# Water Quality Monitoring Program for the Popponesset Bay and Waquoit Bay Estuaries

*(summary of summer 2022 results)*

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***For:***

**Mashpee Water Quality Monitoring Consortium:**

**Mashpee Wampanoag Tribe**
**&**
**Town of Mashpee Waterways Commission**
**&**
**Coastal Systems Program SMAST-UMD**

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## *BACKGROUND AND OVERVIEW:*

The Mashpee Water Quality Monitoring Program is an on-going collaborative effort between the Mashpee Wampanoag Tribe, the Town of Mashpee and the Coastal Systems Program, School of Marine Science and Technology at the University of Massachusetts – Dartmouth (CSP/SMAST). The Monitoring Program has a two-fold goal: 1) sustain a continuing assessment of the nutrient related water quality of the Waquoit Bay and Popponesset Bay estuaries relative to regulatory standards (TMDLs[1]) and 2) monitor improvements in water quality resulting from restoration efforts (*e.g.*, oyster propagation, dredging, N removals by freshwater systems, improvements in wastewater treatment) as undertaken by the Town, Tribe and others. The Monitoring Program goals are achieved through the regular collection and analysis of water samples and associated field parameters relevant to assessing the health of estuarine habitats within both Bay Systems, Cape Cod, MA. (Figure 1). These monitoring data form the basis for: 1) gauging short and long-term trends in water quality, 2) validating the Massachusetts Estuaries Project (MEP) threshold modeling approach for Waquoit Bay + Popponesset Bay, and 3) determining compliance with USEPA and MassDEP TMDL nitrogen targets set under the Clean Water Act by TMDL analysis that has been previously formalized for all of Mashpee's estuarine waters.

In order to develop a sustainable long-term program, a consortium was created whereby sample collection is completed by volunteers recruited by each consortium partner and by public participants, with equipment and analytical costs distributed between the Mashpee Wampanoag Tribe and the Town of Mashpee. The Mashpee Water Quality Consortium was developed under a 2009 Memorandum of Understanding between the Mashpee Wampanoag Tribe, the Town of Mashpee and the Coastal Systems Program (CSP/SMAST). The Consortium is managed through the Mashpee Waterways Commission.

It is an important part of the ongoing efforts to develop nitrogen management plans for the restoration of these systems and to determine the level of "success" through the consistent collection of key habitat quality metrics throughout each system in the most cost-effective manner possible. This program is the only method for providing a cross comparable baseline for gauging long-term changes in water quality, as the Towns of Mashpee, Falmouth and Barnstable implement their nitrogen management alternatives for the restoration of the Waquoit Bay and Popponesset Bay systems.

Nutrient related water quality decline continues to represent one of the most serious threats to the ecological health of nearshore coastal waters in southeastern MA and nationally. Coastal embayments, because of their enclosed basins, shallow waters and large shoreline area, are generally the first indicators of nutrient loading from terrestrial sources. Although each embayment system maintains a capacity to assimilate watershed nitrogen inputs without degradation, as loading increases, a point is reached at which the assimilative capacity is exceeded and nutrient related water quality degradation begins to occur. Continuing increases in nitrogen inputs beyond this threshold level result in further declines in habitat quality. Because nearshore coastal salt ponds and embayments are the primary recipients of nutrients carried via surface and groundwater transport from terrestrial sources, it is clear that activities within the watershed, often miles from the water body itself, can have chronic and long lasting impacts on these fragile coastal environments.

[1] TMDL = Total Maximum Daily Loads. Required provision in the federal Clean Water Act for all impaired waters.


**Figure 1**. **Regional locus map of Waquoit Bay and Popponesset Bay**. The two bays source waters are Vineyard Sound and Nantucket Sound, respectively.

Both the Waquoit Bay and Popponesset Bay Estuarine Systems are highly nitrogen enriched and show impaired nutrient related water quality throughout most of their component basins over the past decade. The MEP assessments and regular reports to the monitoring consortium for both systems documented high nitrogen and chlorophyll concentrations, loss of historical eelgrass, severe degradation of infauna communities, etc. The reports also showed that impairments were diverse with greater impairments in the tidal rivers (Mashpee River, Childs River, Quashnet River) and major tributary basins (Eel Pond/River, Shoestring Bay and Ockway Bay) and less impairments in the main basins. As predicted by the MEP watershed buildout scenarios, conditions have worsened with time as time lags caused by groundwater flow have gradually brought more nitrogen to the bays. Through the annual reviews of collected water quality after the MEP assessments were completed, CSP/SMAST has provided the Mashpee Water Quality Consortium with regular updates in changing conditions in the two bays. The present Technical Report is an update to the water quality baseline to include the results of each summer's sampling program, 2010-2022.

Nitrogen levels are elevated throughout both systems and as watershed development continues, estuarine conditions are projected to decline further until nitrogen management is implemented. The result is that nitrogen management of these estuaries is aimed at restoration, not protection or maintenance of existing conditions. Nitrogen management within Popponesset Bay has already begun with the consistent annual maintenance of the flow through the tidal inlet, capping of the Town of Mashpee landfill, and implementation of Phase I of the CWMP in Mashpee.

## *SITE DESCRIPTION*

### *Popponesset Bay*

The Popponesset Bay Estuarine System is shared by the Towns of Mashpee and Barnstable, on Cape Cod, Massachusetts. The Bay's watershed is primarily distributed among the same two towns, with a small portion of the upper-most region of the watershed located in the Town of Sandwich. The Popponesset Bay Estuarine System exchanges tidal water with Nantucket Sound through a single maintained inlet at the tip of Popponesset Spit. The Popponesset Bay estuarine system consists of five tributary sub-embayments: 1) Popponesset Bay (main basin + Popponesset Creek), 2) Pinquickset Cove, 3) Ockway Bay, 4) Mashpee River (lower or tidal region) and 5) Shoestring Bay (Figure 2).

Within the Popponesset Bay System, the tidal portion of the Mashpee River functions as a Cape Cod tidal river, with extensive bordering salt marsh, tidal flats and large salinity fluctuations. In contrast, Popponesset Bay, Shoestring Bay and Ockway Bay are typical embayments, dominated by open water areas, having only fringing salt marshes, relatively stable salinity gradients and large basin volumes relative to the tidal prism (*i.e.,* the volume of water entering on a flooding tide). Although Shoestring Bay, Ockway Bay, Mashpee River and Pinquickset Cove and the main basin of Popponesset Bay have different hydrologic characteristics, tidal forcing for all of these component systems is generated from Nantucket Sound. Nantucket Sound, exhibits a moderate to low tide range, with a mean range (high to low tide) of about 2.5 ft. Since the water elevation difference between Nantucket Sound and Popponesset Bay is the primary driving force for tidal exchange (flushing), the local tide range naturally limits the volume of nutrient enriched water flushed from the system during each tidal cycle. It should be noted that the Popponesset Bay System is more sensitive to water quality declines from nitrogen enrichment than estuaries bordering Cape Cod Bay or the outer Cape, where the tide range is much higher (*e.g.*, tide range off Stage Harbor Chatham is ~4.5 ft, Wellfleet Harbor is ~10 ft).


**Figure 2. Popponesset Bay System component basins**. Tidal waters enter the Bay through the single inlet from Nantucket Sound. Freshwaters enter from the watershed primarily through 3 surface water discharges (Mashpee River, Santuit River, Quaker Run) and direct groundwater discharge.

In addition to the offshore tide range, tidal damping (reduction in tidal amplitude) within the embayment itself from a constricted tidal inlet or internal channels can further reduce tidal flushing. Fortunately, within the Popponesset Bay System, only minimal tidal damping has been observed. Tidal damping further magnifies the effects of watershed nitrogen inputs. It appears that the tidal inlet continues to operate efficiently due the Town of Mashpee's active and consistent inlet maintenance program. Given the present hydrodynamic characteristics of the Popponesset Bay System, it appears that estuarine habitat quality is primarily dependent on the level of nitrogen loading to bay waters rather than restrictions to tidal flows within the component sub-embayments.

Nitrogen loading to the Popponesset Bay System was assessed during the Massachusetts Estuaries Project and partitioned relative to its five (5) component basins: Pinquickset Cove, Ockway Bay, Mashpee River (lower or tidal region), Shoestring Bay, and Popponesset Bay. The watershed for this estuarine system contains approximately 13,000 acres dominated by single-family residences. The nitrogen loading from the more heavily populated areas of the Town of Mashpee is focused on the northern reaches of the estuarine system. System-wide, approximately three quarters of the nitrogen load from single-family dwellings enters the Shoestring Bay and Mashpee River basins before entering the main basin of Popponesset Bay.

In evaluating management alternatives, it is important to note that Popponesset Bay is a relatively dynamic system. Popponesset Spit is continually expanding and eroding, once nearly extending to the inlet channel to the Three Bays System to the north. The spit frequently experiences periodic overwash (Aubrey and Gaines 1982). The present inlet position is relatively new, resulting from a breach of the spit in the hurricane of 1954. Similarly, within the main Bay, several islands apparent 50 -100 years ago have been incorporated into other landforms with unquantifiable effects on the circulation of Bay waters. Thatch Island and Little Thatch Island within the lower main Bay have “joined” with the spit, most likely due to a combination of the natural processes of overwash of the barrier beach and shoreline retreat. Daniels Island, at the entrance to Ockway Bay, has been joined to the mainland by filled causeways, apparently filling salt marshes and changing the local circulation pattern. Hydrodynamics have also been altered within Popponesset Creek due to dredging and channelization of wetlands.

Within the watershed to Popponesett Bay there have been changes to the freshwater systems which attenuate nitrogen during transport to bay waters. Most notable of the changes has been the modification to riparian zones either through channelization, restriction, or filling of freshwater wetlands and, in some cases, transformation of portions of the watershed to cranberry agriculture. Most of the alterations have reduced the nutrient buffering capacity of these systems, thus magnifying the nitrogen loading to the bay. However, the predominant watershed alteration has been the shifting of fields and pine-oak forest to residential and commercial development, with its resultant increasing nitrogen input to the watershed, aquifer and ultimately bay waters. This recent shift in land-use has likely resulted in this estuary receiving its highest rates of nitrogen loading than at any period over the past 400 years. Previous large shifts in land-use, primarily from forest to agriculture did not have the same resultant enhancement in nitrogen loading. Historically, agriculture practice generally recycled nitrogen (as opposed to modern practice of using commercial fertilizers) and the population

was <10% of today. The present year-round population per square mile is greater than the entire town population of 50 years ago (total population based on 2020 census for the Towns of Mashpee, Sandwich, and Barnstable are 15,061, 20,261 and 48,912 respectively). It appears that the nitrogen attenuation capacity of the freshwater systems has been reduced, as the need to intercept the nitrogen loading to the watershed has increased. While this may be a partial cause of the present estuarine decline, it may also represent a potential opportunity for restoration of bay systems.

## *Waquoit Bay*

The Waquoit Bay embayment system is located within the Towns of Falmouth and Mashpee, Massachusetts on Cape Cod. Like Popponesset Bay, the Waquoit Bay watershed is primarily distributed among the Towns of Falmouth and Mashpee, with a small portion of the upper-most region of the watershed located in Sandwich. The southern shore is a barrier beach that separates the Waquoit Bay System from adjacent Nantucket Sound (Figure 3). Waquoit Bay is composed of a main bay with multiple associated sub-embayments (Quashnet River, Hamblin Pond, Jehu Pond, Eel River/Pond, Childs River). These sub-embayments constitute important components of the region's natural and cultural resources. In addition, like for Popponesset Bay, the large number of sub-embayments greatly increases the shoreline of the system and decreases the travel time of groundwater from the watershed recharge areas to bay regions of discharge. The main bay has two primary openings to Nantucket Sound, a historically open inlet in the main bay and a relatively dynamic inlet that connects Eel Pond to Nantucket Sound. More recently, Hurricane Bob in 1991 created a third inlet immediately east of the Eel Pond entrance; however, this inlet has closed over the past few years. The inlet to the main bay has been fixed with jetties initially in 1918 (east) and 1937 (west), with subsequent lengthening and enhancements. The second inlet has been generally open over the past 50 years. The opening of the second inlet significantly increased the tidal range and flows within the Waquoit Bay System and caused important ecological shifts to its tidal wetlands and possibly other estuarine habitats (Orson and Howes, 1992). Overall, these important "natural and unnatural" hydrodynamic shifts, coupled to anthropogenic alteration of the watershed, supports a highly altered estuarine habitat.

The Waquoit Bay system is located within the Mashpee Pitted Outwash Plain that supports numerous kettle ponds (Oldale 1992). The Quashnet River Estuary is a drowned river valley estuary resulting from rising sea-level flooding the lower reaches of the Quashnet River. Hamblin and Jehu Pond appear to be drowned kettle ponds currently exchanging tidal flows with Waquoit Bay through tidal rivers, Little River and Great River respectively. Both the Hamblin Pond and Jehu Pond subsystems support significant saltwater wetland resources. The tidal reach of the Quashnet River Estuary is located within the Town of Falmouth while much of the freshwater region of the Quashnet River and its watershed is found in the Town of Mashpee.

The Quashnet River is one of the two major surface water inflows to the Waquoit Bay System and originates in John's Pond. Hamblin Pond is divided between the Towns of Falmouth and Mashpee, while Jehu Pond is entirely situated within the Town of Mashpee. Within the Quashnet River, Hamblin Pond, and Jehu Pond sub-embayments geomorphic and hydrologic


**Figure 3. Waquoit Bay and its component sub-embayments.** Tidal waters from Nantucket Sound enter the main Bay through a single armored inlet in the barrier beach and an unarmored inlet to the Eel Pond sub-embayment. Freshwaters enter the estuary primarily through two major surface water discharges (Childs River to Eel Pond and Quashnet River to the main basin), several smaller streams (*e.g.* Red Brook), and direct groundwater discharge.

of riparian zone for cranberry agriculture, as well as the creation of roadways altering tidal circulation around Monomascoy Island. However, the over-riding change affecting these sub-systems appears to have been the shift from pine/oak forest to farming to current residential land-uses, with its associated large increases in watershed nitrogen loading to the estuarine system. Most of the main basin of Waquoit Bay, as well as Eel Pond and Childs River lie within the Town of Falmouth. Their shorelines are highly developed, particularly in the area of Seacoast Shores. As a result of nitrogen entering from its watershed, Childs River is among the more highly impaired estuarine habitats within the region.

The nature of enclosed embayments in populous regions brings two opposing elements together: 1) as protected marine shorelines they are popular regions for boating, recreation, and land development; 2) as enclosed bodies of water, they may not be readily flushed of the pollutants that they receive due to the proximity and density of development near and along their shores. In particular, the Waquoit Bay system and its sub-embayments along the Falmouth and Mashpee shores are eutrophying from high nitrogen loads in the groundwater and runoff from their watersheds. Much of the Waquoit Bay System is currently beyond its nitrogen loading threshold and is currently showing various levels of nitrogen related habitat impairment.

The eastern Waquoit Bay basins, Quashnet River, Hamblin Pond/Little River, Jehu Pond/Great River, and Sage Lot Pond, show clear estuarine characteristics, with extensive salt marsh area, tidal flats and large salinity fluctuations. In contrast, the open water portions of Waquoit Bay and Eel Pond show more typical characteristics of open water areas, having only fringing salt marshes, relatively stable salinity gradients and a large basin volume relative to tidal prism. The tidal forcing for these subsystems, as for Popponesset Bay, is generated from Nantucket Sound. Nantucket Sound adjacent the inlets through South Cape Beach and the southern shore of Washburn Island, exhibits a moderate to low tide range, with a mean range of about 2.5 ft. Since the water elevation difference between Nantucket Sound and Waquoit Bay is the primary driving force for tidal exchange, the local tide range naturally limits the volume of water (and its entrained nutrients) that can flush into and out of the Bay System during a tidal cycle. Similar to Popponesset Bay, its relatively small tide range makes Waquoit Bay proportionally more sensitive to nitrogen related water quality impairments than estuaries on Cape Cod Bay and on the outer Cape with significantly larger tidal ranges, typically 10 ft to 4.5 ft, respectively.

Fortunately, there is minimal tidal damping through the Waquoit Bay inlet. It appears that the main tidal inlet is operating efficiently, possibly due to the active inlet maintenance program and the dual inlet configuration of the overall system. Similarly, within the eastern Waquoit Bay System, the tide generally propagates through the three focal sub-embayments with little attenuation, consistent with relatively unrestricted tidal exchanges. Given the present hydrodynamic characteristics of the Waquoit Bay System, it appears that estuarine habitat quality is primarily dependent on nitrogen loading to bay waters rather than tidal characteristics within the component sub-embayments. Due to the relatively well flushed conditions observed in these three sub-embayment systems, habitat degradation is mostly a result of the high nutrient loads currently being documented in these systems, not restricted tidal flows.

The watershed for this estuarine system contains approximately 10,250 acres, the predominant

land-use based on area being public service/government, including the Massachusetts Military Reservation and protected open space along the Quashnet River. Public service occupies 48% of the total watershed area to Waquoit Bay. In contrast, while single-family residences occupy approximately 25% of the total watershed area to eastern Waquoit Bay, this land use class represents 74% of all the parcels**.** Commercial properties are fairly limited within the watershed. Relative to the Waquoit Bay System, residential land-uses create the major nutrient load.

## *ESTUARINE MONITORING PROGRAM*

The Mashpee Water Quality Monitoring Partnership was established to collect baseline nutrient related water quality data and to track restoration and management "success" in Popponesset Bay and Waquoit Bay relative to the benchmarks established in the MassDEP/USEPA TMDLs for Popponesset Bay[2] and Waquoit Bay.[3] The monitoring program was first established to support the Massachusetts Estuaries Project (MEP) analysis for all of Mashpee's estuarine waters and focuses on the two estuaries within the Town, which provide significant recreational, fisheries and aesthetic resources to the Town's citizenry:

- Popponesset Bay
  - Mashpee River
  - Shoestring Bay
  - Ockway Bay
  - Main Bay
  - Pinquisset Cove
  - Santuit River
  - Off Shore Station

- Waquoit Bay
  - Hamblin Pond – Little River
  - Jehu Pond – Great River
  - Main Bay
  - Childs River
  - Eel Pond
  - Quashnet River
  - Red Brook

As stated above, the concept underlying the establishment of the Monitoring Program by the Mashpee Wampanoag Tribe and the Town of Mashpee was to establish a long-term water quality monitoring effort for Popponesset Bay and Waquoit Bay relative to the TMDL process under the Clean Water Act, and compliance monitoring associated with the TMDLs. The present monitoring effort is significantly reduced over prior sampling efforts for these estuaries. This reduction in sampling intensity was acceptable as the prior high frequency sampling was required to support the MEP analysis, while the present effort is to track long-term changes due to the implementation of management alternatives for restoration of these nitrogen impaired bays. By establishing a stable, low frequency monitoring program and by using trained volunteers, costs of compliance

[2] Massachusetts Department of Environmental Protection. 2006. FINAL Popponesset Bay Total Maximum Daily Loads For Total Nitrogen (Report # 96-TMDL-4, Control #217.0). 31 pp.

[3] Massachusetts Department of Environmental Protection. 2020. FINAL Waquoit Bay System; including Eel Pond, Quashnet River, Hamblin Pond, and Jehu River Total Maximum Daily Loads for Total Nitrogen (Control #378.1). 88 pp.

monitoring to the Town have been significantly lowered making the program sustainable over the long-term. The stream-lined program builds upon the more intensive efforts conducted previously.

The Mashpee Waterways Commission (Steve Pinard 2009-2013; Don McDonald 2014-2021) has been responsible for overall program organization with assistance from Rick York (now retired) and Ashley Fisher (Natural Resources), including the recruiting of volunteers. The Mashpee Wampanoag Tribe Natural Resources Staff have been full partners in this effort and participated in each of the sampling events. The structure of the program relies on volunteers, with each estuary having a "Bay Captain" who oversees the sampling teams for each sampling event and ensures proper sample transfers and submittal of chain of custody forms. The technical aspects of the project were formerly under the direction of Dr. Brian Howes, Director of the Coastal Systems Program at SMAST-UMD and Sara Sampieri Horvet, the Coastal Systems Analytical Facility Manager (ssampieri@umassd.edu).[4] Volunteers were enlisted from each of the three Towns bordering the two estuaries: Falmouth, Mashpee and Barnstable. All field team members are volunteers, regardless of their other affiliations, as all members are dedicated to the restoration and protection of Mashpee's culturally and economically valuable estuarine resources.

Volunteer sampling teams were supplied with the necessary sampling equipment to conduct field measurements of physical parameters as well as to collect water samples for subsequent nutrient analysis by the SMAST Analytical Facility. The physical parameters included: total depth, Secchi depth (light penetration), temperature, estuary state, weather, wind speed and direction, and oxygen content. Laboratory analyses include: salinity, nitrate + nitrite, ammonium, dissolved organic nitrogen, particulate organic nitrogen, total nitrogen, chlorophyll-a pigments and orthophosphate (Table 1). All analytical methodologies have been previously approved for use in the SMAST Analytical Facility by EPA, Mass. CZM, NOAA and NSF and the Massachusetts Estuaries Project.

**Table 1. Summary of estuarine sampling and parameters analyzed.**

| Location | Dissolved Nutrients | Particulate Nutrients | Chlorophyll /Pheophytin | Field Parameters |
|---|---|---|---|---|
| **Waquoit Bay** | | | | |
| **All CR, ER and WB** | X | X | X | X |
| **Popponesset Bay** | | | | |
| **All PB and SR** | X | X | X | X |

As was the case with the prior year's (2021) monitoring effort, the 2022 Mashpee Water Quality Monitoring Program was very successful in its organizational aspects (and % sample capture). The success of the program relative to meeting the sampling goals showed once again that properly implemented volunteer sampling efforts can provide cost effective, high quality data for tracking the status of water quality in both Waquoit and Popponesset Bay Systems, and can support compliance monitoring with the USEPA/MassDEP TMDLS for these systems. In addition, under the recently upgraded program structure, it should be possible to track short-term changes in nutrient related water quality with greater certainty than in previous years.

[4] Dr. Howes passed away in December 2022 and Sara Horvet has continued to provide sampling coordination at CSP/SMAST.

Each volunteer water sampling team was trained/re-trained and outfitted with sampling equipment for collection of water samples at assigned sampling stations. Staff from the Coastal Systems Laboratory within SMAST conducted the training sessions and took part in the field sampling, both to assist the effort, as part of QA/QC procedures, and to insure proper transport and delivery of samples to the Coastal Systems Analytical Facility.[5]

As in previous years, sampling focused on the warmer summer period when nutrient related water quality conditions are the poorest. Sampling of both bays was completed on the same days in 2022: July 15, July 29, August 15 and August 30. Samples were collected at each station at mid-water depth on an ebbing tide for nutrients and surface, mid and bottom for physical parameters including temperature, salinity and dissolved oxygen (depending on the station depth).

The Water Quality Monitoring Program occupied the same sampling sites as in previous sampling years to allow for direct comparisons and track any changes in nutrient related water quality within each of the different basins of each bay. The major change in the 2010-2022 program from the prior effort that was implemented to support the MEP analysis, is the reduction in the overall sampling effort (number of dates/year) while providing the same spatial coverage. This approach allows for incorporation of all historical data, provides the necessary spatial distribution required for management analysis, while also providing a continuing solid assessment of the current nutrient related water quality within the Town's estuaries. Monitoring locations for water quality sample collection were established in order to generate a well distributed network of sampling stations that would yield data at a high enough density with sufficient spatial distribution to ultimately resolve estuarine gradients (Station Maps, Figures 4 and 5). Stations were confirmed by GPS prior to sampling.

The monitoring approaches and parameters assayed are fully consistent with the Quality Assurance Project Plan (QAPP) of the Massachusetts Estuaries Project.[6] Samples and field data were collected at 16 locations within the Popponesset Bay system (inclusive of offshore boundary station) and 19 locations within the Waquoit Bay system.

Monitoring stations are of three types: (1) embayment stations (2) offshore-boundary condition station and freshwater inflow stations. As in previous seasons, a total of 148 water samples for nutrients (including QA samples) were collected in the 2022 field seasons: 80in the Waquoit Bay system and 68 in the Popponesset Bay system. The offshore station is used as one gauge of the boundary conditions in nearshore Nantucket Sound (Tables 2 and 3).

[5] The Coastal Systems Analytical Facility is within the School for Marine Science and Technology, UMASS-Dartmouth at 706 S. Rodney French Blvd, New Bedford, MA. 02744 (Sara Sampieri, 508-910-6325; ssampieri@umassd.edu). The laboratory supports a full range of environmental assays, with detection limits suited for natural waters. The laboratory data is accepted for both research and regulatory (USEPA, MassDEP, MCZM, NOAA) projects.

[6] Quality Assurance Project Plan is reviewed and must be accepted by MassDEP and USEPA for the information generated by a study to be seamlessly incorporated into regulatory planning or proof of compliance studies under the Clean Water Act. All of the approaches, protocols and analytical methods are part of the MEP's QAPP as well as other QAPP's for water quality monitoring in southeastern Massachusetts.

**Table 2. Summary of sampling sites and schedule for the Popponesset Bay and Waquoit Bay systems, summer 2021* Samples include one QA sample**

| Waquoit Bay Sub-Systems and Sampling Stations | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Date** | **Waquoit Bay WB12, 13** | **Childs River CR01, 02, 03** | **Eel River ER01, 02, 03** | **Quashnet River WB06, 07, 08, 09** | **Hamblin Pond WB04, 10** | **Jehu Pond WB01** | **Great River WB02, 03** | **Red Brook WB05** | **Seapit River WB11** | **Total** |
| **July 13** | 3* | 3 | 3 | 4 | 2 | 1 | 2 | 1 | **1** | **20** |
| **July 27** | 3* | 3 | 3 | 4 | 2 | 1 | 2 | 1 | **1** | **20** |
| **Aug 12** | 3* | 3 | 3 | 4 | 2 | 1 | 2 | 1 | **1** | **20** |
| **Aug 26** | 3* | 3 | 3 | 4 | 2 | 1 | 2 | 1 | **1** | **20** |
| **Total** | **12** | **12** | **12** | **16** | **8** | **4** | **8** | **4** | **4** | **80** |

| Popponesset Bay Sub-Systems and Sampling Stations | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Date** | **Mashpee River PB01, 02, 03, 04** | **Shoestring Bay PB05,06, 07** | **Ockway Bay PB09, 10** | **Popp Bay PB08, 11, 12, 13** | **Off Shore PB 14** | **Pinquickset Cove PB15** | **Santuit River SR05** | **Total** |
| **July 13** | 4 | 3 | 2 | 5* | 1 | 1 | 1 | **17** |
| **July 27** | 4 | 3 | 2 | 5* | 1 | 1 | 1 | **17** |
| **Aug 12** | 4 | 3 | 2 | 5* | 1 | 1 | 1 | **17** |
| **Aug 26** | 4 | 3 | 2 | 5* | 1 | 1 | 1 | **17** |
| **Total** | **16** | **12** | **8** | **20** | **4** | **4** | **4** | **68** |

**Table 3. Summary of sampling sites and schedule for the Popponesset Bay and Waquoit Bay systems, summer 2022; * Samples include one QA sample**

| Waquoit Bay Sub-Systems and Sampling Stations | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Date** | **Waquoit Bay WB12, 13** | **Childs River CR01, 02, 03** | **Eel River ER01, 02, 03** | **Quashnet River WB06, 07, 08, 09** | **Hamblin Pond WB04, 10** | **Jehu Pond WB01** | **Great River WB02, 03** | **Red Brook WB05** | **Seapit River WB11** | **Total** |
| **July 15** | 3* | 3 | 3 | 4 | 2 | 1 | 2 | 1 | **1** | **20** |
| **July 29** | 3* | 3 | 3 | 4 | 2 | 1 | 2 | 1 | **1** | **20** |
| **Aug 15** | 3* | 3 | 3 | 4 | 2 | 1 | 2 | 1 | **1** | **20** |
| **Aug 30** | 3* | 3 | 3 | 4 | 2 | 1 | 2 | 1 | **1** | **20** |
| **Total** | **12** | **12** | **12** | **16** | **8** | **4** | **8** | **4** | **4** | **80** |

| Popponesset Bay Sub-Systems and Sampling Stations | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Date** | **Mashpee River PB01, 02, 03, 04** | **Shoestring Bay PB05,06, 07** | **Ockway Bay PB09, 10** | **Popp Bay PB08, 11, 12, 13** | **Off Shore PB 14** | **Pinquickset Cove PB15** | **Santuit River SR05** | **Total** |
| **July 15** | 4 | 3 | 2 | 5* | 1 | 1 | 1 | **17** |
| **July 29** | 4 | 3 | 2 | 5* | 1 | 1 | 1 | **17** |
| **Aug 15** | 4 | 3 | 2 | 5* | 1 | 1 | 1 | **17** |
| **Aug 30** | 4 | 3 | 2 | 5* | 1 | 1 | 1 | **17** |
| **Total** | **16** | **12** | **8** | **20** | **4** | **4** | **4** | **68** |

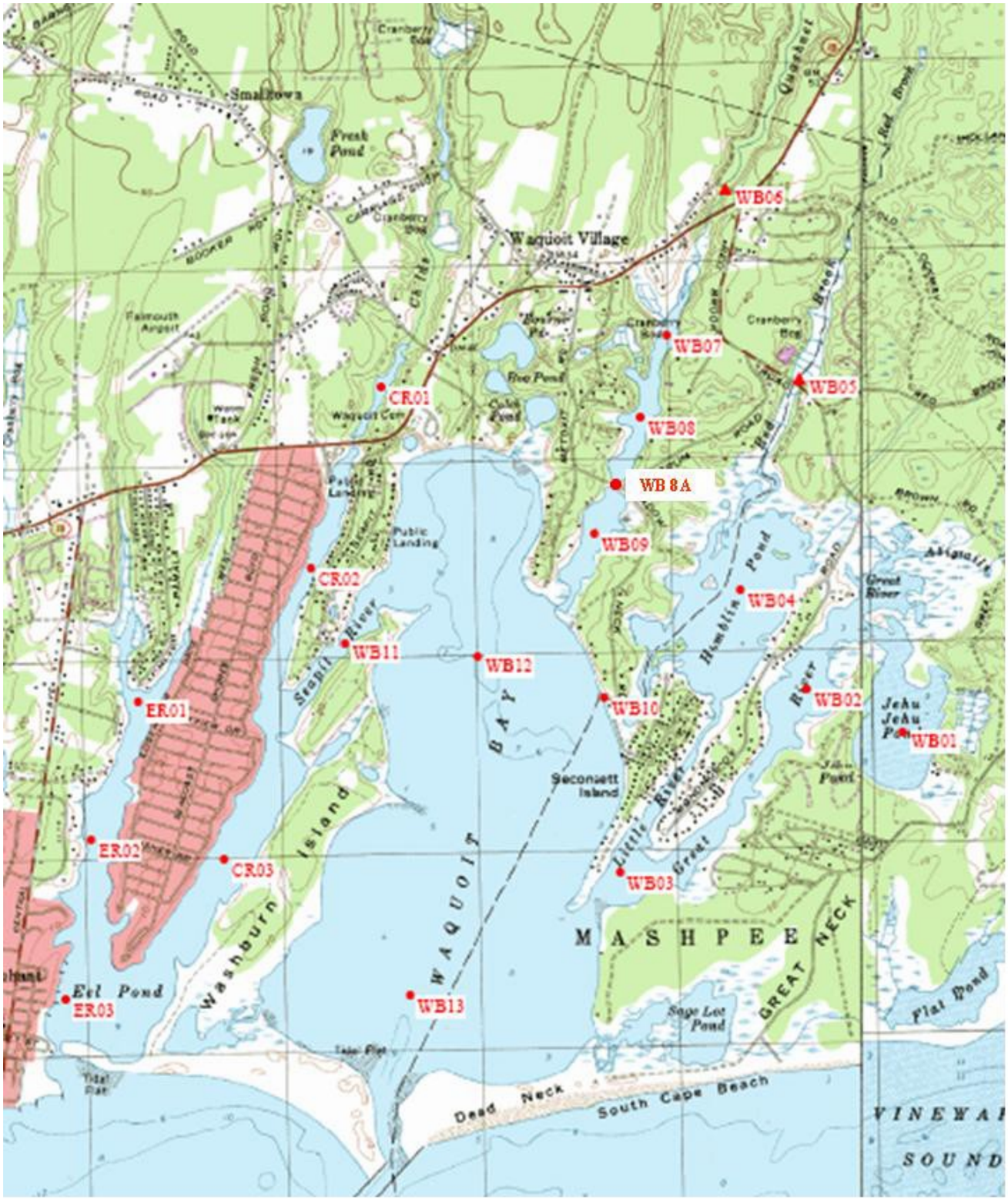


**Figure 4. Mashpee Water Quality Monitoring Program: Waquoit Bay Sampling Stations (2001-2022).** Samples were collected synoptically between 5:30 - 8:30 AM on ebbing tides.


**Figure 5. Mashpee Water Quality Monitoring Program: Popponesset Bay Sampling Stations (2001-2022).** Samples were collected synoptically between 5:30 - 8:30 AM on ebbing tides.

## *MONITORING RESULTS*

In regard to the Popponesset Bay and Waquoit Bay Systems, nutrient-related water quality decline continues to represent the primary environmental problem facing the citizens of Mashpee, Falmouth, Barnstable and Sandwich. Nitrogen management planning and implementation are underway and the Mashpee Water Quality Monitoring Partnership is tracking short and long term changes resulting from continued watershed nitrogen loading increases, variation in tidal flushing, and implementation of nitrogen management alternatives (including propagation of oysters). As implementation is still in its early stages, it is not surprising that the results of the 2022 Mashpee Water Quality Monitoring Program indicate that both Popponesset Bay and Waquoit Bay continue to show poor nutrient related water quality throughout most of their tidal reaches, particularly in the upper portions of each system.

During 2022, both systems had total nitrogen (TN) concentrations that were above their long term average TN concentrations at most stations [Figures 6 (Waquoit) and 10 (Popponesset)]. This finding would be consistent with the general expected trend predicted by the MEP modeling. Both systems had watershed buildout scenarios completed and both systems had projections of higher TN concentrations as all buildable lots were developed and associated populations continued to increase. Past reviews showed that TN concentrations fluctuate from year to year, but this general trend has continued on multi-year timeframes. For example, review of data through 2015 appeared to show some improved water quality in both Popponesset Bay and Waquoit Bay. Unfortunately both bays experienced large blooms and an associated decline in water quality in summers of 2016 - 2018, and both estuaries have impaired habitats and have TN levels that remain greater than the water quality levels set by the MassDEP/EPA.

Compared to 2021 levels, most of the 2022 TN levels in both systems increased. In 2022, TN levels in Popponesset were 4% to 44% higher than 2021 levels at 10 of the 14 individual stations. Waquoit TN levels increased at 11 of 16 monitoring stations with increases of 5% to 54%. Most of the stations in both systems where TN levels decreased were closer to the system inlet; the offshore station TN level decreased by 17% compared to 2021. These type of changes show that year-to-year fluctuations can be significant, something to keep in mind as the system improves after CWMP implementation.

The overall salinity gradients within each estuary in 2010-2022 are generally consistent with historical patterns with increases of 1% to 10% [Figures 7 (Waquoit) and 11 (Popponesset)]. There are notable exceptions at the uppermost tidal portions of the rivers flowing into both estuaries. At MR02 (Mashpee River), WB8 (Childs River), and WB7 (Quashnet River), 2022 salinities were 55% to 112% higher than the long-term mean (1997-2009). These higher levels continue general trends that have occurred since 2009, although preliminary 2023 data shows decreases, perhaps indicating normal fluctuations driven by unmeasured factors. Further data evaluation of streamflow and tidal water levels would be necessary to evaluate why salinity readings increase, but it would be consistent with an increasing tidal range. Another option would be decreasing streamflows and/or groundwater levels, but evaluations in other systems have found that groundwater levels are generally increasing at a faster rate than sea level rise.[7] Groundwater and

[7] Eichner, E., B. Howes, and D. Schlezinger. 2022. Cedar Pond Adaptive Management Monitoring Program: Annual Technical Report, January 2021 to December 2021. Town of Orleans. Coastal Systems Program, School for Marine Science and Technology, University of Massachusetts Dartmouth. New Bedford, MA. 47 pp.

stream discharge is likely happening at the same or a higher rate, but it has likely moved further inland from the long-term sampling stations.

The 2022 chlorophyll pigments in both bays generally showed decreases compared to 2021 concentrations [Figures 8 (Waquoit) and 12 (Popponesset)]. All station concentrations in both bays were greater than the long-term 3 µg/L impairment threshold established in previous monitoring reporting, but concentrations were 9% to 80% lower than 2021 levels. While these decreases are system-wide in both bays, they are largely lower than previous years, which suggest conditions in 2022 were exceptional for some reason. A more detailed review and review of available complementary data (*e.g.*, precipitation, temperature, winds) would be necessary to try to evaluate when 2022 levels were lower.

In contrast to TN, salinity, and chlorophyll pigments, DO levels were different in the two systems in 2022 [Figures 9 (Waquoit) and 13 (Popponesset)]. In Waquoit, the 20% lowest DO concentrations increased from 2021 levels in Childs River, Eel River, Quashnet River, Jehu Pond, and Seapuit River stations. The mid-Quashnet River station (WB08) concentration exceeded the MEP minimum of 6 mg/L. Preliminary data from 2023 generally showed decreases back to 2021 at 4 stations, but reinforced the fluctuations often seen in DO readings. In Popponesset, in contrast, 12 of the 14 stations had decreases in 2022 DO levels compared to 2021 levels. Preliminary review of 2023 data generally showed increases compared to 2022 levels; this will be evaluated further when all 2023 data is available. The average 2022 DO concentration across all stations was 3.6 mg/L while the 2023 average was 3.8 mg/L. Factors that impact DO levels are photosynthesis/plant levels, sediment oxygen demand, winds, and temperature. With the decreases in chlorophyll pigments, photosynthesis additions would have to come from macroalgae. As with the chlorophyll pigments, additional information would be necessary to determine why the changes may have occurred and why there were differences from year to year.

In general, the 2010-2022 sampling results are consistent with the prior years in showing that the Waquoit Bay and Popponesset Bay systems are still well above their assimilative capacity with total nitrogen levels well above their TMDL designated thresholds. The threshold total nitrogen level for all of Popponesset Bay is 0.38 mg/L, while Waquoit Bay has a TN threshold limit of 0.5 mg/L for Quashnet River, 0.446 mg/L for Jehu Pond, and 0.38 mg/L for the rest of the Bay. It should be noted that Hamblin and Jehu Pond had only recently lost their eelgrass habitat at the time of the MEP and therefore may be able to be restored more quickly than other larger basins that are much farther beyond their acceptable nitrogen thresholds. The MEP team also noted that Childs River and Quashnet River show more TN variability due to annual hydrologic variability and, as such, continued monitoring is critical to account for the variability. The consequences of the elevated TN levels can be seen in the high amounts of phytoplankton biomass (measured as chlorophyll-a pigments) and associated depletion of bottom water oxygen.

## *NUTRIENT RELATED WATER QUALITY INDEX*

Past reviews have integrated the key nutrient related parameters collected as part of the monitoring program into a single eutrophication index. The Bay Health Index was developed for Buzzards Bay embayments based upon levels of nitrogen (inorganic and organic), total chlorophyll-a, bottom water oxygen and the depth of light penetration (Secchi depth). **Table 4** show the index reference values; based on measured water quality in a bay, each parameter is rated on a 0% to 100% score and then the scores are average across the parameters. Higher scores (*e.g.*, >70%) indicate high quality conditions. The "Health Index" provides a convenient tool for comparing regions within an estuary and between estuaries, but does not provide a quantitative assessment of habitat health and is not suitable for salt marsh dominated estuaries or freshwater. Nevertheless, it does give a useful general picture of estuarine water quality and spatial gradients within estuaries and may be used to assess temporal trends.

The Bay Health Index has been used previously for the Waquoit Bay and Popponesset Bay estuarine systems based on the multi-year monitoring results [long-term (1997-2009), 2010-2012, 2013-2015, 2016-2018, 2019-2021]. In this report, the 2022 Index results for both systems were compared to both the long term results and the most recent three year period (2019-2021). Average summer conditions throughout the Waquoit Bay and Popponesset Bay Systems were used to parameterize the Index. The scores for each parameter were calculated and the average score for each station (across the five parameters) were calculated for the long-term baseline, 2019-2021, and 2022. It should be understood that the resulting Index and the designation of acceptable ranges for each parameter are approximate and provide less certainty than site-specific analysis which include habitat assessments (*e.g.,* eelgrass, benthic infauna).

In Popponesset, the recent Index results generally showed improvements at all stations. The comparison of long-term baseline, 2019-2021, and 2022 Health Index scores at the monitoring stations shows that there was slight improvement 2022 compared to the baseline, but a larger improvement comparing the 2019-2021 average to the baseline (**Figure 14**). Overall 12 of the 15 stations showed improvements over baseline conditions in 2022, but all stations showed improvements when comparing 2019-2021 averages to baseline conditions. Review of the Index results to the general health status at the individual stations show 5 of the 15 stations have Fair/Poor scores with most of these stations in the Mashpee River. Another 8 stations are in the Moderate or Moderate/Fair categories. Only one station had a 2022 score in the High quality range and that was PB14, the offshore station. Input values are shown in **Table 5**. A summary of Health Index categories of Popponesset Bay stations from 2019 through 2022 is shown in **Figure 15**.

In Waquoit, the improvements were less consistent. Comparison of 2019-2021 index results to long-term baseline showed 9 of the 18 stations showed improvements, but the net score across the system was only +1 (**Figure 16**). Comparison of 2022 index results to baseline conditions showed a slight improvement: 14 of the 18 stations had improvements. Review of the Index results to the general health status at the individual stations show 6 of the 18 stations have Fair/Poor scores and that all of these stations are the estuary portions of the rivers feeding into the system: Childs River, Quashnet River, and Red Brook. Another 8 stations are in the Moderate or Moderate/Fair categories. Only one station had a 2022 score in the High quality range and that was WB13, the main bay station closest to the inlet; the 2022 score was approximately the same as the long-term baseline average. Input values are shown in **Table 6**. A summary of Health Index categories of Popponesset Bay stations from 2019 through 2022 is shown in **Figure 17**.

## *MONITORING CONCLUSIONS AND RECOMMENDATIONS*

Overall, both the Waquoit Bay and Popponesset Bay Estuarine Systems continue to be highly nitrogen enriched and show impaired nutrient related water quality in 2022, similar to the long-term pattern. The tidal rivers (Mashpee River, Childs River, Quashnet River) and major tributary basins (Eel Pond/River, Shoestring Bay and Ockway Bay) are all showing poor to moderate impaired water quality as evidenced by the Bay Health Index. All basins show nitrogen levels above their TMDL thresholds, periodic oxygen depletions below the state water quality standard and levels shown to be stressful to estuarine organisms, paired with periodic major phytoplankton blooms. The main basin of Waquoit Bay continues to show high water quality, but the main basin of Popponesset Bay continues to show TN concentrations greater than the TMDL limit of 0.38 mg/L.

As water development continues, it is anticipated that TN concentrations will continue to increase and Health Index scores will decrease, though it is also anticipated that there will be year-to-year fluctuations. Nitrogen management steps will be implemented soon and the Town should consider whether an updated baseline assessment of key MEP would be beneficial for comparison of anticipated improvements. Updated baseline information would include many of the measurements collected during the MEP, including benthic infauna, tidal elevation, streamflow monitoring, and watershed nitrogen loads. The water column data collected through the Mashpee Water Quality Monitoring Partnership is an important component of a baseline, but these other information are important for assessing the ecosystem conditions prior to the impacts of Phase I sewering.

### *Specific findings:*

(1) Both Waquoit Bay and Popponesset Bay show continuing impairments. All Popponesset Bay and Waquoit Bay stations have TN concentrations greater than the respective MassDEP TMDLs.

(2) Both Waquoit Bay and Popponesset Bay have many individual monitoring stations with Fair/Poor scores on the Bay Health Index. There have been some recent improvements (2019-2021) compared to baseline conditions (1997-2009), but these scores only show high quality scores either near the inlet (Waquoit Bay) or outside of the system (Popponesset Bay).

(3) Oxygen depletion in bottom waters continues to be a persistent impairment in both systems. All Popponesset Bay stations and all but one Waquoit Bay station had 2022 20% lowest dissolved oxygen concentrations less than the MassDEP minimum for SA waters (*i.e.*, 6 mg/L DO).

(4) All Popponesset Bay stations and all but one Waquoit Bay stations also had 2022 total chlorophyll pigment concentrations greater than the 3 µg/L impaired threshold. It is notable, however, that pigment concentrations in 2022 were lower than the long-term baseline.

(5) The monitoring program has become sufficiently robust to be able to detect changes within the estuaries in response to implementation of management alternatives, as well as year-to-year variations. Natural variation in year to year changes is overcome by continued long-term monitoring.

## *Recommendations:*

As the Town moves forward with CWMP implementation, water quality and ecosystem monitoring will become even more important for both assessing improvements and regulatory compliance with MassDEP. With this in mind, it is recommended that the Town consider collecting some of the ecosystem assessment parameters measured during the MEP so that the Town has an update baseline as improvements begin to the measured in water column data through the continuing Mashpee Water Quality Monitoring Partnership activities. These activities would include strategic collection and incubation of sediment cores, collection and assessment of benthic infauna populations, continuous DO and chlorophyll moorings, streamflow readings and water quality, and tidal elevation readings. These dataset could be compared to MEP findings and provide an updated baseline of current impaired conditions. The Town may also want to consider updating watershed nitrogen loads for comparisons to MEP buildout estimates and looking at other refined factors that could impact eelgrass regrowth, such as water column and bottom light recordings. The Town could then have information for discussions with MassDEP about TMDL compliance and current conditions that exist in the system.

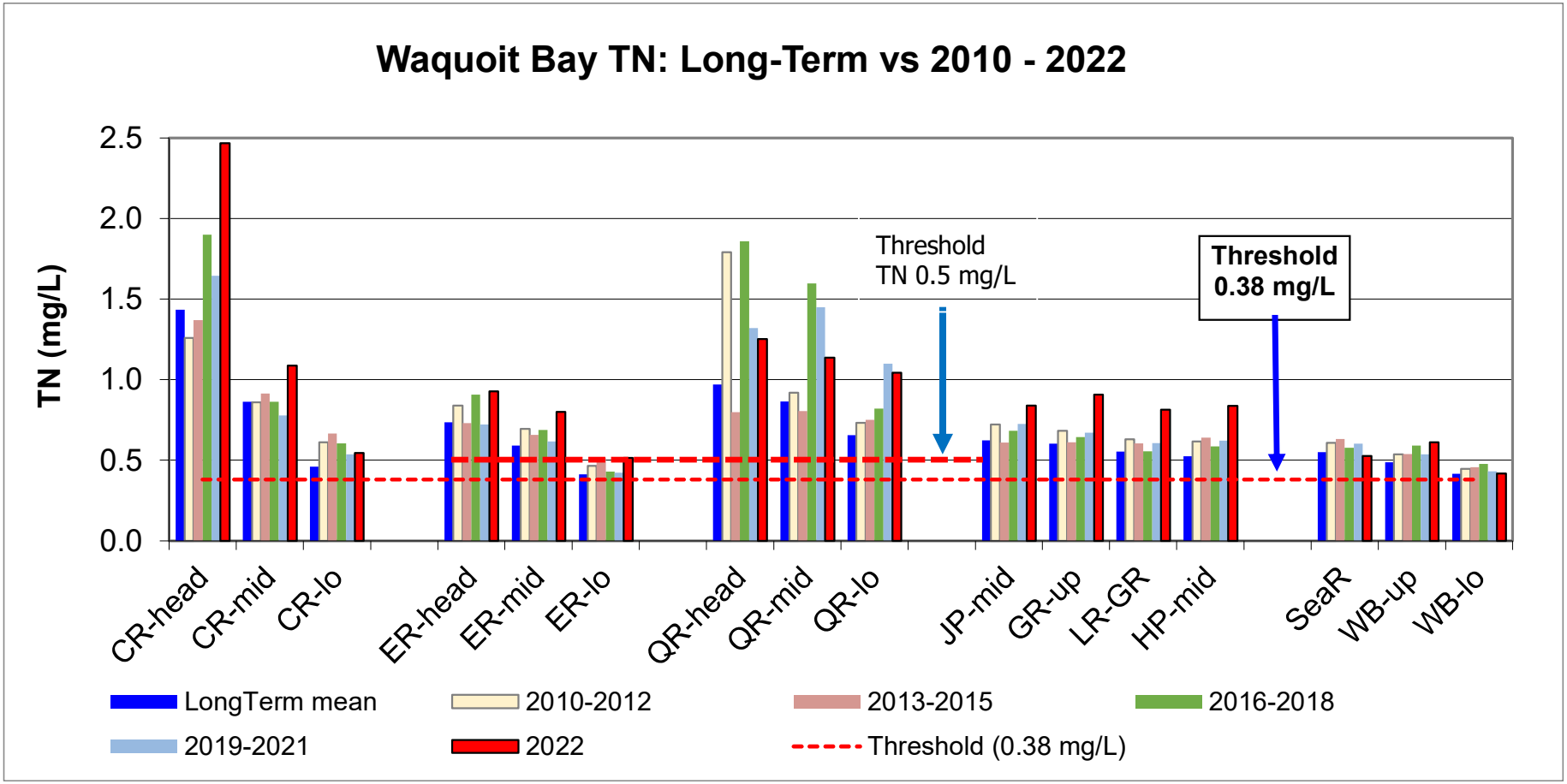


**Figure 6**. Distribution of Total Nitrogen within the Waquoit Bay Estuarine System, long-term and during the summers of 2010 through 2022. Nitrogen enters through groundwater inflows all along the shoreline, with additional "point" loads from the upper regions of the watershed via Moonakis River, Childs River, and Red Brook. These nitrogen loads plus recycling within the estuary mix with the low nitrogen waters of Nantucket Sound entering through the tidal inlets to create the observed gradient. CR - Childs River, ER - Eel River, QR - Quashnet River, JP - Jehu Pond, GR - Great River, LR-GR - Little River-Great River confluence, HP - Hamblin Pond, SeaR - Seapit River, WB - Waquoit Bay main basin; head - uppermost reach, mid - middle reach, lo - lower basin near mouth or inlet. The red lines shows the TMDL threshold TN concentrations (0.38 mg/L for most of the system; 0.5 mg/L for Quashnet River & Upper Eel River) for restoration as adopted by MassDEP. TN levels in 2010-2021 are compared to the long-term averages (1997-2009).

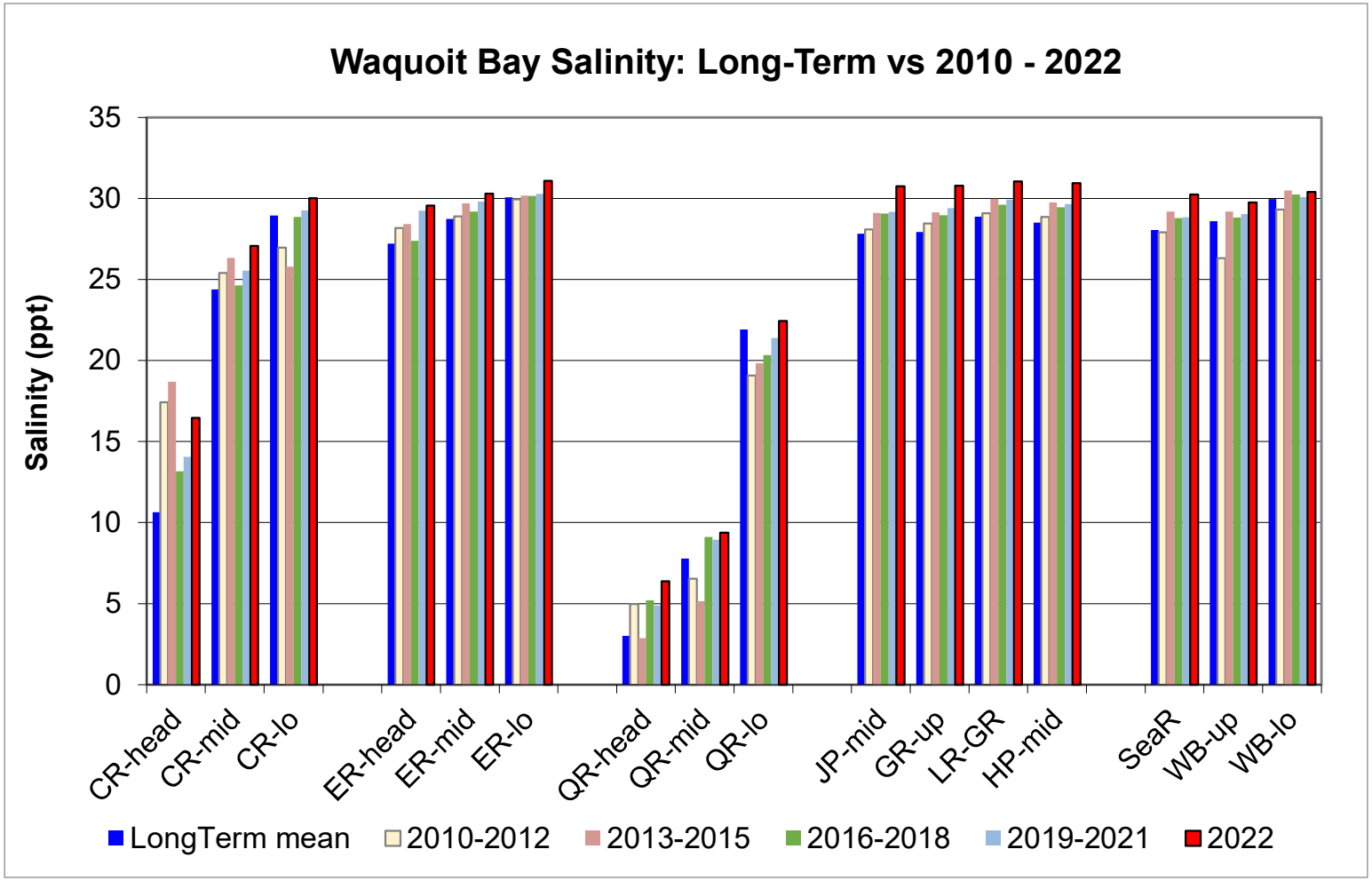


**Figure 7**. Salinity Distribution throughout the Waquoit Bay Estuarine System long-term and in the summers of 2010-2022. Freshwater enters through groundwater all along the shoreline, with additional "point" inflows from the Moonakis River, Childs River, and Red Brook. These freshwaters mix with the saline waters of Nantucket Sound entering through the tidal inlets. CR - Childs River, ER - Eel River, QR - Quashnet River, JP - Jehu Pond, GR - Great River, LR-GR - Little River- Great River confluence, HP - Hamblin Pond, SeaR - Seapit River, WB - Waquoit Bay main basin; head - uppermost reach, mid - middle reach, lo - lower basin near mouth or inlet.

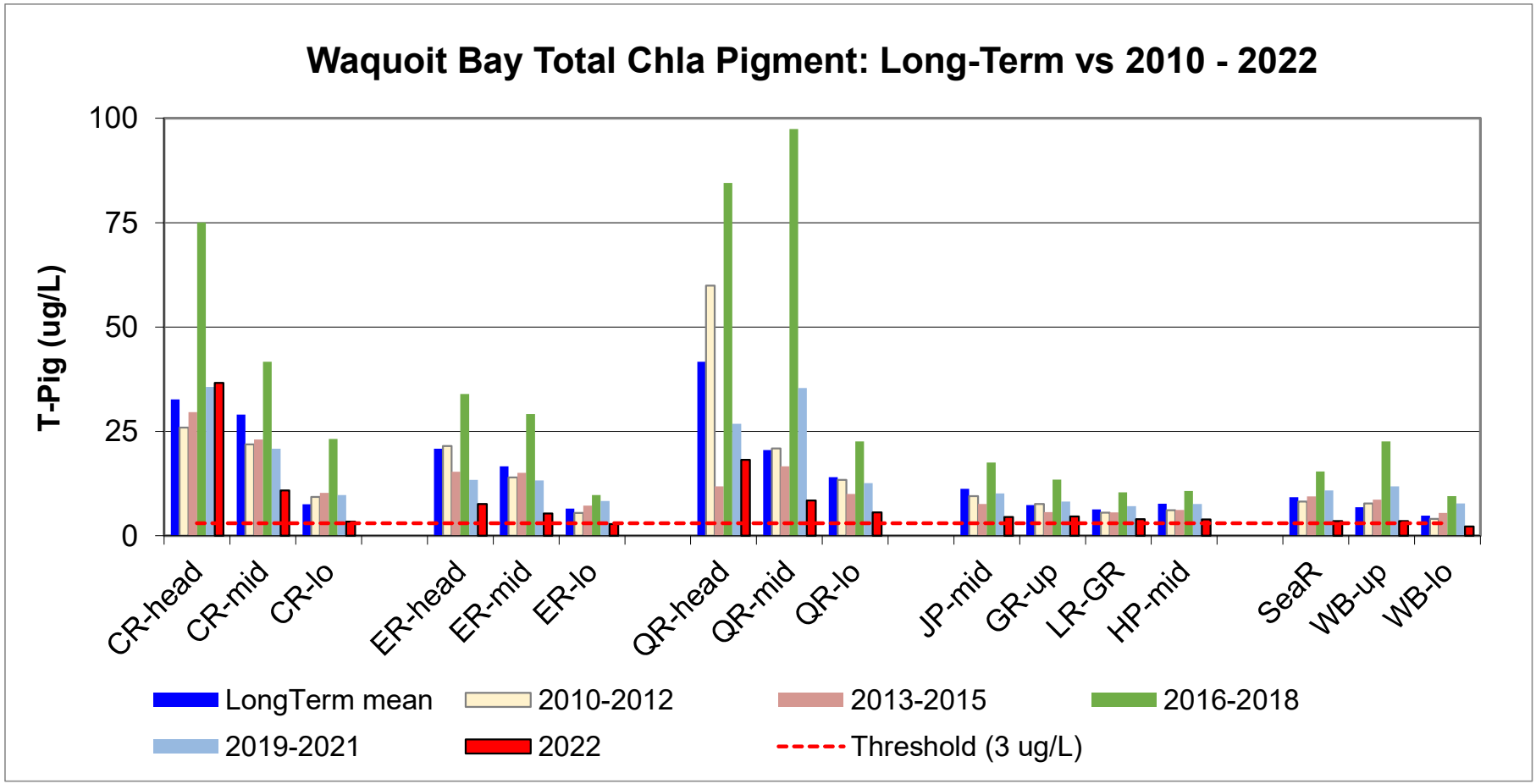


**Figure 8**. Total Chlorophyll-a pigment levels throughout the Waquoit Bay Estuarine System over the long-term and in summers of 2009 through 2021. Phytoplankton pigment levels are a gauge of phytoplankton biomass, which is a response to nitrogen loading. Values over 10 indicate nitrogen enrichment, values $\leq 3$ represent low nitrogen enriched waters (red line). CR - Childs River, ER - Eel River, QR - Quashnet River, JP - Jehu Pond, GR - Great River, LR-GR - Little River-Great River confluence, HP - Hamblin Pond, SeaR - Seapit River, WB - Waquoit Bay main basin; head - uppermost reach, mid - middle reach, lo - lower basin near mouth or inlet.

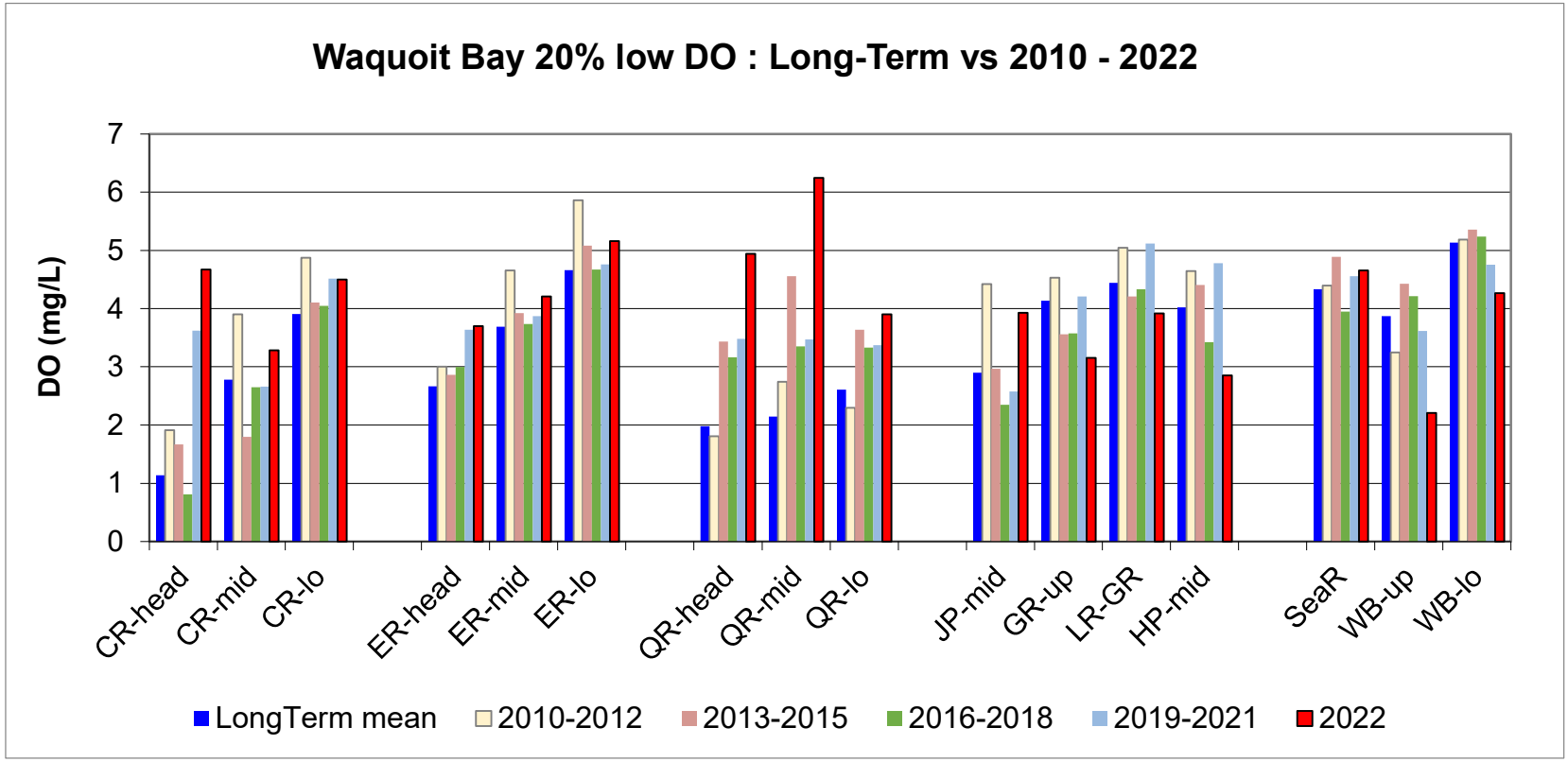


**Figure 9**. Minimum Dissolved Oxygen (DO) levels throughout the Waquoit Bay Estuarine System over the long-term and in the summers of 2010-2022. CR - Childs River, ER - Eel River, QR - Quashnet River, JP - Jehu Pond, GR - Great River, LR- GR - Little River-Great River confluence, HP - Hamblin Pond, SeaR - Seapit River, WB - Waquoit Bay main basin; head - uppermost reach, mid - middle reach, lo - lower basin near mouth or inlet. Massachusetts Surface Water Regulations administered by MassDEP have a minimum DO concentration of 6 mg/L in Class SA coastal waters (314 CMR 4).

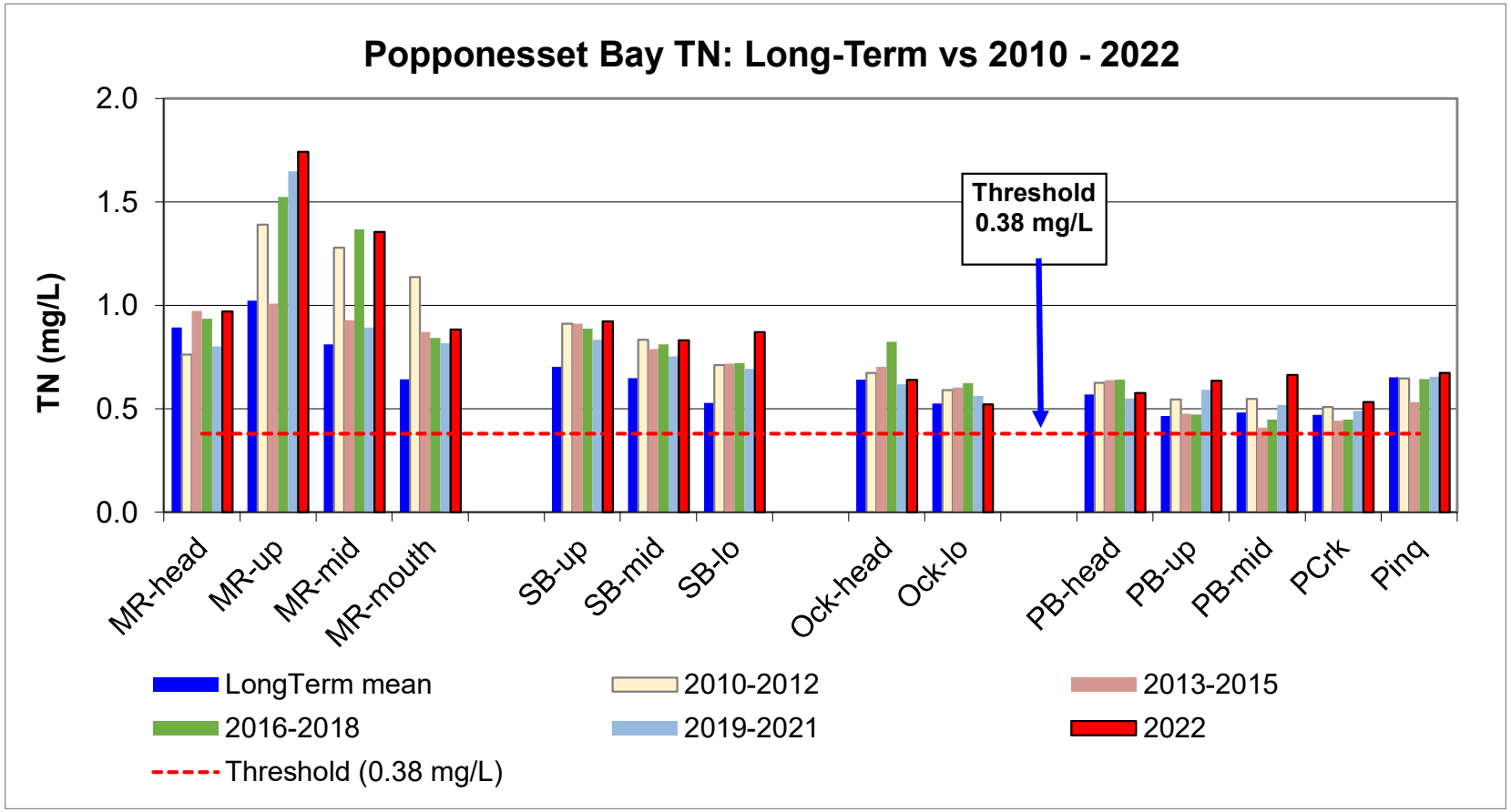


**Figure 10**. Distribution of Total Nitrogen within the Popponesset Bay Estuarine System. Nitrogen enters through groundwater inflows all along the shoreline, with additional "point" loads from the upper regions of the watershed via the Mashpee River and Santuit River to Shoestring Bay. These nitrogen loads plus recycling within the estuary mix with the low nitrogen waters of Nantucket Sound entering through the single tidal inlet to create the observed gradient. MR - Mashpee River, SB - Shoestring Bay, Ock - Ockway Bay, PB - Popponesset Bay, PCrk - Poppenesset Creek, Pinq - Pinquickset Cove. The red line shows the TMDL threshold TN concentration (0.38 mg/L) for restoration as adopted by MassDEP. TN levels in 2010-2021 are compared to the long-term averages (1997-2009).

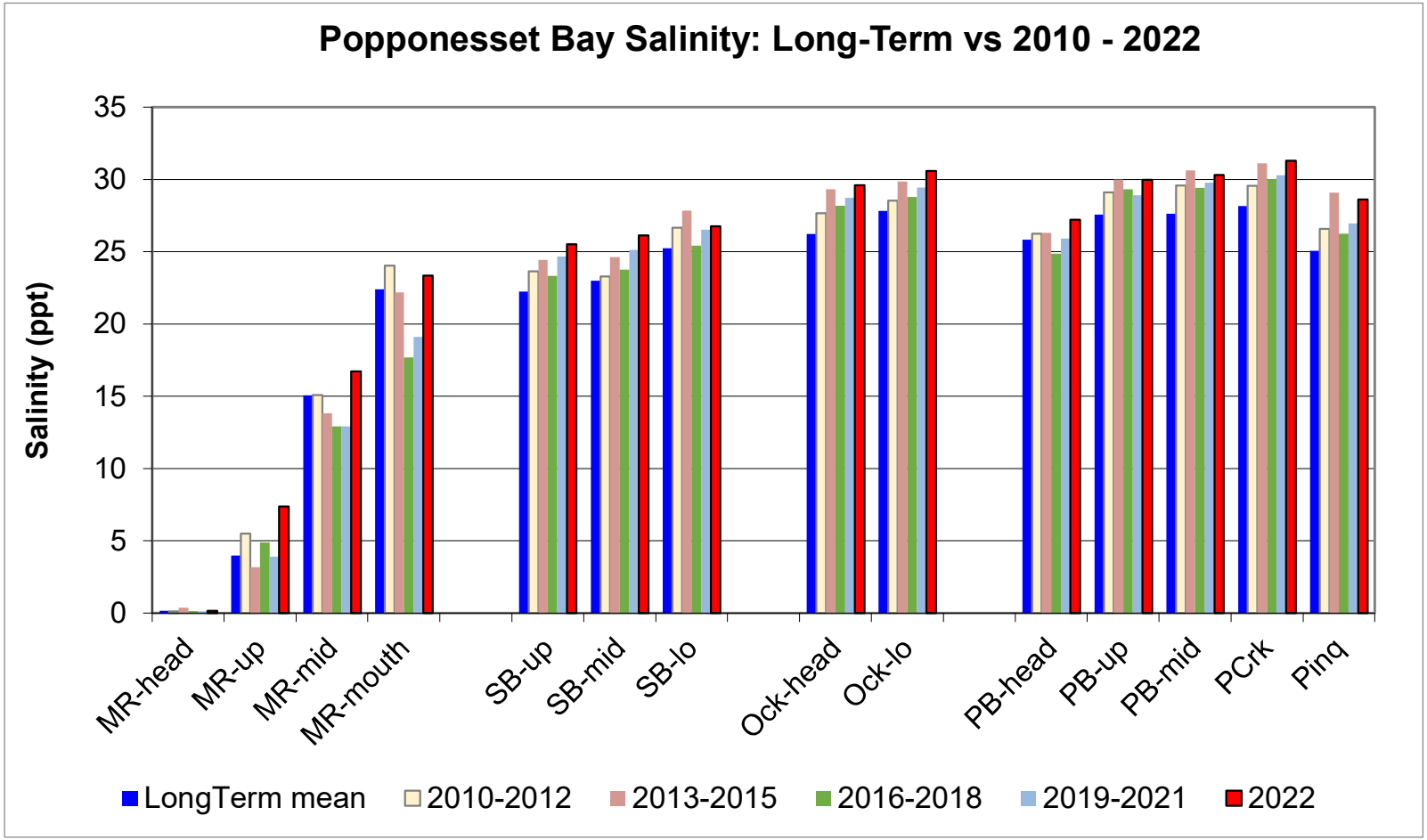


**Figure 11. Salinity Distribution throughout the Popponesset Bay Estuarine System (2010-2022).** Freshwater enters through groundwater all along the shoreline, with additional "point" inflows from the freshwater reach of the Mashpee River and from the Santuit River to Shoestring Bay. These freshwaters mix with the saline waters of Nantucket Sound entering through the single tidal inlet. MR - Mashpee River, SB - Shoestring Bay, Ock - Ockway Bay, PB - Popponesset Bay, PCrk - Popponesset Creek, Pinq - Pinquickset Cove.

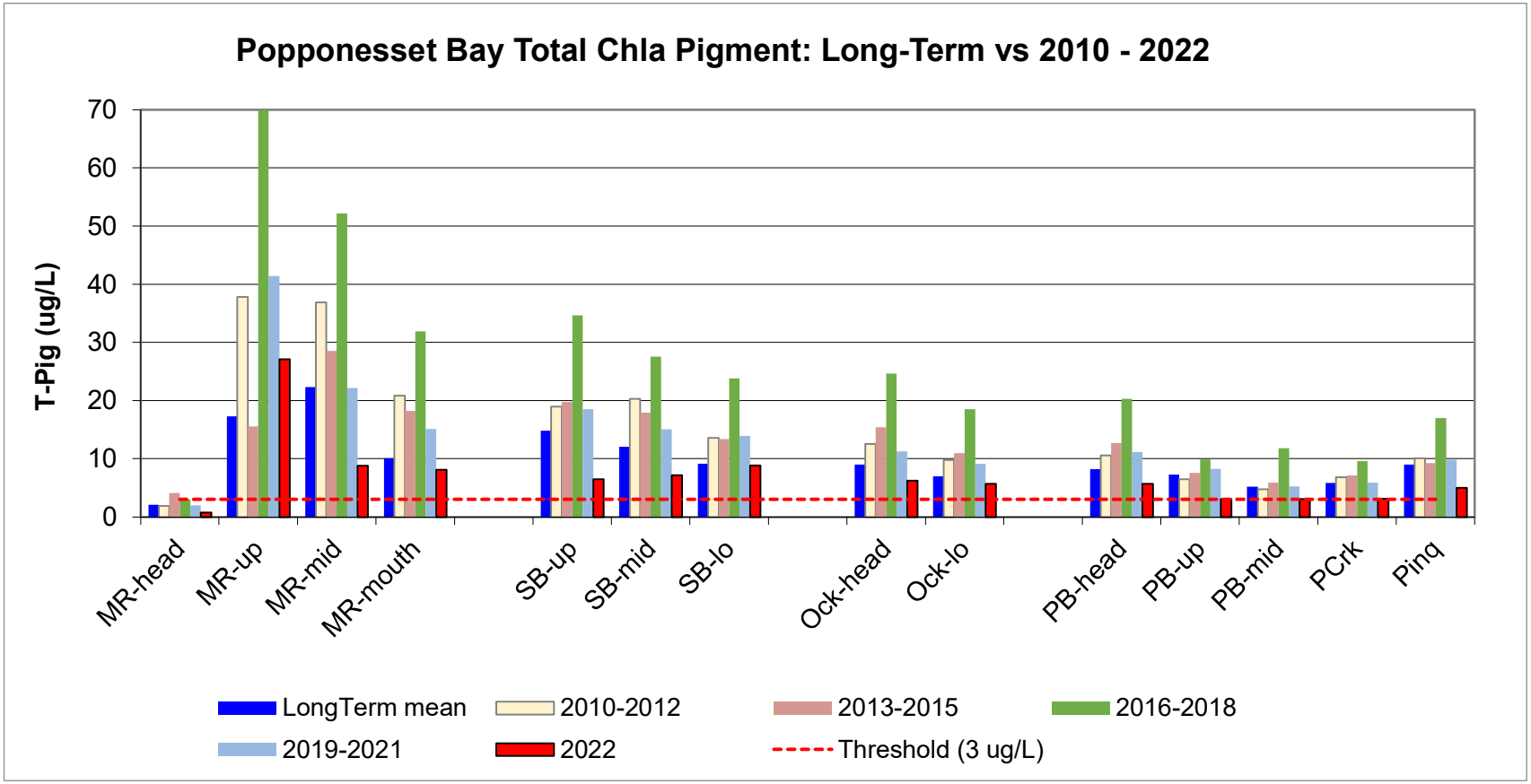


**Figure 12**. Total Chlorophyll-a pigment levels throughout the Popponesset Bay Estuarine System over the long-term and in summer 2010-2022. Phytoplankton pigment levels are a gauge of phytoplankton biomass, which is a response to nitrogen loading. Values over 10 indicate nitrogen enrichment, values $\leq 3$ represent low nitrogen enriched waters (red line). MR - Mashpee River, SB - Shoestring Bay, Ock - Ockway Bay, PB - Popponesset Bay, PCrk - Poppenesset Creek, Pinq - Pinquickset Cove.

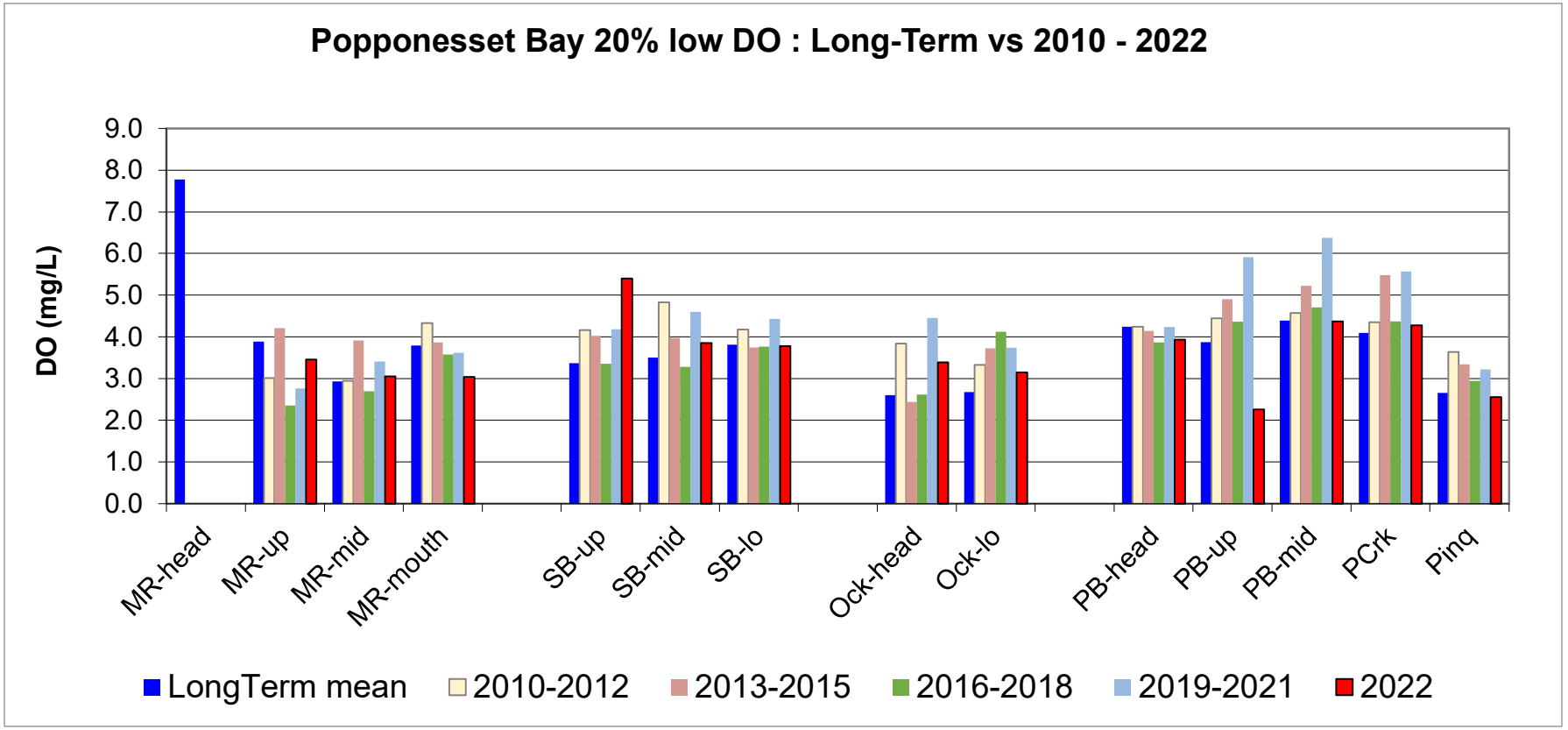


**Figure 13**. Minimum Dissolved Oxygen levels throughout the Popponesset Bay Estuarine System over the long-term and in the summers of 2010 through 2022. MR - Mashpee River, SB - Shoestring Bay, Ock - Ockway Bay, PB - Popponesset Bay, PCrk - Poppenesset Creek, Pinq - Pinquickset Cove. Massachusetts Surface Water Regulations administered by MassDEP have a minimum DO concentration of 6 mg/L in Class SA coastal waters (314 CMR 4).

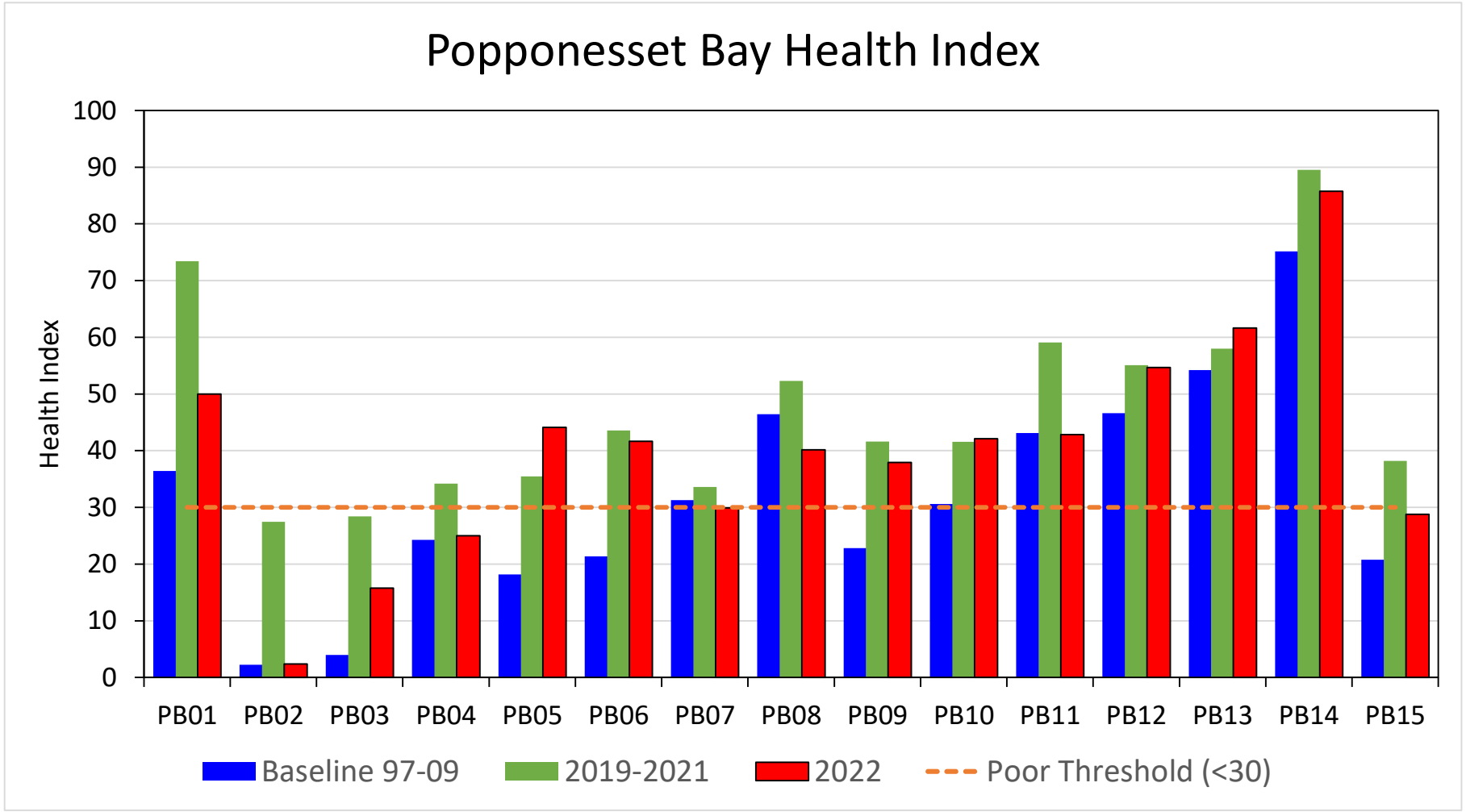


**Figure 14. Popponesset Bay Health Index: 1997-2009 (Baseline), 2019-2021, and 2022.** The comparison of long-term baseline, 2019-2021, and 2022 Health Index scores at the monitoring stations shows that there was slight improvement 2022 compared to the baseline, but a larger improvement comparing the 2019-2021 average to the baseline. Review of the Index results to the general health status at the individual stations show 5 of the 15 stations have Fair/Poor scores with most of these stations in the Mashpee River. Another 8 stations are in the Moderate or Moderate/Fair categories. Only one station had a 2022 score in the High quality range and that was PB14, the offshore station.

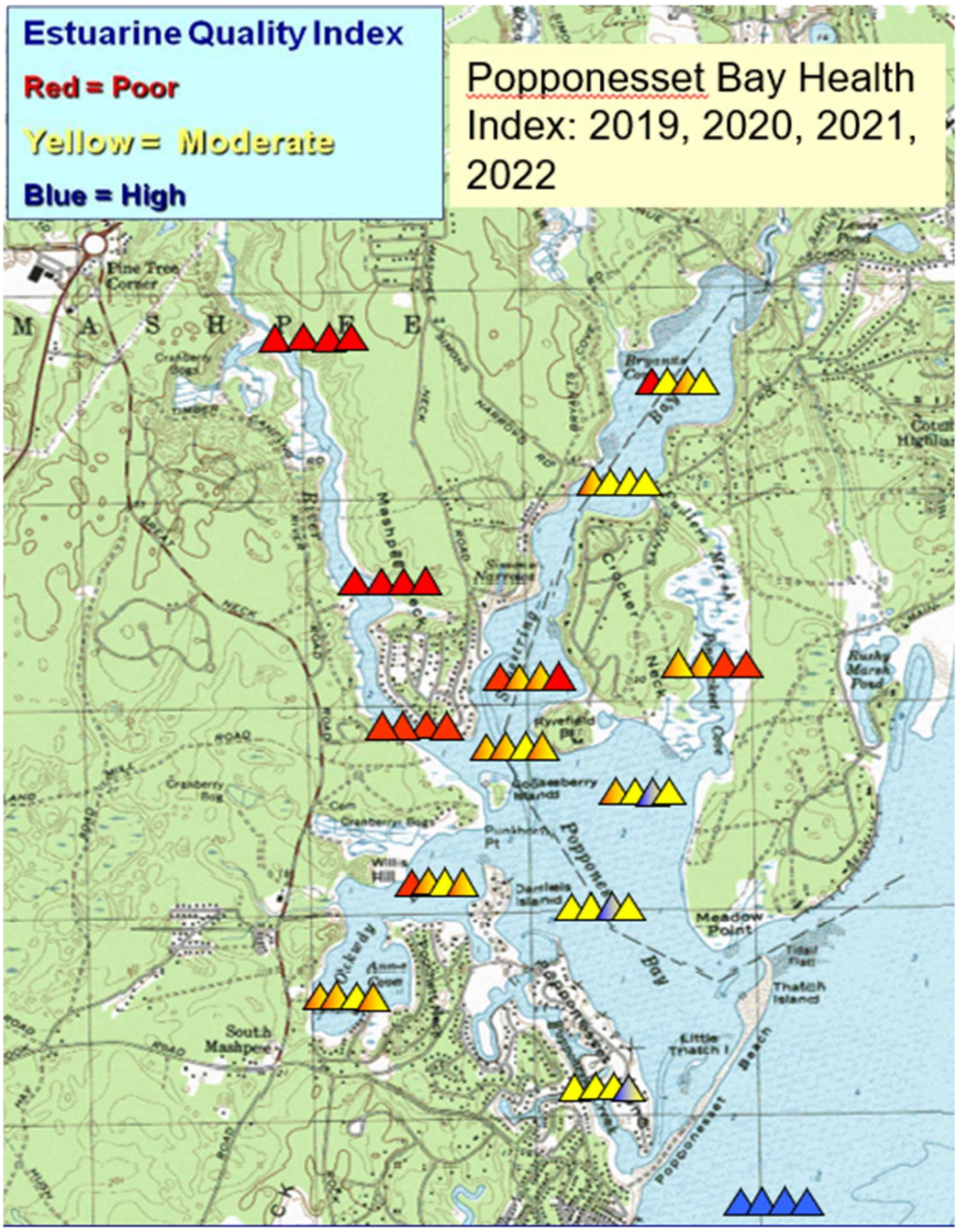


**Figure 15. Popponesset Bay Health Index Summary: 2019, 2020, 2021, and 2022.** Poor health index scores occur at stations in or near the Mashpee River and Pinquickset Cove. The only location with high quality health index score in 2022 is station PB14, which is just outside the system inlet.

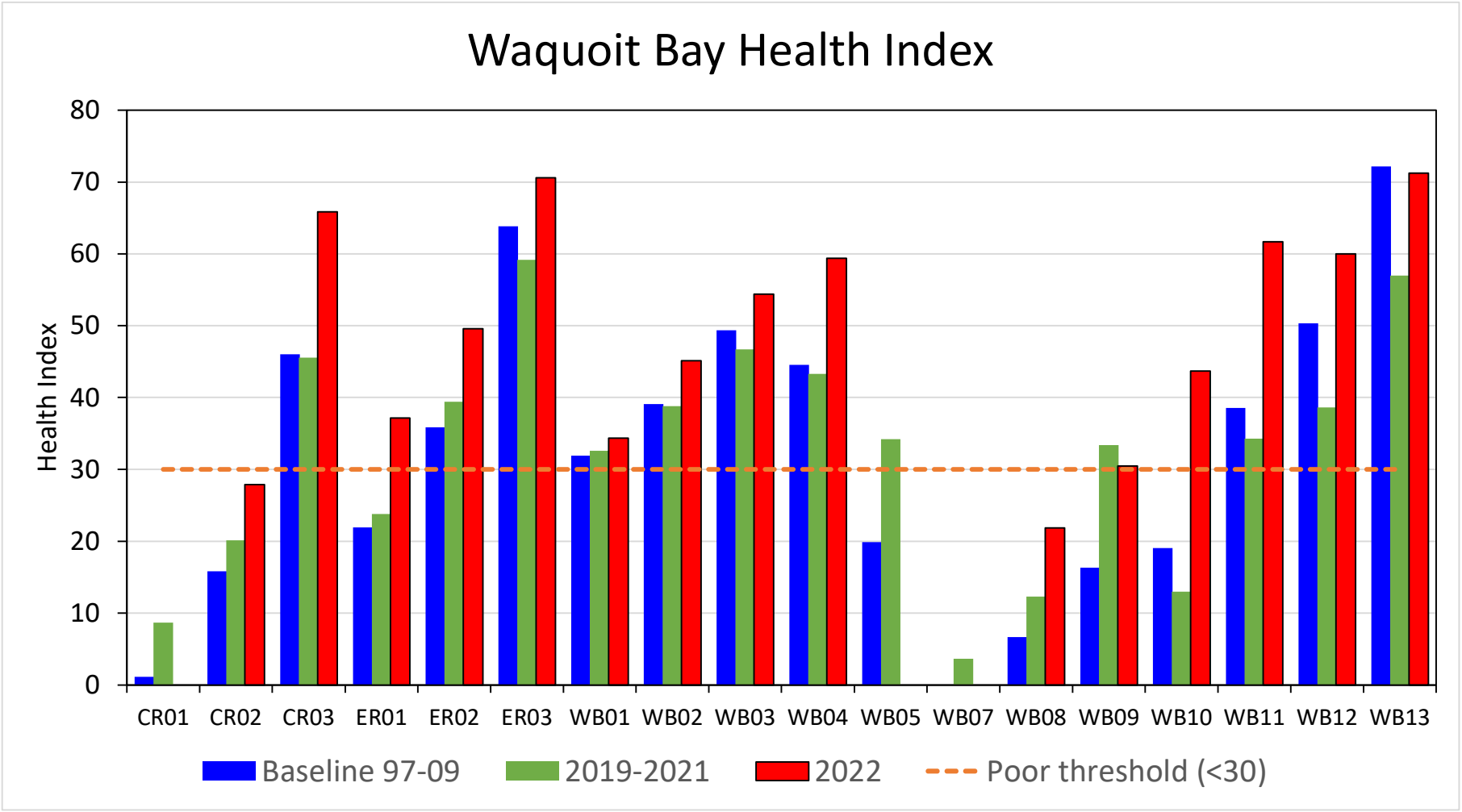


**Figure 16. Waquoit Bay Health Index: 1997-2009 (Baseline), 2019-2021, and 2022.** Comparison of 2019-2021 index results to long-term baseline showed 9 of the 18 stations showed improvements, but the net score across the system was only +1. Comparison of 2022 index results to baseline conditions showed a slight improvement: 14 of the 18 stations had improvements. Review of the Index results to the general health status at the individual stations show 6 of the 18 stations have Fair/Poor scores and that all of these stations are the estuary portions of the rivers feeding into the system: Childs River, Quashnet River, and Red Brook. Another 8 stations are in the Moderate or Moderate/Fair categories. Only one station had a 2022 score in the High quality range and that was WB13, the main bay station closest to the inlet; the 2022 score was approximately the same as the long-term baseline average.

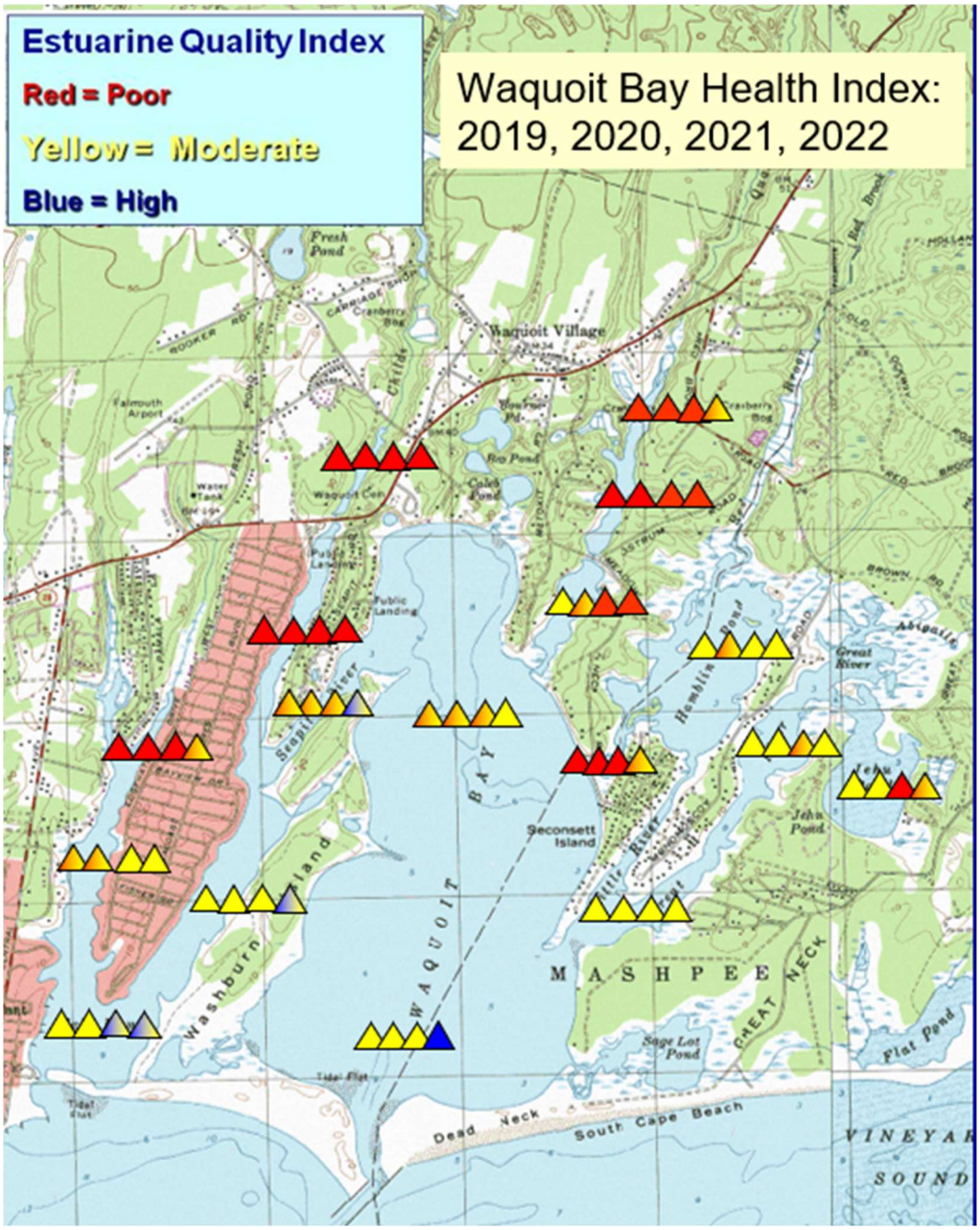


**Figure 17. Waquoit Bay Health Index Summary: 2019, 2020, 2021, and 2022.** Poor health index scores generally occur at stations in or near the Childs River and Quashnet River. The only location with high quality health index score in 2022 is station WB13, which is just inside the system inlet.

**Table 4**. Reference values used in the Bay Health Index. Scores are generated for each parameter and the mean score computed. In some cases where Secchi data is not available, the mean of the other 4 parameters may be used.

| Score | Secchi Depth M | Oxygen Saturation % | Inorganic N mg/L | Total N mg/L | Total Chlorophyll-a Pigments ug/L |
|---|---|---|---|---|---|
| 0% | 0.6 | 0.40 | 0.140 | 0.600 | 10.0 |
| 100 | 3.0 | 0.90 | 0.014 | 0.280 | 3.0 |
| The relationship between 0% to 100% for each parameter is logarithmic. | | | | | |

**Table 5**. Summary of Summer 2022 water quality parameters in Popponesset Bay used in Bay Health Index.

| 2022 Station | Secchi Depth (m) | Total Depth (m) | Secchi as % W.C. | Salinity (ppt) | 20% Low D.O. (mg/L) | 20% Low D.O. (% Sat) | PO4 (mg/L) | NH4 (mg/L) | NOx (mg/L) | DIN (mg/L) | DON (mg/L) | PON (mg/L) | TON (mg/L) | TN (mg/L) | DIN/DIP Molar | T-Pig (ug/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Mashpee River/Popponesset Bay** | | | | | | | | | | | | | | | | |
| PB01 | 0.27 | 0.33 | 0.78 | 0.15 | ND | ND | 0.007 | 0.039 | 0.720 | 0.759 | 0.167 | 0.045 | 0.212 | 0.971 | 242.55 | 0.80 |
| PB02 | 0.55 | 0.64 | 0.89 | 7.38 | 3.46 | 44.00 | 0.008 | 0.020 | 0.134 | 0.154 | 0.347 | 1.240 | 1.588 | 1.742 | 44.98 | 27.12 |
| PB03 | 0.72 | 0.75 | 0.96 | 16.73 | 3.06 | 41.65 | 0.015 | 0.008 | 0.034 | 0.042 | 0.377 | 0.936 | 1.313 | 1.356 | 6.30 | 8.80 |
| PB04 | 0.73 | 0.85 | 0.89 | 23.36 | 3.04 | 49.10 | 0.010 | 0.012 | 0.015 | 0.028 | 0.334 | 0.521 | 0.855 | 0.883 | 6.26 | 8.12 |
| PB05 | 0.69 | 0.78 | 0.85 | 25.53 | 5.40 | 92.40 | 0.008 | 0.021 | 0.003 | 0.024 | 0.407 | 0.491 | 0.899 | 0.923 | 7.03 | 6.50 |
| PB06 | 0.87 | 1.10 | 0.84 | 26.13 | 3.85 | 64.10 | 0.008 | 0.004 | 0.002 | 0.005 | 0.338 | 0.487 | 0.825 | 0.831 | 1.38 | 7.20 |
| PB07 | 0.73 | 0.77 | 0.96 | 26.75 | 3.78 | 62.40 | 0.009 | 0.022 | 0.004 | 0.027 | 0.320 | 0.525 | 0.845 | 0.872 | 6.63 | 8.83 |
| PB09 | 0.90 | 1.19 | 0.76 | 29.62 | 3.39 | 49.16 | 0.004 | 0.002 | 0.002 | 0.003 | 0.236 | 0.401 | 0.637 | 0.641 | 1.69 | 6.25 |
| PB10 | 0.94 | 0.99 | 0.95 | 30.58 | 3.15 | 45.55 | 0.009 | 0.004 | 0.002 | 0.005 | 0.203 | 0.313 | 0.517 | 0.522 | 1.32 | 5.66 |
| PB08 | 1.03 | 1.46 | 0.77 | 27.20 | 3.93 | 0.00<br>57.84 | 0.008 | 0.030 | 0.004 | 0.034 | 0.189 | 0.353 | 0.542 | 0.576 | 9.06 | 5.68 |
| PB11 | 0.99 | 1.27 | 0.88 | 29.98 | 2.26 | 36.60 | 0.015 | 0.017 | 0.003 | 0.020 | 0.357 | 0.259 | 0.616 | 0.636 | 2.91 | 3.07 |
| PB12 | 1.54 | 1.63 | 0.94 | 30.31 | 4.37 | 77.50 | 0.016 | 0.029 | 0.005 | 0.033 | 0.388 | 0.242 | 0.630 | 0.664 | 4.68 | 3.10 |
| PB13 | 1.79 | 2.11 | 0.87 | 31.30 | 4.28 | 56.20 | 0.015 | 0.019 | 0.002 | 0.022 | 0.330 | 0.181 | 0.511 | 0.533 | 3.18 | 3.12 |
| PB15 | 0.55 | 0.62 | 0.91 | 28.62 | 2.55 | 34.36 | 0.013 | 0.016 | 0.003 | 0.019 | 0.314 | 0.340 | 0.655 | 0.674 | 3.35 | 5.01 |
| PB14 | 1.43 | 1.48 | 1.00 | 32.02 | 5.43 | 95.90 | 0.017 | 0.005 | 0.001 | 0.006 | 0.194 | 0.146 | 0.340 | 0.346 | 0.78 | 1.57 |
| **Santuit River** | | | | | | - | | | | | | | | | | |
| SR5 | btm | 0.45 | 0.93 | 9.63 | ND | ND | 0.019 | 0.052 | 0.452 | 0.504 | 0.382 | 0.620 | 1.003 | 1.507 | 59.71 | 6.89 |

Table 6. Summary of Summer 2022 water quality parameters in Waquoit Bay used in Bay Health Index.

| 2022 Station | Secchi Depth (m) | Total Depth (m) | Secchi as %W.C. | Salinity (ppt) | 20% Low D.O. (mg/L) | 20% Low D.O. (% Sat) | PO4 (mg/L) | NH4 (mg/L) | NOx (mg/L) | DIN (mg/L) | DON (mg/L) | PON (mg/L) | TON (mg/L) | TN (mg/L) | DIN/DIP Molar | T-Pig (ug/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Childs River** | | | | | | | | | | | | | | | | |
| CR01 | 0.60 | 0.82 | 0.71 | 13.17 | 0.90 | 13.60 | 0.01 | 0.03 | 0.21 | 0.23 | 0.36 | 1.88 | 2.23 | 2.47 | 43.94 | 36.61 |
| CR02 | 1.03 | 1.54 | 0.67 | 25.73 | 2.60 | 42.50 | 0.01 | 0.01 | 0.01 | 0.01 | 0.46 | 0.61 | 1.07 | 1.09 | 3.82 | 10.88 |
| CR03 | 1.29 | 2.18 | 0.61 | 29.60 | 4.21 | 74.60 | 0.01 | 0.01 | 0.00 | 0.01 | 0.31 | 0.22 | 0.54 | 0.55 | 2.14 | 3.39 |
| **Eel River** | | | | | | | | | | | | | | | | |
| ER01 | 0.94 | 1.34 | 0.70 | 30.76 | 3.22 | 53.10 | 0.01 | 0.00 | 0.00 | 0.01 | 0.47 | 0.45 | 0.92 | 0.93 | 1.71 | 7.57 |
| ER02 | 1.13 | 1.35 | 0.83 | 30.55 | 3.67 | 63.10 | 0.01 | 0.01 | 0.00 | 0.01 | 0.38 | 0.41 | 0.79 | 0.80 | 2.88 | 5.30 |
| ER03 | btm | 1.33 | 1.00 | 30.55 | 4.60 | 78.80 | 0.01 | 0.00 | 0.00 | 0.00 | 0.34 | 0.17 | 0.51 | 0.51 | 0.72 | 2.80 |
| **Waquoit Bay** | | | | | | | | | | | | | | | | |
| WB01 | 1.20 | 1.70 | 0.70 | 29.98 | 1.53 | 25.30 | 0.01 | 0.03 | 0.00 | 0.03 | 0.51 | 0.30 | 0.81 | 0.84 | 5.87 | 4.51 |
| WB02 | 1.18 | 1.39 | 0.85 | 30.19 | 3.55 | 57.00 | 0.01 | 0.02 | 0.00 | 0.02 | 0.58 | 0.31 | 0.88 | 0.91 | 3.72 | 4.63 |
| WB03 | 1.33 | 1.60 | 0.87 | 30.58 | 4.49 | 79.70 | 0.02 | 0.03 | 0.00 | 0.03 | 0.51 | 0.26 | 0.78 | 0.81 | 3.89 | 3.96 |
| WB04 | 1.23 | 1.28 | 0.96 | 30.27 | 4.64 | 82.30 | 0.02 | 0.02 | 0.00 | 0.02 | 0.53 | 0.29 | 0.82 | 0.84 | 1.94 | 3.87 |
| WB05 | btm | 0.20 | 1.00 | 0.15 | NS | ND | 0.03 | 0.43 | 0.69 | 1.11 | 0.28 | 0.80 | 1.08 | 2.19 | 76.44 | 19.32 |
| WB06 | btm | 0.30 | 1.00 | 0.10 | NS | ND | 0.01 | 0.02 | 0.25 | 0.27 | 0.17 | 0.06 | 0.23 | 0.50 | 71.83 | 2.02 |
| WB07 | btm | 0.41 | 1.00 | 6.61 | 1.88 | 38.20 | 0.01 | 0.02 | 0.15 | 0.17 | 0.27 | 0.81 | 1.08 | 1.25 | 57.51 | 18.19 |
| WB08 | 0.83 | 0.88 | 0.94 | 11.47 | 4.16 | 51.60 | 0.02 | 0.01 | 0.04 | 0.05 | 0.36 | 0.73 | 1.09 | 1.14 | 6.26 | 8.52 |
| WB09 | btm | 0.33 | 1.00 | 22.78 | 3.48 | 48.50 | 0.03 | 0.01 | 0.01 | 0.02 | 0.52 | 0.50 | 1.02 | 1.04 | 1.79 | 5.57 |
| WB10 | ND | ND | ND | 29.73 | NS | ND | 0.02 | 0.03 | 0.00 | 0.03 | 0.38 | 0.42 | 0.80 | 0.83 | 3.27 | 4.64 |
| WB11 | 1.75 | 2.35 | 0.76 | 29.74 | 3.83 | 53.00 | 0.01 | 0.01 | 0.00 | 0.01 | 0.31 | 0.20 | 0.51 | 0.53 | 2.35 | 3.53 |
| WB12 | 1.84 | 2.02 | 0.91 | 29.88 | 4.03 | 57.10 | 0.02 | 0.00 | 0.00 | 0.01 | 0.40 | 0.20 | 0.61 | 0.61 | 0.83 | 3.53 |
| WB13 | 1.89 | 2.21 | 0.86 | 31.08 | 4.10 | 60.50 | 0.02 | 0.02 | 0.00 | 0.02 | 0.26 | 0.13 | 0.40 | 0.42 | 3.13 | 2.19 |

Secchi as % of WC is the % of the watercolumn above the secchi depth, values of 100% means that the Secchi was at or below the bottom.

Lowest 20% of D.O. records for a site over the project period.

Btm means that Secchi Disk as on bottom and therefore the depth of disk diappearance could not be determined (never disappears)