Naval Facilities Engineering Systems Command
EXWC Engineering & Expeditionary Warfare Center

Final Technical Report – Final

TR-NAVFAC EXWC-SH-2405

Locating and Quantifying Groundwater and Surface-Water Connections Using Distributed Temperature Sensing (DTS)

NESDI Project Number 591

July 2023

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE ***(DD-MM-YYYY)*** July 31, 2023	**2. REPORT TYPE** Technical Report	**3. DATES COVERED** ***(From - To)*** September 2021 – July 2023

4. TITLE AND SUBTITLE
Locating and Quantifying Groundwater and Surface-Water Connections Using Distributed Temperature Sensing (DTS)

5a. CONTRACT NUMBER
N3943021C2207

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER
NESDI 591

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Navy Environmental Sustainability Development to Integration (NESDI) Program

10. SPONSOR/MONITOR'S ACRONYM(S)
NESDI

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT This research was funded by the Navy Environmental Sustainability Development to Integration (NESDI) Program with resources provided by the Chief of Naval Operations Energy and Environmental Readiness Division. This project demonstrated the benefits and practicality of deploying distributed temperature sensing (DTS) systems for locating and quantifying underwater seeps from sediment into surface water at Navy sites. Locating and quantifying such seeps is an important part of studying many contaminated aquatic sites. The objective of this study was to demonstrate the capability of a DTS system to provide high resolution identification of seepage locations across large areas through time at a relevant Navy site. Secondary objectives, dependent upon collected data, were to estimate seepage flux rates, including comparing flux estimates with those found using seepage meters.

15. SUBJECT TERMS
distributed temperature sensing, DTS, seeps, contaminated sediments

16. SECURITY CLASSIFICATION OF: Unclassified			**17. LIMITATION** UU	**18. NUM**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U			**19b. TELEPHONE NUMBER** ***(include area code)***

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

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ABBREVIATIONS

BRAC	Base Realignment and Closure
cm	centimeter
cVOC	chlorinated volatile organic compound
DoD	Department of Defense
DTS	distributed temperature sensing
EXWC	Engineering and Expeditionary Warfare Center
km	kilometer
m	meter
NAVFAC	Naval Facilities Engineering Systems Command
NCBC	Naval Construction Battalion Center
NESDI	Navy Environmental Sustainability Development to Integration
RPM	Remedial Project Manager

1.0 EXECUTIVE SUMMARY

This project demonstrated the benefits and practicality of deploying distributed temperature sensing (DTS) systems for locating and quantifying under-water seepage from sediment into surface water at Navy sites. Locating and quantifying such seepage is an important part of studying many contaminated aquatic sites.

DTS uses a fiber optic cable that is embedded 5-12 cm (2-5 inches) into the sediment and measures temperature continuously as finely as one-quarter meter (ten inches) spatial resolution. Because the cable can be several kilometers long, it may be deployed in a sinuous pattern that provides good spatial coverage of large areas of sediment. SelkerMetrics has developed analytical methods that use the recorded temperatures to locate and quantify seepage which the cable intersects. Additionally, the rate of sediment scouring and deposition may be estimated in some applications, which can be useful in sediment stability assessments and in remedial design (e.g., cap armoring design).

An initial data set was collected in September 2022 at the NCBC Davisville (BRAC site) near Allen Harbor, Rhode Island. The DTS cable was installed along the shoreline near the Allen Harbor entrance channel and along the eastern beach of Calf Pasture point, facing Narragansett Bay. Data was first collected after an extended drought, and no significant seepage was detected. The cable was left in place and a second data set was collected in March 2023 along the shoreline near the Allen Harbor channel entrance. This data showed seepage at 21 locations spanning 175 m, and supported quantifying seepage rates along the near-shore cable transect. This observed seasonal change highlights potential benefits of the ability to leave the DTS cable in place for extended periods.

Seepage data was also collected using five seepage meters placed along the near-shore transects at locations with and without seepage indicated by the DTS. Four of the five showed seepage rate estimates comparable to those found by the DTS. At one location, the DTS detected a seepage but the meter did not.

A laboratory experiment was also conducted to validate analytical methods used to interpret temperature data from the DTS. The methods were found to accurately reflect cable burial depth and seepage rates to within 5- 30% of actual values in virtually all tested circumstances. These findings validated the DTS analytical methods.

DTS was found to provide greater spatial coverage and resolution monitoring seepage from sediment, continuously through time, than seepage meters or direct-push probes at approximately the same cost.

2.0 INTRODUCTION

2.1 PROBLEM STATEMENT

At many sites, contaminants can be transported from upland areas or from sediment to surface water via groundwater that flows toward, and discharges into, surface water bodies. Such groundwater discharge or seepage occurring below the water surface can be challenging to locate and quantify, but are important for characterizing and understanding contaminant transport and loading, as well as evaluating and designing remediation options.

Traditional sampling methods that identify and quantify seepage can only be deployed at limited and discrete locations. Timeframes for deployment are dependent on access to the areas of measurement and can be labor intensive to repeat measurement or collect long-term datasets. These methods, such as direct-push probes, piezometers, and seepage meters, often provide incomplete information because of significant spatial and temporal variations in seepage. Additional methods that provide more comprehensive areal coverage are needed to improve the characterization of seepage to surface water to support remedial decision making.

2.2 OBJECTIVE OF THE PROJECT

The objective of this study was to demonstrate the capability of a DTS system to provide high resolution identification of seepage locations across large areas through time at a relevant Navy site. Secondary objectives, dependent upon collected data, were to estimate seepage flux rates, including comparing flux estimates with those found using seepage meters.

2.3 BACKGROUND

The Navy has nearly 100 contaminated sediment sites. Sediment contamination remains a significant liability for the U.S. Department of Defense (DoD), with overall liabilities estimated to approach $2 billion.[1] In many instances, contaminated sediments at Navy sites have resulted from the transport of contaminated groundwater from an adjacent upland location. Characterizing groundwater plumes that discharge to surface water was identified by the NAVFAC Sediment Workgroup as one of the top issues. Primary risk drivers at these sites for both human health and ecological receptors include metals, polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), pesticides, chlorinated hydrocarbons, and Per- and Polyfluoroalkyl Substances (PFAS). It is necessary to locate and understand groundwater seeping into surface water at these sites in order to characterize transport processes and design remediation.

Point measurements, with tools like direct-push probes and seepage meters, are often used at sites to identify seepage locations. However, concerns over limited spatial and temporal coverage with such point measurement technologies limits the utility of collected data. There are often situations in which point measurements results leave unknowns about the possibility of contaminants migrating through yet-unidentified seepage locations into surface waters. Seepage may also be intermittent, varying with tides, seasonally, and with groundwater levels, so measurements over limited time spans may inadequately characterize seepage. There is a need to develop better tools and methods to identify and measure seepage.

The importance of developing an understanding of the relationship between upland groundwater and surface water is something that has been known for many years. Limited spatial coverage of potential seepage areas could lead to uncertainties in site conceptual models and questions about the effectiveness of any remediation being implemented, either upland or in the sediment. This is an important limitation at Navy sites that needs to be addressed.

3.0 TECHNOLOGY DESCRIPTION

3.1 TECHNOLOGY OVERVIEW

Temperature has long been used as a tracer to track groundwater-to-surface water discharge.[2] This is possible because when groundwater discharges to surface waters it can create a temperature differential that may be used to identify, locate, and quantify seepage.

The DTS system offers the opportunity to measure sediment temperature at many locations, across large areas, and continuously through extended periods of time. DTS uses the relationship between temperature and scattered light in a fiber optic cable to continuously measure temperatures at sub-meter scale resolution along fiber optic cables which can be multiple kilometers in length. This allows measuring temperature continuously at thousands of locations over extended time periods, thus generating millions of measurements over the course of a study. By providing continuous measurement over extended time, DTS allows for measurements that can capture changes with tides, weather, remedial activities, and seasons.

The fiber optic cable is buried in the sediment to better detect temperature anomalies associated with seepage, typically 5-12 cm (2-5 in) below the sediment surface. This is accomplished using a purpose-built plow, pulled by winch from a boat or shore, which operates underwater to bury the cable while recording the position of the cable placement using a floating GPS unit.

Analytical tools allow processing temperature data to identify and estimate location and flow rates of seepage. The tools vary by situation, with some suited to steady-state conditions and others suited to dynamic environments with temperature fluctuations due to tide, diurnal cycles, or weather patterns.

3.2 TECHNOLOGY DEVELOPMENT

Fiber optic DTS technology was developed in the 1980s, and has seen improvements in resolution, precision, and reliability over time. DTS technology was first introduced to applications within the environmental sciences by Prof. John Selker and others.[3] Progress in environmental DTS technology has included improvements in the distributed temperature sensing instrumentation, cable deployment below the sediment surface, and analytical techniques.

Since 2010 SelkerMetrics has used DTS to identify and quantify seepage at approximately 20 non-DOD sites, many of which are Superfund sites (e.g., Newtown Creek, NY; Passaic River, NJ, Houston Ship Channel, TX; Gowanus Canal, NY; Portland Harbor, OR). SelkerMetrics has pioneered advancements during that time. Improvements in deployment methods have included development of an underwater plow, which achieves consistent cable burial within the sediment while continuously recording location and avoiding the need for divers. SelkerMetrics has also developed new analytical methods which have extended capabilities such as estimating seepage rates in circumstances with strong tidal influence, and monitoring sediment scour and deposition, and estimating cable burial depth over time. These advancements in DTS application have increased the power of DTS for discovering and characterizing groundwater seepage into surface waters and understanding sediment movement.

3.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Use of the fiber optic DTS technology provides several potential benefits to the Navy. First, it is the only technology capable of measuring temperature differences at the shallow sediment interface for use in identifying seepage across large areas. Although infrared thermal imaging can be used to measure temperature at the surface of water, it is often unable to detect seepage due to mixing, dilution, and dispersion that occurs between the sediment and water surfaces. This can lead to both false positives and false negatives regarding groundwater seepage locations and occurrence. DTS, however, pinpoints areas with seepage and rules out areas with low or no seepage. For example, a recent 50-acre DTS study in the Passaic River found seepage occurring in less than 5% of the site area. This would have been unlikely to be discovered using conventional methods. This high-resolution data can increase cost-effectiveness of follow-up investigations and provide regulators increased confidence that the site is well characterized. DTS data has been used and accepted by state and federal regulatory agencies at numerous locations to better understand associated contaminant transport and calibrate and validate transport models.

Second, DTS can provide continuous monitoring over an extended time period. This allows for detecting the influence of tides, groundwater level changes, surface water level changes, and seasonal variations. As found in the current study (see below), seepage may be intermittent, reflecting changes in groundwater level conditions. By monitoring through time, DTS can detect or rule out seepage at certain times, and estimate flow rates and their dependence on site conditions, such as changes in tides, seasons, or groundwater pumping, which can drive pressure head changes affecting seepage rates.

Third, a more complete characterization of seepage across a site can increase the cost-effectiveness of remediation. For example, at a site where capping is under consideration, portions of the site may be found to have little or no seepage and thus require little or no capping, or seepage may be concentrated at a few localized areas. Estimating sediment scour and deposition over time also may help assess natural recovery at a site and assist in evaluating appropriate cap armoring needs.

Fourth, DTS methods have been proven. Commercial clients have found DTS cost-effective at a variety of sites and scales over the past decade. It's likely that DOD sites will recognize similar cost-savings with better information about seepage location and flow rates.

Fifth, DTS is cost effective relative to other monitoring technologies at sites requiring information at many locations. For example, a DTS system can detect seepage at thousands of locations at similar cost to point-measurement studies sampling at only a handful of locations.

In terms of limitations, site factors such as a rocky sediment and extensive underwater obstacles can hamper fiber optic burial and installation. Fiber deployment is also limited by water depth. Most installations have been at water depths of 50 feet or less, though deeper water installations are feasible dependent on site conditions. Sites at which vessels anchoring or the general public activity may disturb the deployed DTS cable also require consideration. Additionally, DTS has limited capabilities to discern groundwater emergence in systems with coarse, open sediment structure such as gravels because hyporheic exchange can reduce the temperature signal associated with seepage. There are also seasonal limitations, since the method requires temperature differences between groundwater and surface water: DTS is most successful during summer and winter seasons, when differences in surface water and groundwater temperature differentials are greatest. Although site bathymetry data is not required for the DTS technology to identify seepage locations, the analytical tools used to estimate seepage rates typically require site bathymetry.

4.0 FACILITY/SITE DESCRIPTION, LOCATION, AND OPERATIONS

The Navy has many sites across the country where groundwater and contaminant plumes discharge to surface water. The project team discussed this project with RPMs who participate in NAVFAC's Sediment Workgroup and solicited possible sites through them. The top two candidates considered for a field demonstration of the DTS technology were former NCBC Davisville (BRAC site) and OU7 located at Norfolk Naval Shipyard. After a review of available data/information regarding site characteristics, and discussions with RPMs regarding additional data needs at these sites, the project team selected the former NCBC Davisville site for the DTS demonstration.

Former NCBC Davisville Site 7 is a BRAC site where the Navy (EXWC) has conducted detailed investigations of a chlorinated volatile organic compound (cVOC) plume.[4] [5] The site is a cVOC-contaminated peninsula (Calf Pasture Point) surrounded by water on three sides (Allen Harbor, Allen Harbor entrance channel, and Narragansett Bay; Figure 1 and Figure 2). Contaminants have been detected at several discrete points using direct-push probes (Trident) and seepage rates were estimated with seepage meters (UltraSeep), including along the shoreline near the entrance channel to Allen Harbor.

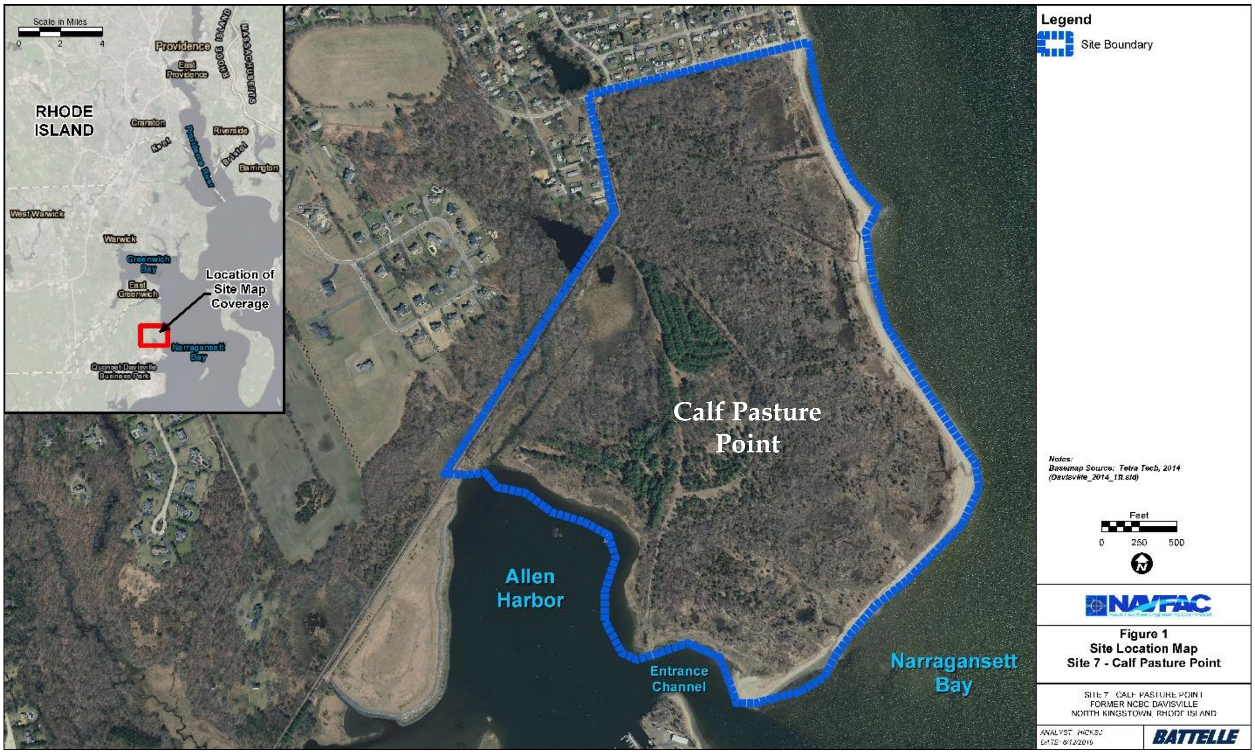

Figure 1. Site Location. The former Naval Construction Battalion Center (NCBC) Davisville Site 7 was located on Calf Pasture Point. Seepage into surface water was previously found in the Allen Harbor Entrance Channel. (Source: Reference 5).

Figure 2. Aerial view looking west into Allen Harbor and the entrance channel. The former Naval Construction Battalion Center (NCBC) Davisville Site 7, in North Kingstown, Rhode Island, was on Calf Pasture Point (on right). **(Source: https://marinas.com/view/harbor/75t6l_Allen_Harbor_Allen_Harbor_RI_United_States)**

Although DTS is suited to many site sizes, this site highlights the ability to cover an extended area, in particular the Allen Harbor entrance channel. Other favorable site characteristics include:

- Soft sediment consisting of silts and sands along the shoreline near the entrance channel to Allen Harbor and sand along the Narragansett Bay shoreline
- Tides and seasonally-affected groundwater, which highlight benefits of continuous monitoring
- Modest currents that simplify installation
- Shallow water (less than 30 feet deep) which additionally simplifies installation, although deeper water installations are possible.

The groundwater aquifer at the Davisville Site 7 consists of unconsolidated coastal sediments overlying glacial till and bedrock. The shallow aquifer consists of mainly sand, silt, and gravel approximately 20 to 25 feet thick along the shoreline. Much of the area was augmented with fill taken from dredged channel deposits. There are also areas of artificial fill along the shoreline. Groundwater level monitoring at the site indicated a generally upward gradient from the deeper aquifer to the shallow aquifer.

Site investigations outlined four main aquifer layers: a surficial sand layer, intermediate sand, and gravel layer, a deep till layer, and a basal bedrock layer. The shallow, unconsolidated, freshwater aquifer is present along the Calf Pasture Point peninsula, with groundwater migrating from the north to the south-southwest toward the channel in the area of interest.

At the shoreline intertidal zone, the groundwater has previously been found to discharge into the bay. The aquifer is affected by tides and waves, resulting in a shallow saline zone at the beach shoreline. The system also exhibits a larger transition zone between saltwater and freshwater. The intertidal area is the area where most mixing was believed to occur, with periods of groundwater discharge to the bay at low tide and periods of saltwater movement into the freshwater aquifer at high tide. However, previous seepage meter results suggested uneven tidal affects across locations (Appendix E). Seasonal changes in groundwater movement had not been studied prior to this study.

It is difficult to predict seepage locations or rates from site stratigraphy and hydrology because small-scale heterogeneities in aquifer properties, including preferential pathways, can be as important as the large-scale site stratigraphy. The presence of a source of groundwater and gradient toward surface water is necessary, but that does not determine specific locations of seepage, which can vary by orders of magnitude even when driven by the same overall stratigraphy and groundwater level. This is why seepage measurement is needed even when a site is well-characterized and modelled.

The shoreline from Calf Pasture Point slopes gradually into the Allen Harbor entrance channel and into Narragansett Bay. Seawater levels typically fluctuate 0.7 to 1.7 meters (2-5 feet) with semi-diurnal tidal cycles. Consequently, the location of the shoreline varies substantially with weather events and daily tides. The Allen Harbor entrance channel has a maximum depth of approximately 4 meters (13 feet).

5.0 TEST DESIGN

5.1 DEVELOPMENTAL TESTING

In-field DTS seepage detection has been used by SelkerMetrics since 2010, thus no developmental testing was required for the field component of this project.

A test of analytical methods was conducted in an off-site laboratory experiment. Results documented the precision of seepage estimates and sensitivities to uncertainties in parameters and measurement. These laboratory test results furthered the development of the method, with the study report attached (Appendix C) and results summarized in Section 5.3.3.

5.2 CONCEPTUAL TEST DESIGN

This study was designed to demonstrate the benefits and practicality of deploying distributed temperature sensing (DTS) systems for locating and quantifying under-water seepage from sediment into surface water. To accomplish this, DTS cable was installed in a sinuous pattern within the sediment along the shoreline near the Allen Harbor entrance channel and in two passes parallel to shore in Narragansett Bay.

The original plan was to only collect one data set immediately following cable installation in September 2022. However, seepage was found to be unmeasurable as a result of drought conditions that occurred in late summer of 2022 (Appendix D). Thus, the cable was left in place at the site, and a second data set was collected in March 2023. Between summer 2022 and the March 2023 data collection the portion of the DTS cable located along the Narragansett Bay shoreline was disturbed (likely by people that pulled the cable up on shore), and determined to be unusable. As a result, the portion of cable installed within sediment near the shoreline of Allen Harbor is the focus of this study.

In order to compare the DTS results with other traditional methods of measuring seepage, seepage meters were installed at six discrete locations along the near-shore DTS transect within Allen Harbor in March 2023.[i] Additionally, DTS analysis methods were validated with a laboratory experiment.

5.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

5.3.1 LABORATORY DTS ANALYSIS TESTING STUDY DESIGN

This project also included a laboratory experiment where an apparatus was constructed off site in which artificial groundwater seepage was created (Appendix C). Controlled seepage rates were analyzed using the same analytical tools applied in the Allen Harbor DTS study in order to validate methods used to analyze DTS data. The experimental set up is shown in Figure 3 and included the following:

- A 200-gallon tank filled with quartz sand with embedded logging thermometers at multiple depths. Grainsize analysis was not conducted on the fill sand, but the mode particle size (D50) is believed to be between 0.5 and 1.0 mm. The tank was in a temperature-stable environment and thermally insulated. The bottom of the tank was designed with a manifold mixing space below a permeable layer of geo-fabric on bar grating. The manifold mixing space was supplied with water by a peristaltic pump with controllable pumping rates and measured temperature. The manifold helped ensure a uniform temperature and pressure, and thus flow rates, across the lower permeable support surface of the column.

- Logging thermometers at various depths (in the source water, at vertical increments within the sand, and in the standing water above the sand) monitored the thermal effect of flow over time. Thermometers functioned as the DTS cable would in the field, but at multiple depths so that different cable burial depths could be evaluated. The deepest thermometers provided lower boundary conditions while the surface water thermometer provided the sediment surface temperature boundary condition

- Surface water heaters were used to create differences between groundwater and surface water temperatures, simulating differences similar to those found in the natural environment.

Each simulated seepage rate condition was typically run for several days to achieve stable temperatures.

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[i] Although seepage meters were use at the site in 2019 (Appendix E), the September DTS data show that seepage is sensitive to timing, so those results could not be used for comparison. Additionally, the locations of those meters were not coincident with the DTS cable.

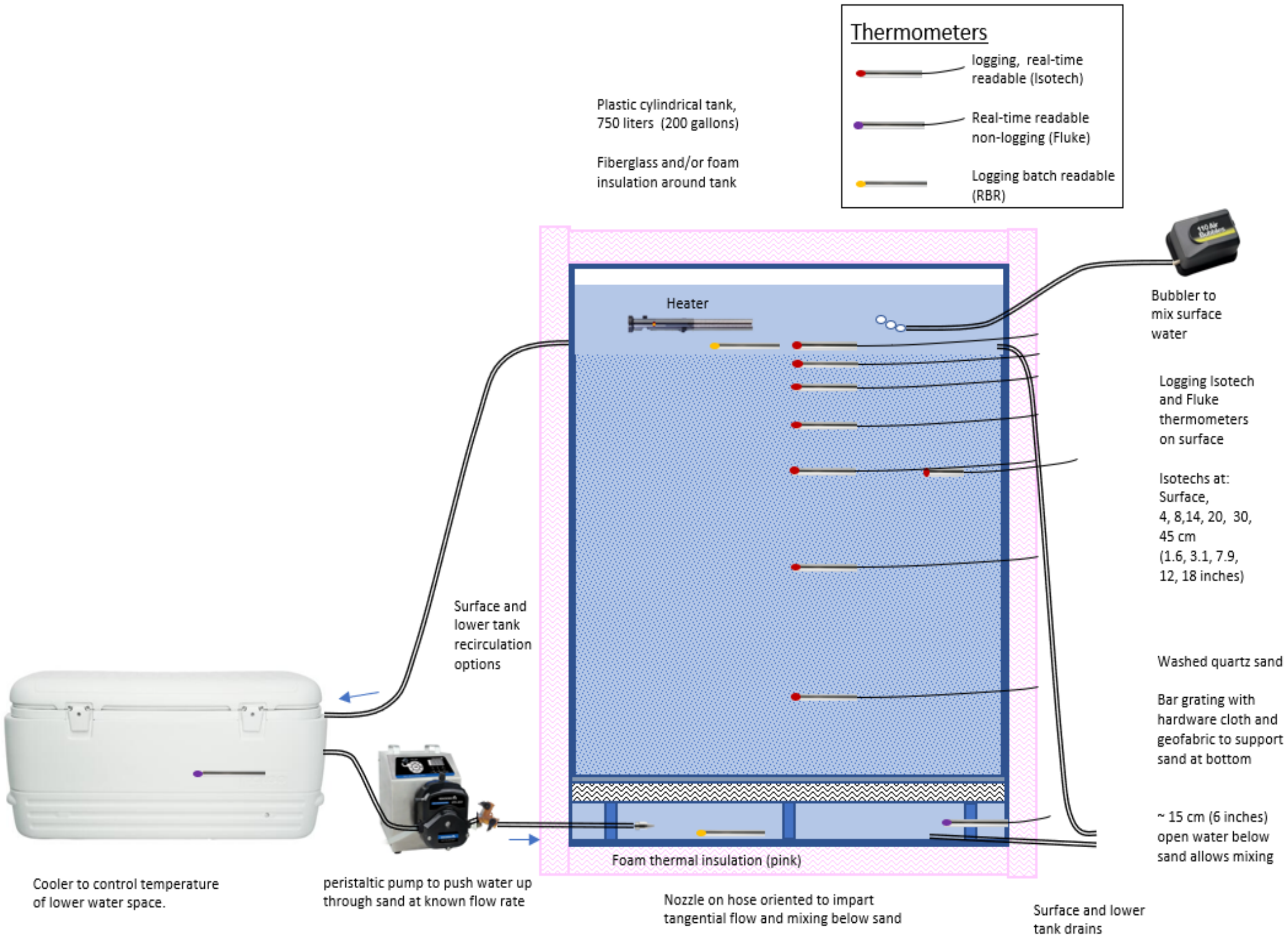


Figure 3. Laboratory setup to test DTS analytical tools for calculating seepage rates and cable depth. A sand tank was equipped to have controlled seepage rate and water temperatures, with thermometers at various depths to provide data similar to what a DTS cable collects. (Source: SelkerMetrics).

5.3.2 DTS FIELD DESIGN

Approximately 2,500 m (8,200 ft) of DTS cable were plowed approximately 7 cm (3 in) into the sediment at Davisville Site 7 (Figure 4). This provided approximately 10,000 temperature measurement locations. Initial plans had included cable installation inside Allen Harbor on the western edge of Calf Pasture Point, but the substrate was found to be too rocky for cable installation; therefore, cable installation was abandoned in this area. The installed cable ultimately scribed a large loop which started and terminated at a University of Rhode Island owned property on the southern edge of the harbor entrance channel. This property provided power and shelter to run the DTS interrogator, and housed the calibration baths. The section of cables that crossed the harbor entrance channel (not shown in Figure 4) was not intended to detect seepage so was deployed on the sediment surface, not plowed into the sediment.

DTS cable was installed in several passes on the north side of the Allen Harbor entrance channel, where previous piezometer, seepage meter, and well monitoring suggested groundwater discharge was occurring. The cable then exited the harbor entrance channel and ran north in Narragansett Bay along the eastern shore of Calf Pasture Point.

Once the cable was installed, the two ends were connected to the DTS interrogator instrument.[6] The interrogator sends laser pulses down the glass fiber, with the frequencies of backscattered light used to calculate temperature along its length. The precise timing of the returned light identifies the locations of each temperature measurement along the cable to within approximately one quarter meter (10 inches). Adjacent measurements are partially correlated due to overlap in measured timing, so fully uncorrelated measurements are at approximately half meter intervals (20 inches).

DTS systems are generally deployed to collect data at a site for one to several weeks. Once data collection is complete, DTS data are calibrated, and data are analyzed. DTS systems take advantage of the temperature differential between surface and groundwater to identify seepage locations. Various statistical and geospatial analytical techniques are employed to identify locations along the cable which correspond to potential seepage locations, and specialized analytical and numerical methods are used to estimate seepage rates.

Following data collection, the fiber optic cable may then be removed or it may be left in place for future use. The cable remains usable for many years at many sites, and can be left in place for follow-on measurements. In this study, the summer 2022 data showed no measurable seepage, so the cable was left in place for a March 2023 dataset that showed seepage. The cable at this site was removed at the completion of the study in early April, 2023.

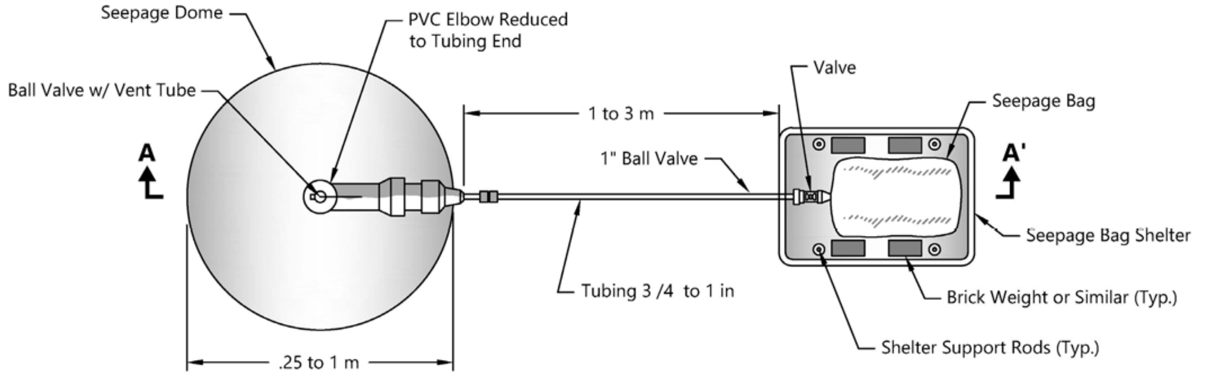
Calibration of summer 2022 data was done using a double-ended calibration approach which used two calibration water baths: one cooler and one warmer than expected measured temperatures. Because part of the cable was severed in Narragansett Bay prior to the March 2023 data collection, the cable was no longer a loop, so a single-ended calibration approach was used for data collected in March 2023. A strength of the initial two-ended loop installation is that cable failures, such as occurred in Narragansett Bay, still allow temperature readings from the two ends of the cable.

Figure 4. DTS cable installation near the Allen Harbor entrance channel (red) and along the Calf Pasture Point beach in Narragansett Bay (blue). These cables were connected around the south side of the sand spit, and each end was taken across the Allen Harbor channel to the interrogator instrument near the Quonset Hut visible near the bottom of the image. Connector cable segments not shown. (Source: SelkerMetrics).

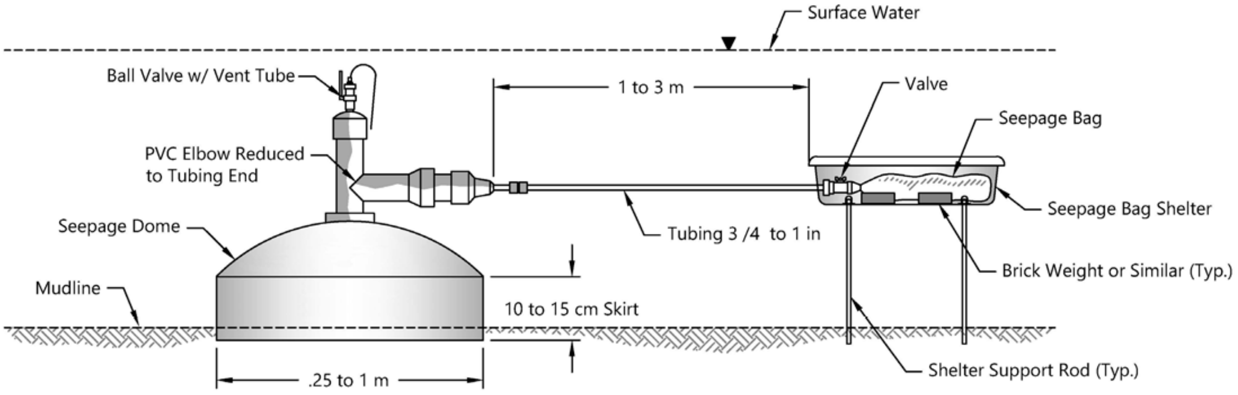
5.3.3 SEEPAGE METER FIELD DESIGN

As described in Section 5.2, seepage meters were installed at six discrete locations along the near-shore DTS transect in order to compare the DTS results with a more traditional method of measuring seepage (seepage meter locations are shown on Figure 12). These six locations were selected based upon a preliminary review of the DTS results, and included a mix of locations that were and were not expected to have seepage. The seepage meters comprised open-ended cylinders 54 cm (21 inches) in diameter which were embedded in the sediment. Total seepage collection area for each meter was 0.23 m^2 (2.5 ft^2). The top of each meter was connected by tubes to thin plastic-film bags which allowed collection of water displaced within the meter due to seepage (Figure 5 and Figure 6). Such seepage meters have been described by a number of sources,[7] [8] including potential sources of errors.[ii] Standard Operating Procedure for the seepage meter deployment and measurement is attached in Appendix B.

If the meter is placed over a location where groundwater seepage is occurring and has a good seal with the surrounding sediment, the emerging groundwater is funneled by the enclosed dome into the collection bag through the connecting tube. Seepage rate data were determined by measuring the change in water volume in the bag using a bucket with graduated volume markings.



Seepage Meter Detail
Not to Scale



Section A-A'
Not to Scale

Figure 5. Schematic seepage meter design. (Source: Appendix B).

[ii] Sources of errors are noted in references 7 and 8 and include: incomplete seal with sediment, insufficient equilibration time, drainage or bubbles associated with low water levels, improper bag attachment, bag resistance, moving water, leaks, measurement (e.g., bag weighing) error, insufficient or excessive measurement duration, trapped gas/bubbles, impacts of observer proximity to meter and handling of bag, improper correction coefficient (they typically under-estimate seepage due to friction, which can be accounted for in part with multipliers), spatial heterogeneity of seepage rates.

Figure 6. Example seepage dome, tube, and bag during low tide (Meter 3). The meters may not funnel seepage when exposed during low tides such as this. (Source: Anchor QEA).

Five of the six meters were installed near the DTS cable, and the results of those five meters have been evaluated below. All locations were on the south side of Calf Pasture Point shoreline near the Allen Harbor entrance channel (Figure 12). The meters were deployed in March 2023 for 3 days, starting immediately after the March 2023 DTS data set was collected.

Data collected by the seepage meters were analyzed for statistical performance and compared to the DTS data. Five of the six locations selected for confirmation seepage measurement were within the intertidal zone where the meters became fully exposed during low tide cycles. Under these exposed conditions during low tide, the meters may not collect or retain seepage discharged (footnote ii). Additionally, it was not practical to install meters in deep water (due to safety concerns), so only near-shore locations were monitored.

6.0 PERFORMANCE OBJECTIVES AND ASSESSMENT

Table 1 shows performance objectives, data requirements, and success criteria for the demonstration project.

Table 1. Performance Objectives, Data Requirements, and Success Criteria

Performance Objective	Data Requirements	Success Criteria	Criteria Met
QUANTITATIVE			
Identify underwater seepage location (primary objective)	DTS data and analysis. Seepage meter results.	Consistency in locating seepage between DTS and conventional point measurements where both are deployed, or detection by DTS that was missed by conventional measurements.	Yes
Collect high-quality temperature data (primary objective)	Collect calibrated DTS data from deployed cables on continuous basis during data collection periods.	Relative precision of 0.05 °C or better along the sensing fiber Spatial resolution of one meter or less Temporal resolution of 60 minutes or less At least 3 days of data	Yes
Quantify seepage flux rates (secondary objective)	Temperature and ancillary data, including cable depth estimate, sufficient to estimate seepage rates	Quantified seepage rates for flow rates between 3 and 20 cm/day Darcy flow Flow rate uncertainty of approximately factor of three	Yes
Validate analyses (primary objective)	Validate analyses with laboratory study	Additional lines of evidence demonstrate flux rates measured with DTS with a high probability	Yes

	Compare seepage rates with seepage meters, as data permits	of being within a factor of two of actual seepage rates.	
QUALITATIVE			
Operational requirements	Mobilization, field days, boat and other equipment rental, labor requirements for deployment, safety considerations	Data collected should be sufficient to determine reliable fixed and variable costs for use of the technology at a site, as well as the main cost drivers	Yes
Ease of use	Feedback from field technician on usability of technology and time requirements; down time; maintenance requirements	Relatively problem free deployment and operation at demonstration site, as per plan	Yes
Benefit	Feedback from the RPM and other stakeholders	The technology produced useful data	Yes

6.1 IDENTIFY UNDERWATER SEEPAGE LOCATION

A primary goal of the study was to identify underwater seepage locations at the site. This was done by identifying locations with anomalous temperatures that fit the pattern of expected seepage. In particular, locations affected by groundwater are cooled in summer and heated in winter relative to un-affected locations.

The initial planned area included areas within Allen harbor, in the harbor channel, and along Narragansett Bay. The area within the harbor was found to have a rocky substrate, so the cable could not be installed there; cable installation was successful across the other two areas.

No seepage was found in either area during the initial data collection of 14 days in late summer 2022, most likely because drought conditions essentially halted seepage activity (Appendix D). Thus, the system was successful in documenting the absence of seepage in the monitored areas under dry conditions.

The cable was left in place, not collecting data, until a second data set was taken in late winter 2023. The cable in Narragansett Bay had been disturbed in the intervening period, rendering it unusable, so data were not collected for those locations. However, the cable in Allen harbor was intact and the second data set supported identifying seepage locations in that area.

Data Requirements: Identifying seepage locations requires temperature measurements from the DTS system supporting the identification of seepage or the lack thereof. The DTS system collected a temperature reading every 10-minutes at a spatial resolution of approximately 0.25 m. During the September summer data collection period in 2022, the DTS monitored approximately 10,000 locations in the Allen Harbor entrance channel and Narragansett Bay at 10-minute intervals for approximately 14 days, for approximately 20 million total measurements. During the winter data collection this provided 6,000 data locations for the length of installed cable and 9 million data points in total between March 13 and March 23, 2023.

Success Criteria: Identification of seepage locations.

Criteria Met: The criterion was not met for the area within Allen harbor because the cable could not be installed there due to the rocky substrate. The criterion was exceeded in the Allen Harbor channel in that two data sets were collected, rather than the expected single data set. This allowed documenting the absence of seepage under dry conditions and the locations of seepage under wetter conditions. The criterion was met in Narraganset bay in that a lack of seepage in dry conditions was documented with the single planned data collection.

6.2 COLLECT HIGH-QUALITY TEMPERATURE DATA

Data Requirements: The DTS system must collect temperature data that is of sufficient precision and spatial and temporal resolution that seepage locations may be identified by their effect on sediment temperature.

Success Criteria: Success criteria included:

- Relative precision of 0.05 ^{o}C or better along the sensing fiber
- Spatial resolution of one meter or less
- Temporal resolution of 60 minutes or less
- At least 3 days of data

Criteria Met:

- Calibration baths showed standard deviation across locations within the baths of 0.026 ^{o}C average for cold and warm baths, better than the 0.05 ^{o}C relative precision for adjacent locations. Some of this variability is due to imperfect mixing and position differences with calibration baths, so DTS average errors across locations will be less than this value.

- Spatial resolution was approximately 0.25 meters. Adjacent locations have some correlation, so resolution of essentially uncorrelated data is 0.5 m. This is better than the one-meter criterion.

- Temporal resolution was 10 minutes, better than the 60-minute criterion.

- Data collection was 14 days in summer 2022 and 10 days in winter 2023, greater than the minimum criterion of 3-days of data.

6.3 QUANTIFY SEEPAGE FLUX RATES

Data Requirements: To locate seepage it is sufficient to identify anomalous temperatures that fit general patterns expected of seepage (previous objective). Quantifying seepage flux rates requires more precise temperature data from sediment/water interface. That is usually obtained by having accurate interface temperature time series at several depths spanning the sampled area, then interpolating to every location based on water depth. However, there was not sufficient bathymetry data at the site to do this for locations other than the near-shore transect in the Allen Harbor channel. These near-shore locations were also where seepage meters were practical to deploy, so were most valuable for comparison with meter results.

Success Criteria: Obtaining seepage rates for locations with sufficient interface temperature data.

Criteria Met: Seepage flux rates were calculated at approximately 700 locations (each 0.25 m interval along 175 m) along the DTS cable for the Allen Harbor DTS transect near to shore. This supported comparisons with seepage meter results.

6.4 VALIDATE ANALYSES

Data Requirements: Analytical methods have been developed by SelkerMetrics to estimate cable burial depth (a critical input for other analyses) and seepage flux rates. These are based on fundamental heat transfer equations and best-fit algorithms seeking optimal matching of measured data with burial depth, seepage rate, and tidal influence.

The project included two methods to demonstrate and validate DTS and analytical findings: (1) an instrumented laboratory seepage tank in which known seepage rates were compared with analytical estimates, and (2) comparison with seepage meters installed at several near-shore locations in Allen Harbor channel.

Success Criteria: The laboratory tank was built and operated with six protocols of seepage rates and changing surface temperatures through time, with each protocol running until sufficient data was collected, between 1.5 to 12 days. The results demonstrated that the analytical methods were within 30% of actual values, and were often within 15%. The discrepancies reflect in part uncertainties associated with tank construction, operation, and measurement, suggesting the analytical methods are quite accurate.

Five seepage meters results were compared with DTS estimated seepage rates. Four of the meters agreed with the DTS findings within uncertainty bounds of the data. This was evaluated by comparing mean results and 95% confidence intervals determined using two-sided t-tests. At one location the DTS reported a significant seepage rate while the meter did not.

Criteria Met: The laboratory test tank validated DTS algorithms for estimating cable depth and seepage rates using multiple approaches (steady-state and non-steady state conditions). Four of the five seepage meters had findings consistent in agreement with the DTS findings. At the one location with differing DTS and meter results it is not known if it is due to slightly different locations or uncertainties with either method.

6.5 OPERATIONAL REQUIREMENTS

Data Requirements: Installation and operational resources and time required.

Success Criteria: The DTS installation was completed in five days, which was as budgeted, with costs and equipment requirements as expected. Cable removal and demobilization was also within budget. The seepage meters were also deployed, operated, and demobilized within expected budgets and time. The second DTS data collection, in March 2023, had not been anticipated in planning or budgeting, but was completed within the original budget. This is because there was little cost associated in waiting for wetter conditions and the analysis of a second data set was completed within budget.

Criteria Met: The DTS and seepage meter systems were deployed, operated, and demobilized within expected field time estimates and budget.

6.6 EASE OF USE

Data Requirements: The DTS deployment involves pulling a purpose-built underwater plow which buries the cable in the sediment. The installation was successful in Allen Harbor Channel and Narragansett Bay, with challenges common to field work. At many sites the plow can be pulled fairly quickly and with little interruption, burying up to 5 km of cable per day. At this demonstration site the plow encountered many rocks at the first attempted location, preventing deployment within Allen Harbor. Installation within Allen Harbor Channel went fairly smoothly, although the curved transects added some time to boat placement and plow movement. Installation on Narraganset Bay was mostly smooth but the cable snagged on the plow and/or obstacles several times, requiring redoing sections of transects. Winds and waves on the exposed Narragansett Bay picked up in the afternoons, limiting time per day, and thus slightly reducing cable length deployment. Finally, the deployment boat had some challenges with the electrical systems and spuds that slowed operations. However, in spite of the challenges, which are not atypical for such field work, deployment was completed within budget.

Removal of the cable was as expected where a vessel travelled along the buried path and cable was pulled from the sediment and wound onto a spool. This process is repeated along the buried cable path with anchor's attached to cable removed as well. Because the cable was left in place for approximately 7 months, there was some algae growth that had to be removed as the cable was spooled in. This straight-forward removal of the intact cable allows for potential reuse of the DTS on other projects. Removal of the portion of the cable that had been brought up on the shore of Narragansett Bay, perhaps by people visiting the beach, necessitated removing damaged sections of cable which had to be collected from shore, cut, and discarded. All deployed DTS cable and associated equipment was removed from the project area

While deploying and removing of the DTS and seepage meters, changes or modifications to work scope as a result of weather conditions or equipment were discussed as a team by stopping work assess and ensure work could continue safely. There were no safety incidents associated with deployment or removal of the DTS.

Seepage meter deployment involved locating targets along the sediment surface and wading to bring necessary equipment to each location. Each seepage meter dome was manually pushed into the sediment at least 10 cm or further if able. The domes were then connected to seepage bags via hose and seepage bags were placed into shelters set onto support rods so that the seepage bag remained at the same approximate water depth as the top of the seepage dome. Deployment of equipment was easy once a target area was chosen free of debris such as wood, large rocks or anthropogenic material. The main deployment challenge was working around the low-tide, allowing workers to wade or walk on sediment, to service each seepage meter.

Removal of seepage meters was accomplished at low-tide by manually removing all equipment an brings to shore for decontamination and removal from the project area.

Success Criteria: Successful and safe deployment and demobilization on field schedule.

Criteria Met: Like most field work, there were challenges, but both deployment and demobilization were completed on schedule and budget without safety incidents occurring.

6.7 BENEFIT

Data Requirements: Collection of cost-effective and high-quality temperature and seepage meter data along with associated data processing to identify seepage can be used to validate a projects conceptual site model(s) as well as refine models to allow for more certainty in evaluation and discussion of contaminant transport.

Success Criteria: Successful use of the collected data allows a project to be more certain and confident in discussing data-supported risk pathways, or lack thereof, for a site. With these additional data, resources can be allocated for a project in a targeted way to ensure real risks are being addressed and resources are not wasted. Long-term monitoring programs may also be undertaken with the increased understanding of seepage locations which could lead to a cost reduction without a loss in protectiveness.

Criteria Met: The collected DTS and seepage meter data are of high quality and will be useful for data-supported refinements of contaminant transport models. This will aid project goals of allocating resources to areas where there are proven risks and can have the most impact.

7.0 RESULTS

7.1 LABORATORY TESTING RESULTS

A separate report providing a detailed description of the laboratory study setup and results is provided in Appendix C.[9] In summary, results indicated that the analytical methods reproduced measured values for both seepage rates and fiber depths to within 5-30% of true values. This was within the expected combined uncertainty of the test sand column and methods, including uncertainties in parameters and boundary conditions. Estimates of cable depth and seepage rates are affected by thermal properties of the sand and temperature variations of surface and groundwater, but the effects of expected ranges of uncertainties generally changed results by less than 10%, and at worst are similar to the ratio of change of those parameters, so uncertainties are not amplified by the methods.

Key findings include:

- A finite difference-based model of temperature profiles within the matched profile temperatures well, with differences generally less than 0.25 °C for surface water temperatures that varied over time from 5 °C - 30 °C.
- Estimates of thermometer burial depth (analogous to DTS cable burial depth) estimation was accurate to within 1.5 cm for datasets with no seepage, and to within 2 cm for datasets with seepage.

- The seepage rate model for steady-state conditions was tested in two versions on data sets with two different seepage rates. In all cases estimated seepage rates were within 25% of the average measured seepage rate. This model was used in the current study.

- The seepage rate model for non-steady state conditions (e.g., with diurnal and/or tidal effects) was tested on two data sets, both of which yielded seepage rate estimates within 20% of the measured seepage rate, except for the shallowest sediment depths in one data set where the difference reached 30%.

- Sensitivity of results to uncertainties in sediment thermal parameters (heat capacity and thermal conductivity) were very low in many cases, and at worst below the percent change in parameters. Thus, at worst the seepage rates will be off about the same percentage as the error in parameter values.

- Sensitivity of results to uncertainties in surface water temperature, typically the most uncertain boundary condition, were found to be low when estimating burial depth (about 1 cm); slightly less than the percent error in surface temperature for seepage rate estimates using the steady-state model; less than 5% for all but the largest temperature offset using the non-steady state model.

The results of these laboratory tests suggest that where there is adequate data regarding sediment properties and boundary conditions (surface and deep-water temperatures), model estimates will be within about 30% of true values. Given the typical a priori orders-of-magnitudes uncertainties, and/or the absence of information about seepage locations and rates, this precision at high spatial resolution over large areas offers substantial insight into seepage from sediment.

7.2 DTS RESULTS

7.2.1 DTS SEPTEMBER 2022 RESULTS

Results from the initial September 2022 data set indicated no detectable seepage was present during the data collection period. An analysis of precipitation and anticipated groundwater recharge suggested a severe summer drought in the area had resulted in low water tables that likely reduced groundwater seepage below the detectable limits of the DTS system (Appendix D). As a result, the DTS cable was left in place for an additional data collection event in March 2023.

7.2.2 DTS MARCH 2023 RESULTS

7.2.2.1 SITE CONDITIONS DURING MARCH 2023 DTS DATA COLLECTION

The March 2023 DTS data collection period was chosen to maximize temperature differential between cold surface water and warmer groundwater. This late winter collection period provided a greater likelihood of detectable groundwater discharge driven by recent snowmelt and rainfall recharging the local aquifer.

Figure 7 shows general site conditions during the March 2023 data collection period. This figure shows temperatures of the air, surface water, sediment pore water at 21 inches below the sediment surface, and groundwater at approximately 13 feet below the ground surface. Groundwater averaged approximately 4.5 °C warmer than surface water during this period, offering a significant temperature differential to reveal seepage locations.

A moderate sized storm dropped approximately 2.0 in of precipitation on the site at the beginning of the data collection period. No additional precipitation of significance fell during the remainder of study period. Air temperatures fluctuated considerably during the period, ranging from -2.8 °C to 15.6 °C.

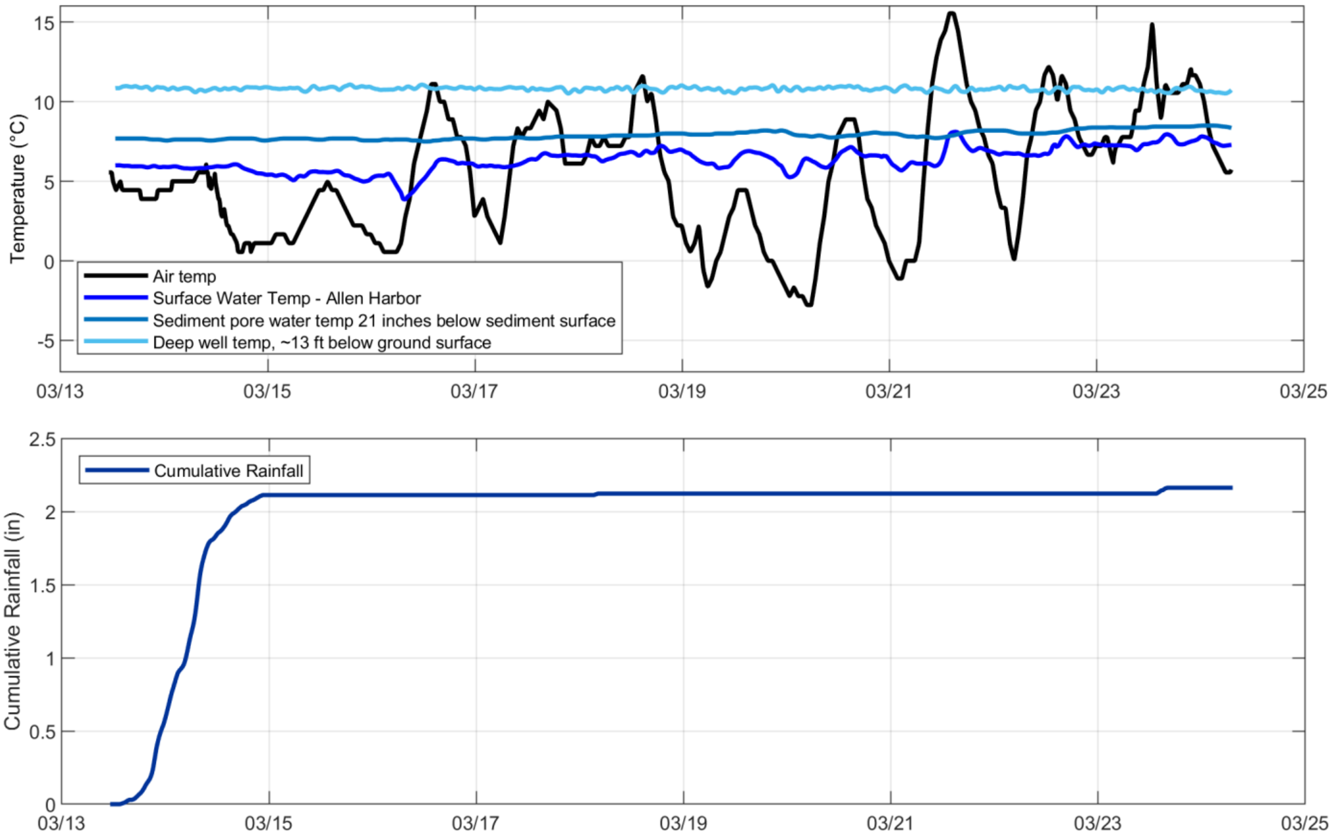


Figure 7 Site conditions at Allen Harbor during the 'late winter' March 2023 DTS and seepage meter collection period. Air temperature data was collected from a private weather station located approximate six miles from the field site (41.706° N, 71.415° W). Sediment pore water temperature was collected in Piezometer P07-09, and Deep well temperature was collected near shore in well MW07-23D. (Source: SelkerMetrics).

During the 11-day data collection period the low tides became lower, and began to expose DTS-monitored sediment at areas closest to shore at around 9 AM on March 19 (Figure 8). This led to large temperature excursions in the near-shore monitoring zone, as exposed sediment temperatures changed with air temperature and solar input. Figure 8 shows that after March 19th mean and median fiber temperature begin to diverge, and the standard deviation of fiber temperature across the site significantly increases. Such variability is not necessarily a challenge for DTS analyses, and in fact can sometimes improve estimates of cable burial depth. However, in the absence of precise bathymetry, it was not possible to determine just when each location became exposed to air. Thus, the less variable data collected during the first 5 days of the study period (March 13-18) were used for groundwater seepage detection and seepage rate calculations.

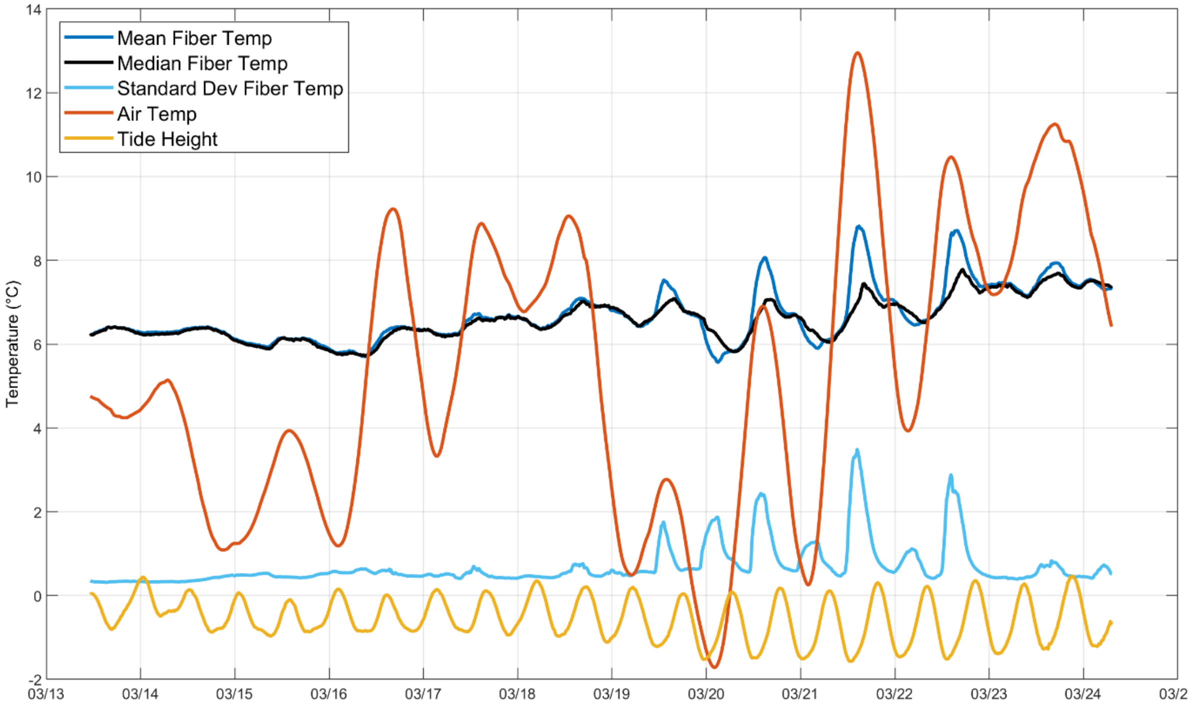


Figure 8. Low tides became lower around March 19, exposing near-shore sediment being monitored by DTS. This led to larger temperature fluctuations, as indicated by increasing standard deviation of temperature along the cable and increasingly variable mean temperatures for the cable. All monitored sediment appears to have remained submerged during earlier periods, and those data from March 13-18 were used for the analysis. (Source: SelkerMetrics).

7.2.2.2 DTS-BASED GROUNDWATER SEEPAGE LOCATION RESULTS

There are many methods (both quantitative and qualitative) to identify the locations of seepage using DTS temperature signatures. Qualitative methods involve identifying locations with temperatures that are anomalous in ways suggesting seepage. For example, during a winter monitoring event, seepage will warm the sediment. Another indicator can be sensitivity to tides, which at many sites can halt seepage and reverse temperature effects (Appendix F). Given uncertainties in temperature measurements, anomalies of a few tenths of a degree Celsius or greater may be suggestive of seepage activity, although that threshold can vary with site conditions and other lines of evidence. Quantitative methods may be used where sufficient data is available. In particular, seepage rate may be estimated where sufficient supporting data is present to characterize boundary conditions for modelling sediment temperature. At this site this was possible for the near-shore transect, for which sediment surface temperatures could be estimated. Deeper areas did not support this, but would have been available for quantification if accurate bathymetry had been available or sediment surface temperatures had been monitored.

Applicability of methods and thresholds depends on site characteristics and what data are collected during the study. Multiple methods are used to increase confidence and details in the findings.

The monitored site showed evidence of 21 groundwater discharge zones, spanning a total of 17 m, ranging in size from less than 1 m to more than 50 meters. Figure 9 presents the fiber optic cable layout overlaid with associated anchors at the end of each transect (red) and locations of groundwater seepage identified from the DTS data (orange). Damage occurred to the section of cable installed along the Narragansett Bay between installation in late summer 2022 and the March 2023 data collection. This damage was due to cable exposure and movement associated, likely associated with human interaction, so no data were collected from this section of fiber, as shown by the fiber ending along the eastern edge of Figure 9.

The DTS system collected a temperature reading every 10-minutes at a spatial resolution of approximately 0.25 m, resulting in 6,000 locations along the length of installed cable and 9 million data points in total between March 13 and March 23. For winter data, seepage present as warm temperature readings relative to colder surface water and sediment temperatures.

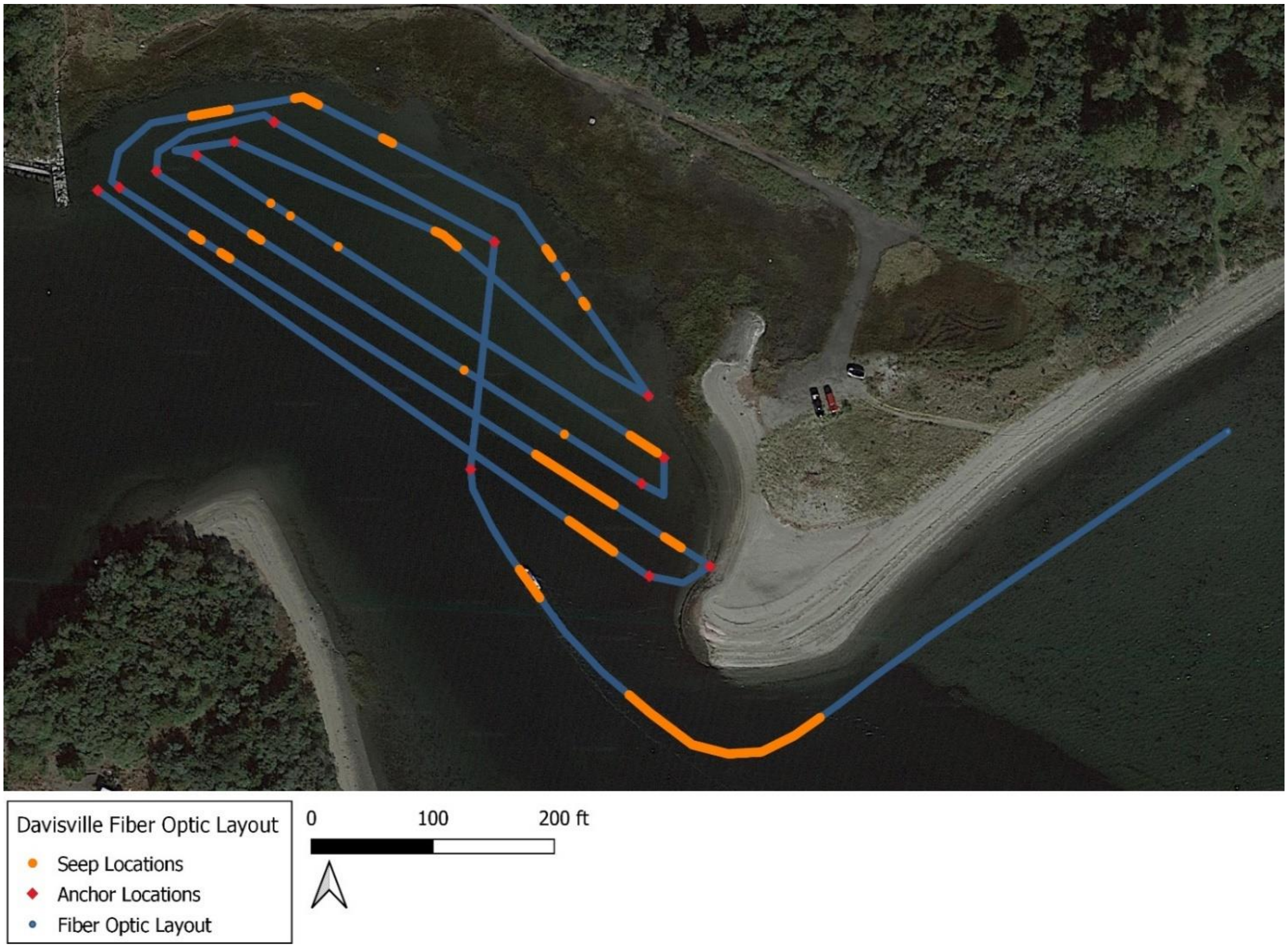


Figure 9 Shows the fiber optic cable layout at Allen Harbor (blue), along with anchors used to hold transects in-place during installation (red), and locations with indications of seepage (orange). Note, exact locations of the two southern-most seepage regions in the Allen Harbor channel are not known. This portion of the fiber optic cable was a connector between the Allen Harbor and Narraganset installations, so was not initially buried nor tracked with a GPS unit for location data. (Source: SelkerMetrics).

Figure 10 presents a series of line plots showing March 2023 temperature data along the length of fiber optic cable. The left side of the plot starts at the west end of the site and works along the cable to the eastern terminus. Vertical lines in the plot represent anchors and are useful to orient a location on the fiber to its location in the field site. The first plot (Figure 10a) shows normalized temperature, which is the average temperature at a location minus the average temperature of all locations through time. Normalized temperature provides the same information as mean temperature, but by removing the average it highlights the degree to which a location deviates from the norm (i.e., how many degrees a location is above or below the average fiber temperature). The warm groundwater presents as upward temperature deviations. Seepage locations are shown with a red dot at their maximum temperature deviation, and the red line below indicates the spatial extent of the seepage zone.

Figure 10b shows the standard deviation of fiber temperature data. The steady discharge and stable temperature of a seepage has the effect of attenuating temperature changes through time. This often results in groundwater seepage zones having reduced standard deviations compared to surrounding non-seepage locations. However, lower standard deviations can also reflect a more deeply buried cable, so burial depth analysis (below) is helpful in combination with variability. Locations with low standard deviations correspond well to locations with warm temperature anomalies in the normalized temperature plot.

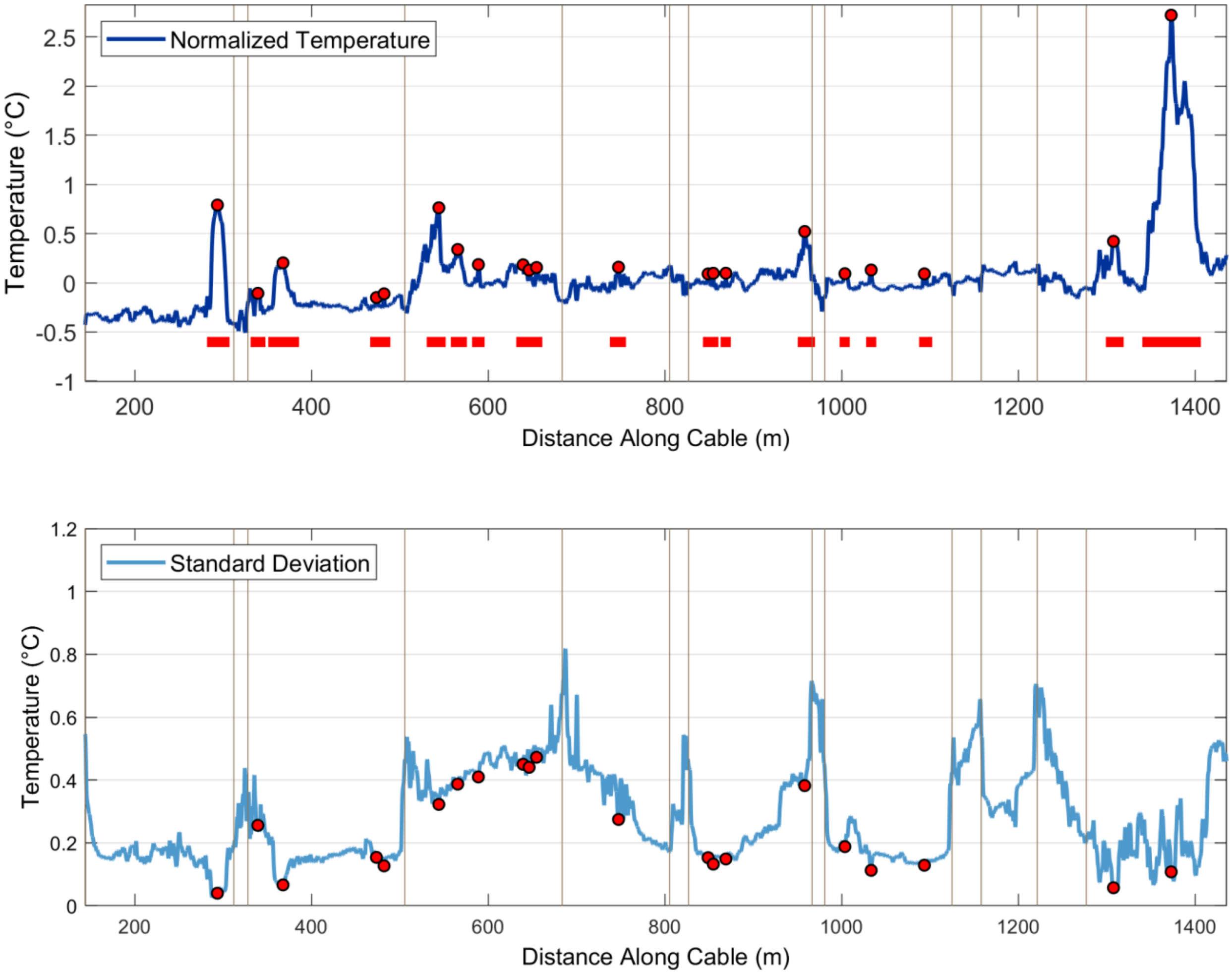


Figure 10. Line plots of temperature data along the length of the fiber optic cable. Normalized temperature and Standard Deviation of the temperature are shown at each location along the fiber. High temperatures and low variability can indicate seepage. Vertical lines are anchor locations shown in Figure 9 and red dots are the location of groundwater seepage maximums. Note that reading the line plots from left to right moves from the northwest end of the fiber in Figure 9 through the transects to the eastern end of the fiber. The near-shore transect runs between the anchor near 500 m the anchor near 700 m. (Source: SelkerMetrics).

Animating the temperature signal through time provides an additional view of the temperature data. Fiber temperatures fluctuate through time with tide changes, water temperature variations, solar input, and air temperature changes, as well as other environmental factors. Seepage locations attenuate temperature variations, and locations resistant to temperature change stand out compared to surrounding locations.

A modeling approach which tracks changes in temperatures through the sediment profile versus cable temperatures also helps identify ambiguous seepage zones. The model uses a fitting algorithm which determines if the observed buried fiber temperature matches the modeled sediment temperature. At locations with groundwater discharge, the upward energy carried by the groundwater produces a sediment temperature profile which does not match the modeled profile that is not seep-affected.

Figure 11 illustrates this analysis. The heavy brown line shows the temperature through time at the sediment surface for a location along the northern most transect nearest shore. The five lighter brown lines are modeled sediment temperatures with each successive line representing a 2.5 cm depth increment, to a total depth of 12.5 cm. In the case of this winter dataset, sediment temperature warms with depth, hence the light brown lines are above the heavy brown line.

The three additional lines in Figure 11 (Blue, Green, and Pink) are fiber optic temperatures observed at three locations along the cable. The blue line is a location with no apparent groundwater discharge, since the temperature profile matches the modeled sediment temperature profiles. The green and pink lines are warmer than the modeled sediment temperature, suggesting that warm groundwater is emerging in these locations and heating the fiber/sediment. Note that all three temperature profiles are similar in shape, implying similar effects of surface water temperature changes and thus similar burial depths.

Through these analyses a total of 21 seepage zones were identified which covered approximately 10% of fiber-monitored locations. Appendix G provides a table with X-Y coordinates for the center of each identified seepage (Table 6).

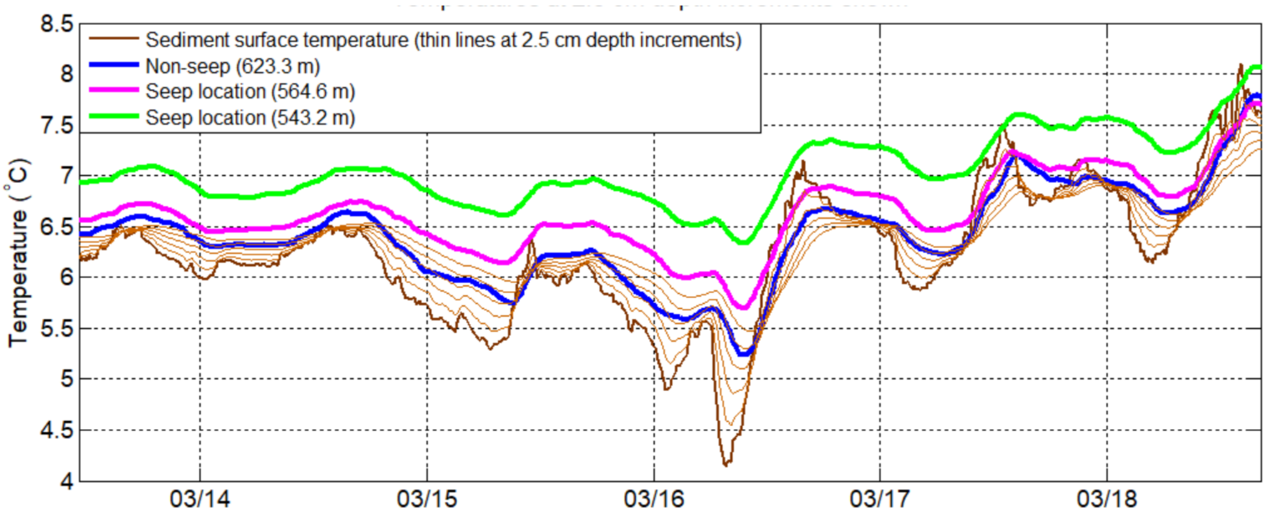


Figure 11. Observed sediment surface temperature through time (heavy brown line) and modeled sediment profile temperatures with increasing depth increments of 2.5 cm (light brown lines). Also plotted are time series of 3 locations on the fiber optic cable: The blue line represents a location not associated with groundwater seepage, while the pink and green lines represent 2 locations perhaps warmed by seepage. In this winter data set, sediment warms with depth and groundwater discharge additionally warms locations hence all temperature profiles are warmer than the sediment-surface boundary. (Source: SelkerMetrics).

7.2.2.3 DTS-BASED SEEPAGE RATE QUANTIFICATION

To demonstrate DTS-based seepage rate quantification, the analysis focused on the northern most near-shore transect in the Allen Harbor entrance channel, where seepage meters were installed and where, in the absence of bathymetry across the site, surface water temperatures were best known.

To estimate seepage rates from observed fiber temperatures, surface water temperature, deep groundwater temperatures, and cable burial depths are required as model inputs. Surface water temperature for the near-shore DTS transect was estimated from sections of cable that were exposed to surface water such as at anchor locations (see Figure 9 for anchor locations). Deep groundwater water temperatures were measured in well MW07-21D.[10]

Regarding cable burial depth, when fiber temperature data are collected immediately after cable installation, the assumption of burial depth being equal to plow-installation depth is valid. However, the March 2023 data were collected approximately 6 months after cable installation, likely resulting in sediment movement across the site and invalidating assumption of burial depth assumption.

To accommodate this situation, SelkerMetrics has developed algorithms to estimate cable burial depth from temperature data. These were applied and results indicated that the near-shore cable burial depth remained similar to installation depth, generally 5-10 cm deep. This suggests that little net deposition or scouring occurred in the Allen Harbor entrance channel installation between late-summer installation and late-winter monitoring.

A steady-state seepage rate analysis was used based on surface water temperatures remaining relatively constant between March 13-18, as well as observing minimal tidal influence on sediment temperatures (Appendix F). This analysis uses a heat-transfer advection and conduction equation to calculate the seepage rate required to warm the cable to the extent observed at locations that are warmer than expected (i.e., locations that are warmed by groundwater discharge).

Figure 12 shows the mean calculated seepage rates along the near-shore transect for data collected between March 13th and March 18th, 2023. Primary seepage activity was located toward the northwestern part of the shoreline, with lower-flux seepage zones along the eastern side of the transect. Mean seepage rates ranged between 0 to 5 cm/day (Darcy flux).

To get a measure of variability of DTS seepage rate measurements, seepage rates were calculated at four times (each a 10-minute average) during the March 14-18th sampling interval when temperatures were most stable. The locations chosen for this analysis were near the seepage meters which are discussed in the following section, so that values and variability may be compared. Table 2 presents estimated seepage rates for these times for the DTS cable locations near each seepage meter. Significant DTS-based seepage rates (two-sided t-test) are found near Meter 5 and Meter 6, with mean Darcy seepage rates of 1.9 cm/d and 5.4 cm/d, respectively. Seepage meter seepage rates are positive but not statistically significantly different from zero at Meters 2, 3, and 4.

Table 2. Seepage rates estimated at four times from DTS temperature data to provide a measure of variability of measurements (cm/day). Values are shown at five locations near seepage meters, for use in comparisons in following sections. P-values are calculated using a two-sided t-test.

DTS Seepage rates (Darcy cm/day)		DTS Cable location closest to:				
		Meter 6	Meter 5	Meter 4	Meter 3	Meter 2
	Distance to Meter (m). Add ~ one meter for GPS uncertainty	0.6	0.5	0.4	0.1	0.7
Time	Time Analyzed					
1	3/14/2023 5:23	3.2	0.6	0.0	0.0	0.0
2	3/15/2023 14:46	5.1	1.7	0.0	0.0	0.0
3	3/16/2023 22:29	6.7	2.7	0.2	1.4	0.2
4	3/18/2023 1:12	6.7	2.6	0.4	2.1	1.4
	Mean	5.4	1.9	0.2	0.9	0.4
	Standard Dev	1.7	1.0	0.2	1.0	0.7
	p-value	*0.01*	*0.04*	*0.26*	*0.25*	*0.39*

7.2.3 SEEPAGE METER RESULTS

Figure 12 shows locations of the six seepage meters that were deployed along the near-shore fiber transect. Meter 1 was not near the DTS cable due to water depth thus it is not analyzed here. Meters 2-6 were within approximately one meter of the DTS cable.

Seepage rates were measured using the seepage meters at 10-time intervals over a four-day period from March 22, 2023 at 12:00 pm to March 25, 2023 at 7:30 am. The first interval was only used at Meter 1 and the second was very brief (approximately one-half hour) so those intervals were not included in the analysis. The remaining 8 intervals (numbered 3-10) are grouped as low-tide (samples 3, 6, and 9), overnight (samples 4, 7, and 10), and high-tide (samples 5 and 8). Figure 13 shows the seepage meter sampling interval in relation to tide cycles during the sampling period.

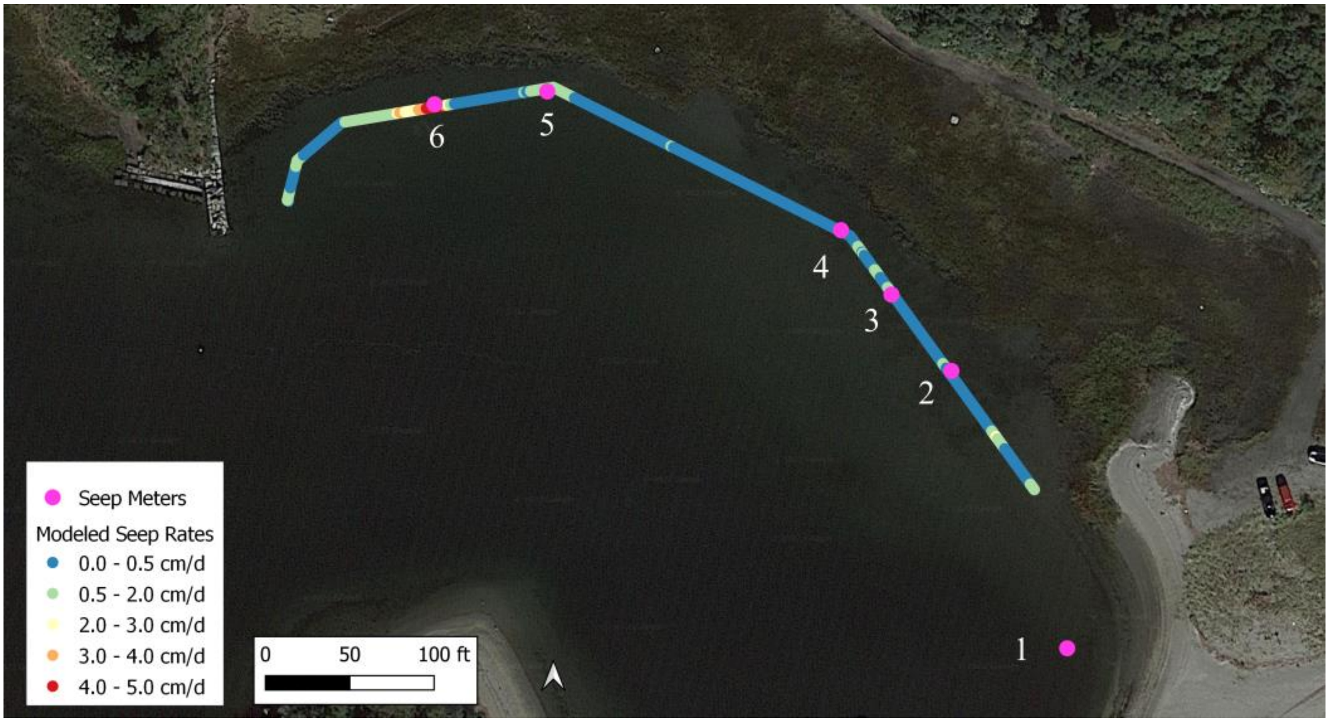


Figure 12 DTS-based seepage rate estimates with seepage meter locations overlaid. (Source: SelkerMetrics).

A challenge during seepage meter deployment was targeting locations within the intertidal zone that became exposed at low tide levels. During the lowest part of the low tide cycle, the seepage meter domes were exposed down to the sediment surface (Figure 6). This can distort readings if the seal of the seepage dome does not remain intact when exposed at low tide. If the seal is not intact, collected water could flow back from the seepage bag, air could enter and become trapped in the seepage dome, or the rise in hydraulic head could prevent water from being collected. Looking at the tides and deployment intervals (Figure 13), this may have occurred for all but perhaps the two high-tide deployments (sample intervals 5 and 8).

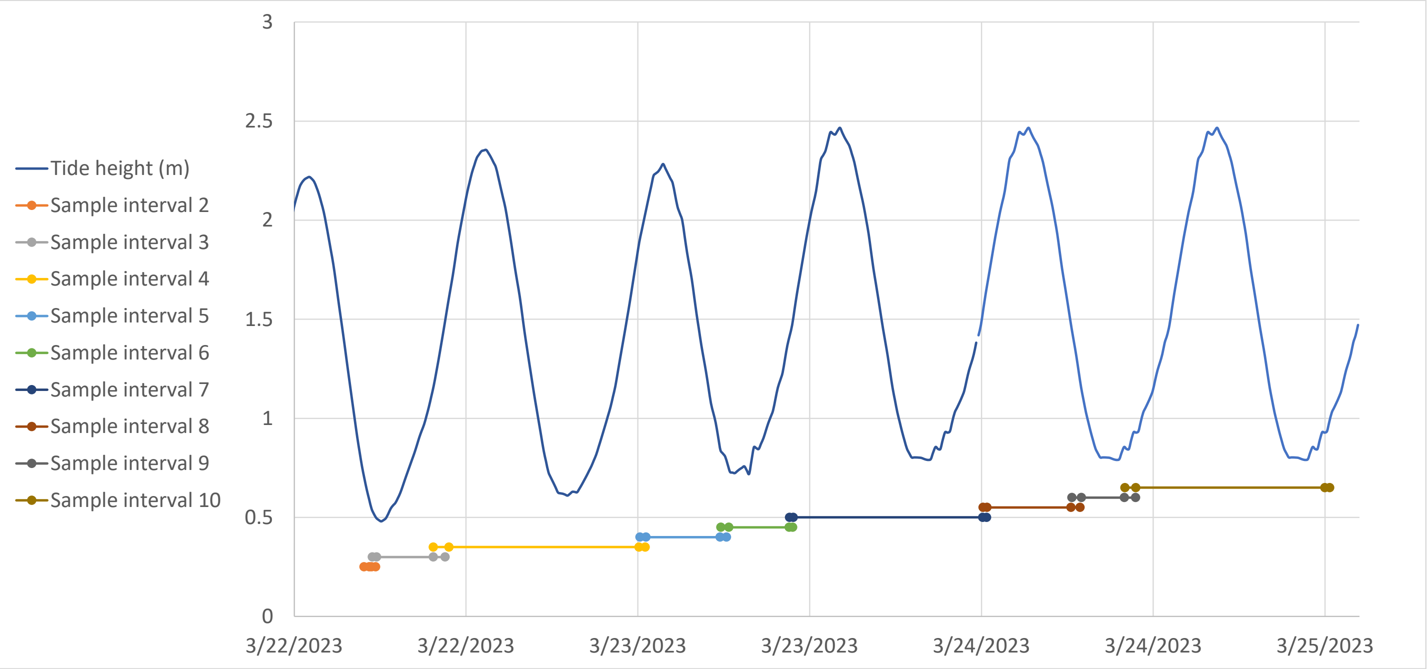


Figure 13. Seepage meter sampling intervals and tides. Most intervals include low-tides, during which meters may not be submerged. Tide height (m) was not measured for the last day so estimated tide heights are shown. (Source: SelkerMetrics).

The seepage meter results are shown in Table 3. A two-tailed t-test of results shows findings were not significantly different from zero (the no-seepage hypothesis) for meters 2, 3, 4 and 6. This is consistent with the observation that the standard deviations of results were greater than the mean values. Meter 5 had a mean seepage rate value of 2.08 cm/day, and a p-value of 0.05. When results are grouped by measurement type (low-tide, overnight, and high-tide), significance declines and no seepage rates were significantly different from zero, including Meter 5.

Table 3. Seepage meter readings by deployment. Seepage values are Darcy flow in cm/day.

Measurement Interval Number	**Meter 2**	**Meter 3**	**Meter 4**	**Meter 5**	**Meter 6**	**Measurement Type**	**Duration (hr.)**
3	0.25	0.73	-0.69	2.10	2.22	Low Tide	5.1
4	1.47	0.05	-0.08	3.14	-0.05	Overnight	14.8
5	0.07	0.10	-0.08	0.84	-0.09	High Tide	6.0
6	1.75	0.24	0.10	6.02	-0.55	Low Tide	5.0
7	0.07	0.04	-0.03	4.44	0.09	Overnight	13.7
8	0.11	0.07	0.16	0.02	0.16	High Tide	6.8
9	-0.24	2.22	0.08	0.07	0.05	Low Tide	4.5
10	0.52	-0.08	0.00	0.00	-0.06	Overnight	14.3
Mean	0.50	0.42	-0.07	2.08	0.22		
Standard Dev.	0.72	0.77	0.27	2.28	0.84		
p-value of results being different from zero	*0.11*	*0.19*	*0.53*	*0.05*	*0.51*		

7.3 COMPARISON OF DTS AND SEEPAGE METER RESULTS

Figure 12 shows the DTS-based seepage rates along with seepage meter locations. Meters 2, 3, 5, and 6 were installed at locations that were identified by the DTS system to have groundwater discharge during preliminary data evaluation. Seepage meter 4 was located where no groundwater discharge was detected by the DTS system, and seepage meter 1 was installed too far from the fiber to warrant including in the analysis.

Comparison between DTS and seepage meter seepage flows, with 95% confidence intervals, are shown in Figure 14. Four of the five locations showed results that are statistically similar between the DTS and seepage meter estimates. Meters 2 and 3 show low seepage rates which, given measurement variability, are not significantly different from zero. These locations may have modest seepage, but the rates were below the detection limits of the DTS and seepage meters during this time. No seepage was observed by either the seepage meter or the DTS system at seepage meter 4's location. Meter 5 shows seepage of 2.08 cm/day, which is statistically indistinguishable from the DTS estimated seepage rate of 1.9 cm/day. Only Meter 6 results differ from DTS results, with the meter showing no statistically significant seepage but the DTS showing a mean seepage rate of 5.4 cm/day. One explanation is spatial heterogeneity. DTS results 3 m from this location showed no seepage. Thus, it's possible that the seepage meter, which is approximately 0.5 m in diameter, did not rest on an area that is seeping while the cable did. There are some uncertainties in location for both DTS and seepage meters due to field conditions and GPS uncertainty, with distance between the two locations likely approximately one meter. Additionally, the low tides may have hindered Meter 6 detecting seepage.

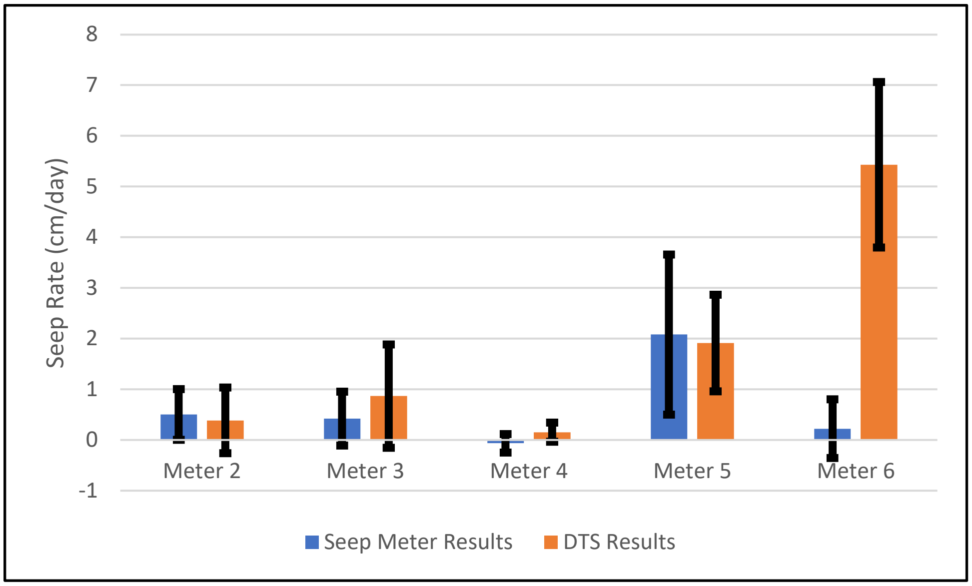


Figure 14. Comparison between seepage meter and DTS-based seepage rates. 95% confidence intervals are shown based on variability of measurements through time. Findings are statistically similar for Meters 2-5, and differ for Meter 6. This could represent measurement errors in either the meter or adjacent DTS, or seepage rate differences between the two locations. (Source: SelkerMetrics).

8.0 COST ASSESSMENT

8.1 COST MODEL AND DRIVERS

The demonstration DTS installation, analysis, and cable removal was completed on budget. This was despite the unexpected need for a second monitoring period and analysis, as well as a significant portion of the fiber cable being damaged during the study period.

The cost of applying DTS to a site is largely determined by:

- Site accessibility and infrastructure (e.g., presence of power and shelter for equipment).
- Size of sediment area to be monitored and length of fiber optic cable required. However, once mobilized to a site, the marginal cost of increased size can be relatively modest.
- Conditions affecting cable placement such as currents, wind, waves, sediment type and water depth.
- Duration of installation and number of times monitoring and analysis are desired.
- Availability of supporting information such as site bathymetry and monitoring wells or piezometers to be used to monitor groundwater temperatures.
- Cost of specialized boats used to deploy and recover the cable.
- Reporting and presentation needs.

In practice, mobilization, planning, installation of the basic components required for a deployment, and analysis/reporting set a lower limit on project cost of approximately $50,000. Typical installations cost $75-175,000. These typically range from 1-5 km of installed DTS cable across 1-20 acres with a sampling resolution of 0.25 m and a monitoring period of 2-15 days, either with or without available power and infrastructure.

8.2 COST ANALYSIS AND COMPARISON

The DTS deployment, data evaluation, and demobilization were budgeted $110,000 for this demonstration. The six seepage meters were budgeted $100,000 for approximately 3 days of monitoring.

During the summer data collection period in 2022, the DTS monitored approximately 10,000 locations in the Allen Harbor entrance channel and Narragansett Bay at 10-minute intervals for approximately 14 days, for approximately 20 million total measurements. During the second monitoring period approximately 6,000 locations in the Allen Harbor entrance channel were monitored at 10-minute intervals for approximately 10 days, for approximately 9 million total measurements. This offers an example of the geographic extent, resolution, and duration that is practical to study using DTS. Further, this highlights how cost-effective DTS can be at providing extensive spatial coverage over extended times in a cost-effective manner.

For comparison, the DTS system monitored thousands of locations continuously over extended duration for seepage at approximately the same cost as 6 seepage meters used in this study, and at about the same cost as the previous study using direct-push probes and seepage meters that monitored 15 locations at the site.

Thus DTS was found to provide greater spatial coverage and resolution monitoring seepage from sediment, continuously through time, than seepage meters or direct-push probes at approximately the same cost.

9.0 CONCLUSIONS, RECOMMENDATIONS, AND IMPLEMENTATION ISSUES

To summarize:

1. The DTS installation demonstrated the ability to locate seepage, to rule out the presence of seepage (September data), and to quantify seepage rates where supporting ancillary data was available.

2. The lack of seepage in late summer 2022 and subsequent seepage identified and quantified in March 2023 highlights a benefit of DTS monitoring in being able to collect data for long periods of time to document such changes in site conditions.

3. The laboratory study validated the DTS analyses methods used to estimate cable depth and seepage rates to within approximately 5-30% of true values.

4. Estimates of groundwater seepage rates measured using more traditional seepage meters were found to be comparable to the DTS findings at four of the five seepage meter locations. At one location, near Meter 6, the DTS detected seepage while the meter did not find significant seepage. This could be due to seepage meter or DTS function (i.e., confounding factors such as the seepage meter dome being exposed during low tide conditions), or to differences in seepage associated with the approximately 1-meter difference in location.

5. DTS provided substantially more spatial coverage and resolution, continuously through time, than seepage meters or direct-push probes at approximately the same cost.

Certain challenges were encountered that are worth considering for applications at other sites:

1. The cable could not be installed within Allen Harbor because the substrate was rocky. DTS monitoring is not suited to rocky substrates.

2. The cable on Narragansett Bay did not survive the winter. While DTS cables have been successfully used for many months or years at some sites, the shallow depth, vigorous wave action, and heavy public use likely led to that section of cable being exposed and moved.

3. The absence of site bathymetry data made it impractical to quantify seepage rates away from the near-shore transect, which alone had good surface water temperature data. Sites with bathymetry data, or sufficient temperature data to estimate surface water temperatures at all locations (e.g., a sediment surface cable), support seepage rate estimations across the site.

4. Seepage meters were challenging to deploy and operate in locations that were either deep (would have required divers) or too shallow such that the domes did not remain submerged during low tide conditions.

APPENDICES

Appendix A: Points of Contact

Table 4. Points of Contact for Project

Name	Organization	E-mail	Role in Project
Joey Trotsky	NAVFAC EXWC	joseph.s.trotsky.civ@us.navy.mil	NESDI Project Manager
Michael Werth	Anchor QEA	mwerth@anchorqea.com	Contractor Project Manager
Frank Selker	SelkerMetrics	fselker@selkermetrics.com	Vendor DTS Technology
David Barney	Navy BRAC	david.a.barney.civ@us.navy.mil	BRAC Environmental Coordinator

Appendix B: Standard Operating Procedure for Seepage Data Collection Via Seepage Meters

Appendix B is in a separate pdf file.

Appendix C: Sand Column Tests

Appendix C is in a separate pdf file.

“Sand Column Tests of Models for Estimating Thermometer Depth and Seepage Rates,” SelkerMetrics study, Feb. 17, 2023. U.S. Navy Environmental Sustainability Development to Integration (NESDI) Program.

Appendix D: September 2022 DTS Data Show Low Seepage Activity During Drought

Analysis of DTS data collected immediately after cable installation in late summer 2022 showed no detectable seepage.

Table 5 summarizes the size of temperature anomalies at five east-coast locations during summer DTS installations. The other four were found to have seepage based on anomalies, but the Allen Harbor data did not show temperature differentials indicative of seepage using September 2022 data.

Table 5. Comparison of DTS recorded temperature anomalies at summer installations. Allen harbor cable show no detectable seepage, perhaps due to regional drought.

Site Location	Site Type	Study Season	Approx. Observed Seepage Differentials (°C)
Allen Harbor, RI	**Marine**	**Summer**	**0.1**
New York	River, Marine	Summer	2.0
New Jersey	River, Marine	Summer	7.0
New York	River/Canal, Marine	Summer	10.0
Pennsylvania	Culvert	Summer	6.0

This is believed to be due to a regional drought which had reduced July and August precipitation from the usual 6.5 inches to 2.2 inches. In September 2022 the U.S. Drought monitor showed Rhode Island in "Severe" to "Extreme" drought.

SelkerMetrics developed a recharge model based on precipitation data and information about evapotranspiration in the area[iii]. This model showed groundwater was unlikely to have been recharged during most of the summer of 2022 likely resulting in reduced seepage rates (Figure 15).

Undetectable seepage was an unexpected but interesting finding. Sites vary seasonally and with conditions, and the long-term and continuous monitoring ability of DTS can elucidate such variability.

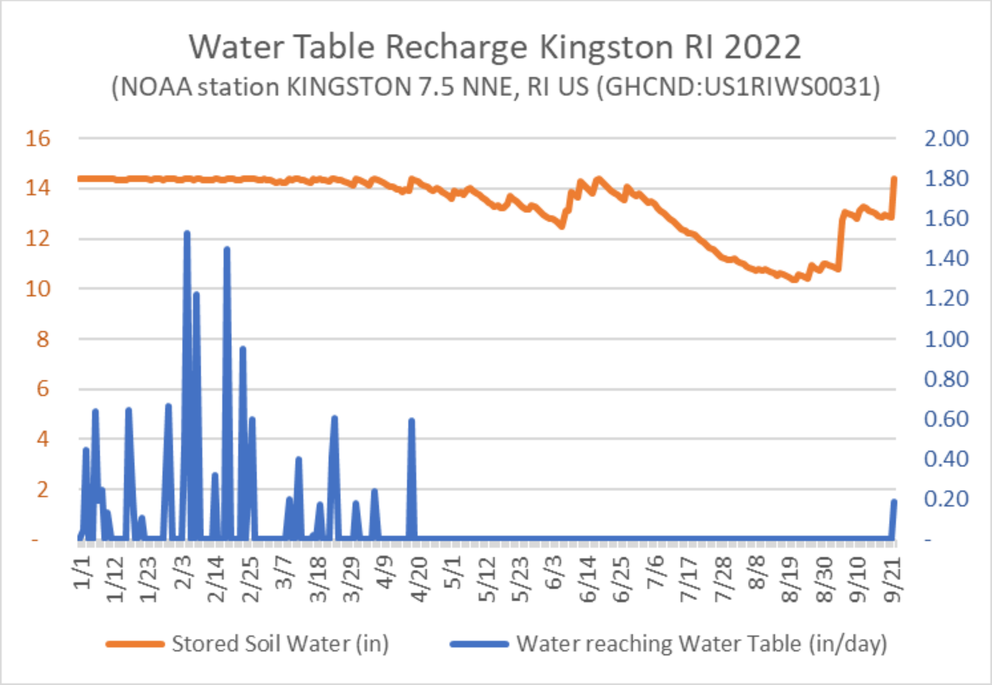


Figure 15. Water table recharge model for Kingston RI for 2022 through time of DTS data collection. Lack of summer precipitation suggests little to no recharge reached the water table from May until late September. (Source: SelkerMetrics).

[iii] The model assumed a vadose zone depth of 10 ft and a soil field capacity of 12%, giving 14.4 inches of water storage capacity of the vadose zone. The soil was assumed to be fully saturated at the beginning of the calendar year (1/1/22). Regional evapotranspiration estimates for the area were used to estimate reductions in this stored water (https://www.nrcc.cornell.edu/wxstation/pet/pet.html). Precipitation in Kingston RI were used to estimate recharge (https://www.usclimatedata.com/climate/kingston/rhode-island/united-states/usri0033).

Appendix E: 2019 UltraSeep Seepage Meter Study

Three UltraSeep electronic meters were deployed during August 2019 as part of a previous study.[5] The meters used for those studies are shown in Figure 16. Their approximate locations are shown in Figure 17 and locations are shown together with seepage meters deployed in the current study in Figure 18. Results from this study are summarized here, although the 3.5 year time difference between the UltraSeep study and the DTS and current seepage meter deployment limits the comparability of seepage rates.

Figure 16. The UltraSeep system used to quantify groundwater seepage at the site in Allen Harbor in previous 2019 study (5). (Source: Reference 5).

Figure 17. Station locations for the 2019 UltraSeep survey in Allen Harbor. (Source: Reference 5).

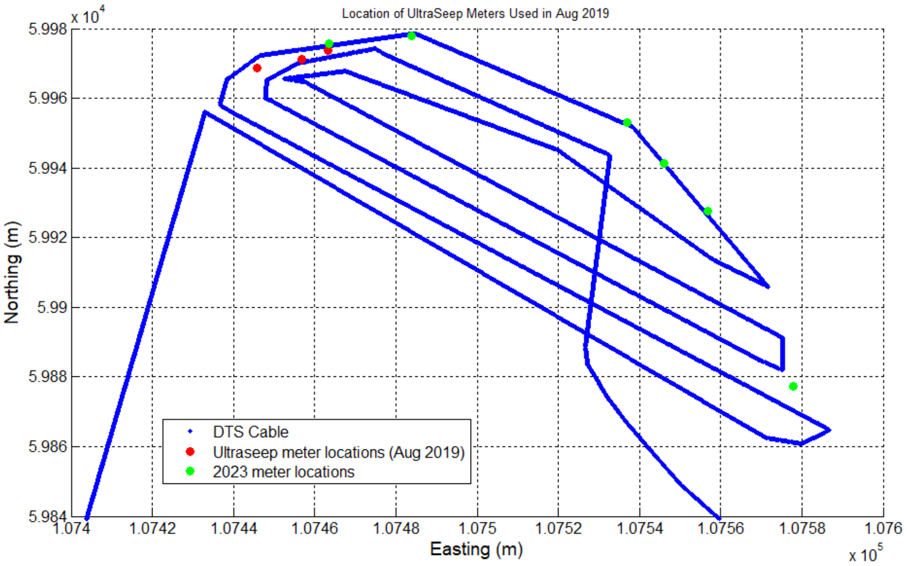


Figure 18. Location of seepage meters deployed in 2023 (green) and Ultraseep seepage meters deployed in August 2019 (red). 2023 seepage meters are numbered from right to left, so meter 6 is farthest left. Ultraseep locations are numbered from left to right, with sampling locations called 2, 3, and 4. Thus Ultraseep location 4 is nearly coincident with 2023 Meter 6. (Source: SelkerMetrics).

Continuous and 50-hour average seepage rates were reported. The continuous seepage figures from the report are reproduced below in Figure 19. These show what appear to be low-noise seepage signals with seepage rates ranging from 1-13 cm/day. Two of the three meters (stations 2 and 3) show seepage rates increasing during low tides, while one (station 4, which is close to where meter 6 was deployed for the current study) shows little tidal influence.

The average 50-hour seepage rates for locations 2, 3, and 4(from west to east) were 6.99, 3.82, and 2.81 cm/day, respectively (Table 3-18 in study report). The closest locations on the DTS cable to stations 2 and 3 showed no significant seepage, and the cable closest to station 4 showed a mean value of 5.4 cm/day across four test times.[11] Thus DTS seepage values do not match those of locations 2 and 3, but are within a factor of two at the UltraSeep station 4. Like the meter at station 4, the DTS does not show clear tidal influence (Figure 20). Being 3.5 years earlier than this study, and with locations 1-2 meters from the cable, our ability to compare with DTS data is limited.

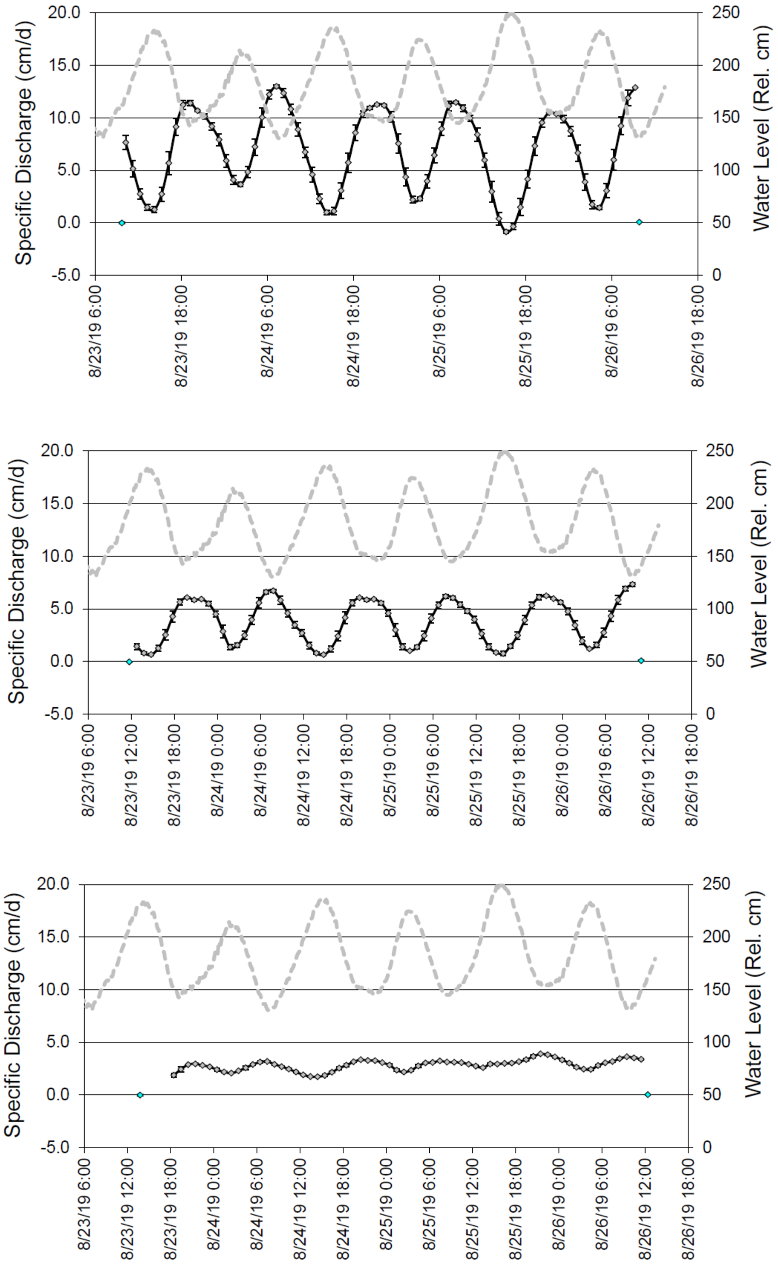


Figure 19. Data from Ultraseep seepage meters at stations 2 (top), 3 (middle) and 4 (bottom) installed in August, 2019 (Figures 3-21, 3-22, 3-23 from study5). The solid black lines with grey diamond symbols are specific discharge. Error bars indicate the standard deviation of specific discharge over the 1-hour averaging period. Blue diamonds are the pre- and post-zero specific discharge measurements. The grey dashed line is water level. (Source: Reference 5)

Appendix F: Tidal Influence on Near-Shore Sediment Temperatures

At some coastal locations, groundwater discharge shows variations with tide height. When this occurs, it is apparent in DTS cable temperatures fluctuating with tide height.

However, inspection of cable temperatures between March 13th and 18th shows little evidence of such variations. For example, the DTS seepage at a location 543.2 meters along the cable, near seepage meter 6 and UltraSeep station 4, does not show a clear tidal influence in temperature (Figure 20). This indicated that the early part of the data set is well-suited to a steady-state analysis.

In order to verify the lack of such variation beyond such an inspection, a Fourier analyses of cable temperatures at each location through time was conducted to look for variations at either the tidal (12.4 hour) or diurnal (24 hour) frequencies. This analysis also showed that temperatures of cable buried in the sediment had little relationship with either.

The latter part of the data set, about March 19 and later, shows strong variability with tides and air temperature because lower tides exposed sediment to air for intervals. This part of the data set was not used due to the absence of bathymetry, which makes it difficult to know exactly when each cable location may have become exposed during the low tides.

Tidal influence on seepage can occur where there is relatively low-head driving the seepage and low resistance to seepage, so a change in head associated with tidal changes has a substantial influence on flow rates. A lack of tidal influence is consistent with seepage being driven by higher head but with resistance to groundwater flow limiting the seepage rate. In this case a small change in head, associated with tides, may have little effect on seepage rates. Previous studies have found tidal influence, although one of the UltraSeep seepage meters showed distinctly less influence than the other two, suggesting there is variability at the site.

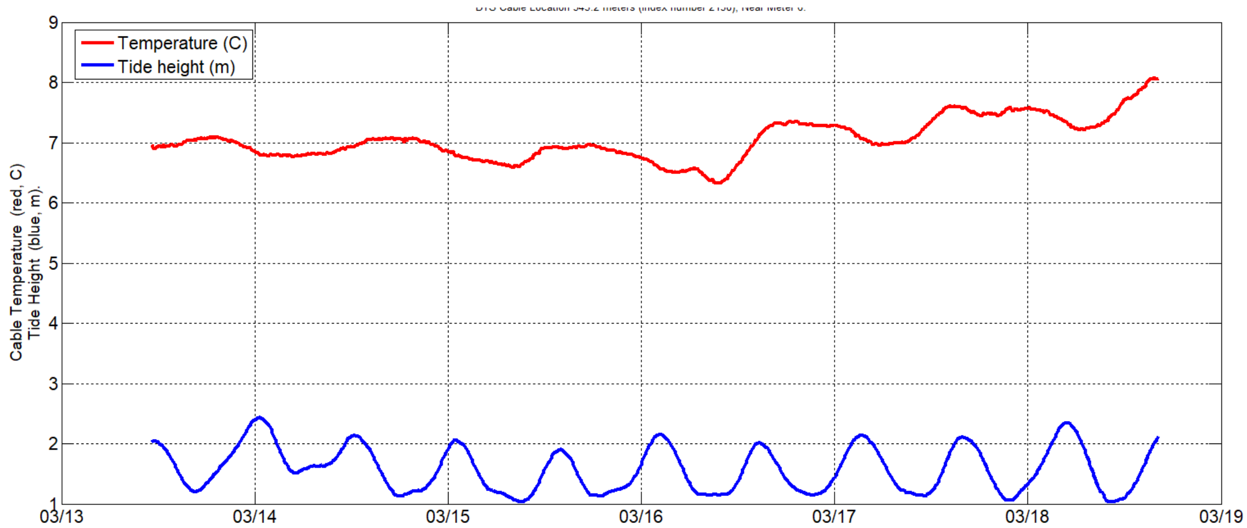


Figure 20. DTS cable temperature (red) over time versus tide height (blue). Location 543.2 m along cable, near Meter 6 and UltraSeep Station 4 of previous study. There is no clear tidal influence on temperature. (Source: SelkerMetrics).

Appendix G: DTS-Based Seepage Center Locations

Table 6 Center coordinates for DTS identified seeps

Rhode Island State Plane Coordinates (NAD83)	
Easting	**Northing**
352874.40891	196432.71323
352944.21808	196425.95149
352866.16913	196474.29978
352576.26932	196653.88154
352552.57499	196668.55928
352573.55724	196769.14853
352639.99660	196780.18070
352709.08612	196745.63135
352842.99303	196655.01906
352855.83913	196637.33632
352871.53749	196615.72760
352756.52391	196669.45334
352613.37878	196695.66651
352629.49084	196685.60862
352668.72378	196661.11765
352914.63309	196507.61006
352855.06064	196511.88650
352772.49363	196562.93957
352605.23843	196666.35722
352823.87560	196396.51617
352981.97554	196259.64491

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[10] Technical Note: Evaluation of seepage zones and the natural Attenuation capacity of the groundwater/surface water interface. NAVFAC. 2021.

[11] The standard deviation across the four times, which were the same times used above for DTS seepage estimates, was 2.6. Cable burial depth assumed to be 7.5 cm; surface water temperatures from nearby cable locations appearing to be unburied, mean values of cable index values 3241:43 and 4552:4554.