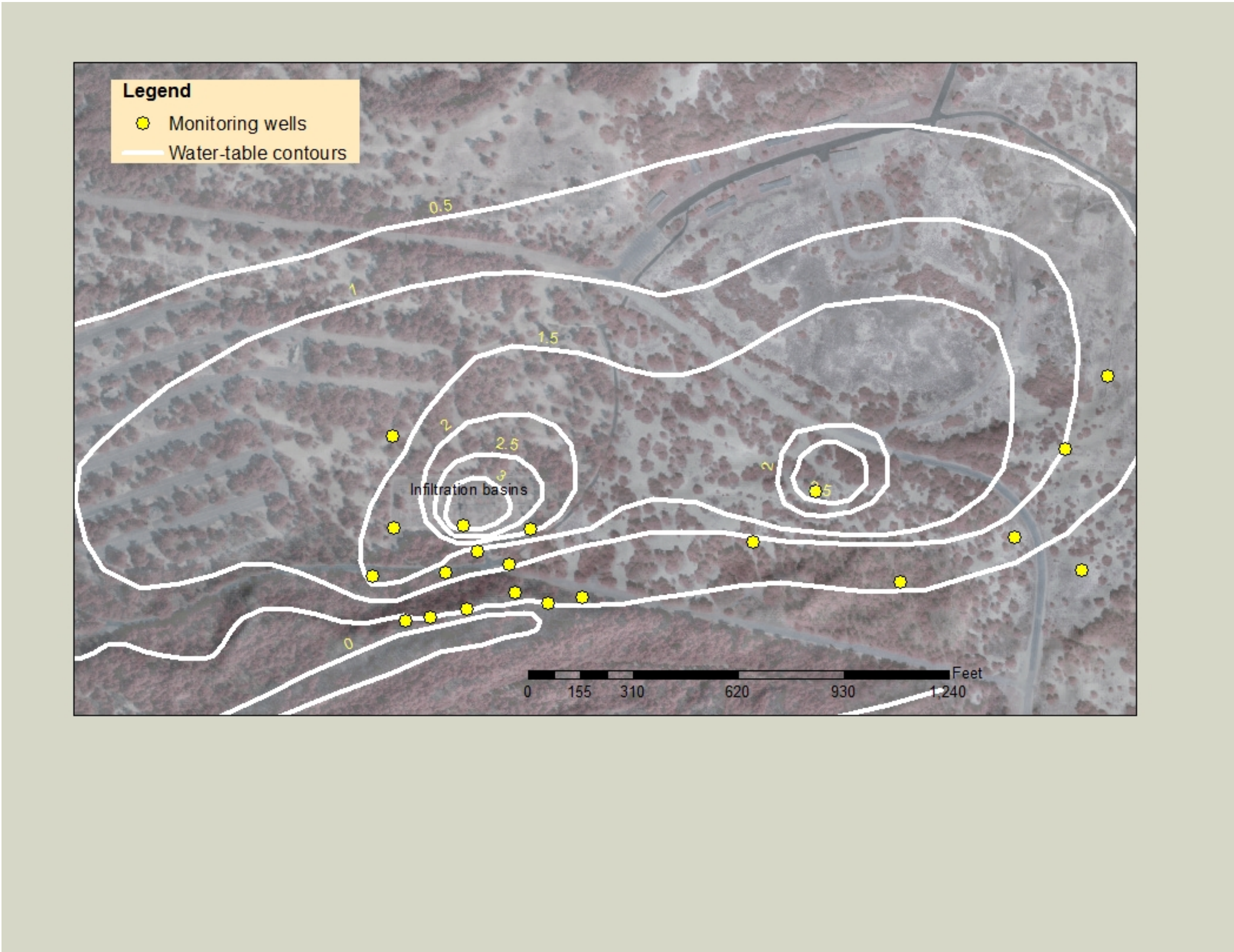

Figure 10. Water-table contour map for April 2009. Elevations are in feet, NAVD 1988.

Hydraulic Testing Results

Hydraulic conductivity (K) values determined from slug tests conducted in our study area range over one order of magnitude and are generally similar to results of pumping test reported by Leis (1974) (Table 1). Evaluation of K data (Appendix C) indicates that the interaction between well construction and geology affects K observations. Slug test data from wells with 15-foot long screens that span the water table and are open to dune, spit, and swamp/marsh deposits are noisy and indicate problems with non-instantaneous displacement (Butler, 1998). Butler (1998) suggests that this problem may lead to overestimation of K by at least 20 percent. Wells located in the SCS and constructed with 2 to 3 feet of screen that are open to both freshwater swamp and spit deposits have K values four to five times lower than those observed in wells with 15 ft of screen. Test data from these wells were less noisy than those from the wells with 15 ft of screen.

A third group of wells constructed by the U.S. Army Corps of Engineers were constructed with longer screens (>5 ft), are open to dune and possibly spit deposits, have less than 5 ft of standing water, and have K values intermediate between the long screen wells and wells in the swamp and spit deposits. Though there are no wells that are constructed to provide an estimate of saturated K of an individual unit, the data indicate that the well-sorted and coarse-grained dune deposits tend to be more permeable than the more heterogeneous and much finer grained freshwater swamp deposits. Results of a multi-well aquifer test reported by Leis (1974) are from wells with long (>15 ft) screens that are open to spit and shoreline deposits. The mean K value (94 ft/d) reported by Leis (1974) indicates that hydraulic properties of spit deposits are only slightly less than those of dune sands.

Table 1. Results of hydraulic tests. Hydraulic conductivities in ft/d determined from slug tests. Group A includes wells with 15 ft screens, group B includes wells with 2 to 3 ft screens, group C includes wells installed by the US Army Corp of Engineers that have less than 10 ft of saturated material adjacent to the well screens. On the basis of a multi-well aquifer pumping test, Leis (1974) reports a mean K of 94 ft/d.

	Group A	Group B	Group C
Minimum	103	6.2	22
Mean	140	25	49
Maximum	179	49	70
Standard Deviation	26	19	20
Count	8	5	4

The K values of the dune and spit deposits are similar to those reported for clean sands of the Beaverdam, Bethany, and Cat Hill Formations (Andres, 2004; Andres and Klingbeil, 2006; DGS internal database). K values from the wells with 2 to 3 ft screens that are open to swamp/marsh deposits are greater than K values from swamp deposits of the Cypress Swamp Formation (mean K 7.7 ft/d, n=13; Andres and Howard, 2002, Table 2). However, considering that wells tested in this study are open to both swamp/marsh deposits and more permeable spit deposits, the K values of the swamp/marsh deposits at Cape Henlopen are likely to be similar to those observed at the Cypress Swamp.

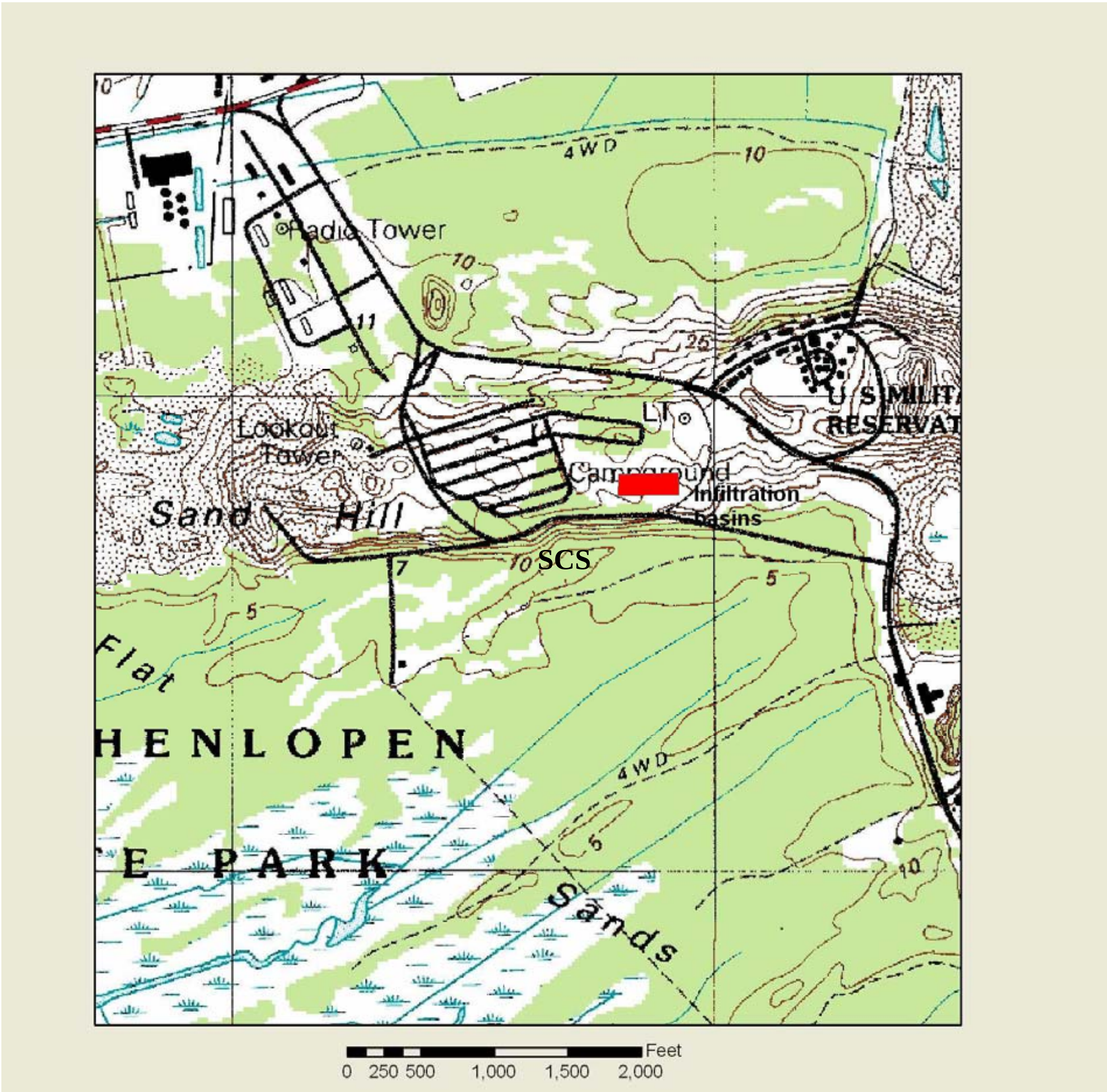

Figure 11. Reproduction of 1992 digital raster graphic topographic map. Note that blue line streams extend into some portions of the SCS area but not the area just south of the infiltration basins.

Infiltration rates (Table 2) resulting from double ring infiltration tests (ASTM D3385) conducted on both surficial and shallow (< 2 feet bls) subsurface materials indicate that the materials in the basins should be classified as excessively well drained. Infiltration tests indicate higher infiltration rates in non-vegetated areas than in vegetated areas. This finding is consistent with greater proportions of silt sized particles in the vegetated areas.

Table 2. Results of infiltration tests. Values are in feet per day.

DGSID	Constant Head			
	Date	Minimum	Average	Maximum
Ni45-76	7/30/2009	16	197	645
	6/23/2009	35	135	290
Ni45-73	7/9/2009	110	300	799
Ni45-77	7/1/2009	60	166	210
Ni45-74	6/23/2009	6	118	808
Ni45-70	7/1/2009	20	67	304

Water-Table and Water-Level Fluctuations

Groundwater levels in an unconfined aquifer in a coastal area are expected to change in response to changes in climate (e.g., precipitation and evaporation), water pumped from wells, transpiration by plants, changes in tides, and artificial discharge of water to the water table. Our records and interviews with CHSP personnel indicate that there are no active pumping wells in the park.

Groundwater levels appear to vary according to proximity to the SCS. Wells in and near the SCS appear to be influenced by short term climatic variations (Appendix D, Figure 12). The SCS is frequently inundated after rainfall. Water levels measured in well Ni45-42, located in the SWS, respond to individual storm events within hours (Figure 12, Figure 2a, Appendix A). Wells located at higher elevations on the dune show progressively lesser water level response to storm events with greater distances from the SCS. For example, water levels in Ni45-37 (Figure 12, Figure 2a, Appendix A) respond to storms in the same time frame as Ni45-42, but water levels in wells located farther from the SCS (e.g., Ni45-35, Figure 13; Ni45-43, Ni45-44, Appendix D, locations Figure 2a, Appendix A) do not appear to respond to storms. The lack of response to precipitation is likely due to the greater depth to water at these locations. It is noted that the one-day pattern observed in these hydrographs is related to effluent disposal (see below).

Semi-diurnal tides are not readily apparent in groundwater-level records. Water-level records exhibit fluctuations with a period of roughly one day (Figures 12, 13). This pattern occurs throughout the year and is in contrast to the tidal records from Breakwater Harbor (http://tidesandcurrents.noaa.gov/data_menu.shtml?stn=8557380%20Lewes,%20DE&type=Tide%20Data) and Rehoboth Bay (USGS Station 01484670), which have a semi-diurnal period.

Groundwater levels appear to vary with proximity to the infiltration beds. Water-level records from data loggers installed in wells located near the infiltration basins (Ni45-43, Figure 13; Ni45-44, and 46, Appendix D, locations Figure 2a, Appendix A) show a recurring pattern of higher water levels on eight-day and two-day cycles. The patterns of peaks from an individual well are not in phase with patterns from other wells indicating that the patterns reflect switching of discharge among the eight beds. These wells also show a one-day period thought to reflect the daily patterns of visitors and water use in the park. The one-day period is present in all data-logger-recorded water levels (Appendix D). It is not clear if water-level records show weekly increases in water levels associated with increased discharge rates that occur on weekends in response to greater numbers of park visitors and increased water use.

Given the dense vegetation and shallow water table in the SCS, it was expected that plant uptake of water would be significant. Water-level records from Ni45-42 (Figure 12, location Figure 2a, Appendix A) indicate that fluctuations caused by effluent disposal mask fluctuations due to transpiration. Transpiration measurement experiments were not conducted; however, summertime groundwater elevations in the swamp are at times below 0 feet NAVD88 (Appendix D). Because there is a lack of tidal influence on groundwater in the SCS and no pumping wells in the park, water elevations less than this value can only be caused by transpiration.

Water temperatures and water-level fluctuations

Groundwater and soil temperatures recorded by dataloggers and effluent temperature measurements provide additional indications of the impacts of effluent disposal on the aquifer (Appendix D). Five effluent temperature measurements varied from a low of 11.6 degrees C measured in April 2009 to a high of 22.3 degrees C measured during July 2009. Groundwater temperatures greater than 20 degrees C were observed in wells located under (Ni45-43), immediately adjacent (Ni45-44, Ni45-46) to the infiltration beds, and in Ni45-35 located about 80 ft downflow of the infiltration beds (Figure 14, Appendix D, locations Figure 2a, Appendix

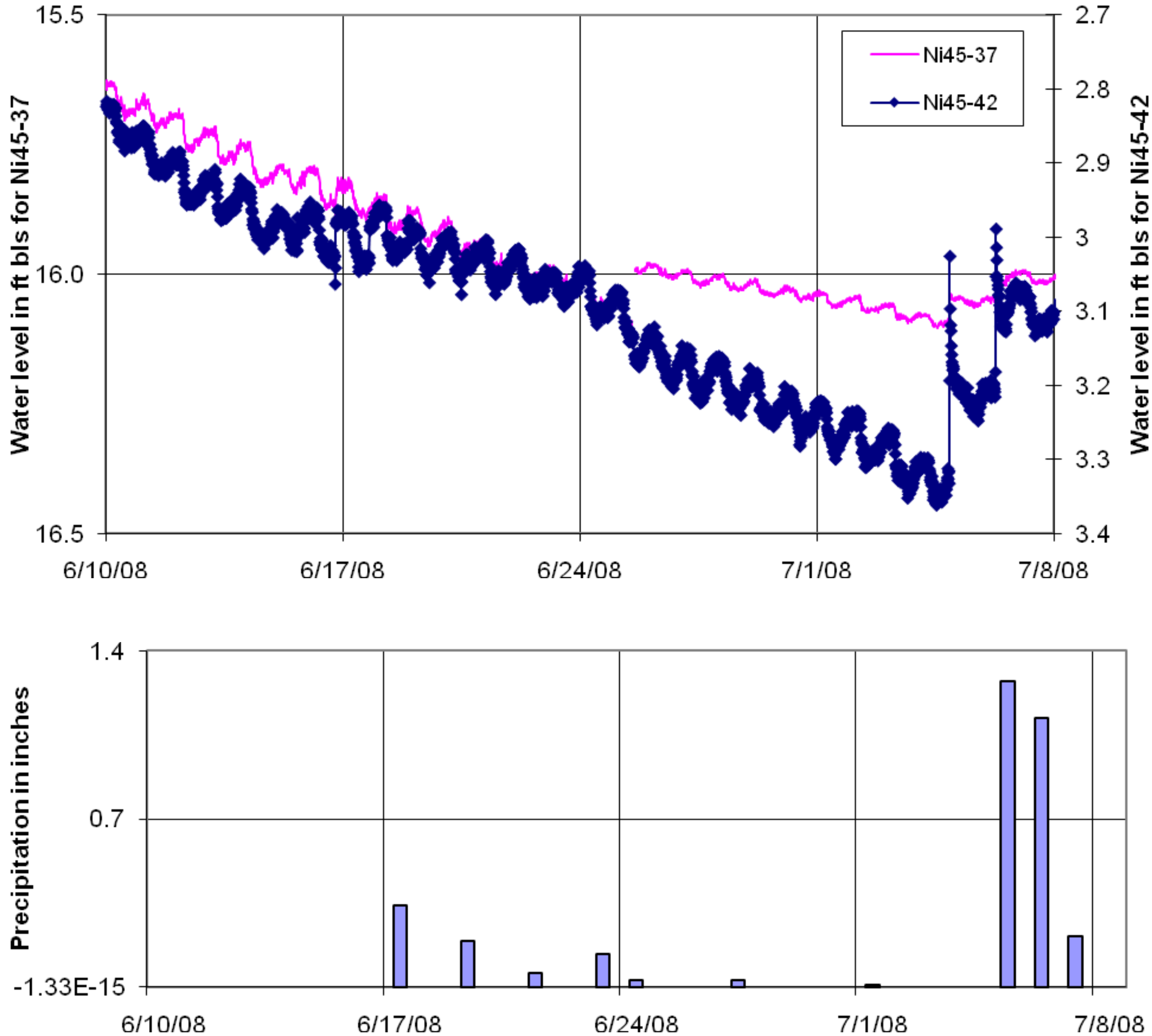

Figure 12. Example of hydrographs showing response to storm events. Precipitation measured at Lewes, DE. Note that water levels in well in swamp (Ni45-42) exhibit larger, more rapid response to storms between July 1 and July 8 than those in nearby well Ni45-37. See figure 2a for well locations.

A). Daily mean groundwater temperatures in Ni45-43, 44, and 46 also show summertime daily increases indicative of the effects of discharge of warm effluent. The 20 degrees C value is considered significant as groundwater temperatures greater than this have not been observed in any other shallow (<30 ft deep) water-table wells in Delaware having more than five years of continuous record (unpublished data from DGS database). Of note is the relatively small variation of temperature in Ni45-33 (Appendix D), located north of the infiltration beds. Although water levels show the daily pressure signal due to wastewater discharge, the lack of a

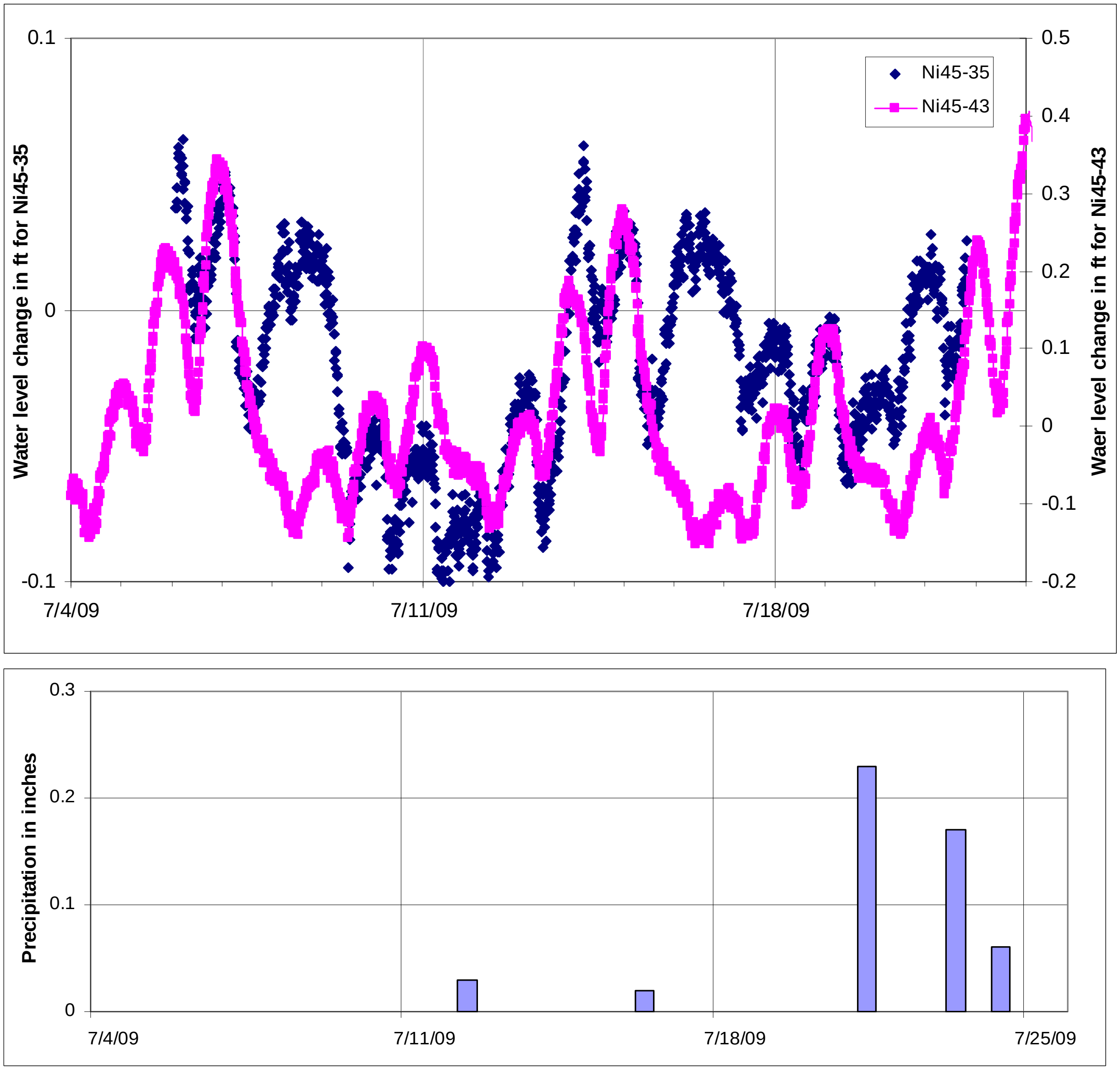

Figure 13. Examples of hydrographs showing effects of effluent discharge. Precipitation measured at Lewes, DE. Water levels have been processed using method illustrated in Figure 3 to enhance comparison of timing and magnitude of changes.

strong temperature signal indicates that there is not much flow directed from the infiltration beds towards the north. Further, the relatively small magnitude of annual groundwater temperature range in Ni45-33 compared to soil temperatures indicates that the greater depth to groundwater in this well buffers groundwater temperature compared to seasonal atmospheric temperature fluctuations.

The temporal pattern and magnitude of temperature fluctuations observed in soil temperature probes and in wells Ni45-35, 43, and 45 (Figure 14) and Ni45-44 and 46, Appendix D) indicate the movement of warmer effluent from the area under the infiltration beds toward the SCS. The maximum groundwater temperatures are several degrees higher than soil temperatures and occur in the wells nearest the infiltration beds (listed in order of increasing distance from the infiltration beds, Ni45-43, 44, 46, and 35). Groundwater temperatures should not exceed soil temperatures unless there is an external source of heat, such as warm wastewater.

The groundwater temperature signal also appears to vary with distance from the infiltration beds, with temperatures responding first in Ni45-43, closest to the infiltration beds, next in Ni45-35, located approximately 90 ft from Ni45-43 and 80 feet from the nearest infiltration basin, and last in Ni45-45 located approximately 160 ft from Ni45-43 and about 150 feet from the nearest infiltration bed (Figure 14). Offsets of times of minimum temperatures between wells indicate apparent transport times of about 45-55 days between Ni45-43 and Ni45-35 and 90-100 days between Ni45-43 and Ni45-45. These distances and times indicate apparent flow velocities between 1.6 and 2 ft/d.

Flow Magnitude and Velocity

An analysis of the gridded water-table configuration data was done with simple Darcy's Law calculations and particle tracking. In this steady state model, the average K from slug tests conducted on site and measured groundwater levels were used to define the K and pressure inputs. Other key assumptions in this model are two-dimensional flow and a homogeneous, isotropic aquifer. As with nearly all models there are differences between model assumptions and field conditions. At this site, there is likely to be a three-dimensional component to groundwater flow and hydraulic testing indicates K varies by a factor of 10 to 15. As such, we understand that the model cannot precisely reproduce field conditions models but as formulated does provide useful information to compute and interpret flow directions and velocities.

Model results indicate that inter-monthly variations in flow velocities are on the order of a factor of 2 or less (Figure 15). The lack of greater velocity during wetter months (i.e., greater inter-monthly variation) when the water-table elevation is higher indicates that wastewater discharge smoothes normal climate-induced variability. Intra-monthly differences between maximum and minimum velocities are on the order of 3 to 6.5 with the maximum velocities associated with particle tracks directed from the southern half of the infiltration basins toward the SCS (Figure 16). Given the positive correlation between flow velocity and water flux, particle tracks indicate preferential flow towards the SCS.

Results of a 180-day particle tracking simulation using average water-table elevations (Figure 16) show that many of the flow paths originating along the southern side of the infiltration basins reach the SCS within 180 days. We anticipate that any groundwater flow in the vertical direction would have proportionally more impact on the lengths and orientation of the shorter flow paths directed toward the north, east, and west than on the flow paths directed toward the SCS.

Particle tracking simulations are a first cut for assessing potential effects of RIBS on ground and surface water. Because field data show that aquifer K and thickness (b) are spatially heterogeneous, and because water-table gradients vary from month to month, the flows computed from homogeneous grids and long-period averaged water-table elevations have an unknown amount of uncertainty. Quantification of uncertainty in flow paths and flow magnitudes can be improved through use of three-dimensional numerical models that incorporate spatially heterogeneous aquifer conditions and transient differences in flow.

CONCLUSIONS

A hydrogeologic investigation of a rapid infiltration basin system (RIBS) at CHSP was used to develop a conceptual model of the hydrogeologic framework in the vicinity of the infiltration basins and nearby discharge area. The water-table aquifer exists in geologically young (<1000 years) dune, spit, swamp, and marsh deposits. There is an underlying leaky confining layer formed by marine deposits. Infiltration testing of dune deposits in the vadose zone indicates that these deposits are excessively well drained. Slug tests indicate that the water-table aquifer is moderately permeable.

Groundwater flow is driven by wastewater discharge, topographic, and climatic factors. There are no apparent tidal forcing factors. The effects of storms and wastewater discharge on the water-table aquifer are clearly shown in water levels and temperatures measured by datalogging instruments. These data show that wastewater discharge is the dominant forcing mechanism driving most flow from the infiltration beds toward a swampy discharge area located at sea level and between 250 and 330 ft south of the infiltration beds. An uncertain, but thought to be minor amount of flow, is directed from the infiltration beds towards the north. Future analysis of geochemical data will provide additional evidence with which to evaluate flow directions and magnitudes.

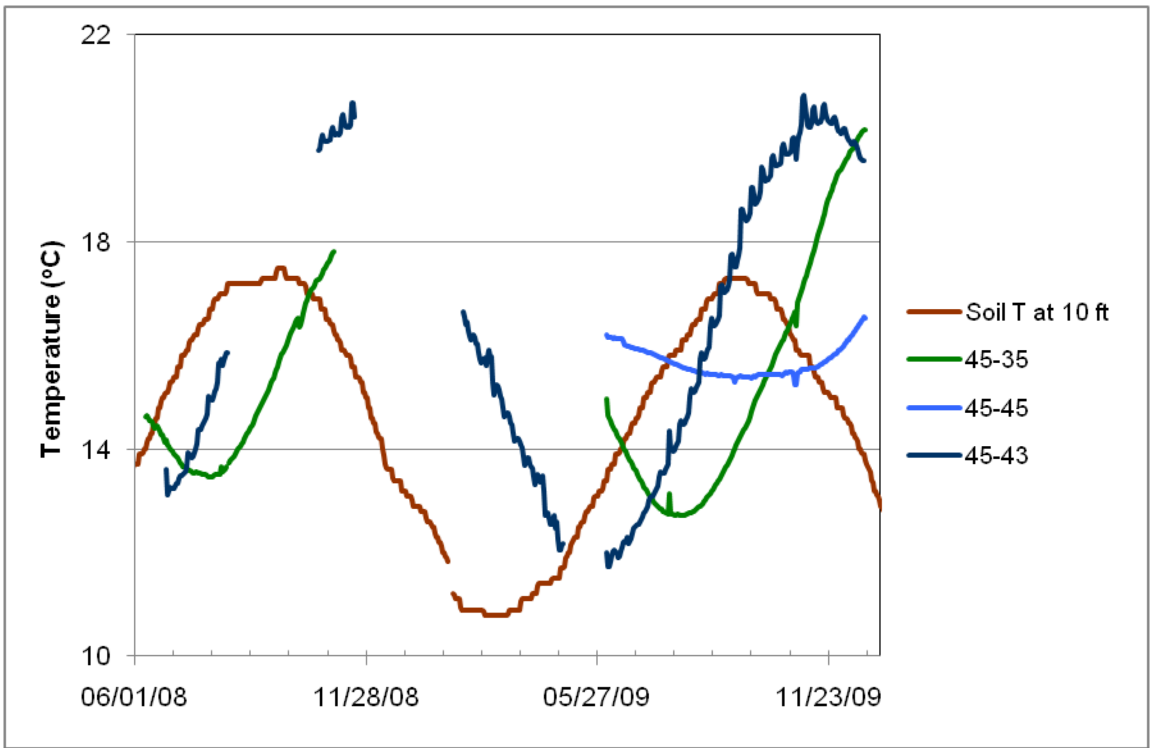

Figure 14. Soil temperature at 10 ft bls and groundwater temperatures in wells Ni45-35, 43, and 45. Soil temperature data provided by John Wehmiller of the University of Delaware Department of Geological Sciences (personnel communication). Measurement site located approximately 2500 ft west of infiltration beds at E491635, N4291684, altitude 22.8 ft. Coordinates in UTM18-83 in meters, altitude in ft NAVD88.

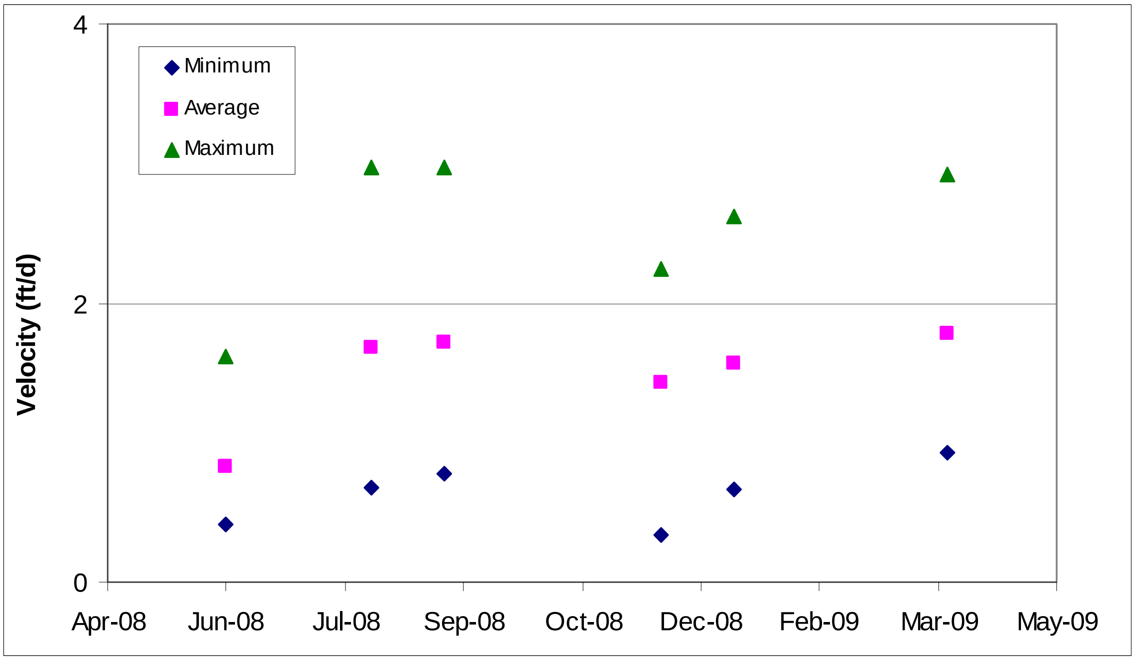

Figure 15. Comparison of monthly flow velocities as determined by simple two-dimensional particle tracking.

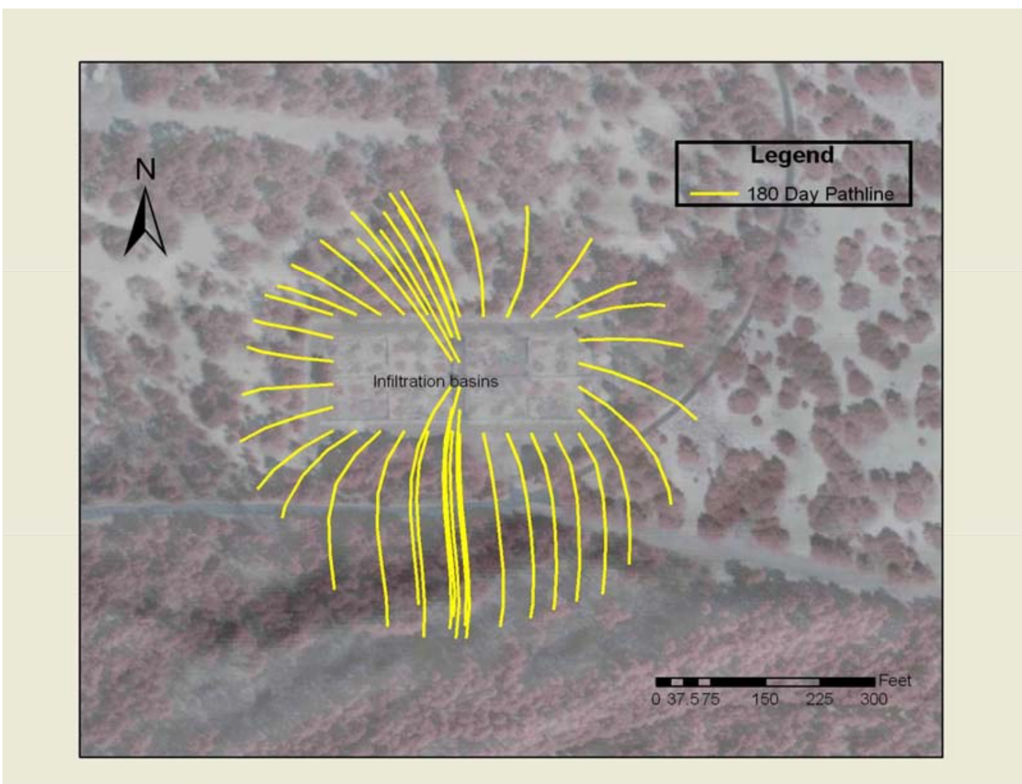

Figure 16. Results of particle tracking for 180 day simulation under average flow conditions. Base map image is 2002 false color infrared aerial photograph with LIDAR-derived shaded relief DEM.

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