FINAL HYDROGEOLOGIC ASSESSMENT REPORT

CHARACTERIZATION FOR DESIGN OF PILOT-SCALE PERMEABLE REACTIVE BARRIERS FOR NITROGEN REDUCTION IN GROUNDWATER ON CAPE COD

VINLAND DRIVE, DENNIS, MA

May 30, 2017

Prepared for:

US Environmental Protection Agency, Region 1
Contract #: EP-BPA-13-W-0001

Prepared by:

Danna Truslow, P.G., C.G.
Sarah Large
Anna Boudreau
Peter Shanahan, Ph.D., P.E.
Emily DiFranco
Ken Hickey

WaterVision, LLC

481 Great Road, Suite 3
Acton, Massachusetts 01720
(978) 263-1092

and

454 Court Street, Suite 304
Portsmouth, NH 03801
(603) 766-6670

Table of Contents

List of Figures **Page**

List of Tables Page

Appendices

Introduction and Purpose

The Vinland Drive site in Dennis, MA was chosen for completion of a Full Hydrogeologic Assessment (FHA) from the five sites evaluated as part of the Initial Site Evaluation phase of the United States Environmental Protection Agency, Region 1 project entitled Site Characterization for Design of Pilot-Scale Permeable Reactive Barriers for Nitrogen Reduction in Groundwater on Cape Cod. The Dennis site is located in a residential neighborhood adjacent to Kelley's Bay, off the tidal Bass River.

The initial site characterization (ISC) completed during the winter and spring of 2016 included installation of six water table wells and a cluster of six piezometers. Two rounds of water quality sampling and water level measurement were completed and a summary report was prepared for the project (WaterVision, 2016). Based on this initial work the following site characteristics were observed:

- Subsurface materials are largely medium to coarse sand with a one-to-two-foot-thick shallow clay lens. A substantial clay layer was detected at about 66 ft. below ground surface (bgs). Thus the hydrogeologic sequence from surface to depth is an upper sand unit, a shallow clay layer, a lower sand unit, and a lower clay layer.
- The depth to groundwater was found to be approximately 35 to 41 ft. bgs across the site.
- The groundwater velocity was estimated at 9.0 ft./day in the upper sand unit.
- Nitrate-N concentrations were found between 1.2 to 6.2 mg-N/L at water table wells.
- Nitrate-N concentrations at piezometers were between 2.4 to 4.3 mg-N/L with the greatest concentrations at the shallowest piezometer. No significant reducing geochemical zone was encountered.
- Elevated chloride and specific conductance in water table wells and shallow piezometers suggest anthropogenic influences from road salt and/or septic systems.
- The shallow clay layer appears to act as a partial confining unit based on strong upward gradients between piezometers below and above the clay layer.
- Groundwater within the upper sand unit appears to discharge to local surface water based on strong upward gradient potential. The shallow clay layer was hypothesized during the ISC to likely be discontinuous (this finding has been re-evaluated in this study) and to not prevent migration of nitrate

to surface water. No boundary marsh is present at the water's edge at Kelley's Bay.

- The deeper clay encountered at about 66 ft. bgs appears to bound anthropogenic influences to a 20-foot interval between the water table and the lower clay unit.
- The mass flux of nitrate-N in the treatment and saturated zone over the study depth was estimated at 19 g/day/m based on an estimated groundwater velocity in the upper sand.

A detailed scope of work was developed for the FHA to further refine subsurface hydrogeology, water quality, and mass flux of nitrate. The FHA field program included:

- Installation of three additional water table wells - VL-7, VL-8, and VL-9. Two-inch PVC wells were completed with 5-foot or 10-foot screens across the water table.
- Installation of three additional well clusters at VL-4, VL-6, and VL-7. Four wells were completed at each location and were constructed of two-inch PVC with a one-foot screen.
- Installation of two-inch PVC wells completed in the lower sand unit at the VL-1, VL-2, VL-8, and VL-9 locations with a 7-to-10-foot-long screen.
- Completion of continuous cores at all new well locations.
- Completion of three full rounds of water level measurements.
- Automated water level measurement at two water table (upper sand) wells and four wells completed in the lower sand unit to observe tidal influence on groundwater levels.
- Completion of a full round of water quality sampling for selected analytes including samples at selected wells for stable nitrogen isotope analyses.
- Sampling of shallow groundwater and surface water near the shoreline of Kelley's Bay
- Sieve analyses of subsurface sediment samples.
- Completion of slug tests at selected wells.

The purpose of the FHA was to collect data needed to design a pilot scale permeable reactive barrier for the site. In particular, the FHA was intended to quantify hydraulic properties that affect the mass flux of nitrate beneath the site, to define where and to what depth a PRB should be constructed, and to define the geochemical conditions that need to be considered.

Questions included:

a. How does subsurface lithology change across the site and how does it differ from the ISC characterization?

b. Is the groundwater flow direction and horizontal gradient estimated during the ISC correct for the larger Vinland Drive neighborhood?

c. How do the groundwater flow direction and gradient differ between the upper sand unit and the lower sand unit?

d. What is the hydraulic conductivity of the upper and lower sand units and how does it change across the site?

e. How do nitrate concentrations change across the site and with depth?

f. Is denitrification occurring in the upper or lower sand units?

g. What are the geochemical characteristics of the upper and lower sand units that affect or are important to the design of nitrate treatment using the PRB approach?

Work Performed

Continuous Sediment Cores and Well Installation –
October and November 2016 and May 2017

The new wells, cores, and piezometers were installed in mid-October and late November 2016 and in May 2017. Boring advancement and well installations were performed using a Geoprobe direct-push drilling rig operated by New England Geotech, Inc. of Jamestown, Rhode Island. A truck-mounted Model 6600 Geoprobe was used for site work. Danna Truslow, PG of WaterVision LLC (WV) oversaw boring advancement, well installation, and sampling.

As borings were advanced, a five-foot core was collected into a clear plastic sleeve. NE Geotech opened the sleeve for measurement, sediment description, and sample collection by WaterVision LLC. The length of the core recovered was recorded along with subsurface characteristics including degree of saturation. Samples were placed into zip-lock plastic bags and labeled by well location and sample depth for later inspection and sieve analyses.

Water table wells were constructed from two-inch diameter PVC riser and were completed with five- or ten-foot screens. Wells were screened across the water table as estimated by initial saturation encountered during core advancement. Well clusters were also completed with two-inch PVC and one-foot screens. Wells installed in the lower sand adjacent to VL-1, VL-2, VL-8, and VL-9 were completed with eight- to ten-foot screens.

Well locations and elevations were surveyed by Comprehensive Environmental Inc. (CEI) in December 2016 and January 2017. CEI returned to the site on April 19, 2017 to re-survey several existing and all new well locations and elevations. At that time wells were resurveyed to the benchmark elevation at RM15 at Leif Erickson Drive and Old Bass River Road (NGVD 29) then converted to NAVD88. The elevation was also measured at the top flange bolt of the hydrant at the corner of Vinland and Thorwald Drive to provide a benchmark that is more local to the project site.

During the ISC only one cluster of multi-level wells had been installed. These one-inch PVC piezometers were referred to as VLZ-44 to VLZ-66 with the suffix representing the total depth of the piezometer. The piezometer identifier did not include a reference to the corresponding water table well location, VL-2. The three additional well clusters installed for the FHA at VL-4, VL-6, and VL-7 are named VLZ-4 a, b, c, or d, etc., to refer to the adjacent water table well location (4, 6, or 7) and the relative depth from shallow (a) to deep. The locations of wells and piezometers at each site are shown in Figure 1. Well construction details for the existing and new wells are included in Table 1. Detailed maps of piezometer and cluster well locations are included in Appendix A. Detailed descriptive well completion and boring logs and summarized well completion and boring logs are included in Appendix A.

Water Level Measurement and Water Quality Sampling

Water quality samples were collected and water levels measured for the Full Hydrogeologic Assessment (FHA) at Vinland Drive in December 2016 and January 2017. Field data collection occurred over several field visits to expedite collection of samples for Stable $^{15}N–NO_3$ analysis scheduled for late December 2016 at UC–Davis Stable Isotope Laboratory. Weather and field conditions were also a factor. Samples were also taken at the Barnstable and Falmouth-Shorewood site during this time period. The field activities occurred on December 12 to 14, 2016, January 12, 13, and 19, and May 5, 2017 and included:

1. Development and purging wells and piezometers/multi-level wells;
2. Measurement of water levels at water table wells (five full rounds);
3. Measurement of water levels at piezometers/multi-level wells (five full rounds); and,
4. Measurement of field water quality parameters and sampling at each water table well, piezometer/multi-level well, and surface water well points for laboratory analysis for a range of parameters (Table 2).

Danna Truslow, Sarah Large, and Emily DiFranco of WaterVision LLC completed all field measurements and sampling.

Upon arrival at the site all wells and piezometers were opened and well caps removed to allow equilibration with the atmosphere. If dedicated tubing was present in the wells this was also removed to allow water level measurement. Water levels were then measured to the nearest hundredth of a foot with a Solinst water level meter and recorded in the Cape PRB field book and field sampling sheets.

Calibration of field parameter meters was also completed before sampling began each day. Field parameters values on each meter were also checked at the end of each day against parameter standards to gauge any drift during the day. Two meters were used for field parameter sampling: a Yellow Springs Instrument (YSI) Model 556 multi-parameter sonde and an YSI Professional Series multi-parameter sonde.

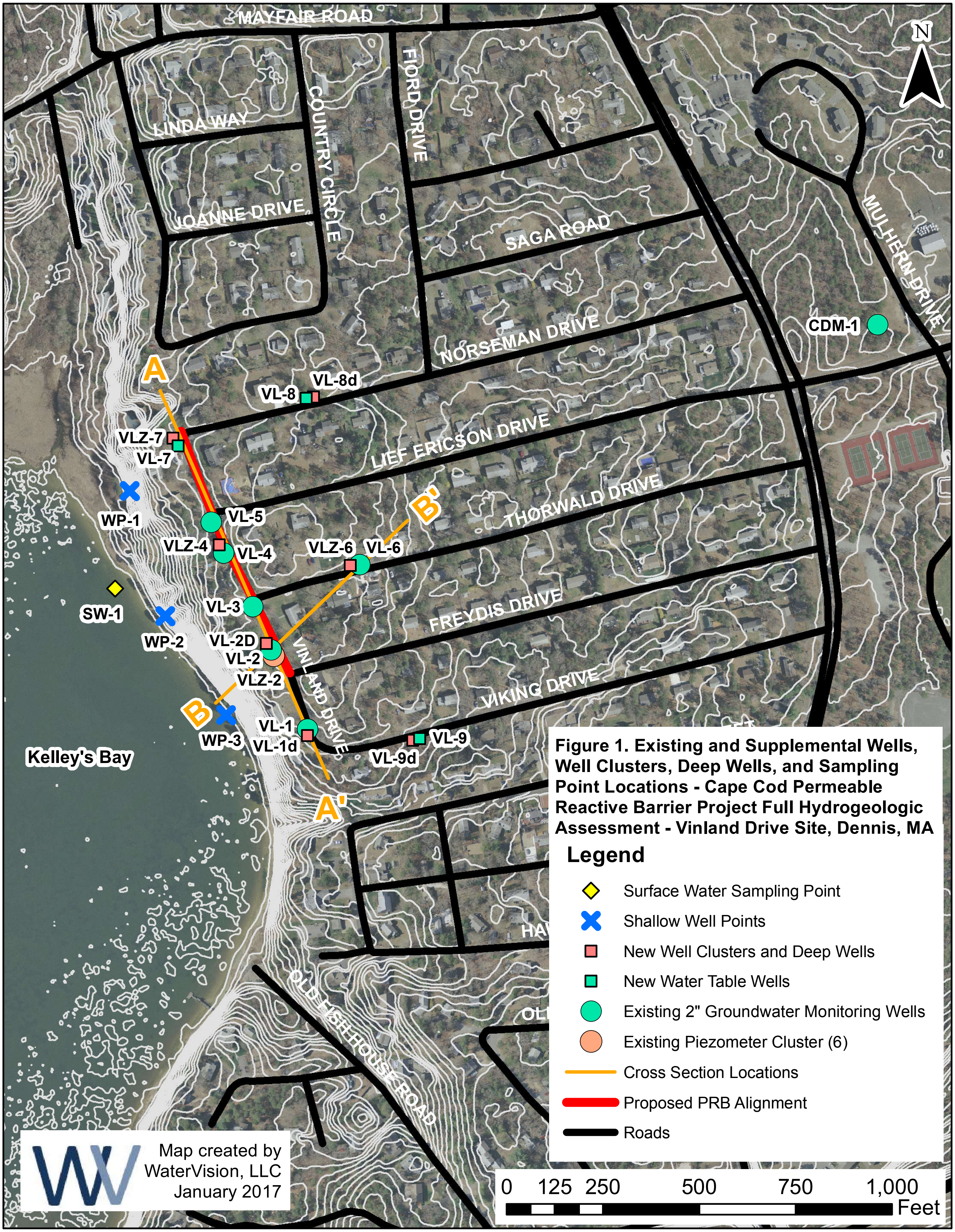


Figure 1. Existing and Supplemental Wells, Well Clusters, Deep Wells, and Sampling Point Locations - Cape Cod Permeable Reactive Barrier Project Full Hydrogeologic Assessment - Vinland Drive Site, Dennis, MA

Sources: Roads and Aerial Photograph from Mass GIS. Contours from the Cape Cod Commission. PRB Alignment, Suface Water Sampling Points, Shallow Well Sampling Points, Existing and New Groundwater Monitoring Well Locations, Existing Piezometer Locations, New Well Cluster Locations and Cross Section Locations from WaterVision LLC.

Table 1 - Well and Piezometer Construction Details
Permeable Reactive Barrier Full Hydrogeologic Assessment - Vinland Drive, Dennis, MA

Well Designation	Date of installation	Land surface elevation (ft. msl)	Top of PVC casing (ft. msl)	Well diameter (inches)	Total depth of boring/ core (ft.)	Total depth of well (ft.)	Top of screen (ft. bgs)*	Bottom of screen (ft. bgs)	Elevation of top of screen (ft. msl)	Elevation of bottom of screen (ft. msl)	Completed in upper or lower sand?
VL-1	2/18/16	42.8	42.35	2	50	40	35	40	7.8	2.8	upper
VL-1D	5/4/17	42.7	42.49	2	70	63	53	63	-10.3	-20.3	lower
VL-2	2/18/16	47.3	47.00	2	46	46	41	46	6.3	1.3	upper
VL-2d	10/17/16	47.4	47.02	2	65	62	52	62	-4.6	-14.6	lower
Piezometers installed adjacent to VL-2:											
VLZ-44	2/17/16	47.3	47.05	1	44	44	43	44	4.3	3.3	upper
VLZ-48	2/17/16	47.2	47.03	1	48	48	47	48	0.2	-0.8	upper
VLZ-52	2/17/16	47.2	47.01	1	52	52	51	52	-3.8	-4.8	lower
VLZ-56	2/17/16	47.2	46.97	1	56	56	55	56	-7.8	-8.8	lower
VLZ-61	2/17/16	47.3	46.96	1	61	61	60	61	-12.8	-13.8	lower
VLZ-66	2/17/16	47.3	47.06	1	66	66	65	66	-17.7	-18.7	lower
VLZ-core	2/17/16	47.3			80						
VL-3	2/19/16	46.7	46.35	2	50	44	39	44	7.7	2.7	upper
VL-4	2/16/16	45.8	45.51	2	50	43	38	43	7.8	2.8	upper
VLZ-4a	11/28/16	45.8	45.43	2	45	45	44	45	1.8	0.8	upper
VLZ-4b	11/28/16	45.8	45.53	2	52	52	51	52	-5.2	-6.2	lower
VLZ-4c	11/28/16	45.9	45.51	2	58	58	57	58	-11.2	-12.2	lower
VLZ-4d	11/28/16	45.9	45.70	2	65	63	62	63	-16.1	-17.1	lower
VL-5	2/16/16	43.0	42.54	2	50	40	35	40	8.0	3.0	upper
VL-6	2/18/16	46.3	45.75	2	50	35	40	40	6.3	6.3	upper
VLZ-6a	11/29/16	46.3	45.88	2	41	41	40	41	6.3	5.3	upper
VLZ-6b	11/29/16	46.3	45.89	2	47	47	46	47	0.3	-0.7	upper
VLZ-6c	11/29/16	46.3	45.99	2	58	58	57	58	-10.7	-11.7	lower
VLZ-6d	11/29/16	46.3	46.13	2	70	64	63	64	-16.7	-17.7	lower
VL-7	10/17/16	42.9	42.52	2	65	40	35	40	7.9	2.9	upper
VLZ-7a	10/18/16	43.0	42.62	2	40	40	39	40	4.0	3.0	upper
VLZ-7b	10/18/16	43.0	42.65	2	53	53	52	53	-9.0	-10.0	lower
VLZ-7c	10/18/16	43.0	42.69	2	57	57	56	57	-13.0	-14.0	lower
VLZ-7d	10/18/16	43.1	42.79	2	61	61	60	61	-16.9	-17.9	lower
VL-8	11/30/16	48.0	48.46	2	55	46	41	46	7.0	2.0	upper
VL-8d	5/4/17	48.0	48.50	2	70	65	55	65	-7.0	-17.0	lower
VL-9	11/30/16	37.8	37.54	2	70	40	30	40	7.8	-2.2	upper
VL-9d	5/4/17	37.9	37.71	2	70	61	53	61	-15.1	-23.1	lower

Surveyed by CEI Engineers benchmark NGVD29 converted to NAVD 88

* bgs- below ground surface

Well purging and sampling commenced after water level measurement was complete. Because the depth to water exceeds 25 feet below land surface all sampling of 2-inch wells was conducted with a GeoSub, Grundfos, or Whale submersible pump powered by a marine battery. Fine sand was encountered in several wells and caused pump fouling and clogging so backup equipment was required during these sampling rounds. A Waterra Hydrolift pump was used to purge the 1–inch-diameter piezometers. Wells were purged of at least three well volumes or until field parameter measurements stabilized.

The samples at surface-water locations WP-1, WP-2, and WP-3 (Figure 1) were taken using a "PushPoint" sampler developed by Mark Henry of MHE Products. This is a ¼-inch-diameter stainless steel tube that is slotted at the tip. The sampler was advanced by hand into shallow sediment in or adjacent to a water body and a groundwater sample extracted using a peristaltic pump.

A surface water sample was also collected by taking a grab sample with a cleaned glass container for field parameter measurement and transferring it directly into sample bottles for the laboratory analyses. The surface water samples taken for dissolved metals and dissolved organic carbon were laboratory filtered rather than field filtered. The surface water sampling station was approximately 10 feet from the shoreline as shown on Figure 1.

Field measurements of water temperature, pH, dissolved oxygen (DO), specific conductance, and oxidation/reduction potential (ORP) were regularly measured using the YSIs during well purging. A visual description of the purged water was also noted. All samples were monitored for field parameters using the flow-through chamber. All field measurements and observations were noted on field sheets.

Water samples were taken in laboratory-provided pre-preserved sample bottles for the parameters listed in Table 2.

Table 2 – Laboratory Analyzed Water Quality Parameters, Full Hydrogeologic Assessment, Vinland Drive, Dennis, MA PRB

Name	Type
Nitrate-N, Nitrate and Nitrate-N, Nitrite-N, Total Kjeldahl Nitrogen	General chemistry
Chloride, Sulfate, Total Alkalinity	General chemistry
Organic carbon (dissolved)	Carbon analyses
Iron (dissolved), Manganese (dissolved), Arsenic (dissolved)	Metals
Stable Nitrogen Isotopes in Nitrate ($\boldsymbol{\delta^{15}}\mathbf{N}\text{–}\mathbf{NO_3}$)	Isotope analyses

Groundwater samples taken for δ^{15}N-NO_3 analyses were first field-filtered with a 0.01-micron cartridge filter before collection into sample bottles. Two sample bottles were filled at each sample location. These samples were to be fully frozen before laboratory delivery so adequate headspace was provided in these bottles to allow for water expansion during freezing.

Groundwater samples were then taken for dissolved iron, manganese, and arsenic and for dissolved organic carbon analyses. These samples were field-filtered with a 0.45-micron cartridge filter before collection into sample bottles. Water samples collected for the remaining analyses were not field-filtered.

Field-collected samples for standard laboratory analyses were kept on ice in laboratory-provided coolers until delivery to Alpha Analytical Laboratory in Westborough, Massachusetts.

The stable-isotope nitrogen samples were immediately cooled, then frozen for approximately 24 hours. The samples were carefully wrapped and placed into insulated shipping containers with blue ice packs to keep the samples frozen. The samples were then overnight-shipped to the University of California at Davis Stable Isotope Laboratory in Davis, California. Duplicate samples for stable nitrogen analysis taken at all well locations were kept frozen and on reserve in case the initial samples did not stay frozen or were deemed unusable by the laboratory upon delivery. When the results of the nitrate-N general-chemistry analyses were received from Alpha Analytical, these results were provided to UC-Davis to guide the isotope analyses; isotope analyses were conducted only on samples with nitrate levels known to be above detection limits.

WaterVision LLC maintained custody of all samples until delivery to Alpha Analytical laboratory or via overnight delivery by Federal Express to the University of California at Davis Stable Nitrogen Isotope Laboratory in Davis, California.

December 12th to 14th, 2016

The weather during December 12 to 14, 2016 was cloudy with temperatures in the mid to high 30s and a slight breeze. There were some morning showers before fieldwork began on December 14th. The following wells were sampled on December 12th: VLZ-6a, VLZ-6b, VLZ-6c, VLZ-6d, and VLZ-4d. On December 14th, VLZ-4c was sampled. No duplicate was taken during the December 12th sampling at Dennis. Both Dennis and Barnstable were sampled on December 14th and the field duplicate was taken at Barnstable during that sampling day.

January 12th and 13th, 2017

The weather during January 12 and 13th was clear with a slight breeze; temperatures were in the high 40s. On January 12th, VL-3, SW-1, WP-1, WP-2, and WP-3 were sampled and VLZ-6b was sampled again for QA/QC purposes since sampling needed to be split up between two time periods. The Shorewood site was also sampled on January 12th and the duplicate was taken at that location.

The following wells were sampled on January 13th: VL-5, VL-6, VL-7, VL-8, VLZ-4a, VLZ-4b, VLZ-7a, VLZ-7b, VLZ-7c, and VLZ-7d. VL-4 could not be sampled because the well had too little water. On the same day VLZ-7c could not be sampled because the well was filled with fine sand and silt and clogged two pumps. VL-9 could not be sampled on 1/13/17 because the well went dry after purging 4 gallons of water. A duplicate sample was taken at VL-6b (VL-6b DUP) for this sampling round.

January 19th, 2017

The weather for January 19th was cloudy with temperatures in the mid to high 30s and a slight breeze. On January 19th, VL-1, VL-2, VL-2d, VL-4, and V-6, and VLZ-48 through VLZ-66 were sampled. VLZ-44 was not sampled on January 19th because there was not enough water in the well for the Waterra pump to purge. Sampling was again attempted at VLZ-7c with both the Waterra Hydrolift and a submersible pump but was unsuccessful due to excessive fine sand and silt in the well. A duplicate sample was taken at VL-4 (VL-4 DUP).

Water Level Measurement to Evaluate Tidal Influences at Wells

Two HOBO pressure transducers programmed to collect water level measurements every 15 minutes were placed in water table wells VL-5 and VL-6 in order to measure water level changes over time and to determine if tide influences water levels in the upper sand unit. VL-5 was chosen as it was the well closest to Kelley's Bay. VL-6 is located on Thorwald Drive approximately 600 feet from Kelley's Bay and was presumed to experience less tidal influence. The transducer at VL-5 recorded water levels from November 28, 2016 to January 11, 2017. The VL-6 transducer recorded water levels from October 20, 2016 to January 19, 2017.

In order to assess tidal influence on water levels in the lower sand unit, water level was also measured continuously at four wells completed in this zone. Water level was measured using HOBO pressure transducers programmed to collect data at 10-minute intervals at VL-2d, VLZ-4d, VLZ-6d, and VLZ-7d. These measurements were taken between April 7 and May 4, 2017.

Grain Size Analyses and Slug Testing to Determine Hydraulic Conductivity

Grain-Size Analyses

Grain-size analyses were completed by Alpha Analytical Laboratory using ASTM Method D-422-63. WaterVision LLC requested that all sieve sizes be used to provide the most complete range in grain size for hydraulic conductivity estimation. Samples from representative depths from the VL-2, VL-3, VL-4, VL-6, VL-7, and VL-9 monitoring well locations were subjected to grain-size analysis for a total of 19 samples. The samples prepared for analysis were taken from continuous core samples collected during well installation during the ISC work in February 2016 and the follow-up FHA work in October and November 2016.

Slug Testing

Slug tests were completed on March 1, 2017. Testing was completed with a Midwest Geosciences $H_{(o)}$ PVC slug designed to achieve a 24-inch displacement in a two-inch-diameter well. The slug is tapered on each end and has an overall length of 3.8 feet and a diameter of 1.1 inches. Tests were completed in 11 water table or cluster wells. Water level change was measured using an Onset Hobo pressure transducer programmed to collect water level measurements at one-second intervals. Water levels were measured before each well test and several tests were completed at each well to assure that a good response was captured.

Results

Subsurface Geology

Continuous cores were collected at all locations prior to installation of monitoring wells, piezometers, or well clusters during the ISC and FHA field programs. Continuous cores were collected to the top of the lower clay at VL-1, VL-2, VL-4, VL-6, VL-7, VL-8, and VL-9 well locations.

Based on the characteristics encountered in the subsurface, the units have been broken down into four overall categories for reference in this study. The saturated zone above the upper clay layer is referred to as the *upper sand* and the saturated zone between the upper clay layer and lower clay layer is referred to as the *lower sand.* The two clay units are referred to as the *upper clay a*nd the *lower clay layers*.

Table 3 summarizes the site lithology by depth, elevation, and overall thickness of the units identified based on the new subsurface data. The highest groundwater level measured during the study period defines the top of the saturated upper sand. Also included in this table is subsurface information from a well installed on Mulhern Drive off Bob Crowell Drive approximately 0.5 miles from Vinland Drive (CDM-1) shown on Figure 1. The well installation and boring log compiled by CDM-Smith for well CDM-1 is also included in Appendix A. Figures 2 and 3 are hydrogeologic cross sections that illustrate the subsurface lithology and water levels measured at the wells and piezometers during the FHA. The locations of the cross-section lines are shown on Figure 1.

Table 3 - Summary of Site Lithology
Permeable Reactive Barrier Full Hydrogeologic Assessment - Vinland Drive, Dennis, MA

Well designation / Continuous core location	Land surface elevation (ft. msl)*	Total depth of boring/ core (ft)	Top of saturated upper sand (depth bgs)++ *	Top of upper clay layer (depth bgs)	Top of lower sand (depth bgs)	Top of lower clay layer (depth bgs)	Top of saturated upper sand (ft. MSL)**	Top of upper clay layer (ft. MSL)	Top of lower sand (ft. MSL)	Top of lower clay layer (ft. MSL)	Thickness of upper sand (ft)	Thickness of upper clay layer (ft)	Thickness of lower sand (ft)
VL-1	42.8	70	36.5	46.8	52.8	65.6	6.3	0.5	-10.0	-22.8	5.8	10.5	12.8
VL-2	47.3	46	40.1	48.5	51.5	66.2	7.2	-1.2	-4.2	-18.9	8.4	3.0	14.7
VL-3	46.7	50	39.4	45.2	NA	NA	7.3	NA	NA	NA	NA	NA	NA
VL-4	45.8	70	38.4	45.5	50.4	63.8	7.4	0.3	-4.6	-18.0	7.1	4.9	13.4
VL-5	43.0	50	35.0	47.2	NA	NA	8.0	-4.2	NA	NA	12.2	NA	NA
VL-6	46.3	50	35.0	46.8	55.6	65.6	11.3	-0.5	-9.3	-19.3	11.8	8.8	10.0
VL-7	42.9	65	34.7	41.5	52.1	61.3	8.2	1.4	-9.2	-18.4	6.8	10.6	9.2
VL-8	48.0	55	37.9	47.1	55.1	65.6	10.1	0.9	-7.1	-17.6	9.2	8.0	10.5
VL-9	37.8	70	28.8	45.7	52.2	63	9.0	-7.9	-14.4	-25.2	16.9	6.5	10.8
CDMS-1 ***	40.1	63	26.0	45.0	52.0	NA	14.1	-4.9	-11.9	NA	19.0	7.0	>11

++ groundwater depth based on shallowest water level measurements in water table wells

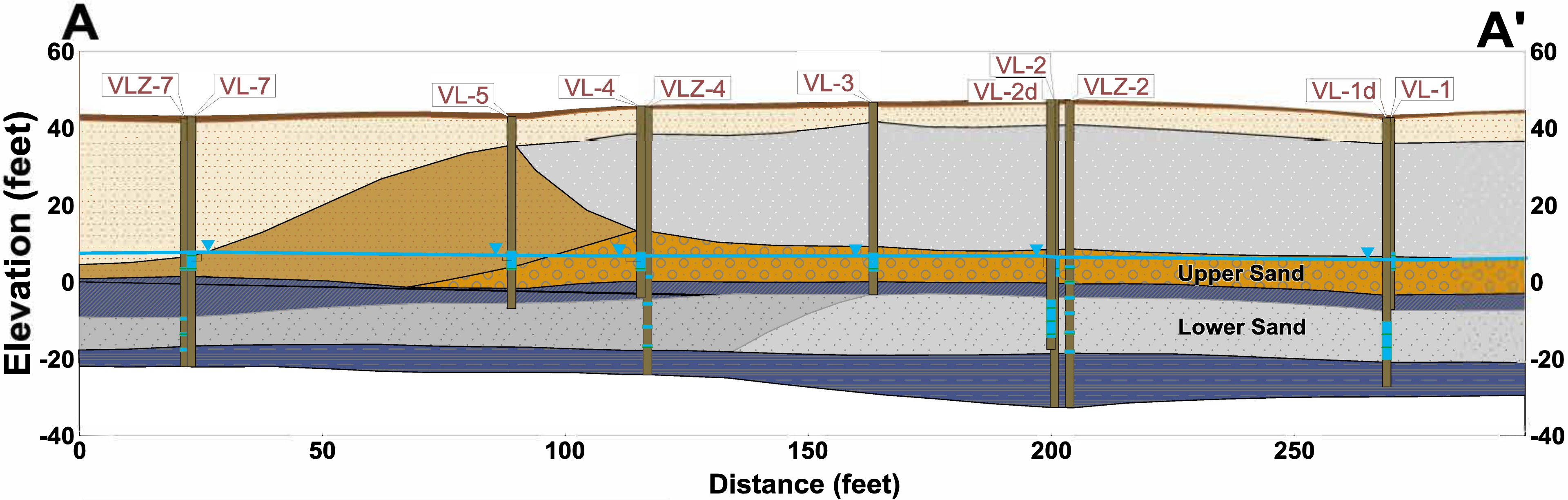
* bgs - below ground surface

** Surveyed by CEI Engineers benchmark NGVD29 converted to NAVD 88

*** Boring log provided by CDM-Smith for well installed off Bob Crowell Drive

NA - Core not completed to the depth of this unit

Figure 2 - Cross-Section A-A'
Cape Code PRB Vinland Drive, Dennis, MA



Location Map

Stratigraphy

- ▨ A- soil/ surface organics
- ▨ B- medium to coarse sand (tan/orange)
- ▨ C- medium to coarse sand (grey)
- ▨ H- fine to coarse sand (tan)
- ▨ D- medium to coarse sand & gravel (banding of orange/tan/red with grey)
- ▨ E- clay (grey) with some silt and sand
- ▨ F- medium and coarse sand (grey)
- ▨ I- fine to medium sand (grey) with minor coarse sand; silty sand at depth
- ▨ G- clay (grey)

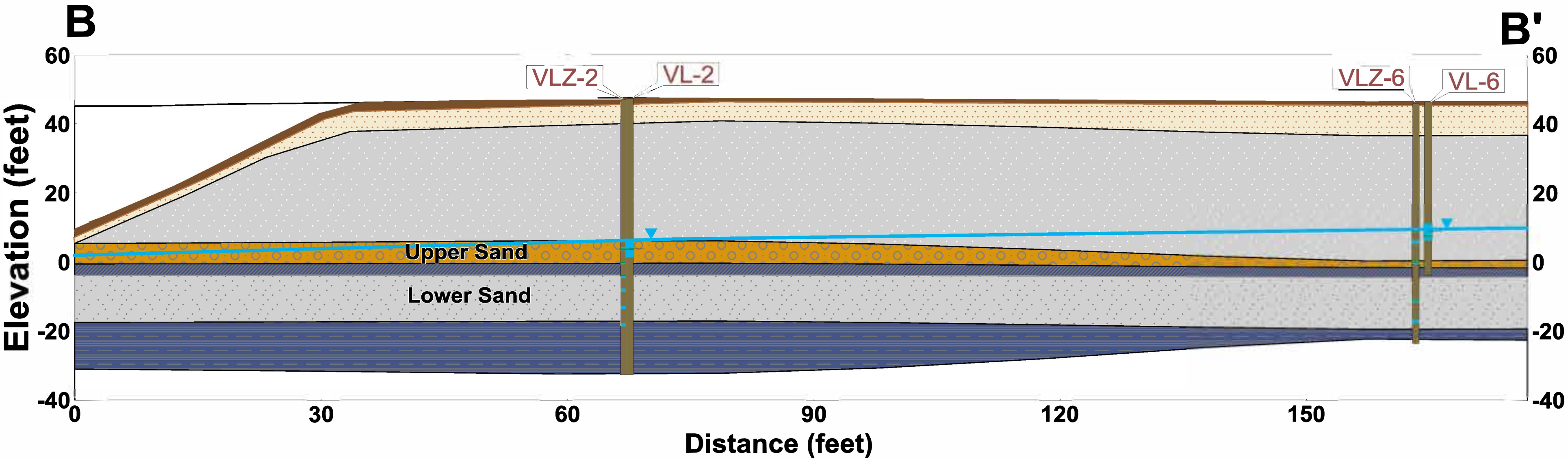
Wells

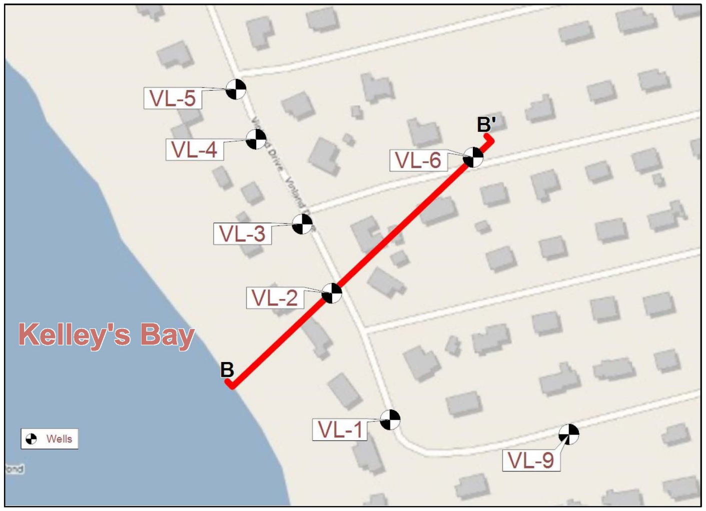
- ▨ Casing
- ▨ Screen

▼ *Water Table (ft)*

5/5/17

Figure 3 - Cross-Section B-B'
Cape Code PRB Vinland Drive Dennis, MA





Location Map

Stratigraphy

- 🟫 A- soil/ surface organics
- ▨ B- medium to coarse sand (tan/orange)
- ▨ C- medium to coarse sand (grey)
- ▨ D- medium to coarse sand & gravel (banding of orange/tan/red with grey)
- ■ E- clay (grey) with some silt and sand
- ▨ F- medium and coarse sand (grey)
- ■ G- clay (grey)

Wells

- ■ Casing
- ■ Screen

▼ *Water Table (ft)*
5/5/17

The additional borings and the grain size analyses completed during the FHA illustrate that the grain size and thickness of these units changes from place to place at the site. During the ISC the *upper sand* was characterized as medium to coarse sand with some zones of coarse sand and gravel. Based on the newest boring information, this unit was found to be 5.8-feet to nearly 17-feet thick depending on location, with the greatest thickness at VL-5 and VL-9. The upper clay layer was found to be 3- to 4.3-feet thick at VL-2 and VL-6 during the ISC. Additional definition of this layer shows that it thickens to both the north and south towards VL-7 and VL-1.

The lower sand was found to be approximately 15-feet thick during the ISC and was characterized as medium to coarse sand. These lithologic units were further defined with new boring information. This unit also thins to the north and is thickest between VL-1 and VL-4. The new boring information also shows that both the upper and lower sand become finer to the north and west near VL-7 compared to coarser materials found at VL-2 and VL-6.

Multiple zones of coarse oxidized red-brown sand were encountered in both the upper and lower sand units at multiple locations and may act as zones of preferential flow. This is especially apparent in sediments immediately above the upper clay layer.

Groundwater Flow Directions and Gradients

Water Levels and Horizontal Flow

Upper Sand Unit

The water level measurements completed during this phase of work at the existing and new wells confirm the overall water table flow direction of west to southwest towards Kelley's Bay (Figure 4, Table 4a). Water levels were one to two feet lower in December 2016 and January 2017 compared to May 2016 when the highest water levels were observed at the site. Water levels had rebounded to nearly the same high elevation by May 2017. The greatest variation in water levels was found at VL-6 where the water level changed by 2.75 feet between May 2016 and January 2017.

The horizontal gradient calculated between VL-6 and VL-3 (Table 4b) was found to be modestly lower based on the FHA water level measurements in May 2017,

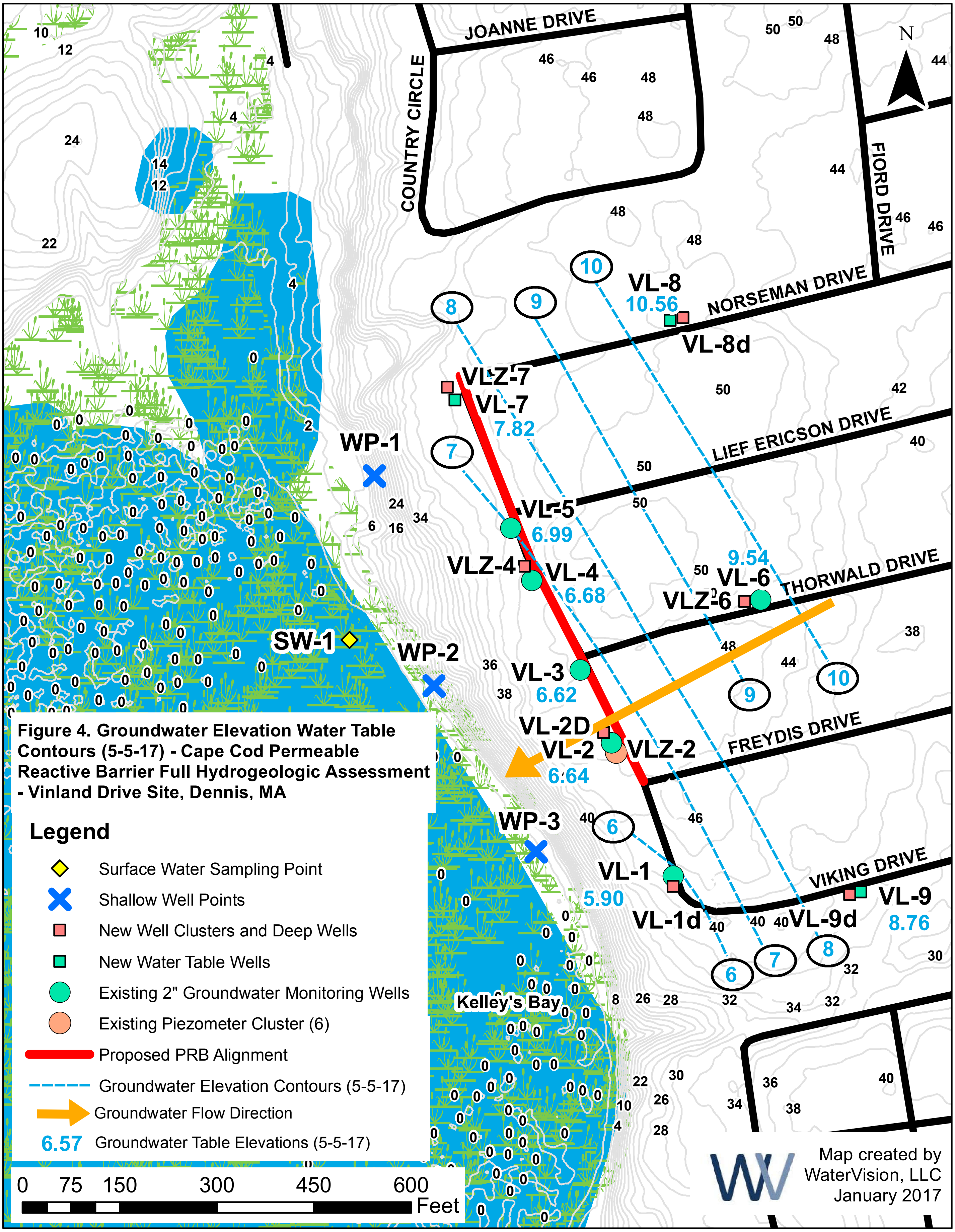


Figure 4. Groundwater Elevation Water Table Contours (5-5-17) - Cape Cod Permeable Reactive Barrier Full Hydrogeologic Assessment - Vinland Drive Site, Dennis, MA

Sources: Surface Water Sampling Points, Shallow Well Sampling Points, Existing and New Groundwater Monitoring Well Locations, Existing Piezometer Locations, New Well Cluster Locations, Groundwater Elevations and Contours, and Groundwater Flow Direction from WaterVision LLC. Roads and Kelley's Bay from Mass GIS, Contours from Cape Cod Commission, and Wetlands from the National Wetlands Inventory (NWI).

Table 4a - Groundwater Levels and Elevations
Permeable Reactive Barrier Full Hydrogeologic Assessment - Vinland Drive, Dennis, MA

			Depth to Water (feet)						Water Surface Elevation (feet above mean sea level)*					
Well	Top of PVC casing (ft. msl)*	Screened in upper or lower sand?	3/31/16	5/6/16	12/14/16	1/13/17	4/24/17	5/5/17	3/31/16	5/6/16	12/14/16	1/13/17	4/24/17	5/5/17
VL-1	42.35	upper	36.48	35.98	37.68	37.78	36.48	36.45	5.87	6.37	4.67	4.57	5.87	5.90
VL-2	47.00	upper	40.40	40.05	41.70	41.77	40.40	40.36	6.60	6.95	5.30	5.23	6.60	6.64
VL-3	46.35	upper	39.77	39.38	41.07	41.12	39.78	39.73	6.58	6.97	5.28	5.23	6.57	6.62
VL-4	45.51	upper	38.86	38.40	40.16	40.21	38.93	38.83	6.65	7.11	5.35	5.30	6.58	6.68
VL-5	42.54	upper	35.40	34.98	36.98	36.95	35.62	35.55	7.14	7.56	5.56	5.59	6.92	6.99
VL-6	45.75	upper	35.82	35.33	37.95	38.08	36.30	36.21	9.93	10.42	7.80	7.67	9.45	9.54
VL-7	42.52	upper			36.17	36.24	34.74	34.70			6.35	6.28	7.78	7.82
VL-8	48.46	upper			39.78	39.90	38.02	37.90			8.68	8.56	10.44	10.56
VL-9	37.54	upper			30.48	30.57	28.85	28.78			7.06	6.97	8.69	8.76
CDM-1	42.20	upper						27.82						14.38

			Depth to Water (feet)						Water Surface Elevation (feet above mean sea level)*					
Well	Top of PVC casing	Screened in upper or lower sand?	3/31/16	5/6/16	12/14/16	1/13/17	4/24/17	5/5/17	3/31/16	5/6/16	12/14/16	1/13/17	4/24/17	5/5/17
VL-1	42.35	upper						36.45						5.90
VL-1d	42.49	lower						33.68						8.81
VL-2	47.00	upper			41.70	41.77	40.40	40.36			5.30	5.23	6.60	6.64
VL-2d	47.02	lower			39.52	39.65	38.11	37.98			7.50	7.37	8.91	9.04
VLZ-44	47.05	upper	40.40	40.02	41.72	41.78	40.45	40.38	6.65	7.03	5.33	5.27	6.60	6.67
VLZ-48	47.03	upper	40.35	40.03	41.65	41.71	40.39	40.30	6.68	7.00	5.38	5.32	6.64	6.73
VLZ-52	47.01	lower	37.81	37.12	39.42	39.56	38.08	37.98	9.20	9.89	7.59	7.45	8.93	9.03
VLZ-56	46.97	lower	37.64	37.27	39.40	39.55	37.98	37.89	9.33	9.70	7.57	7.42	8.99	9.08
VLZ-61	46.96	lower	37.72	37.12	39.41	39.57	38.05	37.91	9.24	9.84	7.55	7.39	8.91	9.05
VLZ-66	47.06	lower	37.82	37.24	39.47	39.65	38.13	37.97	9.24	9.82	7.59	7.41	8.93	9.09
VLZ-4a	45.43	upper			40.06	41.12	38.86	38.75			5.37	4.31	6.57	6.68
VLZ-4b	45.53	lower			37.85	38.05	36.50	38.32			7.68	7.48	9.03	7.21
VLZ-4c	45.51	lower			37.83	38.03	36.52	36.33			7.68	7.48	8.99	9.18
VLZ-4d	45.70	lower			37.98	38.21	36.69	36.50			7.72	7.49	9.01	9.20
VLZ-6a	45.88	upper			38.15	38.25	36.48	36.38			7.73	7.63	9.40	9.50
VLZ-6b	45.89	upper			38.10	38.24	36.46	36.35			7.79	7.65	9.43	9.54
VLZ-6c	45.99	lower			37.90	38.08	36.48	36.29			8.09	7.91	9.51	9.70
VLZ-6d	46.13	lower			38.05	38.15	36.54	36.35			8.08	7.98	9.59	9.78
VLZ-7a	42.62	upper			36.18	36.16	34.81	34.65			6.44	6.46	7.81	7.97
VLZ-7b	42.65	lower			35.18	35.51	33.93	33.67			7.47	7.14	8.72	8.98
VLZ-7c	42.69	lower			35.01	35.35	33.85	33.70			7.68	7.34	8.84	8.99
VLZ-7d	42.79	lower			34.91	35.31	33.92	33.54			7.88	7.48	8.87	9.25
VL-8	48.46	upper						37.90						10.35
VL-8d	48.50	lower						38.15						10.56
VL-9	37.54	upper						28.78						8.76
VL-9d	37.71	lower						28.33						9.38

*Surveyed to NGVD29 benchmark at Old Bass River Road and Leif Ericson Drive and converted to NAVD 88

Table 4b - Horizontal and Vertical Hydraulic Gradients at Wells and Piezometers
Permeable Reactive Barrier Full Hydrogeologic Assessment - Vinland Drive, Dennis, MA

Well	Top of PVC Casing (ft msl)	Screened in upper or lower sand?	Horizontal Gradient VL-6 to VL-3 3/31/16	Horizontal Gradient - VL-6 to VL-3 5/6/16	Horizontal Gradient VL-6 to VL-3 12/14/16	Horizontal Gradient - VL-6 to VL-3 5/5/17
VL-1	42.35	upper				
VL-2	47.00	upper				
VL-3	46.35	upper	0.011	0.012	0.008	0.010
VL-4	45.51	upper				
VL-5	42.54	upper			**Horizontal Gradient VL-8 to VL-7 12/14/16**	**Horizontal Gradient VL-8 to VL-7 5/5/17**
VL-6	45.75	upper			0.007	0.008
VL-7	42.52	upper				
VL-8	48.46					
VL-9	37.54	upper				
						Horizontal Gradient - VLZ-8d to VL-7d 5/5/17
VLZ-6d	46.13	lower				0.004
VLZ-66	47.06	lower				

Well	Top of PVC Casing (ft msl)	Screened in upper or lower sand?	Vertical gradient between adjacent screens 3/31/16		Vertical gradient between adjacent screens 5/6/16		Vertical gradient between adjacent screens 12/14/16		Vertical gradient between adjacent screens 5/5/17	
VL-1	42.35	upper								
VL-1d	42.49	lower							0.127	strongly upward
VL-2	47.00	upper								
VL-2d	47.02	lower					0.200	strongly upward	0.150	strongly upward
VLZ-44	47.05	upper								
VLZ-48	47.03	upper	0.008	upward	-0.007	slightly downward	0.013	upward	0.015	upward
VLZ-52	47.01	lower	0.630	strongly upward	0.723	strongly upward	0.552	strongly upward	0.575	strongly upward
VLZ-56	46.97	lower	0.033	upward	-0.048	downward	-0.005	slightly downward	0.012	upward
VLZ-61	46.96	lower	-0.018	downward	0.028	upward	-0.004	slightly downward	-0.006	slightly downward
VLZ-66	47.06	lower	0.000	flat	-0.004	slightly downward	0.008	sightly upward	0.008	sightly upward
VLZ-4a	45.43	upper								
VLZ-4b	45.53	lower					0.330	strongly upward	0.076	strongly upward
VLZ-4c	45.51	lower					0.000	flat	0.328	strongly upward
VLZ-4d	45.70	lower					0.008	slightly upward	0.004	slightly upward
VLZ-6a	45.88	upper								
VLZ-6b	45.89	upper					0.060	upward	0.008	slightly upward
VLZ-6c	45.99	lower					0.027	strongly upward	0.015	upward
VLZ-6d	46.13	lower					-0.001	slightly downward	0.006	slightly upward
VLZ-7a	42.62	upper								
VLZ-7b	42.65	lower					0.079	strongly upward	0.078	strongly upward
VLZ-7c	42.69	lower					0.053	strongly upward	0.002	slightly upward
VLZ-7d	42.79	lower					0.050	strongly upward	0.065	strongly upward
VL-8	48.46	upper								
VL-8d	48.50	lower							0.013	upward
VL-9	37.54	upper								
VL-9d	37.71	lower							0.030	upward

Vertical gradient rankings
0.05 or greater - strongly upward
0.009 to 0.049- upward
less than 0.009 - slightly upward
-0.05 or greater - strongly downward
-0.009 to 0.049- downward
less than- 0.009 - slightly downward

** benchmark NGVD29 converted to NAVD 88 decreasing to 0.010 from the gradient of 0.012 observed during the ISC. As a check on the horizontal gradient over a wider area, a well installed in the upper sand unit during the fall of 2016 by CDM-Smith near the corner of Mulhern Street and Bob Crowell Road (Figure 1) was also evaluated with respect to the hydraulic gradient in the upper sand unit. This well is approximately 1800 feet northeast of VL-3. The water table elevation measured at CDM-1 was 14.38 ft. msl on May 5, 2017. Using the groundwater elevation of 6.68 ft. msl at VL-3 measured on the same date, the hydraulic gradient is 0.004, approximately half the gradient than measured between VL-6 and VL-3 on May 5, 2017.

Lower Sand Unit

Geologic and hydrologic data collected during the ISC suggested that the overlying upper clay layer hydrogeologically confines the lower sand unit. Water level data collected in December 2016 and January 2017 suggested that the flow direction and gradient in the lower sand differed from the upper zone flow direction and gradient. Initially, the direction of horizontal groundwater flow in the lower sand was estimated by comparing the water levels measured in the deepest piezometer or well in the VL-2, VL-4, VL-6, and VL-7 clusters. After further evaluation of data, measurements of tidal influence on the lower zone (described in a following section), and installation of additional wells in the lower sand, a full round of water level measurements were again made to provide a nearly synoptic measurement of the piezometric surface in the lower sand. The 13 wells completed in the lower sand were all measured over the span of about one hour on May 5, 2017.

The resulting flow direction and gradient are based on a full round of water level data collected on May 5, 2017 using the water levels measured in the deepest piezometer or well in the VL-2, VL-4, VL-6, and VL-7 cluster wells and in VL-1d, VL-9d and VL-8d completed in the lower sand unit. The May 5, 2017 water level measurements are shown in Figure 5. The estimated flow direction is southwest toward Kelley's Bay similar to the upper sand unit. The horizontal gradient is less than in the upper sand. The gradient calculated between VLZ-7d and VLZ-6d is 0.004 based on the May 5, 2017 round of measurements.

Evaluation of Tidal Influence on Groundwater Levels and Horizontal Gradients

Figure 6a illustrates the continuous water level measurements made at water table wells VL-5 and VL-6 from November 2016 to January 2017. The depths were then converted to water level elevation for the plot. VL-5 is located on Vinland Drive and is less than 200 feet from the bay (Figure 1). VL-6 is located on Thorwald Drive and is more than 500 feet inland from Kelley's Bay. The daily precipitation measured at Hyannis Airport in Barnstable over that time is also included on Figure 6a (Weather

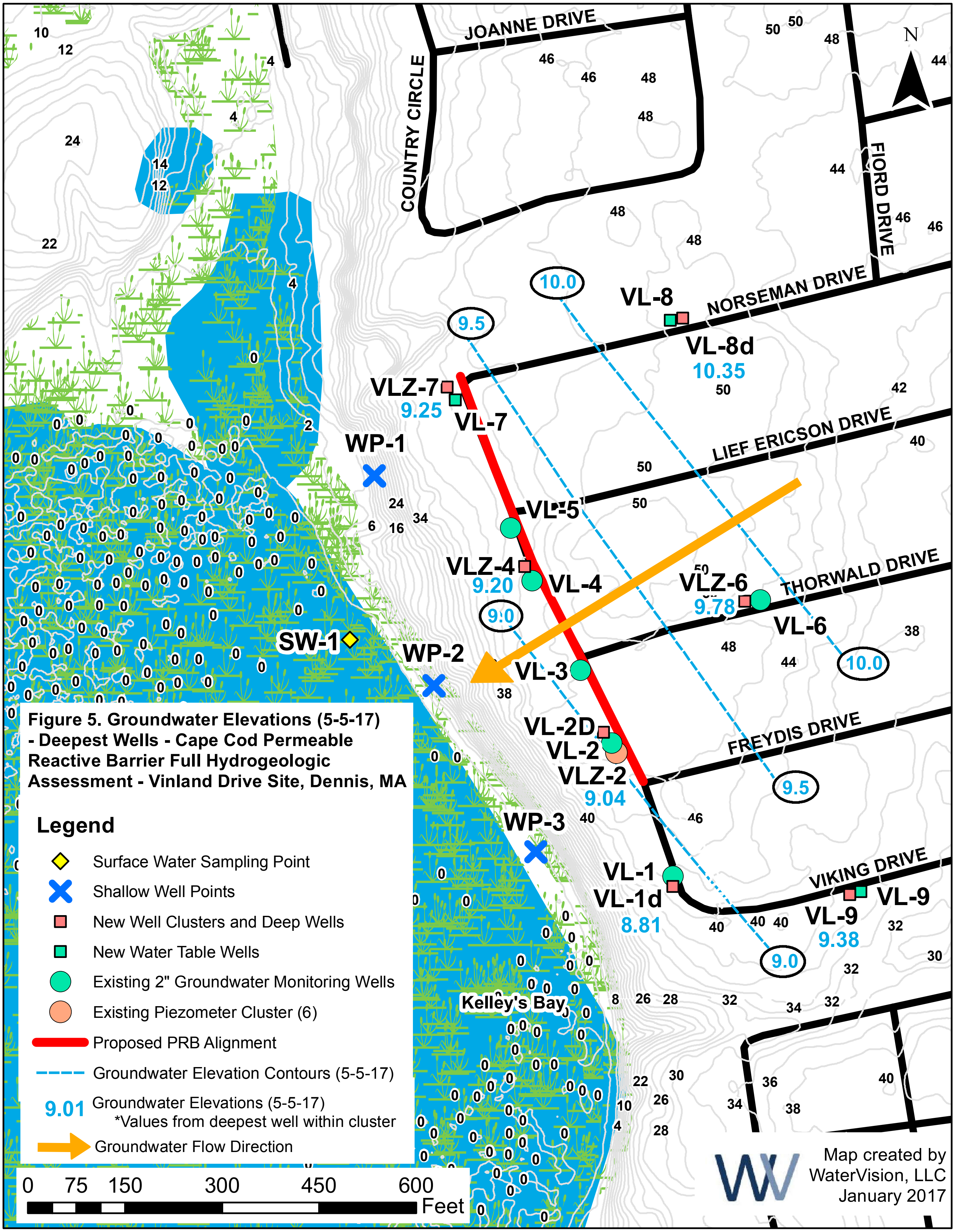
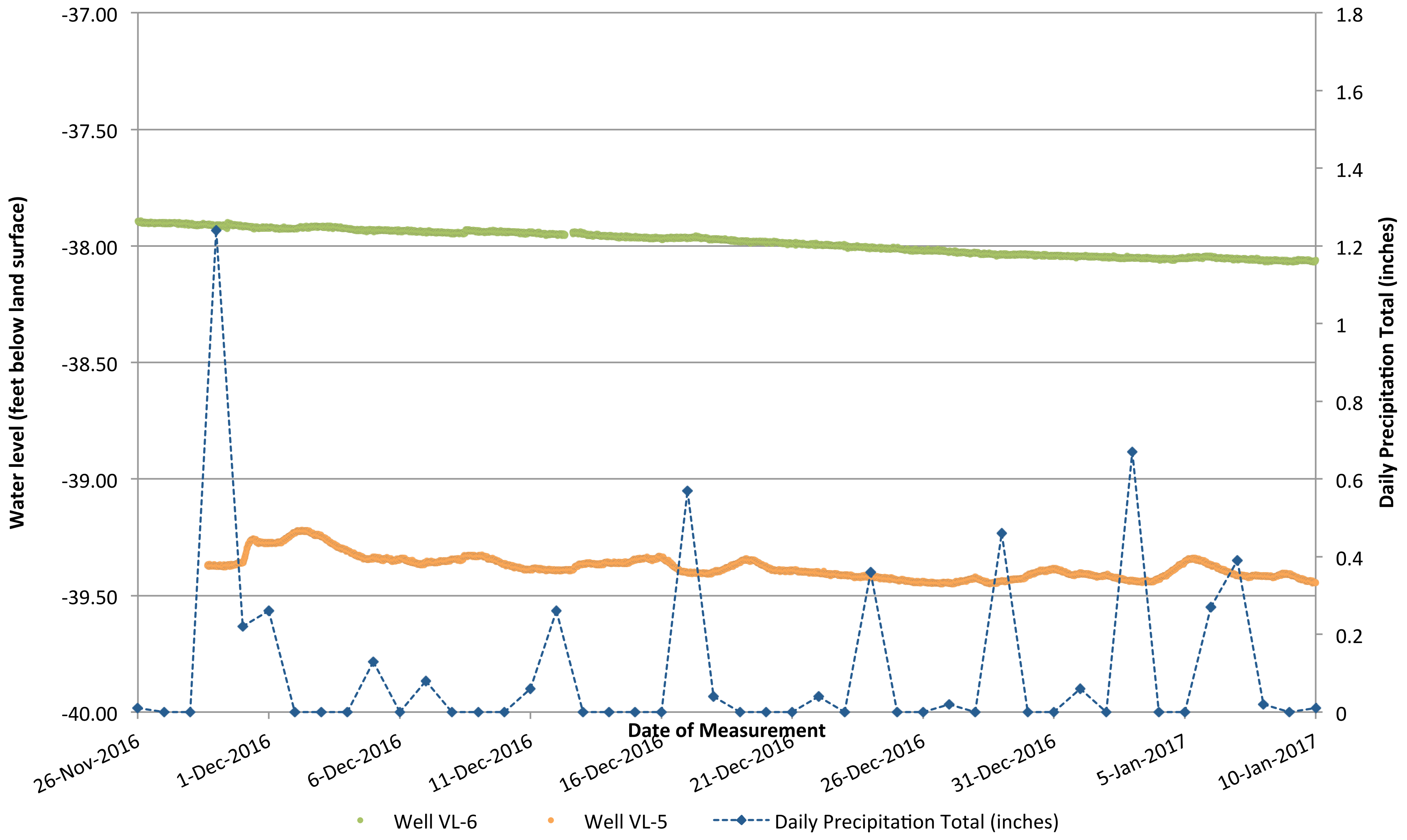


Figure 5. Groundwater Elevations (5-5-17) - Deepest Wells - Cape Cod Permeable Reactive Barrier Full Hydrogeologic Assessment - Vinland Drive Site, Dennis, MA

Sources: Surface Water Sampling Points, Shallow Well Sampling Points, Existing and New Groundwater Monitoring Well Locations, Existing Piezometer Locations, New Well Cluster Locations, Groundwater Elevations and Contours, and Groundwater Flow Direction from WaterVision LLC. Roads and Kelley's Bay from Mass GIS, Contours from Cape Cod Commission, and Wetlands from the National Wetlands Inventory (NWI).

Figure 6a - Groundwater Levels at Wells VL- 5 and VL-6, November 26, 2016 to January 10, 2017



Underground, 2017). Both wells exhibit a slow decline in water level over this time period, consistent with expected seasonal patterns, although the decrease at VL-5 was less than that at VL-6. At VL-6, the water level dropped approximately 0.15 feet over the measurement period and was not obviously influenced by tides.

In contrast, the water level declined less than 0.1 feet at VL-5 but there were also changes in water level at the well that appear to be responses to precipitation events rather than tidal influence. The VL-5 well is less than 10 feet from a leaching catch basin just west of Vinland Drive. The noticeable increases in water level at VL-5 appear to occur one to two days after storms. The discharge of runoff to the storm drain is likely causing these occasional rises in water level at VL-5.

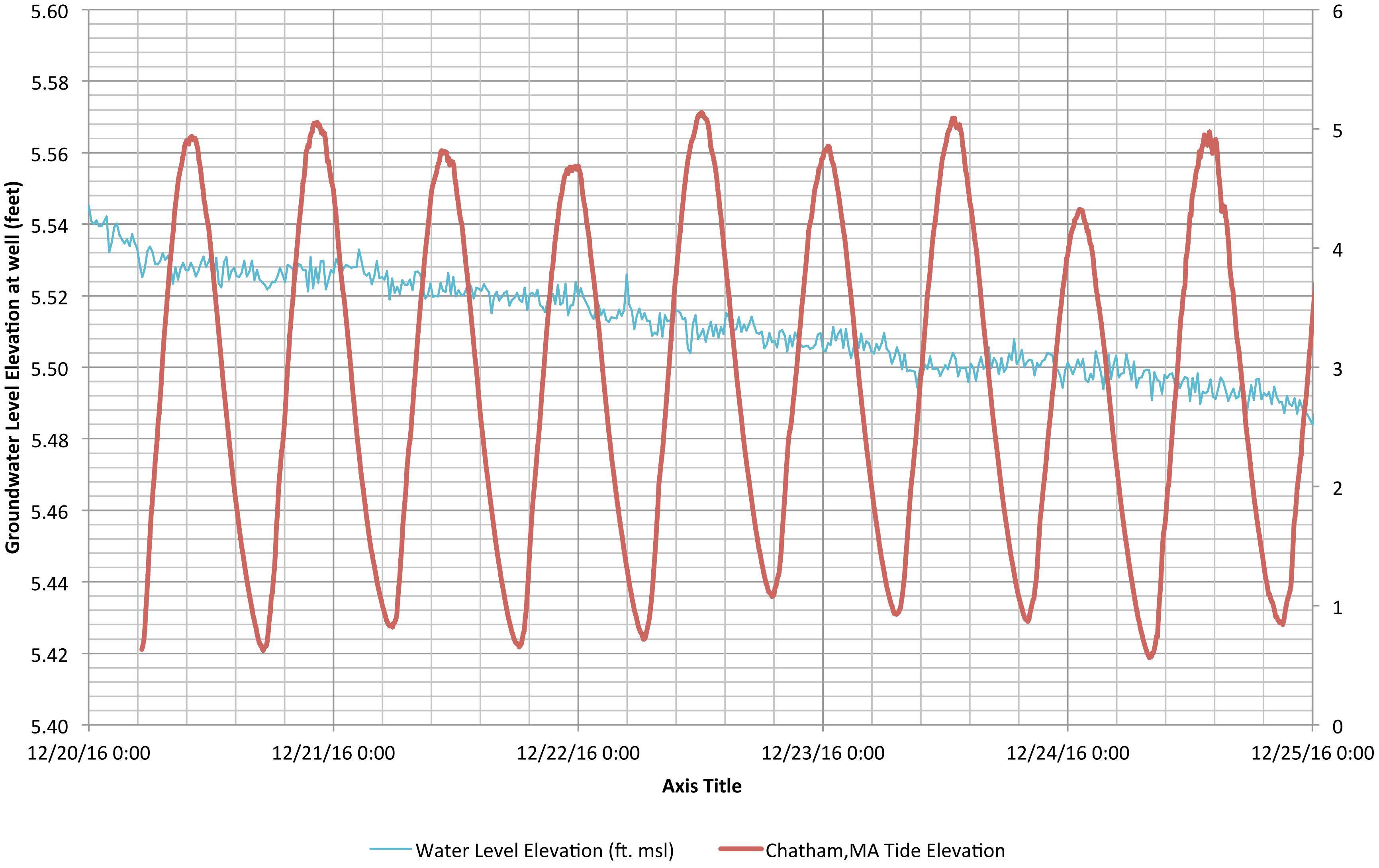
A graph of continuous water level elevation measurements at VL-5 over a five-day period in December 2016 (Figure 6b) when no precipitation was measured shows that there may be a very slight tidal influence on water levels in the upper sand. Also included in this figure are tidal elevations from the Chatham, MA tide gage (NOAA, 2017).

Figure 7 illustrates continuous water level elevations measured from April 17 to April 21, 2017 at VLZ-4d and VLZ-6d in the lower sand unit. Also included in this figure are tidal elevations from the Chatham, MA tide gage (NOAA, 2017). Over this measurement period there was approximately 0.15 feet of variation due to tidal influence at VLZ-4d and VLZ-6d compared to a tidal range of over 5.2 feet measured in Chatham.

In summary, there appears to be little variation in water levels (on the order of 0.01 feet) in the upper sand unit due to tidal fluctuations. In contrast the tidal influence on water levels in the confined lower sand is significantly greater with as much as 0.15 feet of variation over the 12.5-hour tidal cycle.

Because estimating the mass flux of nitrate-N at the site is an important aspect of this study, gradient variations that could impact flux were evaluated in the lower sand due to the obvious influence of tidal change on this confined aquifer. Although the water level changes appear to be synchronous there was difference in the amplitude of change between the upgradient well VLZ-6d and the lower well VLZ-4d. The variation in the horizontal hydraulic gradient due to tidal change in the lower sand unit is illustrated in Figure 8. VLZ-6d and VLZ-4d do not fall exactly along a groundwater flow line but the gradient between the two wells can be estimated by subtracting the difference in elevation between the wells then dividing by the projected distance between the wells along a flow line. This results in a modest variation in horizontal hydraulic gradient between 0.0025 and 0.0029 over four tide cycles in sync with tidal variation.

Figure 6b - Groundwater Levels at Well VL- 5, December 2016



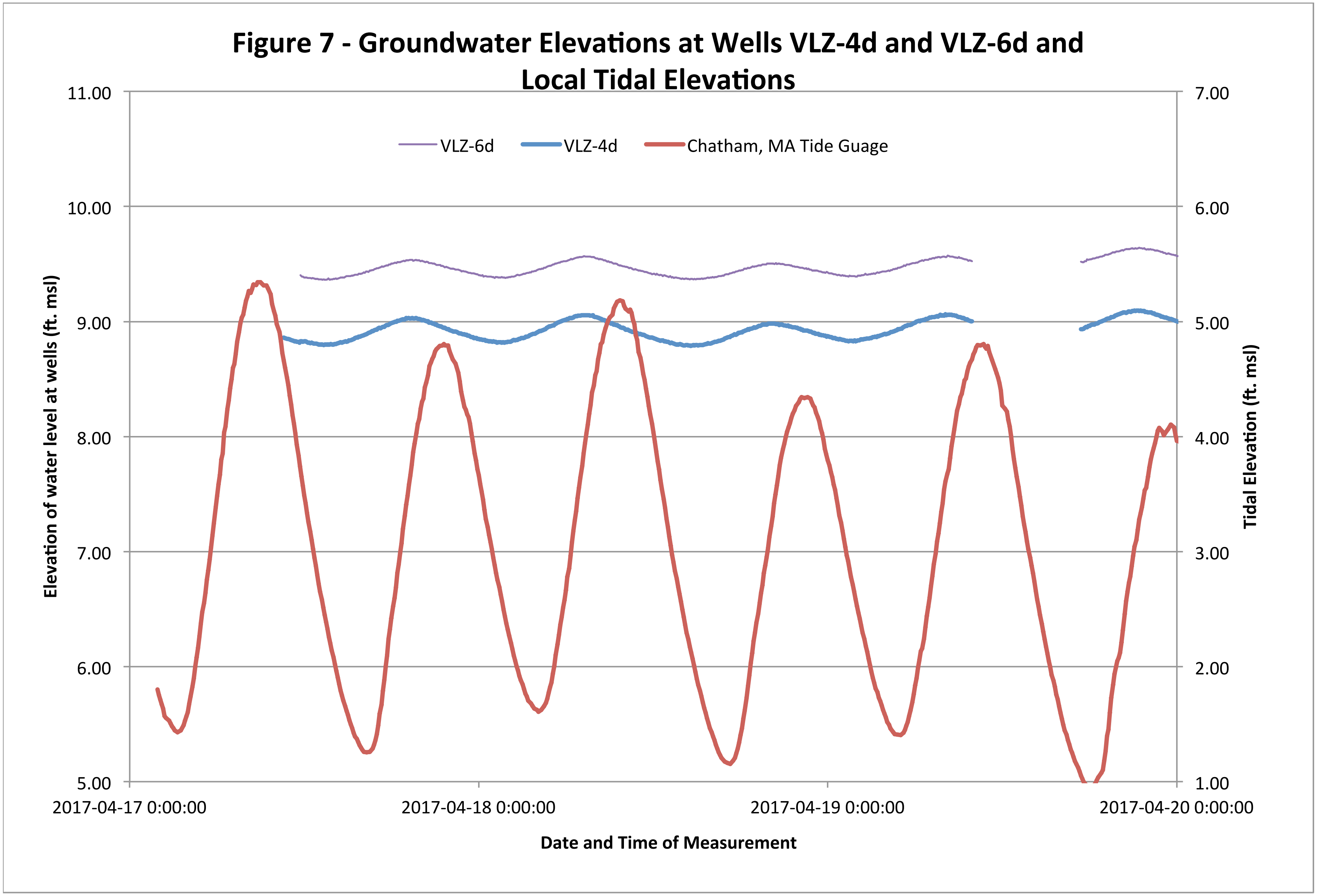


Figure 7 - Groundwater Elevations at Wells VLZ-4d and VLZ-6d and Local Tidal Elevations

Vertical Hydraulic Gradients

Vertical gradients (Table 4b) were measured only at VL-2 during the ISC, as that was the only location where a cluster of progressively deeper wells had been installed (VLZ-44 to VLZ-66). These ISC measurement documented upward gradients between adjacent piezometers in the upper sand and a strongly upward gradient between piezometers immediately above and below the upper clay layer.

With the installation of additional wells, similar vertical flow characteristics were documented. Upward gradients were documented in the upper sand. The greatest upward gradients are in wells completed along Vinland Drive approximately 200 to 300 feet from the shoreline of Kelley's Bay. At well pairs or clusters 500 to 700 feet from the shoreline—VL-8, VL-6, and VL-9—upward gradients are more moderate.

Summary of Water Levels and Groundwater Flow

Groundwater flows to the southwest towards Kelley's Bay in both the upper and lower sand units. The horizontal gradient is over two times greater in the upper sand than in the lower sand unit. Vertical gradients are upward from the lower to the upper sand with the largest gradient observed in the well clusters closest to the bay.

The data collected during this round confirm that the lower sand unit is confined based on the observed vertical gradients between the lower and upper sand, the stronger tidal influence on the lower sand, and by the confirmed presence of the upper clay layer at all site wells. The thickness of the upper clay layer varies from 3 to 10.6 feet. This is contrary to the conclusions of the ISC that inferred that the clay layer was locally discontinuous.

Hydraulic Conductivity Estimates

The hydraulic conductivity of the upper and lower sand was estimated by evaluating both grain size and slug test data.

Hydraulic Conductivity from Grain Size Distributions

Both the Kozeny-Carmen and Alyamani & Sen solutions were used to estimate hydraulic conductivity from the grain size data generated by sieve analyses. The laboratory reports are contained in Appendix B. Since samples with unique characteristics from discrete depths were selected for sieve analyses, the estimated hydraulic conductivity values are likely representative of small intervals of the hydrogeologic units tested. For instance at VL-2, a zone visually described as a fine to coarse sand as well as a sample visually described as a coarse grained sand and fine gravel were both selected for grain size analysis to represent the range of sediment properties and hydraulic conductivity at a given horizontal location. Table 5 provides a summary of the analyses completed and the sediment grain size fraction values used in the analysis.

The Kozeny-Carmen equation is suitable for a wide variety of soil conditions except for clayey soils or those with an effective grain size above 3 mm (Odong, 2007).

$$K = \rho \frac{g}{\nu}\left[\frac{n^3}{(1-n)^2}\right]\frac{{d_{10}}^2}{180} \tag{1}$$

where K = hydraulic conductivity (m/s)
ρ=density of water at 10°C (10^6 g/m^3)
g=acceleration due to gravity (9.8 m/s^2)
ν=dynamic viscosity of water at 10°C (1.307 m^2/s)
n = porosity of sediment sample (dimensionless), 0.30 was assumed for all locations
d_{10}=effective grain size where 10% of grains are finer and 90% are coarser (m)

The calculation spreadsheet for this formula is included in Appendix B.

The Alyamani & Sen formula was also used to estimate K. This method is appropriate for sediments with a uniformity coefficient of 20 or less. The uniformity coefficient is the ratio of the d_{60} and d_{10} effective grain size for a given sample (Odong, 2007). All samples analyzed are below this suggested ratio limit, but VL-2 (45.4'-46.3' depth) is very close at 19.8.

$$\mathrm{K} = 1300[\mathrm{i} + 0.025(\mathrm{d}_{50} - \mathrm{d}_{10})]^2 \tag{2}$$

where K = hydraulic conductivity (m/day)

i = intercept on grain size axis from line between d_{50} and d_{10}

d_{10}=effective grain size where 10% of grains are finer and 90% are coarser (m)

d_{50}=effective grain size where 50% of grains are finer and 50% are coarser (m)

The graphically derived intercept estimates are included in Appendix B along with the calculation spreadsheet.

Table 5 summarizes the results of the grain-size-derived hydraulic conductivity values. Values are highly variable within the core sample location and between locations. The Kozeny-Carmen approach yields the lower values of K. The K values derived at each location with the two methods were averaged for each sample and then averaged again for the hydrogeologic unit (upper sand and lower sand) at that location. K values were highest at VL-2 and VL-6, with averages of 186 and 327 ft./day in the upper and lower sand units respectively. Lower K values were estimated at VL-4 and VL-7, with averages of 6 and 127 ft./day in the upper and lower sand units respectively.

Slug Test Analyses

Slug test analyses were completed using the USGS Bouwer & Rice spreadsheet program (Halford & Kuniansky, 2002). Several slug tests were completed at each well. For all water table wells where the screen was not completely entirely within the saturated zone, only rising head tests were analyzed. For wells where screens were completely entirely within the saturated zone, falling head tests were generally chosen for analysis. Consistent with the permeable sand sediments, most of the wells recovered very quickly after slug addition or removal. Because the two-inch PVC wells were completed within 2½- inch boreholes, gravel pack effects should be minimal. Tests attempted at VL-2d, completed with a 10-foot screen within the lower sand, were not successful as the water levels recovered too quickly to analyze.

Table 5 - Results of Hydraulic Conductivity Calculations from Sieve Analyses
Vinland Drive, Dennis MA

Well location	Depth (ft)	d10 (mm)	d50 (mm)	Kozeny-Carmen Solution (ft/day)	Alyamani & Sen Solution (ft/day)	Averaged Hydraulic Conductivity (ft/day)	Hydrogeologic Unit	Average Hydraulic Conductivity for hydrogeologic unit tested (ft/day)
VL-2	45.5-46.3	0.76	9.89	375	864	620	upper sand	328
VL-2	46.3-47	0.12	0.24	9.5	61.4	35.5	upper sand	
VL-2	51.25-52.8	0.26	0.67	43.6	206	125	lower sand	213
VL-2	55-56.2	0.34	0.93	73.7	288	181	lower sand	
VL-2	56.2-57.5	0.25	0.38	41.8	246	144	lower sand	
VL-2	60-62	0.44	0.67	123	682	403	lower sand	
VL-4	41-45	0.08	0.33	3.7	10.7	7.2	upper sand	7.2
VLZ-4	50.4-52.5	0.31	0.68	62.8	267	165	lower sand	127
VLZ-4	60-63.4	0.20	0.34	24.9	154	89.4	lower sand	
VLZ-7	40-41.5	0.08	0.33	4.6	7.52	6.0	upper sand	6.0
VLZ-7	52.1-53.4	0.15	0.24	15.4	123	69.3	lower sand	42.9
VL-7	55-58.2	0.15	0.25	13.9	95.9	54.9	lower sand	
VL-7	60-61.3	0.07	0.10	2.7	6.16	4.5	lower sand	
VL-6	40-42.8	0.21	0.49	29.1	138	83.6	upper sand	187
VLZ-6	45-46.7	0.42	1.31	116	464	290	upper sand	
VLZ-6	55.6-57.4	0.30	0.62	58.2	334	196	lower sand	302
VLZ-6	60-62.5	0.25	0.51	41.3	226	133	lower sand	
VLZ-6	65-65.55	0.51	1.05	168	982	575	lower sand	
VL-9	30-37.6	0.20	0.53	26.9	109	68.0	upper sand	68.0

The results of these analyses are included in Appendix C. Tests were performed at the VL-2, VL-3, VL-4, and VL-6 water table wells and at the VL-4 and VL-6 well clusters. Results are summarized in Table 6. At VL-2, screened over much of the upper sand, the resulting K was 110 ft./day. Data collected during the VL-2d test did not yield results that could be analyzed due to quick water level recovery although the analysis showed that the hydraulic conductivity value was at least 370 ft./day. At VL-3, also a water table well screened in the upper sand, the K value was found to be 140 ft./day. At VL-4, hydraulic conductivity values were lower in the upper sand at 52 ft./day than at other locations. In the lower sand at VL-4, values of 23 to 110 ft./day were documented. Tests at VL-6, VLZ-6a, and VLZ-6b, all screened in the upper sand, resulted in K values of 32 to 370 ft./day. At VLZ-6c and -6d, K values were 120 and 300 ft./day respectively. These values are somewhat lower than those reported by LeBlanc et al. (1986)—200 to 300 ft./day—although those values were determined at public water-supply wells and are likely biased high.

Although computed hydraulic conductivity values varied widely between wells and screened intervals, the overall pattern suggests that the hydraulic conductivity of sediment is highest in the central portion of the Vinland Drive site (near VL-2 and VL-6) but is lower to the north near VL-4 and VL-7 due to the presence of finer grained sediments and fewer coarse-grained sand zones.

Summary of Hydraulic Conductivity Estimation

The purpose of the hydraulic conductivity analyses was to refine the mass flux estimates made during the ISC, for which hydraulic conductivity was assumed to be 300 ft. per day uniformly. The hydraulic conductivity values derived from the slug test analyses were averaged to result in the values listed in Table 6b. The estimated average concentration for the upper sand is 50 ft./day and for the lower sand is 70 ft./day in the vicinity of VL-4 and VL-7 and 150 and 260 ft./day respectively in the vicinity of VL-2 and VL-6.

Table 6a - Calculation of Hydraulic Conductivity from Slug Tests Vinland Drive, Dennis MA

Well location	Hydrogeologic Unit	Screened interval (ft bgs)	Slug Test K (ft/day)
VL-2	upper sand	41-46	110
VL-2d	lower sand	52-62	> 370*
VL-3	upper sand	39-44	140
VL-4	upper sand	38-43	52
VLZ-4b	lower sand	51-52	23
VLZ-4c	lower sand	57-58	110
VL-6	upper sand	35-40	32
VLZ-6a	upper sand	40-41	86
VLZ-6b	upper sand	46-47	370
VLZ-6c	lower sand	57-58	120
VLZ-6d	lower sand	63-64	300

* Estimate - well recovered too quickly to evaluate test

Table 6b - Summary of Average Hydraulic Conductivity from Slug Test Analyses - Upper and Lower Sand Units

Vinland Drive, Dennis MA

Hydraulic Conductivity (ft./day)	**Vinland Drive Area**
50	upper sand VL-4 to VL-7 area
70	lower sand VL-4 to VL-7 area
150	upper sand VL-2 to VL-6 area
260	lower sand VL-2 to VL-6 area

Groundwater Velocity Estimates

Using the lithologic characterization and hydraulic gradients developed from the field data for the Vinland Drive site, we used Darcy's Law to estimate groundwater velocity:

$$V = (K\ i_x)/n \tag{3}$$

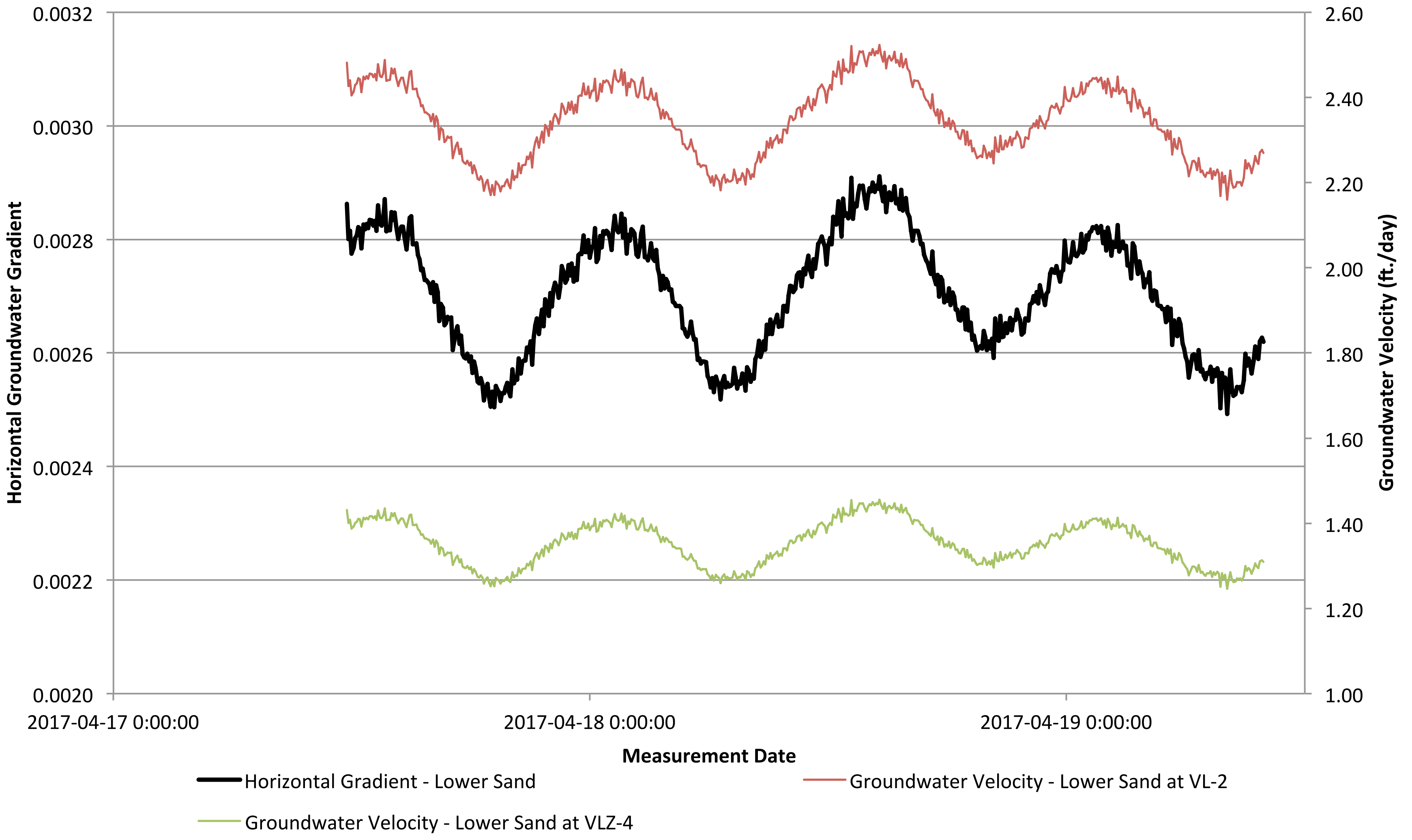
where:

V is the groundwater velocity (ft./day);
K is the hydraulic conductivity (ft./day) from recent tests;
i_x is the horizontal hydraulic gradient (ft./ft.); and
n is the porosity (dimensionless), assumed to be 0.3.

The horizontal hydraulic gradient in the upper sand unit estimated from the May 2017 field data is 0.010 ft./ft., The estimated hydraulic conductivity values for the water table wells in the VL-4 and VL-2 areas is 50 and 150 ft./day respectively. This results in an estimated velocity range of 1.7 feet per day to 5.0 feet per day. This contrasts with the ISC value of 9 ft./day based on the greater estimated hydraulic conductivity and the greater horizontal gradient of 0.012 measured in spring 2016.

In the lower sand unit, the velocity of flow was estimated using the hydraulic gradient of 0.004 measured in May 2017. Using the estimated lower sand hydraulic conductivity for VL-4 and VL-2, the velocity range is estimated at 2.0 to 3.5 ft./day. An evaluation of the change in groundwater velocity due to changing hydraulic gradient due to tidal fluctuation is shown in Figure 8. The velocity change between 2.2 and 2.5 feet per day for wells completed in the higher conductivity areas such as VL-2. Using the somewhat lower hydraulic conductivity at VLZ-4, the velocity varies between 1.3 and 1.4 feet per day.

Figure 8 - Horizontal Groundwater Gradient and Velocity Variation Due to Tidal Influence - Lower Sand Unit



Water Quality Data Evaluation

Water Table Wells

Table 7 lists the field-measured and laboratory-analyzed constituents for the Winter 2016-2017 sampling at existing and new water table wells and the previous two rounds of sampling in April and May 2016. Dissolved oxygen (DO) and nitrate-N are highlighted in blue and green respectively for ease of table review.

Field-measured pH at water table wells ranged from 4.6 to 5.3. Field-measured specific conductance (SC) was measured between 127 and 406 μS/cm with the highest readings at VL-3 and VL-8. Field-measured DO was generally high, varying between 7.6 and 9.6 mg/L.

Figure 9 shows the concentrations of selected constituents at water table wells. Nitrate-N was highest at VL-4 and VL-8, at 7.0 and 7.5 mg-N/L respectively, with lower nitrate-N levels, 1.7 to 4.2 mg-N/L, at other water table wells. These concentrations are higher overall than those observed in spring 2016. All nitrate-N levels are sufficiently elevated to be indicative of the presence of wastewater.

DOC concentrations were at or below 1 mg/L in all wells as in 2016. Total Kjeldahl Nitrogen or TKN (the sum of organic nitrogen and ammonia nitrogen) was the highest at VL-5 and VL-7 at 1.7 and 3.8 mg-N/L respectively and below detection limits at most other wells. Ammonia-N was not analyzed in this round since values were generally very low in spring 2016, so these elevated TKN values suggest that either ammonia-N or organic N is higher at these wells.

Concentrations of dissolved iron were generally low, less than 1 mg/L. Sulfate concentrations were between 10 and 16 mg/L at all wells with the highest concentration at VL-8. Chloride in VL-3 and VL-8, with concentrations of 71 and 85 mg/L respectively, was elevated compared to other wells, consistent with the field-measured SC values.

Piezometer and Well Clusters

Differences in constituent concentrations with depth at the piezometer cluster location at VL-2 and the well clusters at VL-4, VL-6, and VL-7 are illustrated in Figures 10 through 12. A line representing the top of the upper clay layer is included in each graph. Table 8 includes the laboratory analyses at the VL-2 piezometer cluster and Table 9 lists the results for the recently installed well

Table 7- Water Quality at Water Table Wells Permeable Reactive Barrier Full Hydrogeologic Assessment - Vinland Drive, Dennis, MA

Sample ID/Location	**VL-1**						**VL-2**						**VL-3**					
Sampling Date	4/1/16		5/6/16		1/19/17		3/31/16		5/6/16		1/19/17		4/1/16		5/6/16		1/12/17	
Field Measurements																		
pH (SU)	4.6		5.4		4.8		4.8		5.0		4.8		4.5		5.2		4.6	
Temperature (°C)	12.3		15.1		11.8		11.9		12.9		11.8		12.3		12.2		12.3	
Dissolved Oxygen (DO; mg/L)	8.7		9.4		9.3		29.4	R	9.3		8.0		9.1		10.0		9.5	
Specific Conductance (uS/cm)	218		200		127		277		286		146		280		323		320	
Redox Potential (ORP; mV)	308		347		216		256		312		218		259		345		281	
Laboratory Analyses																		
pH (SU)	4.4		4.3		NM		5.0		4.5		NM		4.6		4.4		NM	
Nitrate as N (mg/L)	2.2		2.6		1.8		4.4		4.5		4.2		5.8		7.1		4.2	
δ^{15}N-NO$_3$ ($^0/_{00}$)	NM		NM		NM		NM		NM		NM		NM		NM		5.53	
Nitrite as N (mg/L)	<0.01		<0.01		<0.019		<0.01		<0.01		<0.019		<0.01		<0.01		<0.019	
Ammonia as N (mg/L)	<0.028		0.037	J	NM		<0.028		<0.028		NM		0.032	JE	<0.028		NM	
Total Kjeldahl Nitrogen (TKN) (mg/L)	0.308		0.083	J	<0.066		0.392		0.3	U	<0.066		0.351	JE	<0.132	E	0.072	J
Total Nitrogen (mg/L)	2.5		2.6		1.8		4.8		4.5		4.2		5.8		7.1		4.2	
Orthophosphate (mg/L)	0.007		0.008		NM		0.005		0.008		NM		0.011	E	0.007		NM	
Total Alkalinity (mg/L CaCO3)	2.20		2.2		2.2		3.50		2.9		2.7		2.90		2.5		ND	
Chloride (mg/L)	41.4		34.3		32.6		72.2		40.9		37.6		56.0		42.8		71.2	
Sulfate (mg/L)	14.1		10.2		12.9		11.1		10.6		9.46		13.6		11.8		11.2	
Dissolved Iron (mg/L)	0.39		0.042	J	<0.01		1.3		<0.02		<0.01		6.0	E	<0.02		0.03	J
Dissolved Manganese (mg/L)	0.0277		0.0263		0.016		0.0717		0.0429		0.036		0.0871	E	0.0449		0.063	
Dissolved Boron (mg/L)	0.0188	J	0.0174	J	NM		0.0369		0.0328		NM		0.0343		0.0286		NM	
Dissolved Arsenic (mg/L)	<0.002		<0.002		0.004	J	0.0033	J	<0.002		0.003	J	0.0073	E	<0.002		<0.002	
Dissolved Organic Carbon (mg/L)	0.72	J	1.1		0.73	J	0.95	J	0.79	J	0.7	J	1.0	J	0.97	J	0.85	J

Notes:

J - Data indicates a presence of a compound that meets the identification criteria. The result is less than the quantitation limit but greater than zero. The concentration given is an approximate value.
R - Suspected error in field DO measurements
NS - Not Sampled / NM -Not Measured
E - Exceeds RPD of 20% with duplicate sample
Grey cell means data questionable and should not be relied upon

Table 7- Water Quality at Water Table Wells Permeable Reactive Barrier Full Hydrogeologic Assessment - Vinland Drive, Dennis, MA

Sample ID/Location	**VL-4**			**VL-5**			**VL-6**		
Sampling Date	4/1/16	5/6/16	1/19/17	4/1/16	5/6/16	1/13/17	4/1/16	5/6/16	1/19/17
Field Measurements									
pH (SU)	4.4	5.5	5.2	4.7	6.0	5.0	5.2	6.1	5.2
Temperature (°C)	12.2	13.5	12.2	11.7	12.9	12.3	12.4	14.2	12.2
Dissolved Oxygen (DO; mg/L)	7.1	7.3	9.2	9.8	9.8	9.4	10.0	10.3	9.4
Specific Conductance (uS/cm)	303	278	186	166	90	136	179	131	157
Redox Potential (ORP; mV)	298	336	190	297	290	294	225	285	178
Laboratory Analyses									
pH (SU)	4.6	4.4	NM	5.0	5.0	NM	5.8	4.9	NM
Nitrate as N (mg/L)	6.2	7.4	7	1.9	1.0	1.7	1.2	0.41	3.8
δ^{15}N-NO$_3$ ($^{0}/_{00}$)	NM	NM	NM	NM	NM	NM	NM	NM	NM
Nitrite as N (mg/L)	<0.01	<0.01	<0.019	<0.01	<0.01	<0.019	<0.01	0.014 J	<0.019
Ammonia as N (mg/L)	<0.028	0.047 J	NM	0.035 J	<0.028	NM	0.089	<0.028	NM
Total Kjeldahl Nitrogen (TKN) (mg/L)	2.41	0.164 J	<0.066	0.384	0.098 J	1.7	4.36	0.169 J	<0.066
Total Nitrogen (mg/L)	8.6	7.4	7	2.3	1	0.19 J	5.6	0.41	3.8
Orthophosphate (mg/L)	0.006	0.007	NM	0.006	0.009	NM	0.005	0.007	NM
Total Alkalinity (mg/L CaCO3)	3.60	2.4	2.1 E	4.10	5.9	3.3	12.30	4.8	3.8
Chloride (mg/L)	56.6	43	44.8	29.6	15.5	24.5	32.3	20.1	41.1
Sulfate (mg/L)	11.9	11.7	8.2	10.6	4.49	10.3	15.6	13.6	10
Dissolved Iron (mg/L)	1.7	<0.02	<0.01	0.12	0.023 J	<0.009	0.15	<0.02	<0.01
Dissolved Manganese (mg/L)	0.0637	0.0497	0.063	0.0204	0.013	0.0221	0.0321	0.0157	0.035
Dissolved Boron (mg/L)	0.0237 J	0.018 J	NM	0.0198 J	0.0112 J	NM	0.0134 J	0.0101 J	NM
Dissolved Arsenic (mg/L)	0.0033 J	<0.002	0.003 J,E	<0.002	<0.002	<0.0019	<0.002	<0.002	0.0049 J
Dissolved Organic Carbon (mg/L)	0.86 J	0.84 J	0.69 J	0.89 J	1.2	0.63 J	0.79 J	1.1	0.71 J

Notes:

J - Data indicates a presence of a compound that meets the identification criteria. The result is less than the quantitation limit but greater than zero. The concentration given is an approximate value.
R - Suspected error in field DO measurements
NS - Not Sampled / NM -Not Measured
E - Exceeds RPD of 20% with duplicate sample
Grey cell means data questionable and should not be relied upon

Table 7- Water Quality at Water Table Wells Permeable Reactive Barrier Full Hydrogeologic Assessment - Vinland Drive, Dennis, MA

Sample ID/Location	**VL-7**		**VL-8**		**VL-9**	
Sampling Date	1/13/17		1/13/17		1/13/17	
Field Measurements						
pH (SU)	5.0		4.9		5.3	
Temperature (°C)	11.9		11.9		11.6	
Dissolved Oxygen (DO; mg/L)	9.6		8.4		7.6	
Specific Conductance (uS/cm)	204		406		197	
Redox Potential (ORP; mV)	259		279		307	
Laboratory Analyses						
pH (SU)	NM		NM		NM	
Nitrate as N (mg/L)	2.4		7.5		2.8	
δ^{15}N-NO$_3$ ($^0/_{00}$)	NM		NM		NM	
Nitrite as N (mg/L)	<0.019		<0.019		<0.019	
Ammonia as N (mg/L)	NM		NM		NM	
Total Kjeldahl Nitrogen (TKN) (mg/L)	0.654		3.8		0.189	J
Total Nitrogen (mg/L)	3		11		2.8	
Orthophosphate (mg/L)	NM		NM		NM	
Total Alkalinity (mg/L CaCO3)	3.3		3.1		6	
Chloride (mg/L)	41.6		85.3		41.9	
Sulfate (mg/L)	10.9		16		5.82	
Dissolved Iron (mg/L)	0.036	J	0.26		0.24	
Dissolved Manganese (mg/L)	0.0289		0.0478		0.0206	
Dissolved Boron (mg/L)	NM		NM		NM	
Dissolved Arsenic (mg/L)	<0.0019		<0.0019		<0.0019	
Dissolved Organic Carbon (mg/L)	0.63	J	0.98	J	0.69	J

Notes:

J - Data indicates a presence of a compound that meets the identification criteria. The result is less than the quantitation limit but greater than zero. The concentration given is an approximate value.
R - Suspected error in field DO measurements
NS - Not Sampled / NM -Not Measured
E - Exceeds RPD of 20% with duplicate sample
Grey cell means data questionable and should not be relied upon

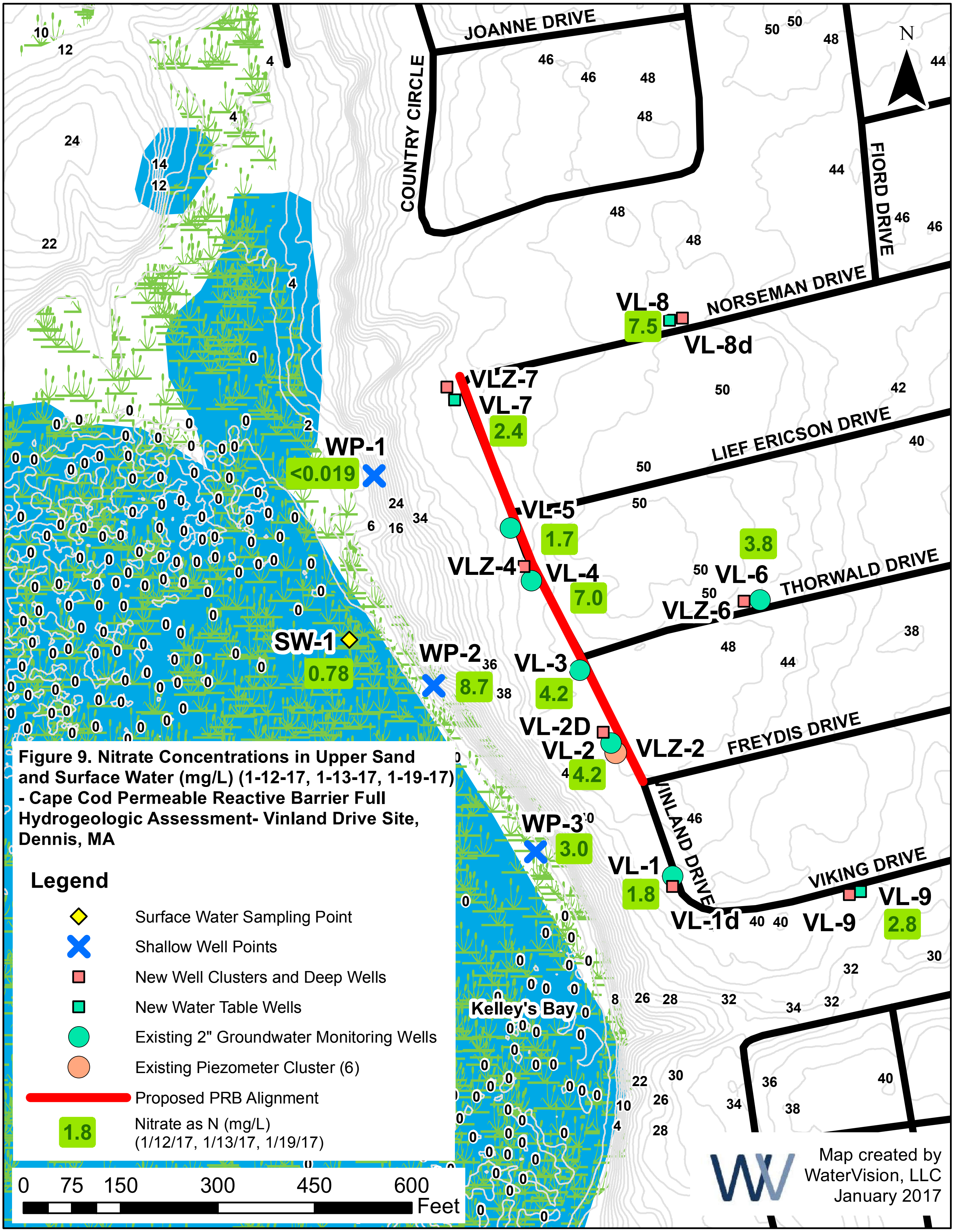


Figure 9. Nitrate Concentrations in Upper Sand and Surface Water (mg/L) (1-12-17, 1-13-17, 1-19-17) - Cape Cod Permeable Reactive Barrier Full Hydrogeologic Assessment- Vinland Drive Site, Dennis, MA

Sources: Surface Water Sampling Points, Shallow Well Sampling Points, Existing and New Groundwater Monitoring Well Locations, Existing Piezometer Locations, New Well Cluster Locations, and Nitrogen Concentrations from WaterVision LLC. Roads and Kelley's Bay from Mass GIS, Contours from Cape Cod Commission, and Wetlands from the National Wetlands Inventory (NWI).

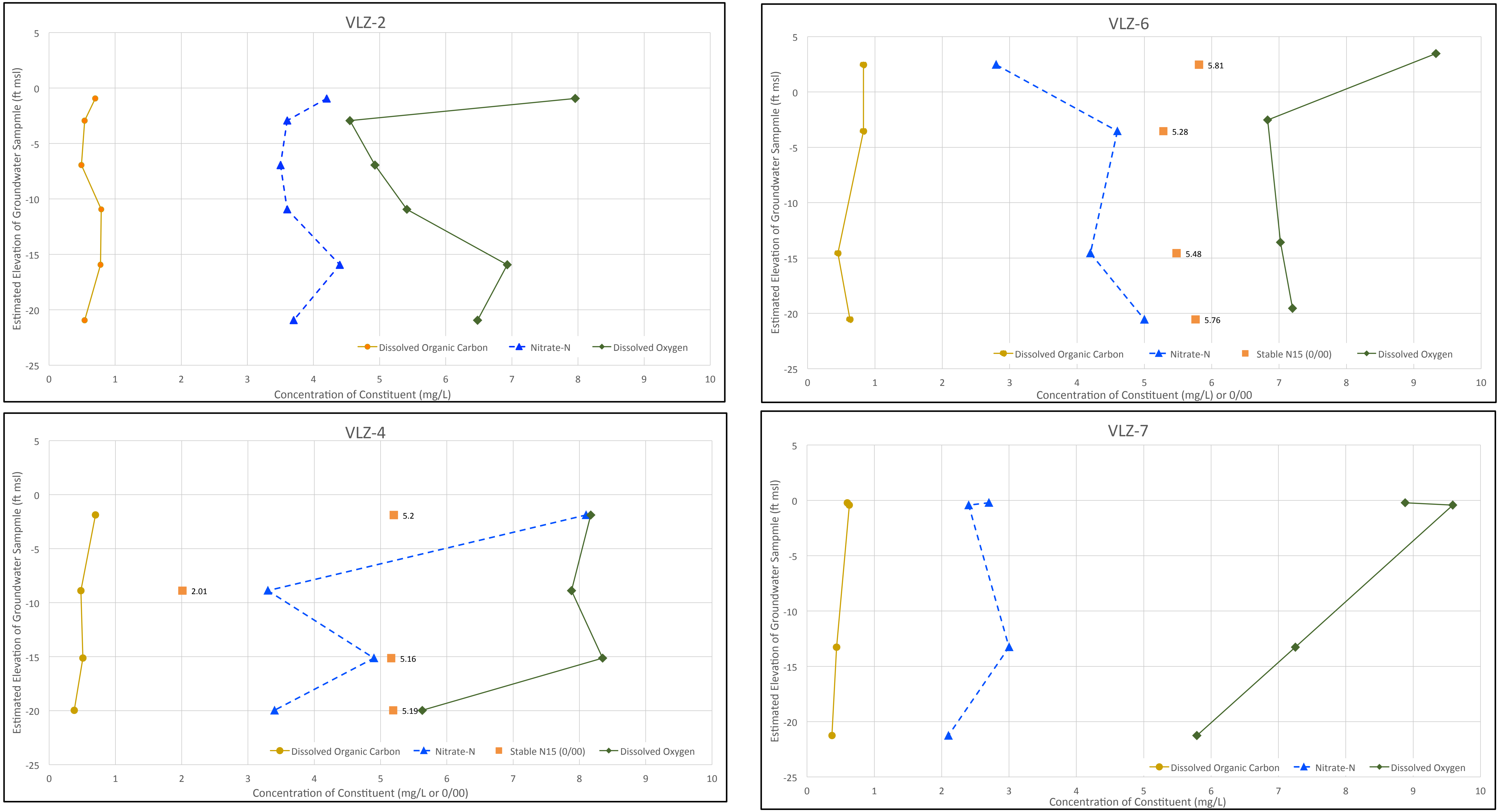


Figure 10 - Variation of Nitrate-N, Dissolved Oxygen, Dissolved Organic Carbon, and Stable Nitrogen Isotope Ratios
Vinland Drive, Dennis, MA, Dec 2016 to Jan 2017

Figure 11 – Variation of Nitrate-N, Total Alkalinity, Chloride, and Sulfate
Vinland Drive, Dennis, MA, Dec 2016 to Jan 2017

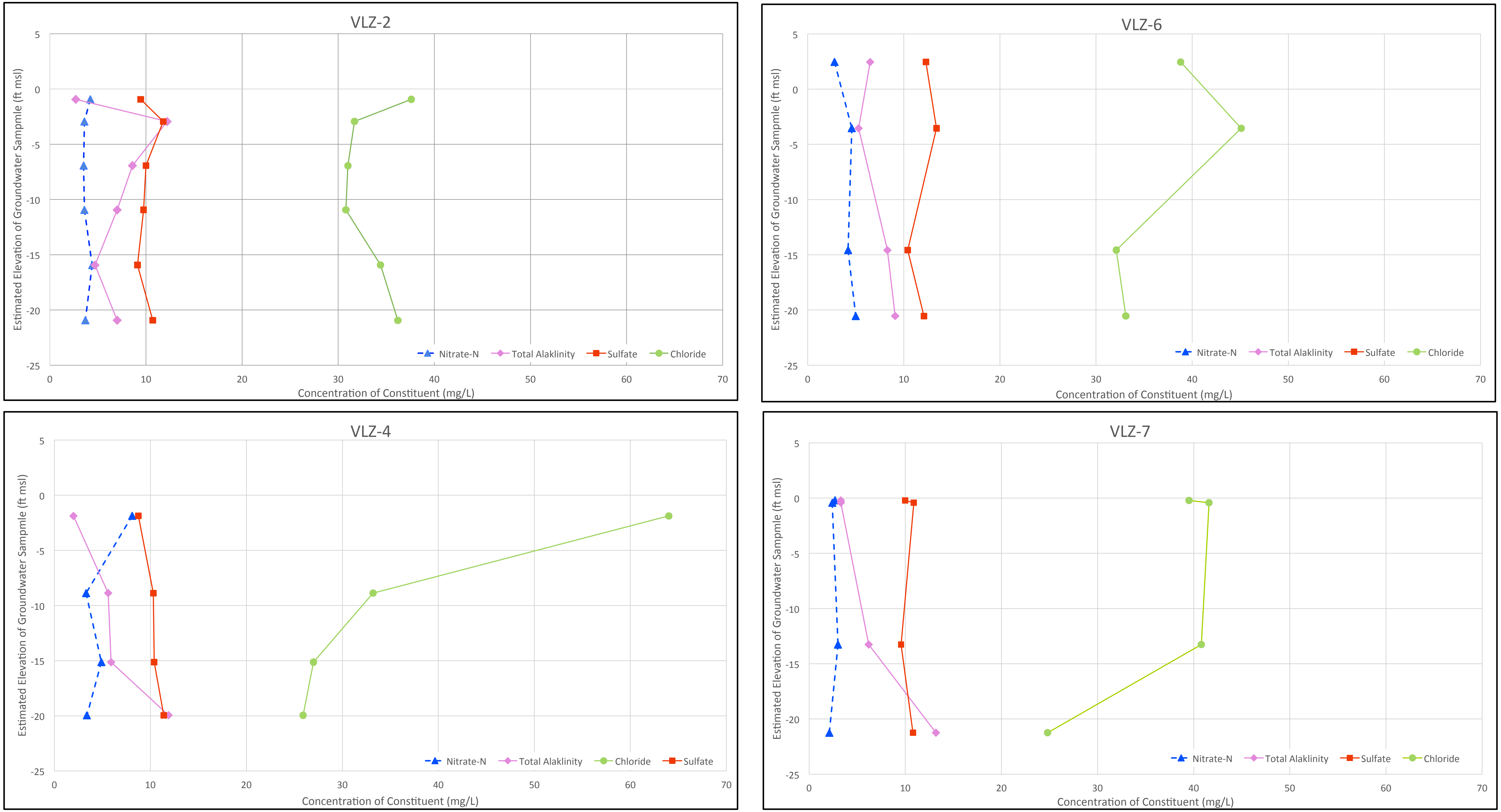


Figure 12 -Variation of Nitrate-N, Dissolved Iron, Dissolved Manganese, and Dissolved Arsenic
Vinland Drive, Dennis, MA, Dec 2016 to Jan 2017

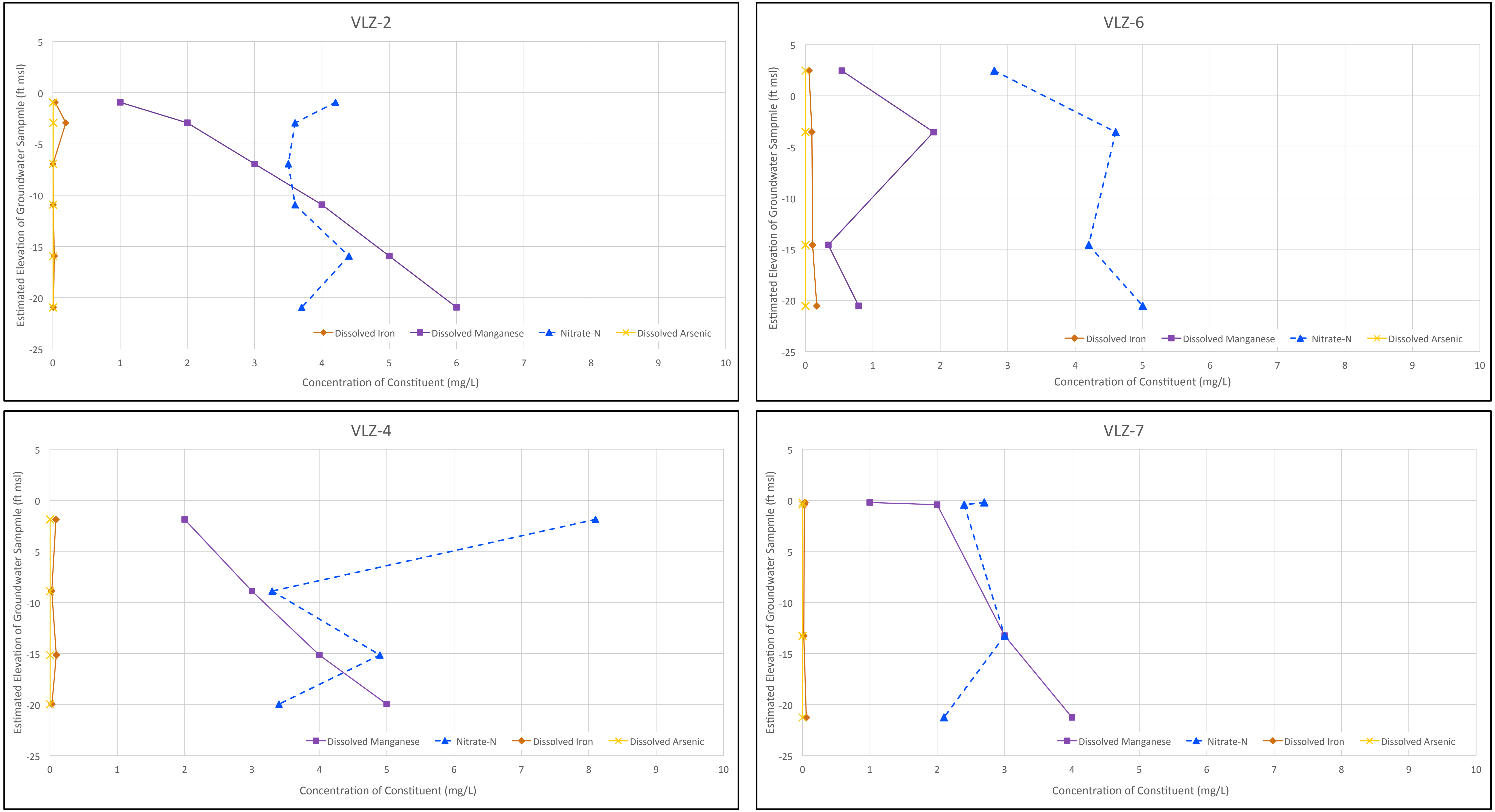


Table 8 - Water Quality at One-Inch Piezometers
Permeable Reactive Barrier Full Hydrogeologic Assessment - Vinland Drive, Dennis, MA

Sample ID/Location	**VLZ-44**						**VLZ-48**						**VLZ-52**					
Screen bottom elevation (ft msl)	**3.3**						**-0.8**						**-4.8**					
Sampling Date	4/1/16		5/6/2016*		1/19/2017*		4/1/16		5/6/16		1/19/17		4/1/16		5/6/16		1/19/17	
Field Measurements																		
pH (SU)	4.7		5.0		NS		5.8		5.7		5.7		5.7		5.3		5.6	
Temperature (°C)	11.7		12.9		NS		11.6		11.8		11.7		12.3		11.87		11.3	
Dissolved Oxygen (DO; mg/L)	7.1		9.3		NS		4.2		4.1		4.6		6.3		4.7		4.9	
Specific Conductance (uS/cm)	381		286		NS		235		219		196		206		185		180	
Redox Potential (ORP; mV)	301		312		NS		127		100		271		220		137		304	
Laboratory Analyses																		
pH (SU)	4.8		NS		NS		5.9		5.5		NM		5.8		5.3		NM	
Nitrate as N (mg/L)	4.3		NS		NS		2.4		2.5		3.6		4.0		3.9		3.5	
Nitrite as N (mg/L)	<0.010		NS		NS		<0.010		<0.010		<0.019		<0.010		<0.010		<0.019	
Ammonia as N (mg/L)	<0.028		NS		NS		0.029	J	0.036	J	NM		0.031	J	<0.028		NM	
Total Kjeldahl Nitrogen (TKN) (mg/L)	<0.066		NS		NS		<0.066		0.35		0.23	J	1.09		0.66		<0.066	
Total Nitrogen (mg/L)	4.3		NS		NS		2.4		2.8		3.6		5.1		3.9		3.5	
Orthophosphate (mg/L)	0.005		NS		NS		0.006		0.006		NM		0.02		0.019		NM	
Total Alkalinity (mg/L CaCO3)	2.50		NS		NS		14.4		14.2		12.2		10.0		9		8.6	
Chloride (mg/L)	88.9		NS		NS		34.3		36.2		31.7		31.5		30.1		31	
Sulfate (mg/L)	11.6		NS		NS		18.1		16.3		11.8		11.3		10.7		10	
Dissolved Iron (mg/L)	0.19		NS		NS		0.93		0.51		0.027	J	3.6		0.9		<0.0090	
Dissolved Manganese (mg/L)	0.0636		NS		NS		0.466		0.419		0.194		0.108		0.104		0.0027	J
Dissolved Boron (mg/L)	0.0415		NS		NS		0.0250	J	0.0202	J	NM		0.0306		0.0271	J	NM	
Dissolved Arsenic (mg/L)	0.0031	J	NS		NS		<0.0020		<0.0020		0.0052		0.0052		0.0027	J	0.0028	J
Dissolved Organic Carbon (mg/L)	0.72	J	NS		NS		0.57	J	0.57	J	0.54		0.68	J	0.69	J	0.49	J

Notes:

J - Data indicates a presence of a compound thatmeets the identification criteria.The result is less than the quantitation limit but greater than zero. The concentration given is an approximate value.

R - Suspected error in field pH and ORP measurements

NS - Not Sampled / NM -Not Measured

E - Exceeds RPD of 20% with duplicate sample

*NS - low water level did not permit collection of a groundwater sample

Grey cell means data questionable and should not be relied upon

Table 8 - Water Quality at One-Inch Piezometers Permeable Reactive Barrier Full Hydrogeologic Assessment - Vinland Drive, Dennis, MA

Sample ID/Location	**VLZ-56**						**VLZ-61**						**VLZ-66**					
Screen bottom elevation (ft msl)	**-8.8**						**-13.8**						**-18.7**					
Sampling Date	4/1/16		5/6/16		1/19/17		3/31/16		5/6/16		1/19/17		3/31/16		5/6/16		1/19/17	
Field Measurements																		
pH (SU)	5.4		5.2		5.3		4.9		5.0		5.1		5.4		5.4		5.4	
Temperature (°C)	12.1		11.6		11.7		10.6		11.6		11.4		11.3		11.1		11.1	
Dissolved Oxygen (DO; mg/L)	6.5		6.2		5.4		7.2		6.5		6.9		6.5		7.1		6.5	
Specific Conductance (uS/cm)	212		188		177		169		179		192		189		197		200	
Redox Potential (ORP; mV)	212		152		299		212		142		292		234		94		266	
Laboratory Analyses																		
pH (SU)	5.4		5.2		NM		5.4		5.1		NM		5.5		5.3		NM	
Nitrate as N (mg/L)	4.2		3.9		3.6		2.8		3.2		4.4		3.2		3.2		3.7	
Nitrite as N (mg/L)	<0.010		<0.010		<0.019		<0.010		<0.010		<0.019		<0.010		<0.010		<0.019	
Ammonia as N (mg/L)	<0.028		<0.028		NM		<0.028	E	<0.028		NM		0.030	J	0.031	J	NM	
Total Kjeldahl Nitrogen (TKN) (mg/L)	<0.066		0.288	J	<0.066		<0.066	E	0.203	J	<0.066		<0.066		0.074	J	<0.066	
Total Nitrogen (mg/L)	4.2		3.9		3.6		2.8		3.2		4.4		3.2		3.2		3.7	
Orthophosphate (mg/L)	0.008		0.009		NM		0.004	JE	0.012		NM		0.008		0.013		NM	
Total Alkalinity (mg/L CaCO3)	6.70		6.8		7		5.40		4.7		4.7		7.20		8.4		7	
Chloride (mg/L)	33.3		31.9		30.8		31.9		32.2		34.4		36.8		33.8		36.2	
Sulfate (mg/L)	10.8		10.3		9.76		12.0		9.42		9.11		12.6		11.8		10.7	
Dissolved Iron (mg/L)	0.038	J	0.69		0.01	J	0.13	E	0.022	J	<0.0090		0.14		0.67		<0.0090	
Dissolved Manganese (mg/L)	0.0105		0.0263		0.0059	J	0.0275		0.0209		0.0220		0.0141		0.0464		0.0080	J
Dissolved Boron (mg/L)	0.0329		0.029	J	NM		0.0325		0.0283	J	NM		0.0366		0.0306		NM	
Dissolved Arsenic (mg/L)	0.0025	J	<0.0020		0.0028	J	0.0024	J	<0.0020		0.0038	J	<0.0020		0.002		0.0025	J
Dissolved Organic Carbon (mg/L)	0.68	J	0.75	J	0.79	J	0.49	JE	0.69	J	0.78	J	0.55	J	0.66	J	0.54	J

Notes:

J - Data indicates a presence of a compound thatmeets the identification criteria.The result is less than the quantitation limit but greater than zero. The concentration given is an approximate value.

R - Suspected error in field pH and ORP measurements

NS - Not Sampled / NM -Not Measured

E - Exceeds RPD of 20% with duplicate sample
*NS - low water level did not permit collection of a groundwater sample
Grey cell means data questionable and should not be relied upon

Table 9 - Water Quality at Two- Inch Well Clusters Permeable Reactive Barrier Full Hydrogeologic Assessment - Vinland Drive, Dennis, MA

Sample ID/Location	**VL-2d**	**VLZ-4a**	**VLZ-4b**	**VLZ-4c**	**VLZ-4d**	**VLZ-6a**	**VLZ-6b**	
Screen bottom elevation (ft msl)	**-14.6**	**0.8**	**-6.2**	**-12.2**	**-17.1**	**5.3**	**-0.7**	
Sampling Date	1/19/17	1/13/17	1/13/17	12/14/16	12/12/16	12/12/16	12/12/16	1/12/17
Field Measurements								
pH (SU)	5.6	4.7	5.4	6.4	5.6	4.7	4.8	4.7
Temperature (°C)	11.5	11.8	11.7	13.2	11.7	12	11.7	11.7
Dissolved Oxygen (DO; mg/L)	8.0	8.2	7.9	8.4	5.6	9.3	6.8	7.9
Specific Conductance (uS/cm)	189	303	183	176	167	195	243	251
Redox Potential (ORP; mV)	279	298	261	155	182	193	180	193
Laboratory Analyses								
pH (SU)	NM	NM	NM	NM	NM	NM	NM	NM
Nitrate as N (mg/L)	4.4	8.1	3.3	4.9	3.4	2.8	4.6	4.6
δ^{15}N-NO$_3$ ($^{0}/_{00}$)	NM	5.2	2.01	5.16	5.19	5.81	5.28	5.34
Nitrite as N (mg/L)	<0.019	<0.094	<0.019	<0.019	<0.019	<0.019	<0.019	<0.019
Ammonia as N (mg/L)	NM	NM	NM	NM	NM	NM	NM	NM
Total Kjeldahl Nitrogen (TKN) (mg/L)	<0.066	0.65	0.3	<0.066	<0.066	2.20 E	<0.066	0.121 J
Total Nitrogen (mg/L)	4.4	8.8	3.6	4.9	3.4	5.0	4.6	4.6
Orthophosphate (mg/L)	NM	NM	NM	NM	NM	NM	NM	NM
Total Alkalinity (mg/L CaCO3)	6.3	2	5.6	5.9	11.9	6.5 E	5.3	ND
Chloride (mg/L)	33.3	64	33.2	27.0	25.9	38.8	45.1	46.9
Sulfate (mg/L)	10.1	8.76	10.3	10.4	11.4	12.3	13.4	13.8
Dissolved Iron (mg/L)	<0.01	0.02 J	<0.0090	0.53	0.10	0.54 E	1.9	0.06
Dissolved Manganese (mg/L)	0.025	0.0906	0.0274	0.0951	0.032	0.054	0.096	0.047
Dissolved Boron (mg/L)	NM	NM	NM	NM	NM	NM	NM	NM
Dissolved Arsenic (mg/L)	<0.002	<0.0019	<0.0019	<0.0019	<0.002	<0.002	<0.002	0.002 J
Dissolved Organic Carbon (mg/L)	0.53 J	0.7 J	0.48 J	0.51 J	0.38 J	0.83 J	0.83 J	0.72 J

Notes:

J - Data indicates a presence of a compound that meets the identification criteria. The result is less than the quantitation limit but greater than zero. The concentration given is an approximate value.

R - Suspected error in field DO measurements

NS - Not Sampled / NM -Not Measured

E - Exceeds RPD of 20% with duplicate sample

Grey cell means data questionable and should not be relied upon

Table 9 - Water Quality at Two- Inch Well Clusters Permeable Reactive Barrier Full Hydrogeologic Assessment - Vinland Drive, Dennis, MA

Sample ID/Location	**VLZ-6c**		**VLZ-6d**		**VLZ-7a**		**VLZ-7b**		**VLZ-7c**		**VLZ-7d**	
Screen bottom elevation (ft msl)	**-11.7**		**-17.7**		**3.0**		**-10.0**		**-14.0**		**-17.9**	
Sampling Date	12/12/16		12/12/16		1/13/17		1/13/17		1/13 & 1/19/2017		1/13/17	
Field Measurements												
pH (SU)	5.1		5.2		5.1		5.7		NS		6.0	
Temperature (°C)	11.9		13.4		11.8		11.5		NS		11.6	
Dissolved Oxygen (DO; mg/L)	7.0		7.2		8.9		7.3		NS		5.8	
Specific Conductance (uS/cm)	189		197		197		206		NS		156	
Redox Potential (ORP; mV)	140		135		245		211		NS		185	
Laboratory Analyses												
pH (SU)	NM		NM		NM		NM		NS		NM	
Nitrate as N (mg/L)	4.2		5.0		2.7		3.0		NS		2.1	
δ^{15}N-NO$_3$ ($^{0}/_{00}$)	5.48		5.76		NM		NM		NS		NM	
Nitrite as N (mg/L)	<0.019		<0.019		<0.019		<0.019		NS		<0.019	
Ammonia as N (mg/L)	NM		NM		NM		NM		NS		NM	
Total Kjeldahl Nitrogen (TKN) (mg/L)	0.073	J	<0.066		0.988		0.23	J	NS		0.932	
Total Nitrogen (mg/L)	4.2		5.0		3.7		3.0		NS		3.0	
Orthophosphate (mg/L)	NM		NM		NM		NM		NS		NM	
Total Alkalinity (mg/L CaCO3)	8.3		9.1		3.3		6.2		NS		13.2	
Chloride (mg/L)	32.1		33.1		39.5		40.8		NS		24.8	
Sulfate (mg/L)	10.4		12.1		10		9.56		NS		10.8	
Dissolved Iron (mg/L)	0.34		0.79		0.052		<0.0090		NS		0.37	
Dissolved Manganese (mg/L)	0.108		0.169		0.0346		0.019		NS		0.0569	
Dissolved Boron (mg/L)	NM		NM		NM		NM		NS		NM	
Dissolved Arsenic (mg/L)	<0.002		<0.002		<0.0019		<0.0019		NS		<0.0019	
Dissolved Organic Carbon (mg/L)	0.45	J	0.63	J	0.6	J	0.44	J	NS		0.37	J

Notes:

J - Data indicates a presence of a compound that meets the identification criteria. The result is less than the quantitation limit but greater than zero. The concentration given is an approximate value.

R - Suspected error in field DO measurements

NS - Not Sampled / NM -Not Measured

E - Exceeds RPD of 20% with duplicate sample

Grey cell means data questionable and should not be relied upon

clusters. The VLZ-44 piezometer was not sampled during the winter 2017 round, as water levels were too low to properly purge and sample the piezometer. Additionally VLZ-7c was not sampled due to the high volume of fine sand and silt in the well.

At the VLZ-2 piezometers, the field-measured pH varies between 5.7 and 5.2 with the highest value in the shallow piezometer. At the new well clusters, pH varied between 4.7 and 6.4 with the lowest values at VLZ-4a and highest at VLZ-4c. SC values were similar at all piezometers (180 to 200 µS/cm). At the well clusters, SC was measured at 160 to 300 µS/cm with the higher values measured in the upper sand.

Figure 10 illustrates the concentrations of nitrate, DOC, and DO versus elevation. Stable nitrogen isotope ratios were analyzed for samples from the VLZ-4 and VLZ-6 clusters and are also shown on the graph, but are discussed in a following section.

Nitrate-N concentrations (the dashed blue lines in Figure 9) are 2.1 to 8.1 mg-N/L depending on depth and location. Although each well cluster has a unique pattern of DO (solid green lines) concentration with depth, the upper sand generally has slightly higher DO concentrations (9.3 to 4.6 mg/L) than the lower sand (8.4 and 5.6 mg/L). DOC concentrations are all below 1 mg/L in both the upper and lower sand units. At VLZ-2 and VLZ-4 the DO and nitrate-N concentrations vary similarly with depth.

Figure 11 illustrates variation in chloride, alkalinity, and sulfate with elevation. Chloride at multilevel wells is as high as 64 mg/L but drops to 25 mg/L in the deepest sampling interval in the lower sand. Total alkalinity varies from 2.0 to 12.2 mg/L but generally increases with depth. Sulfate varies only slightly between 8.8 and 13.4 mg/L at all well clusters.

Figure 12 illustrates the concentration patterns for dissolved oxygen, dissolved iron, dissolved manganese, and dissolved arsenic. Arsenic is at or below the method detection limit at all well clusters and piezometers. The concentration of dissolved iron hardly varies with depth and is nowhere higher than 0.8 mg/L. Manganese concentrations generally increase from the surface to just above the lower clay at all well clusters but VLZ-6. Dissolved manganese was below the limit of detection at many wells and the remaining concentrations were still very low except at VLZ-6 where higher concentrations of manganese were detected at all depths. Although manganese and iron follow similar dissolution patterns as a function of redox state, manganese is more sensitive to DO concentration and will dissolve at higher DO levels than iron. The highest manganese concentration was detected at VLZ-6b (at an elevation of -0.7 ft. msl), which is just above the upper clay layer.

Shallow Well Points and Surface Water

Shallow groundwater (less than 2 feet below land surface) was sampled in three locations near the edge of Kelley's Bay (Figure 8, Table 10). At WP-1, sampling was attempted close to the water's edge, but the elevated SC measured in the water suggested that the sample was brackish and not freshwater. Several samples further inland were attempted closer to the edge of the bluff, but even at a distance of greater than 150 feet from the shoreline where WP-1 was finally taken, the SC was still elevated compared to fresh water. Nitrate-N at this location was below detection limits. The SC, chloride, sulfate, and alkalinity concentrations of this sample all suggest that groundwater was brackish at the time of sampling. The presence of brackish water is consistent with tidally-driven water exchange between the bay and groundwater. Water samples from WP-2 and WP-3 were fresh groundwater based on SC (less than 300 µS/cm). At WP-2 and WP-3 the nitrate was 8.7 and 3.0 mg/L respectively. The DO was unusually low at 2.9 and 2.5 mg/L compared to groundwater from the upper sand measured along Vinland Drive. Dissolved iron and arsenic were close to or below detection limits and manganese was below 1 mg/L for both points.

A sample of surface water from Kelley's Bay was also sampled for all parameters (Table 10). Nitrate-N was 0.78 mg/L and SC, chloride, sulfate, and alkalinity were all at elevated concentrations typical of saline waters.

Stable Nitrogen Isotope Analysis

The two stable isotopes of nitrogen are ^{15}N and ^{14}N. The organisms (anaerobic bacteria) that cause denitrification preferentially utilize ^{14}N so that ^{15}N becomes enriched compared to ^{14}N during these biological reactions (Pabich, 2001). The ratio of $^{15}N/^{14}N$ is captured as $\delta^{15}N$ (reported in parts per thousand, $^0/_{00}$):

$$\delta^{15}\mathrm{N} = 1000\,\frac{\mathrm{s-a}}{\mathrm{a}} \tag{4}$$

where, a = relative abundance of ^{15}N in atmospheric air, and
s = relative abundance of ^{15}N in the sample.

$\delta^{15}N$ has a stable value of 0.366 $^0/_{00}$ in air in the atmosphere (Kendall, 1998). This ratio can be analyzed for NH_4, NO_3, or N_2 in groundwater to determine the ratio $\delta^{15}N$. The δ^{15} of nitrate-N was analyzed for this study since it is the species of interest at the Vinland Drive site. For clarity, stable nitrogen isotope analyses completed for this study are listed as $\delta^{15}N{-}NO_3$ to specify that the ratio was

Table 10 - Water Quality Shoreline Well Points and Surface Water

Permeable Reactive Barrier Full Hydrogeologic Assessment - Vinland Drive, Dennis, MA

Sample ID/Location	**SW-1**		**WP-1**		**WP-2**		**WP-3**	
Sampling Date	1/12/17		1/12/17		1/12/17		1/12/17	
Field Measurements								
pH (SU)	5.6		6.0		5.4		5.1	
Temperature (°C)	6.7		7.1		10.3		10.9	
Dissolved Oxygen (DO; mg/L)	10.5		7.5		2.9		2.5	
Specific Conductance (uS/cm)	21179		16395		291		223	
Redox Potential (ORP; mV)	348		74		125		138	
Laboratory Analyses								
Nitrate as N (mg/L)	0.78		<0.019		8.7		3	
Nitrite as N (mg/L)	<0.019		<0.019		<0.094		<0.019	
Total Kjeldahl Nitrogen (TKN) (mg/L)	0.683		0.578		0.085	J	<0.066	
Total Nitrogen (mg/L)	1.5		0.58		8.7		3	
Total Alkalinity (mg/L CaCO3)	45.60		27.4		ND		3.3	
Chloride (mg/L)	7000		5170		49.4		43.6	
Sulfate (mg/L)	953		684		9.13		11.1	
Dissolved Iron (mg/L)	0.11		1.5		<0.01		0.01	J
Dissolved Manganese (mg/L)	0.0215		0.1		0.108		0.016	
Dissolved Arsenic (mg/L)	<0.0019		0.007		<0.002		0.002	J
Dissolved Organic Carbon (mg/L)	8	J	13	J			0.74	J

Notes:

J - Data indicates a presence of a compound that meets the identification criteria. The result is less than the quantitation limit but greater than zero. The concentration given is an approximate value.

R - Suspected error in field DO measurements

NS - Not Sampled / NM -Not Measured

E - Exceeds RPD of 20% with duplicate sample

Grey cell means data questionable and should not be relied upon

measured in nitrate-N. Measurements of δ^{15}N–NO$_3$ have been used at a variety of sites to understand the extent of denitrification in groundwater and to evaluate the sources of nitrate-N detected in groundwater based on apparent enrichment of ^{15}N (Cravotta, 1997; Robertson & Merkely, 2009; Kendall et al., 2007; Degnan et al., 2015).

The variation in δ^{15}N–NO$_3$ values in groundwater can reflect different sources of nitrate-N and fractionation due to biological processes. Since the Vinland Drive site is in a developed area underlain by a sand and gravel water table aquifer, there are likely multiple sources of nitrate contributing to the subsurface concentrations. These include infiltrating precipitation, vehicle emission deposition, fertilizer, and septic discharge. A review of stable isotope concentrations by Kendall et al. (2007) indicates the following ranges of δ^{15}N–NO$_3$ for these sources:

Precipitation for the Cape Cod area -	-5.4 to -3.5 $^{0}/_{00}$
Vehicle emissions -	-13 to +3.7 $^{0}/_{00}$
Fertilizer – inorganic-	-4 to +4 $^{0}/_{00}$
Fertilizer – organic -	+2 to +30 $^{0}/_{00}$
Animal and human waste	+10 to +20 $^{0}/_{00}$

A recent study of the impacts of blasting on water quality also provided some ranges of δ^{15}N–NO$_3$ from septic systems in southern New Hampshire (Degnan et al., 2015). Groundwater downgradient of septic influence was found to have ratios between 11.4 and 15.3 $^{0}/_{00}$. The higher ratio was in an area of low DO, where denitrification may have been active. Others reported δ^{15}N–NO$_3$ in groundwater downgradient of septic systems as 7 $^{0}/_{00}$ (Fogg et al., 1998) and 8.1 to 13.9 $^{0}/_{00}$ (Aravena et al., 1993). It is likely that the nitrate-N detected in the subsurface at Vinland Drive is the result of a mixture of precipitation, vehicle emissions, septic waste, and fertilizer sources. The most effective means of identifying sources uses a combination of stable oxygen and stable nitrogen isotope analysis of nitrate-N in soil and groundwater. To determine the impact of denitrification on δ^{15}N–NO$_3$, additional analyses such as DO, DOC, and dissolved metals are needed (Kendall et al., 2007).

The sampling of selected locations and depths at the Vinland Drive site (Figure 10) identified δ^{15}N–NO$_3$ in groundwater between 5.2 and 5.8 $^{0}/_{00}$ at most wells with one much lower delta-value detected at VLZ-4b at 2.0 $^{0}/_{00}$. UC- Davis was asked to re-run this sample to verify this lower value and the re-analysis yielded 1.9 $^{0}/_{00}$ compared to the original value of 2.0 $^{0}/_{00}$.

Overall, measured $\delta^{15}N-NO_3$ ratios do not suggest that denitrification is occurring to any great extent within the upper or lower sand zone. The subsurface conditions do not appear to be conducive to denitrification with a generally high DO and low DOC. Manganese does appear to be more soluble with depth indicating that some chemical reduction is occurring at in the lower sand unit.

Summary of Upper and Lower Sand Water Quality

The upper sand hydrogeologic unit is 6 to 17 feet thick in the Vinland Drive area and the lower sand is 9 to 15 feet thick. Although nitrate-N concentrations differ between well locations, the highest concentrations have been detected in the upper sand with the highest concentration found near the shoreline at WP-2 and at VL-4. DO is generally higher in the upper sand as well (greater than 7 mg/L) except at one VLZ-2 piezometer completed just above the upper clay. The exception is at the shallow groundwater well point samples WP-2 and WP-3 where the DO is below 3 mg/L. This may reflect local conditions such as proximity to anaerobic mud in shoreline and bay sediments. Chloride is elevated at some upper sand wells but most other ionic species are found only at low concentrations and dissolved metals are also at low concentrations or below detection limits.

Nitrate-N in the lower sand hydrogeologic unit is below 5 mg-N/L at all sampled locations in contrast to the higher concentrations found in the upper sand unit. DO is still relatively elevated in the lower sand with the lowest concentration at VLZ-4d at 5.8 mg/L. Dissolved ionic compounds are generally low in the lower sand with minor increases in alkalinity with depth. Dissolved manganese increases with depth in the lower sand at most locations.

Overall, there do not appear to be geochemical conditions that suggest active denitrification in groundwater in the area studied. This is confirmed by the relatively consistent and low $\delta^{15}N-NO_3$ in samples recently analyzed in both the upper and lower sand units.

Analysis of Nitrate-N Mass Flux

The mass flux analysis completed as part of the ISC was updated to reflect the lithology, hydraulic conductivity, and nitrate-N concentrations observed during completion of the FHA. Four mass flux analyses were completed for both the upper and lower sand unit using data from the VLZ-2, VLZ-4, VLZ-6, and VL-8 well locations, which bracket the overall range of conditions at the Vinland Drive FHA study site. The 2016 hydraulic gradient of 0.012 was used for mass flux analysis in the upper sand as it was measured over several months and is likely to represent a seasonal high value. The gradient between VL-8d and VLZ-7d (0.004) was used for evaluating mass flux in the lower sand. Table 11 summarizes the mass flux at these locations. Appendix D contains a description of the mass flux methodology and the calculation tables. The modest changes in horizontal gradients due to tidal influence in the lower sand were not included in the mass flux calculations. As described in a following section, the PRB will be designed to provide a three-day travel time through the treatment zone, therefore changes in gradient and velocity over the 12-hour tidal cycle will be averaged out during passage through the PRB. For this reason, the tidal variation in velocity should not greatly influence the overall mass flux of nitrate-N at Vinland Drive.

Table 11 – Summary of Mass Flux of Nitrate-Nitrogen
Vinland Drive, Dennis, MA

Well Location	Sand Unit Designation	Weighted Average Nitrate-N Concentration (mg-N/L)	Saturated Thickness of Treatment Zone (ft.)	Nitrate-Nitrogen Mass Flux in Sand Unit (g/day/m)	Total Nitrate-Nitrogen Mass Flux at Well Location (g/day/m)
VLZ-2	upper	3.8	9.5	5.8	11
	lower	3.7	14.7	5.5	
VLZ-4	upper	8.1	6.5	2.9	4
	lower	3.9	13.4	1.0	
VLZ-6	upper	4.0	13.0	6.9	11
	lower	4.5	14.1	4.5	
VL-8	upper	7.5	9.0	11.3	14
	lower	3.2	10.6	2.5	

Mass flux in the upper sand is estimated between 2.9 g/day/m (VL-4), and 11.3 g/day/m (VL-8). In the lower sand, mass flux is estimated at 1.0 to 5.5 g/day/m with the lower values at VL-4 and VL-8. The total mass flux over both units ranges from 4 g/day/m at VL-4 to 14 g/day/m at VL-8. At VL-8 the higher concentration of nitrate-N (7.5 mg/L) and coarse upper sand sediment contributed to the higher flux estimate at this location.

Summary of Nitrate-N Mass Flux

Nitrate-N concentrations varied across the site between well sites, but overall concentrations were similar at wells sampled during both the ISC and FHA. This areal variability contributed to differences in the computed mass flux across the site. Additionally hydrogeologic differences contributed to mass flux variation. Although medium to coarse sands are predominant throughout the site, sediment cores recovered at VL-4 and VL-7 and especially in the lower sand unit contained more fine sand and silt than sediments collected at other well locations in the study area. This resulted in lower hydraulic conductivity values based on slug test analyses in this northwestern area of the site. The measured hydraulic conductivity for the upper sand at VL-2 and VL-6 was somewhat lower than originally estimated for the ISC as well. Finally, the hydraulic gradient in the lower sand is 0.004, which is considerably more moderate than the gradient measured in the upper sand.

The re-estimated values of mass flux of nitrate-N at the site are somewhat lower than those calculated for the ISC at VLZ-2 (19.4 g/day/m). This change reflects the additional hydrogeologic and water quality data collected during the FHA.

Evaluation of Nitrate-Reducing PRB Technology at the Dennis Site

The section presents a conceptual design of a pilot-scale PRB at the Dennis site. This initial design will help in determining the additional analyses required before pilot implementation and provides preliminary estimates of substrate type and usage. Several practitioners were contacted for additional information on PRB layout and substrate (C. Jacob, personal communication, 2016; F. Hostrop, personal communication, 2017; B. Elkins, personal communication, 2017) and design and estimating tools were used to evaluate substrate requirements (EOS Inc, website 2017; Henry, 2010). For the purposes of this evaluation it was assumed that the PRB would consist of injected liquid substrate along an appropriate width and length within the chosen treatment zone at depth.

Conceptual Design Factors

The conceptual design of the pilot PRB requires the determination of the following factors:

The PRB orientation and width (perpendicular to groundwater flow). Based on the FHA results, Vinland Drive is roughly perpendicular to groundwater flow and would be a convenient location for the PRB. A of 100 feet (measured perpendicular to flow) is assumed for a pilot PRB.

The PRB length (parallel to groundwater flow). This distance should adequate to allow adequate contact with injected substrate to allow denitrification but not great enough to allow reactions to proceed to strongly reducing conditions. A three to four day contact period was advised to meet these requirements.

Treatment zone depth – Treatment of both the upper and lower sand unit was evaluated.

The type and formulation of substrate to be injected that will provide a carbon source for anaerobic bacteria to denitrify groundwater through respiration. A liquid injected substrate (also known as injectate) will be appropriate given the depth to and the hydraulic conductivity of the treatment zone. Emulsified Vegetable Oil (EVO) appears to be the most effective substrate for the Vinland Drive site. It is designed for higher groundwater velocities (0.5 ft./day), can be formulated to adhere to sand grains without reducing hydraulic conductivity, and has a high carbon content and hydrogen yield (Hostrop & Begley, 2017; Henry, 2010). There are several commercial sources of this product.

The volume of substrate needed and the frequency of replenishment required to continue treatment.

Evaluation of Anaerobic Treatment Efficiency

The hydrogeologic and water quality information collected as part of the Dennis FHA was evaluated using the Substrate Estimating Tool for Enhanced Aerobic Bioremediation of Chlorinated Solvents spreadsheet analysis tool (Henry, 2010) to further evaluate placement of a pilot PRB and to estimate the volume of substrate that may be required.

The spreadsheet tool provides a stoichiometric analysis of reducing reactions based on known site hydrogeologic and geochemical conditions and general characteristics of substrates. Reducing reactions include (in order of thermodynamic favorability and thus reaction sequence): aerobic respiration (utilization of oxygen to produce anaerobic conditions), denitrification, sulfate reduction, manganese reduction, iron reduction, and methanogenesis. For nitrate treatment only the first two reactions listed are needed, but some sulfate reduction, metals reduction, and methanogenesis may occur.

Each commercially available substrate has unique characteristics that may not be fully represented in the analysis. Appendix B of the background documentation for the spreadsheet tool (Henry, 2010) explains the conceptual model and methodology. Although developed for chlorinated solvents, it can also be used for analyzing the effectiveness of various PRB substrates for denitrification. This may overestimate the use of substrate as it assumes that reactions will proceed to reducing conditions sufficient for breakdown of chlorinated solvents by dechlorination and denitrification occurs at less reducing conditions as detailed above. This evaluation only provides broad guidance in evaluating PRB treatment, as other in-situ factors must be considered in the design and implementation of a treatment PRB through column testing and additional in-situ analyses.

Table 12 highlights chemical and physical characteristics that can impact substrate utilization. The conditions found at the Vinland Road site (in blue text) in Dennis, MA may require substrate amendment to accommodate these conditions.

Table 12 - Example Enhanced Bioremediation System Modifications, from Henry, 2010

Potential Condition	Modification
Low pH or low buffering capacity	• **Addition of a buffering compound** • **Use of water push for soluble substrates** • **Use of slower-release substrates**
Low permeability/groundwater velocity	• Closely spaced injection points • Targeted injections into low permeability horizons
High permeability/groundwater velocity	• **Higher substrate loading rates** • **More frequent injections** • **Multiple rows of injection wells or biowalls** • **High retention (coarse droplet) EVO products**

(Modified from AFCEE et al., 2004 and Suthersan et al., 2002.)

As indicated in Table 12 the low pH and low alkalinity of groundwater at the site may require addition of a buffering compound to the PRB injectate. Incorporation of granulated limestone in the injectate to enhance alkaline conditions has been suggested (F. Hostrop, personal communication 2017). EVO substrate also incorporates the suggested water push (injection of additional water or dissolution of substrate in water) and slower-release substrate by modifying the droplet size and adherence to particles (stickiness) for EVO injections. The high permeability and groundwater velocity at the site may require higher substrate loading, use of several rows of injection sites to achieve the correct PRB thickness, and injectate amended to be strongly retained on sediment. Further, zones of coarse sand which may allow for preferential groundwater flow could require still greater rates of EVO usage compared to areas of lower hydraulic conductivity.

Our analysis assumed a PRB that is 100 feet wide (perpendicular to groundwater flow) and 24 feet long (parallel to groundwater flow) to achieve the necessary reaction time based on site groundwater velocities, with a 1-year performance period for the pilot study. A safety factor of three was incorporated into the estimate of the volume of injectate needed. Between the safety factor and the inclusion of sulfate reduction and methanogenesis in the reactions, the estimated volume of injectate is likely very conservative. The saturated thickness of the aquifers was varied based on well site characteristics. Most hydrogeologic and water quality input parameters necessary for the calculation was assessed as part of the FHA, but for a few parameters for which field data were unavailable, values from a similar evaluation in Falmouth, MA were used (F. Hostrop, personal communication, 2017). Appendix E contains the input data pages and the output data pages produced by the spreadsheet tool. At VL-2, geochemical conditions at VL-6 and VL-2 were averaged for spreadsheet input. At VL-8 lower sand, geochemical conditions for VL-4 were assumed, as VL-8d was not sampled during the FHA.

Table 13 summarizes the results of this analysis and initial results are also graphically presented in Figure 13. Denitrification will occur after aerobic respiration is complete. The EVO demand is conservatively calculated to include sulfate reduction and methanogenesis, Iron and manganese reduction and dechlorination reactions are not represented in Table 13 or Figure 13 as they are either a very small fraction of the overall total or do not apply to this site evaluation.

This evaluation determined that 17 to 22% of the total electron acceptor demand for PRB treatment would be utilized for aerobic respiration and 42 to 60% would be used for denitrification. Some sulfate reduction (13 to 25% of the estimated demand) and methanogenesis (8-14%) may also occur but the pilot test would be used to evaluate these reactions and minimize excess EVO usage for the final PRB design. The volume of EVO estimated by the spreadsheet tool for the pilot test for aerobic respiration and denitrification only, depending on location and sand unit falls between 500 and 650 gallons for a year-long pilot test

Depending on well locations, nitrate reduction would utilize 42 to 60% of the EVO injected based on electron receptor demand. The upper sand at VL-8 and the upper sand at VL-4 represent the highest utilization of EVO for denitrification and the lowest utilization was estimated at VL-8 in the lower sand. Variability of

Table 13 - Summary of Permeable Reactive Barrier Characterics and Emulsified Vegetable Oil Substrate Requirements
Vinland Drive, Dennis, MA

PRB Characteristics Modeled	VL-2 Upper Sand	VL-2 Lower Sand	VL-4 Upper Sand	VL-4 Lower Sand	VL-8 Upper Sand	VL-8 Lower Sand	Units
Width (perpendicular to groundwater flow)	100	100	100	100	100	100	feet
Length (parallel to groundwater flow)	24	24	24	24	24	24	feet
Saturated Thickness (based on lithology and measured water levels)	8.4	14.7	7.1	13.4	9.2	10.5	feet
Design Period of Performance - pilot test	1	1	1	1	1	1	years

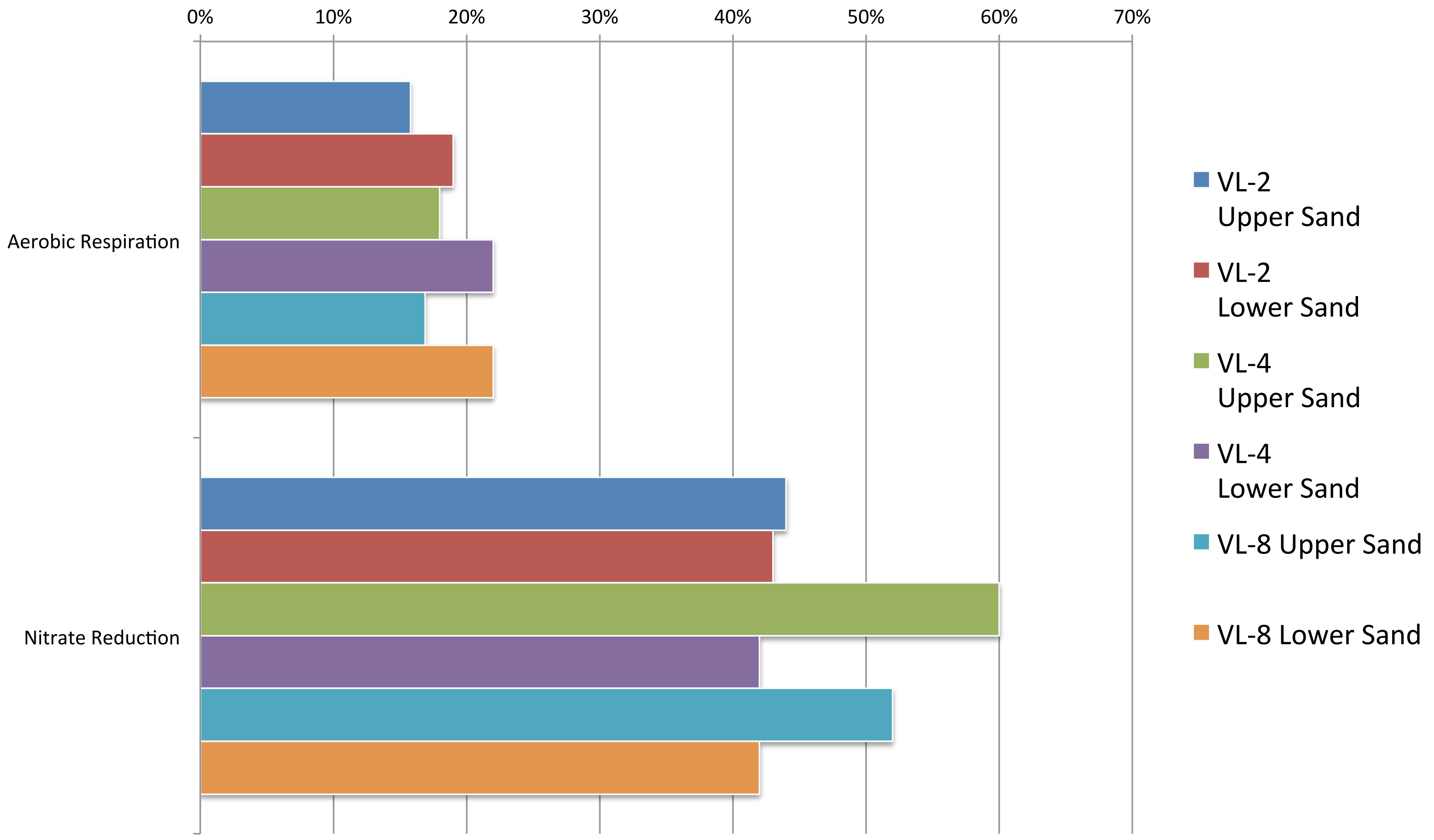
Percent of Total Electron Receptor Demand *	VL-2 Upper Sand	VL-2 Lower Sand	VL-4 Upper Sand	VL-4 Lower Sand	VL-8 Upper Sand	VL-8 Lower Sand
Aerobic Respiration	16%	19%	18%	22%	17%	22%
Nitrate Reduction	44%	43%	60%	42%	52%	42%
Sulfate Reduction	25%	22%	13%	21%	21%	22%
Methanogenesis	12%	13%	9%	12%	8%	12%

Estimated EVO use for Design Period (gallons)	500	520	650	530	570	530
Estimated Mass Flux of Nitrate-N (g/day/m) **	5.8	5.5	2.9	1.0	11.3	2.5
Gallons of EVO required to denitrify 1 g/day/m of nitrate-N mass flux	90	100	220	530	50	210

* Based on Evaluation using the Substrate Estimating Tool for Enhanced Bioremediation of Chlorinated Solvents Environmental Security Technology Certification Program - (Henry, 2010), Appendix E

** Based on mass flux evaluation completed for the FHA, Appendix D

Figure 13 - Percent of Total Electron Acceptor Demand for Denitrification at PRB - Vinland Drive Site, Dennis, MA



hydrogeologic characteristics and geochemistry between well locations accounts for the variation in estimated electron donor usage and efficiency with respect to denitrification.

A rough evaluation of EVO usage efficiency was estimated by calculating the estimated number of gallons of EVO needed per unit mass flux of nitrate-N at each location. This suggests that the PRB would be less efficient in treating nitrate-N within the lower sand at VL-4 compared to the other sites evaluated.. This difference in efficiency arises at this location because the concentration of dissolved oxygen is higher relative to the concentration of nitrate at VL-4 and thus a higher portion of the substrate is utilized by aerobic respiration. VL-8 upper sand would utilize the lowest number of gallons per 1 g/m/day mass flux for the pilot-scale test.

Conclusions

As stated in the introduction, the purpose of the FHA was to gather sufficient data to design a pilot scale permeable reactive barrier for the site and, in particular, to answer questions about subsurface properties that will be used to predict mass flux of nitrate-nitrogen beneath the site, to define where and to what depth a PRB should be constructed, and to determine if there are unique geochemical conditions that will need to be considered. The following summary answers the questions posed in the introduction to this report and to provide the site characteristics that will be relevant to pilot PRB design.

- Subsurface materials are largely fine to coarse sands with a 3- to 10-foot-thick shallow clay layer that separates the upper sand from the lower sand unit. The upper sand is 6- to 17-feet thick. It appears to be thickest to the south and east. The lower sand is 9- to 15-feet thick. Sediments are coarsest in the central portion of the neighborhood surrounding VL-2 and VL-6 and become finer to the northwest in the vicinity of VL-7. Contrary to what was suggested by the ISC results, the shallow clay layer appears to be continuous within the study area.

- In both the upper and lower sand units, lenses of coarse sand may act as preferential flow paths. Many coarse zones were noted during boring advancement and may be responsible for the elevated hydraulic conductivity values estimated at VL-2 and VL-6.

- A substantial clay deposit underlies the lower sand unit. This deep clay layer appears locally to bound anthropogenic influences to water quality to a 26- to 35-foot interval between the water table and the lower clay unit.

- The depth to the water table from the ground surface is approximately 28 to 40 ft. across the site. Water levels at most wells varied less than two feet over the seasons. At VL-6, which is farthest from Kelley's Bay, water levels varied 2.75 feet over the last year.

- The coastal tide in Kelley's Bay causes only minor variation in water levels in wells on Vinland Drive in the shallow sand unit.

- Tidal variation affects water levels in the lower sand unit. The water level at VL-4d, which is 200 feet from the shoreline, varied approximately 0.22 feet over a tidal cycle. Similarly, the water level at VL-6d, which is approximately 550 feet from the shoreline, varied 0.18 feet over a tidal cycle. Water level measurements in wells screened in the lower sand, therefore, are sensitive to timing and should be taken over a short time span in order to correctly estimate groundwater flow direction and gradient.

- Groundwater in both the upper and lower sand units flows southwest towards Kelley's Bay and is roughly perpendicular to Vinland Drive. The gradient in the upper sand has been measured between 0.008 and 0.012 over the study period. The lower sand unit has a horizontal gradient of 0.004 based on a full round of water level data at deep wells in May 2017. The gradient in the lower sand exhibits a 0.0004 change overall in synch with the tidal cycle.

- The shallow clay layer acts as a confining unit based on strong upward gradients between piezometers screened below and above the clay layer. Groundwater in the upper and lower sand unit appears to discharge to local surface water based on strong upward gradients.

- Hydraulic conductivity has been estimated to vary between 50 ft./day to 260 ft./day within the upper and lower sand units. The sediments in the central portion of the site are more conductive than the sediment to the northwest between VL-4 and VL-7. The estimated groundwater velocity is 1.7 to 6 ft./day based on estimated hydraulic conductivity and horizontal gradients. This velocity varies slightly with the tide cycle in the lower sand.

- Nitrate-N concentrations are found between 1.7 to 8 mg-N/L at water table wells. Shallow groundwater (upper sand) sampled near the shoreline at Kelley's Bay contained 3.0 to 8.7 mg-N/L nitrate-N.

- Nitrate-N concentrations in the lower sand are 2.1 to 5 mg-N/L.

- Nitrate-N was measured at 0.78 mg/L at SW-1, a surface water sample from Kelley's Bay at the Vinland Drive shoreline.

- No significant reducing zone was encountered although DO was found to decrease with depth at most well clusters. DO was also low near the shoreline in the vicinity of well points WP-2 and WP-3. Manganese solubility increases with depth in the lower sand.

- The nitrogen isotope ratio δ^{15}N–NO_3 does not change significantly with depth, which appears to confirm the conclusion that denitrification is not a dominant geochemical process in upper or lower sand units.

- Elevated chloride and specific conductance in water table wells and the shallow piezometers suggests anthropogenic influences from road salt and/or septic systems.

- The mass flux of nitrate-N in the treatment and saturated zone over the study depth is estimated between 4 and 13 g/day/m with the higher flux in the center of the site surrounding VL-2 and VL-6 and at VL-8 where nitrate-N is elevated. The tidal influence in the lower sand was not felt to change the mass flux enough to impact PRB specifications.

- A spreadsheet tool by Henry (2010) was used to make preliminary estimates of electron donor utilization by bacteria, the EVO needed to create reducing conditions, and the chemical reduction of oxygen, nitrate, and sulfate These factors vary according to site-specific geochemical conditions and hydrogeologic characteristics. Based on the results of the spreadsheet tool, aerobic respiration will utilize 16 to 22% of electron donor demand during treatment and nitrate reduction will require 42 to 60% of electron donor demand in PRB treatment. Because this evaluation presumes that reducing conditions will drive to the level required for sulfate reduction and methanogenesis, it likely overestimates the volume of EVO required, as only the aerobic restoration reaction must occur before the denitrification process can proceed.

Pilot PRB Design Recommendations

The results of the FHA suggest the following PRB design parameters:

PRB Alignment - Groundwater flows along a similar path in the upper and lower sand—predominantly southwest towards Kelley's Bay. A PRB alignment along Vinland Drive would be perpendicular to groundwater flow, which is the desired orientation. This alignment is approximately 200 feet from the shoreline, which is the recommended setback distance to reduce possible negative impacts to surface water from PRB treatment constituents and geochemical change.

PRB Location – The concentration of nitrate-N varies across the site, but repeated analysis of this parameter at several locations suggests that the concentrations have remained similar over the past year. Plumes from individual on-site septic systems probably remain fairly distinct leading to the observed areal variability of nitrate-N and other constituents associated with septic system discharge.

A pilot PRB could be most effectively tested in areas with higher nitrate-N such as the upper sand near VL-4 and near VL-8. If simultaneous treatment in both the upper and lower sand is tested, the mass flux and hydrogeologic characteristics at VL-2 suggest similar PRB efficiencies in the upper and lower sand and between sites. Testing two sites with differing hydraulic conductivity could also prove useful for PRB pilot test evaluations for typical hydrogeologic conditions on Cape Cod.

Water levels at PRB locations – Water levels fluctuate approximately two feet over the year in the upper sand with the lowest water levels measured in winter. PRB substrate injection should be planned to accommodate these water level changes.

Additional sample collection – A bench-scale column test using sediment cores from the site is recommended where pilot testing is planned to better evaluate in-situ conditions. A core of sediment from the zone of interest would be taken, sealed, and sent to a laboratory for testing with EVO to determine required amendments to adjust for the low alkalinity and pH and elevated dissolved oxygen and the relatively high groundwater velocity documented at the site. Groundwater from that location would also be collected for use in the column test. Groundwater samples for analysis of carbon dioxide and methane gas concentrations are also recommended to better define existing biological activity.

Monitoring network evaluation– The existing monitoring network would suffice for pilot testing but additional wells could be useful for monitoring EVO migration and utilization. The pilot test will provide valuable information on the degree of chemical reduction beyond nitrification so the PRB thickness and injection volume and frequency can be modified to reduce unnecessary geochemical reactions. Thorough review of the results of recent pilot testing at the Orleans, MA pilot PRB site would also be helpful to determine the optimal spacing and parameters for testing.

Cited references:

AFCEE, Naval Facilities Engineering Service Center (NFESC), and the Environmental Security Technology Certification Program (ESTCP). 2004. *Principles and Practices of Enhanced Anaerobic Bioremediation of Chlorinated Solvents*. Prepared by Parsons Infrastructure & Technology Group, Inc., Denver. Colorado. August. (available at http://www.afcee.brooks.af.mil/ products/techtrans/).

Aravena, R., M. L. Evans, and J. A. Cherry, 1993. Stable isotopes of oxygen and nitrogen in source identification of nitrate from septic systems. *Ground Water*. Vol. 31, No. 2, Pg. 180-186. March-April 1993.

Cravotta, Charles A., 1997. Use of stable isotopes of carbon, nitrogen, and sulfur to identify sources of nitrogen in surface waters in the lower Susquehanna River Basin, Pennsylvania. USGS Water-Supply Paper 2497.

Degnan, J.R., J.K. Bohlke, K. Pelham, D.M. Langlais, G.J. Walsh, 2015, Identification of Groundwater Nitrate Contamination from Explosives Used in Road Construction: Isotopic, Chemical, and Hydrologic Evidence. *Environmental Science and Technology*. Vol. 50, No. 2, Pg. 593-603.

Elkins, Brad. 2017. Personal communication regarding the estimate of EVO substrate and use of the ESTCP ER-0627 estimating tool.

EOS Remediation LLC, 2017, EOS Design Tool, http://www.eosremediation.com/, Website accessed May 2017

Fogg, G. E., D. E. Rolston, D. L. Decker, D. T. Louie, and M. E. Grismer, 1998. Spatial Variation in Nitrogen Isotope Values beneath Nitrate Contamination Sources. *Ground Water*. Vol. 36, No. 3, Pg. 418-426. May-June 1998.

Halford, K.J and E. L. Kuniansky, 2002, Documentation of Spreadsheets for the Analysis of Aquifer-Test and Slug-Test Data. U.S. Geological Survey Open-File Report 02-197

Henry, B., 2010. Loading Rates and Impacts of Substrate Delivery for Enhanced Anaerobic Bioremediation. ESTCP Project ER-0627. Environmental Security Technology Certification Program. February 2010. (https://cluin.org/download/contaminantfocus/dnapl/Treatment_Technologies/ER-0627-FR-1.pdf)

Hostrop, F. and J. Begley, 2017, Emulsified Vegetable Oil, What it is, how it removes nitrate, how it compares, how it's manufactured, and why and how we inject it. Waquoit Bay National Estuarine Research Reserve Conference, April 5, 2017.

Hostrop, Fritz. 2017. Personal communication regarding the estimate of EVO substrate and use of the ESTCP ER-0627 estimating tool. TerraSystems, Inc.

Jacobs, Clint. 2016. Personal communication regarding PRB design. Landau Associates, Inc.

Kendall, C., 1998. Tracing anthropogenic inputs of nitrogen to ecosystems. In: Kendall, Carol, and J.J. McDonnell, Editors. *Isotope Tracers in Catchment Hydrology.* Elsevier Science B.V., Amsterdam. pp. 519-576.

Kendall, C., E.M. Elliott, and S.D. Wankel, 2007. Tracing anthropogenic inputs of nitrogen to ecosystems. In: Michener, R. and K. Laitha, editors, 2007. *Stable isotopes in ecology and environmental science*, 2nd ed. Blackwell Publishing, Malden, MA. Chapter 12.

LeBlanc, D. R., J. H. Guswa, M. H. Frimpter, and C. J. Londquist, 1986. Ground-water resources of Cape Cod, Massachusetts. Hydrologic Investigations Atlas HA-692. U.S. Geological Survey, Washington, D.C.

MT Environmental Restoration, 2015. Falmouth Acapesket Peninsula Groundwater Investigation Phase 2 Report. December 21, 2015.

NOAA, 2017, Tides & Currents page. National Oceanic and Atmospheric Administration. , https://tidesandcurrents.noaa.gov/inventory.html?id=8447505, April 2017.

Odong, Justine, 2007, Evaluation of Empirical Formulae for Determination of Hydraulic Conductivity based on Grain-Size Analysis, Journal of American Science. Vol. 3, No. 3, pg. 54-60.

Pabich, W. J., 2001. Denitrification of Anthropogenic Nitrogen in Groundwater: Measurement and Modeling Using Stable Isotopic and Mass Balance Approaches. Ph.D. Thesis. Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts.

Robertson, W.D., and L.C.C. Merkley, 2009. In-Stream Bioreactor for Agricultural

Nitrate Treatment. *Journal of Environmental Quality*. Vol. 38, No. 1, pp. 230–237.

Suthersan, S.S, Lutes, C.C., Palmer, P.L., Lenzo, F., Payne, F.C., Liles, D.S., and Burdick, J. 2002. *Final Technical Protocol for Using Soluble Carbohydrates to Enhance Reductive Dechlorination of Chlorinated Aliphatic Hydrocarbons*. Submitted to ESTCP and AFCEE under Contract #41624-99-C-8032. December 19, 2002.

WaterVision LLC, 2016. Cape Cod Permeable Reactive Barriers Initial Hydrogeologic Site Characterization Results and Evaluation of Site Suitability for Permeable Reactive Barrier Installation, Vinland Drive Site, Dennis, Massachusetts, September 30, 2016.