“Southern New England Collaborative Research Initiative” (SNECRI)
Final Report (Revised 25 September 2014)

Part I:

1. Project Title: An assessment of quahog larval supply and distribution in the upper Narragansett Bay with a focus on spawning sanctuaries and alternative area management strategies.

2. NOAA Award Number and CFDA Number:
NOAA Award # NA08NMF4720595
CFDA # 11.472

3. Project Team:

Main Contact for Research:

Dale Leavitt, Associate Professor
Roger Williams University
220 Marine and Natural Sciences Building
One Old Ferry Road
Bristol, RI 02809
Phone: (401) 450-2581
Email: dleavitt@rwu.edu

Secondary Contact for Research:

Scott Rutherford, Associate Professor
Roger Williams University
225 Marine and Natural Sciences Building
One Old Ferry Road
Bristol, RI 02809
Phone: (401) 254-3208
Email: srutherford@fox.rwu.edu

Main Contact for Fishermen:

Michael McGiveney, President
Rhode Island Shellfishermen’s Association
62 East Shore Drive
Coventry, RI 02816
Phone: (401) 573-7244
Email: MClamDigger@aol.com

Team Members:

Dennis Erkan, Jeff Mercer & Mark Gibson
RI-DEM Marine – Div. of Fish and Wildlife
Marine Fisheries Section
3 Ft. Wetherill Rd.
Jamestown, RI 02835

Tim Scott
Roger Williams University
Marine & Natural Sciences Building
One Old Ferry Road
Bristol, RI 02809

Chris Kincaid & Dave Ullman
URI-GSO
215 South Ferry Road
Narragansett, RI 02882

4. Period of Project:
Start: 1 June 2011 Finish: 30 December 2013

5. Identification of supporting institution/organization:

Commercial Fisheries Research Foundation
P.O. Box 278
Saunderstown, RI 02874

6. Total amount of sub-award: $99,959

7. List of equipment purchased ($5,000 or more in value) during project: None

8. Summary of tasks scheduled:

Objectives and Timeline:

1) Compile past and current quahog standing stock resource assessments from published and grey literature and from surveys by RI-DEM Marine Fisheries for upper Narragansett Bay (NBay) to indicate potential areas for spawning activity
2) Develop a cooperative assessment of quahog standing stock and reproductive condition in the upper NBay with commercial fishermen
   a. Conduct side-by-side quahog stock assessments comparing the efficacy of the RI DEM's standard method (hydraulic dredge) with the commercial bullrake and diver quadrat sampling
3) Through the application of the Regional Ocean Modeling System (ROMS) Hydrodynamic Model for NBay, simulate specific quahog larval release points (spawning areas) based on stock assessments (derived from Objectives 1 & 2) and predict sites of juvenile recruitment resulting from these releases
4) Using the results of the model, validate predicted larval settlement sites through a combined effort of surface drifter deployments and monitoring for the occurrence of quahog larvae, identified with a polarized laser video plankton sampler (LIHDaT),
5) Apply the prediction of quahog larval sources and sinks to the development of a bay-wide quahog management plan currently under discussion within RI-DEM Marine Fisheries Division.

```
                                           2011          2012               2013
Task                                       A S O N D J F M A M J J A S O N D J F M A M J J
 1) Compile historical stock data                 ******
 2) Coordinate with Marine Fisheries              *******************************************
 3) Cooperative sampling intercalibration                   *******
 4) Sample for reproductive condition                 **********             ********
 5) Stock Assessment                                    ***********
 6) Run ROMS simulations                              *****************
 7) Validate model (drifters)                            *****                  *****
 8) Sample for quahog larvae in situ                        ******                ****
 9) Analyze data                                      *********             **************
10) Prepare reports & Transfer information          **                     **          ******
```

9. Summary of tasks accomplished

- The bullrake, in the hands of an experienced fisherman, was proven as a valid assessment tool that can deliver defensible data for quahog fisheries management.
  - Sampling quahog stock density with the bullrake is relatively simple and can potentially be conducted with relatively inexpensive equipment.
- The ROMs hydrodynamic model for NBay was utilized to simulate larval distribution at settlement using various sites as larval sources.

    - Year-to-year variability in larval dispersal due to variability in environmental forcing is likely to be significant in Narragansett Bay.
    - Simple larval behavior, upward swimming early in larval period and downward swimming late, results in increased larval export from the Bay.
- We designed a drifter that, when deployed in Narragansett Bay, was able to collect data and not run aground for 5-10 days post-deployment.
    - Drifter tracks (49) were collected from six release points that corresponded to particle release points utilized in the ROMS model for tracking quahog larval distributions in NBay.
    - On the whole, the results of the drifter deployment supported the particle distribution patterns generated by the ROMS.
    - Based on the drifter tracks, there may be areas in the ROMS model (i.e. Greenwich Bay) where work is needed to improve the ability of the model to forecast particle transport from hydrodynamic forces.
- A plankton pump was developed to sample plankton at the level of 0.5 m from the substrate surface.
    - The pump was utilized at seven sampling sites on five sampling days that corresponded to a time interval when late-stage quahog larvae should be present in the water column and where model projections indicated that the locations would either have high or low concentrations of larvae in the vicinity.
    - No bivalve larvae were collected at any of the locations during any of the sampling attempts.
- The current information generated by the ROMs model on sources and sinks of quahog larvae is being utilized by RIDEM to improve their quahog management strategies.
- Discussions are currently are underway with RIDEM Marine Fisheries as to how and when a commercial quahogger research fleet can be utilized to assist in the annual quahog stock assessment program.
- The information generated by this study is being integrated in to the RI Shellfish Management Plan through the actions of all of the PIs on the project.

10. Explanation of any problems encountered or differences between the scheduled and accomplished tasks

- The compilation of quahog stock assessment data was deferred to RIDEM as their new Shellfish Biologist stepped in to assemble that information.
- No quahog larvae were collected during the field sampling of competent larvae suggesting that their pre-metamorphic behavior differs from what was anticipated in the study.

11. Summary of major project results

- Developing a community science approach to quahog stock assessment brings local fishermen into the quahog management process and allows for a more interactive and collaborative management strategy.
- Simulations of particles representing larvae that are passive (no behavior) indicate that potential spawning sanctuaries in the Providence River and Greenwich Cove are the most effective in maximizing larval retention, while Rome Point is a very poor site.
- Funding has been secured to continue improvement of the model with direct application to management of quahog fisheries in the state.
- The results of a lack of competent quahog larvae in the field plankton samples suggest that the late-stage pre-metamorphic larvae may be more closely associated with the substrate than previously thought.

Part II:

1. Project Title: An assessment of quahog larval supply and distribution in the upper Narragansett Bay with a focus on spawning sanctuaries and alternative area management strategies.

2. NOAA Award Number and CFDA Number:

NOAA Award # NA08NMF4720595
CFDA # 11.472

3. Project Team:

Main Contact for Research:

Dale Leavitt, Associate Professor
Roger Williams University
220 Marine and Natural Sciences Building
One Old Ferry Road
Bristol, RI 02809
Phone: (401) 450-2581
Email: dleavitt@rwu.edu

Secondary Contact for Research:

Scott Rutherford, Associate Professor
Roger Williams University
225 Marine and Natural Sciences Building
One Old Ferry Road
Bristol, RI 02809
Phone: (401) 254-3208
Email: srutherford@fox.rwu.edu

Main Contact for Fishermen:

Michael McGiveney, President
Rhode Island Shellfishermen's Association
62 East Shore Drive
Coventry, RI 02816
Phone: (401) 573-7244
Email: MClamDigger@aol.com

Team Members:

Dennis Erkan, Jeff Mercer & Mark Gibson
RI-DEM Marine – Div. of Fish and Wildlife
Marine Fisheries Section
3 Ft. Wetherill Rd.
Jamestown, RI 02835

Tim Scott
Roger Williams University
Marine & Natural Sciences Building
One Old Ferry Road
Bristol, RI 02809

Chris Kincaid & Dave Ullman
URI-GSO
215 South Ferry Road
Narragansett, RI 02882

4. Period of Project:

Start: 1 June 2011 Finish: 30 December 2013

5. Abstract:

The northern hard clam, identified locally as the quahog (*Mercenaria mercenaria*), is the basis for an important fishery throughout its range along the Atlantic coast of North America from New Brunswick, Canada to Florida. In Rhode Island during 2012, the quahog fishery harvested 39.1 million clams with a landed value of $5.15 million.

In November 2008, the Narragansett Bay Commission's Combined Sewage Overflow (CSO) Abatement Project came online. The improvement of water quality due to the CSO abatement will lead to increased fishing pressure on upper NBay, an area that is frequently considered a quahog larval source for the bay. To better understand the dynamics of increased fishing pressure on the bay and to assist with the stock assessment efforts currently expended by RIDEM Marine Fisheries, we proposed to develop a means by which commercial quahoggers can participate in the annual stock assessment program and to investigate the sources and sinks of quahog larvae in NBay using a hydrodynamic model.

In collaboration with the Rhode Island Shellfishermen's Association (RISA), we developed a means for commercial quahoggers to quantitatively sample quahog density and size/age class distribution at designated sites in NBay. These data have been demonstrated to be equivalent to the data currently collected via the RIDEM hydraulic dredge quahog assessment program. Discussions are now underway to complete the intercalibration between dredge and bullrake and to integrate a commercial quahogger research fleet into the stock assessment process.

The Regional Ocean Modeling System (ROMS) is a 3-dimensional hydrodynamic model that solves the set of primitive hydrodynamic equations under the hydrostatic and Boussinesq approximations. Taking advantage of the recent development of the ROMS for Narragansett Bay, we used our developing knowledge of quahog bivalve behavior and distribution in the bay, the ROMS characterization of the hydrodynamics of the bay, and measured observations of fecundity of specific populations in the upper Bay to predict the distribution of post-metamorphic quahog juveniles. These model predictions were used to test potential source areas for quahog larvae and their fate over the 10-15 day larval development period. The model predicted areas of high larval recruitment in NBay and was tested by deploying small surface drifters, which showed close similarities in their tracks to projected larval distributions from the ROMS.

The information gained with these studies will contribute to the current program developing a shellfish management plan for Rhode Island and will be provided to the shellfish biologists at RIDEM for use in their deliberations on improving shellfish management in the state.

Overall Introduction:

The primary objective of this work was to investigate potential sources and sinks of bivalve larvae in Narragansett Bay. The need for this information was prompted by the recent development of the Providence Combined Sewage Overflow (CSO) tunnel and its potential to increase the harvest pressure on quahogs from conditional areas A and B in upper Narragansett Bay (Figure 0-1). It has been suggested that Areas A and B, and the upper Bay in general, are an important source of quahog larvae to the bay at large (Rice 2006). If so, increased fishing pressure in Areas A and B may impact bay-wide larval supply and recruitment.

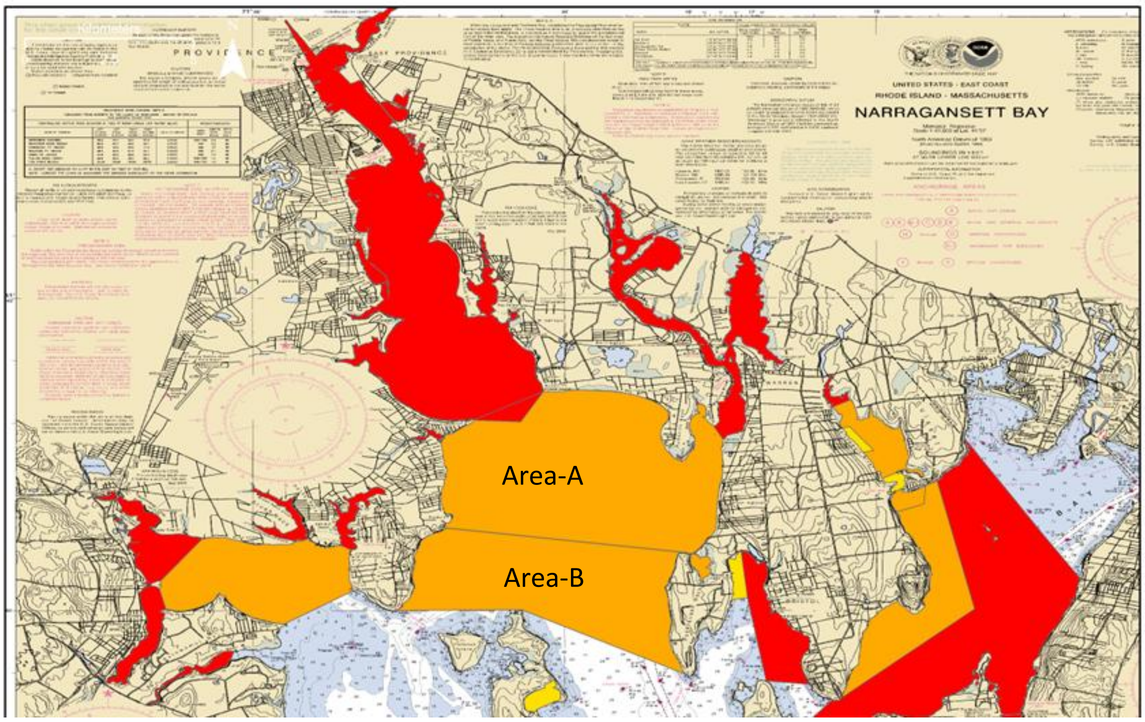


Figure 0-1: Shellfish Management Areas A & B and the lower Providence River (RI-DEM 2008). Areas in red are continuously closed to fishing, whereas areas in orange are conditionally closed depending on rainfall events and water quality.

The quahog (*Mercenaria mercenaria*) fishery is an important one for coastal Rhode Island and is subjected to stringent harvest controls based on human health risks and management for sustainable harvest. A significant portion of upper Narragansett Bay (Providence River and Areas A & B, approximately 9,500 acres of prime quahog resource area, Figure 0-1) is carefully managed, with harvest access dictated by rainfall events, combined sewer outfall discharges and presence of indicator pathogens.

In November 2008, the Narragansett Bay Commission's CSO Abatement Project came online. Phase I of the CSO consists of a 16,500 foot underground tank capable of diverting 1.5" of rain-induced CSO run-off from direct discharge into the upper bay. Although the projected impacts of the Abatement Project on upper bay water quality are promising—including extending the availability of shellfish resources for harvest in the upper bay, spatially and temporally—there are significant bay-wide management implications. As stated in the RI-DEM Shellfish Management Plan for 2009, "The Narragansett Bay Commission's combined sewer overflow project will potentially result in measurable water quality improvements in the Providence River as well as decrease the number of rainfall-induced closures in Conditionally Closed Areas "A" and "B" (RIDEM 2009). The high density of quahog broodstock observed in the Providence River combined with prior rainfall-induced closures in the Conditionally Closed Areas have resulted in a significant and sustained level of harvest. In order to sustain this harvest, it is recommended that an area-specific management plan be developed and implemented for the Providence River, Conditional Area “A” and Conditional Area “B”. Alternatives include, but are not limited to, establishing new shellfish management areas, establishing area-specific fishing periods, and adopting realistic possession limits” (RIDEM 2009).

In addition to Areas A and B, there are other locations that may be important larval sources and should be included in bay-wide management strategies to ensure sufficient larval supply. We assessed quahog reproductive activity at seven of these locations in the Bay as well as the potential for these areas to disperse larvae throughout the Bay. Finally, we developed a method by which commercial quahoggers can participate in the assessment of the standing stocks of quahogs in the NBay through a combined effort of dredge sampling and bull raking.

References:

Rice, M.A. 2006. Quahog (*Mercenaria mercenaria*) spawner sanctuaries: does size or location matter? *J. Shellf. Res.* 26:671.

RI-DEM. 2009. 2009 Management Plan for the Shellfish Fishery Sector. Jan. 16, 2009. Rhode Island Department of Environmental Management Division of Fish and Wildlife, Marine Fisheries Section. Jamestown, RI. 13 pgs.

Objective 1 – Introduction:
The northern hard clam, identified locally as the quahog (*Mercenaria mercenaria*), is the basis for an important fishery throughout its range along the Atlantic coast of North America from New Brunswick, Canada to Florida (Harte 2001). The quahog represents the largest commercial fishery for bivalves in the US, with a reported catch of 2,431.8 metric tons of clams (meat weight excluding shell) having a landed value of $35,312,277 in 2012 (NMFS 2014).

In Rhode Island, the quahog fishery originated with use of the bivalve by Native Americans, prior to the European colonization of the area, and was sustained at a very low level until the 1920's (Figure 1-1, DeAlteris *et al.* 2000). With the demise of the Narragansett Bay (NBay) oyster fishery in the 1930's, the shellfish harvesters switched their efforts to the quahog. Fishing pressure dramatically increased through the late 1940's resulting in a peak quahog harvest of approximately 5 million pounds in 1955 (2,268 metric tons; Figure 1-1). Due primarily to overfishing, quahog harvests rapidly declined during the 1960's through the early 1970's. In 1974 the bullrake was introduced into the fishery, leading to increased access to quahogs in deeper waters and a second harvest peak followed by a steady decline in the fishery, primarily due, once-again, to overfishing (DeAlteris *et al.* 2000, McHugh 2001).

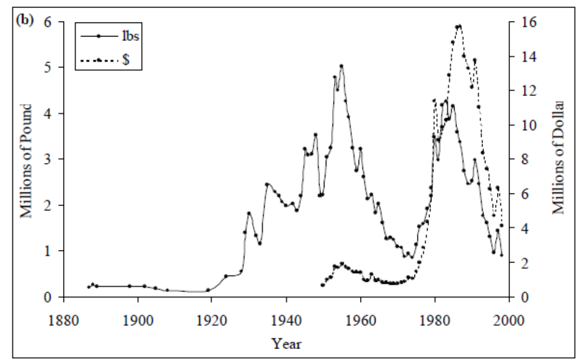


Figure 1-1: Rhode Island quahog production history (from DeAlteris *et al.* 2000).

Following the decline from 1979 to 1995, due to overfishing, the implementation of "precautionary management" by the RI-DEM Marine Fisheries Division resulted in the stabilization of the standing biomass at a level substantially below that needed to provide a sustainable yield (B_{MSY}) (Figure 1-2A, RIDEM 2008). Through management efforts currently in place to rectify overfishing, including entry limitations, management closures, and a rotational harvest/transplant program, the effort was decreased to allow for recovery of the B_{MSY} (Figure 1-2B, RIDEM 2008) resulting in a recent upward turn in RI quahog commercial landings since 2010 (Figure 1-3, Mercer 2013). The recent increase in landings may originate from management restrictions, including implementation of possession limits and seasons, reduction of fishable areas due to pollution closures, limited number of licenses available and reduction in the number of participants (RIDEM 2009).

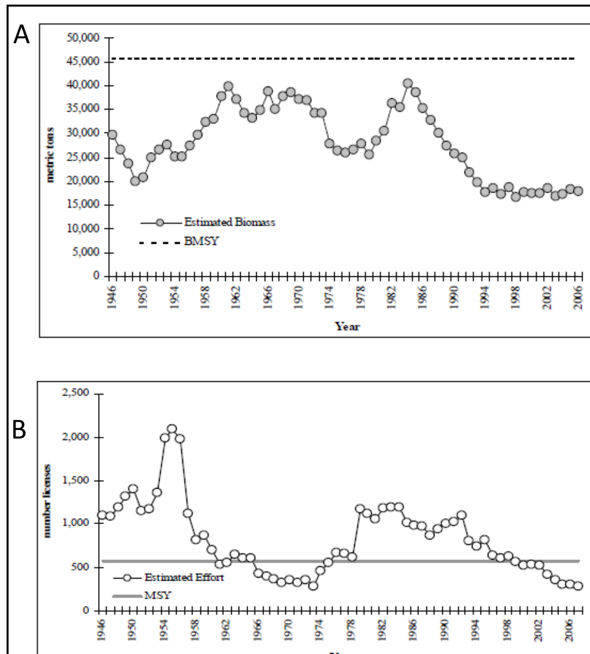


Figure 1-2: A. Estimated stock biomass of quahog in Rhode Island relative to estimated biomass necessary to provide maximum sustainable yield (MSY). B. Estimated fishing effort in Narragansett Bay quahog fishery relative to estimated level of MSY (RIDEM 2008).

Of particular importance to overall quahog management, is that 44.5% of the total quahog landings in 2012 (Figure 1-4, Mercer 2013) originated from Areas A & B in the upper NBay while an additional 14.4% were harvested from Greenwich Bay (Mercer 2013). McHugh (2001) indicated that Areas A & B were only open 40 to 50% of the time (and in some years considerably less) but the harvest averaged 70% of the total catch for the bay. Even with

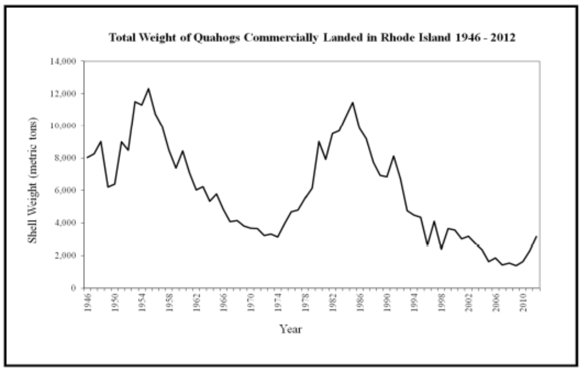


Figure 1-3: Total weight of quahogs commercially landed in Rhode Island, 1946-2012 (Mercer 2013).

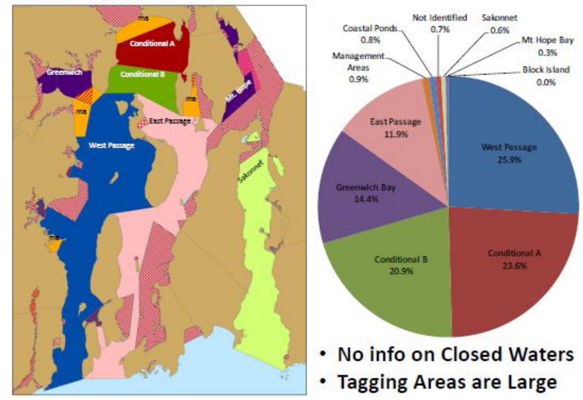


Figure 1-4: Relative distribution of the RI quahog harvest, separated by region (Mercer 2013).

these areas subjected to strict limitations on harvest, their relative importance to the state's quahog fishery is considerable. Therefore, RIDEM Marine Fisheries has identified these areas as high priority areas for exploring area management strategies, particularly with the improvement of water quality resulting from the CSO Abatement Project (M. Gibson, pers. comm.; RIDEM 2009).

To further improve on the resource availability, RIDEM Marine Fisheries has considered area specific regulation based on a bay-wide management strategy that will allow the agency to fine tune their control of landings from specific areas (RIDEM 2009). The management strategy being considered is based on standard resource surveys (Ganz *et al.* 1999) and an improved landings reporting system (Standard Atlantic Fisheries Information System – SAFIS, RIDEM 2009). Surveys of standing stock are a regular component to a fishery management program, where a fishery independent assessment of stock density and size distribution are utilized to examine the impacts of fishing efforts and the biological capacity of the population to sustain itself (Cooper 2006). As such, any program investigating a specific fishery management plan needs to be aware of the current and historical information available on standing stock.

Statement of research question or problem investigated:

The contribution of upper NBay to the overall quahog fishery suggests that the standing stock of quahogs in the area is significant. Saila *et al.* (1967) estimated the standing stock of quahogs in the Providence River (17.5 km^2) to be 400-425x10^6 individuals. There have been many studies directed at describing the quahog stocks in NBay and more specifically in the upper Bay area. The following publications provide a partial listing of stock survey information for parts or all of NBay:

Tiller (1950) surveyed Greenwich Cove,
Pratt (1953) surveyed NBay to correlate quahog distribution with sediment types,
Stringer (1955) surveyed Greenwich Bay,
Stickney and Stringer (1957) surveyed Greenwich Bay,
Stringer (1959) looked at sediment influence on quahog distribution throughout NBay,
Canario and Kovach (1965a) surveyed East Passage,
Canario and Kovach (1965b) surveyed Providence River,
Saila *et al.* (1967) analyzed data from Canario and Kovach (1965b),
Kovach (1968) surveyed Wickford Harbor,
Kovach *et al.* (1968) surveyed West Passage,
Gray (1969) surveyed West Passage,
Russell (1972) investigated dredge sampling methods in NBay,
Sisson (1976) surveyed upper NBay and Providence River,
Ganz and Sisson (1977) surveyed Quonsett-Davisville area,
Pratt (1988) surveyed NBay,
Rice *et al.* (1989) investigated effect of fishing pressure on NBay stocks,
Pratt *et al.* (1992) described quahogs in NBay,
Rice (1992) compiled existing studies between 1946 and 1992,
Lazar *et al.* (1994) surveyed Greenwich Bay,
Gibson (1999) provided an NBay assessment.

While not exhaustive, this list indicates the large amount of published information currently available to characterize standing stock of quahogs throughout the bay. In addition to the published literature, a series of quahog surveys have been undertaken within NBay by resource management agencies, including the US Fish and Wildlife Service (1951-1957) and RIDEM (1993 to present) (Lazar *et al.* 1994, Ganz *et al.* 1999). An effort of this proposal was to compile the historical information currently available on quahog standing stock distributions throughout the bay to provide a baseline to the quahog survey information collected during this study.

Goals and Objectives of research project:

As a means to initiate this research program, we proposed to compile the past and current quahog standing stock resource assessments from published and grey literature and from surveys by RI-DEM Marine Fisheries for upper Narragansett Bay (NBay) to indicate potential areas for spawning activity.

Methodology:

The overall approach was to compile existing stock assessment information, both in published literature and the data collected by RI-DEM through their hydraulic dredge stock assessment program, which has been collecting stock data since 1994 (with some interruptions - Ganz *et al.* 1999). These data were to be catalogued and used to set the stage for the subsequent stock assessment research proposed as further objectives with the project.

Analysis techniques:

The strategy was to compile existing stock assessment information to provide a historical backdrop to the proposed research. No specific analytical procedures were warranted with this section.

Results:

As this project was launching in 2011, RI-DEM Marine Fisheries restructured their Shellfish Team and added a new staff member, Jeff Mercer. One of Mr. Mercer's primary responsibilities was to oversee the operations of the shellfish stock assessment program. Mr. Mercer also understood the necessity of compiling the existing stock assessment data as his logical starting point to managing the quahog fishery, as we had proposed. With that in mind, Mr. Mercer undertook the same series of analyses that we suggested. Some of his information was included in the introduction to this section of the report and was presented as a component to the 12th Annual Baird Symposium on "The Future of Shellfish in Rhode Island" held on 14-15 November 2013. Rather than duplicate Mr. Mercer's efforts, we selected to defer this aspect of the project to his work such that we could focus our efforts on expanding the data collection aspects to the proposed research.

References:

Canario, M.T., and K.A.M. Kovach 1965a. Shellfish survey of the East Passage channel. *Rhode Island Division of Conservation Leaflet No. 16*.

Canario, M.T., and K.A.M. Kovach 1965b. Shellfish survey of the Providence River. *Rhode Island Division of Conservation Leaflet No. 17*.

Cooper, A.B. 2006. A Guide to Fisheries Stock Assessment – From Data to Recommendations. NH Sea Grant College Program, Durham, NH. 44 pgs.

DeAlteris, J.T., M. Gibson, and L.G. Skrobe. 2000. Fisheries of Rhode Island. *Narragansett Bay Summit 2000 White Paper*, Working Draft (4/14/00). http://www.nbep.org/publications-other.html, (Accessed on 30 May 2009.)

Ganz, A.R., and R.T. Sisson. 1977. Inventory of the fishery resource of the Quonset-Davisville area. *Rhode Island Division of Fish and Wildlife Leaflet No. 48.*

Ganz, A., A. Valliere, M. Gibson, and N. Lazar. 1999. Narragansett Bay quahaug management plan. R.I. Dep. Environ. Manage., Div. Fish Wildl., Coastal Fish. Lab., Wakefield, pgs. 93.

Gibson, M.R. 1999. Assessment of quahaugs (*Mercenaria mercenaria*) in Narragansett Bay: Technical analyses in support of a bay wide management plan. *Rhode Island Division of Fish and Wildlife.*

Gray, G.W. 1969. A shellfish survey of the West Passage, Narragansett Bay. *Rhode Island Division of Conservation Leaflet No. 26.*

Harte, M.E. 2001. Chapter 1: Systematics and taxonomy. In: J.N. Kraeuter and M. Castagna (eds.) *Biology of the Hard Clam.* Elsevier, Amsterdam, NL. Pp. 3-52.

Kovach, K.A.M. 1968. Shellfish survey of Wickford Harbor. *Rhode Island Division of Fish and Wildlife Leaflet No. 24.*

Kovach, K.A.M., M.T. Canario, and G.Gray. 1968. Shellfish survey of the West Passage of Narragansett Bay. *Rhode Island Division of Fish and Wildlife Leaflet No. 26.*

Lazar, N., A. Ganz, and A. Valliere. 1994. Quahog stock assessment and an interim management plan in Greenwich Bay, RI. In: M.A. Rice and E. Gibbs (eds.) *Proceedings of the Third Rhode Island Shellfish Industry Conference.* Rhode Island Sea Grant, University of Rhode Island, Narragansett, RI. Pp. 5-30.

McHugh, J.L. 2001. Chapter 13: Management of hard clam stocks, *Mercenaria mercenaria*. In: J.N. Kraeuter and M. Castagna (eds.) *Biology of the Hard Clam.* Elsevier, Amsterdam, NL. Pp. 631-650.

Mercer, J. 2013. Following the quahog – through time and space. 12th Annual Ronald C. Baird Sea Grant Science Symposium, RI Sea Grant Program. http://www.slideshare.net/riseagrant/jeff-mercer-following-the-quahog-through-time-and-space-baird-symposium (accessed 19 January 2014).

NMFS. 2008. Fisheries of the United States. *Current Fisheries Statistics.* National Marine Fisheries Service, Office of Science and Technology, Silver Spring, MD. http://www.st.nmfs.noaa.gov/commercial-fisheries/commercial-landings/annual-landings/index (accessed 19 January 2014).

Pratt, D.M. 1953. Abundance and growth of *Venus mercenaria* and *Callocardia morrhuana* in relation to the character of the bottom sediments. *J. Mar. Res.* 12:60-74.

Pratt, D.M. 1988. Status of the hard clam fishery in Narragansett Bay. *Draft report to the Narragansett Bay Project*, U.S. Environmental Protection Agency. 89 pgs.

Pratt, S.D., M.A. Rice, and A.R. Ganz. 1992. A Species Profile of the Quahog in Rhode Island. Rhode Island Sea Grant, University of Rhode Island, Narragansett, RI.

Rice, M.A. 1992. Overview of quahog management studies in Narragansett Bay, 1946 to 1992. *Proceedings of the Second Rhode Island Shellfish Industry Conference.* Rhode Island Sea Grant, University of Rhode Island, Narragansett, RI. Pp. 49-59.

Rice, M.A., C. Kickox, and I. Zehra. 1989. Effects of intensive fishing effort on the population structure of quahogs, *Mercenaria mercenaria* (Linnaeus 1758), in Narragansett Bay. *J. Shellf. Res.* 8:345-354.

RI-DEM. 2008. Rhode Island Stock Status & Management: 2007 in Review. December 2008. Rhode Island Department of Environmental Management, Division of Fish and Wildlife, Marine Fisheries Section. Jamestown, RI. 32 pgs.

RI-DEM. 2009. 2009 Management Plan for the Shellfish Fishery Sector. Jan. 16, 2009. Rhode Island Department of Environmental Management Division of Fish and Wildlife, Marine Fisheries Section. Jamestown, RI. 13 pgs.

Russell, H.J. 1972. Use of a commercial dredge to estimate hard clam populations by stratified random sampling. *J. Fish. Res. Board Can.* 29:1731-1735.

Saila, S.B., J.M. Flowers, and M.T. Cannario. 1967. Factors affecting the relative abundance of *Mercenaria mercenaria* in the Providence River, Rhode Island. *Proc. Nat. Shellf. Assoc.* 57:83-89.

Sisson, R.T. 1976. Hard clam resource assessment study in the upper Narragansett Bay and Providence River, Rhode Island. *Rhode Island Division of Fish and Wildlife Leaflet No. 49.*

Stickney, A.P., and L.D. Stringer. 1957. A study of the invertebrate bottom fauna of Greenwich Bay, Rhode Island. *Ecology*. 38:111-122.

Stringer, L. D. 1955. Greenwich Bay hard clam productivity studies. U.S. Fish Wildl. Serv., Clam Invest. Conf., *Clam Research.* 5:1–9.

Stringer, L.D. 1959. The population abundance and effect of sediment on the hard clam. In: U.S. Fish and Wildlife Service (ed.) *Hurricane Damage Control, Narragansett Bay and Vicinity, Rhode Island and Massachusetts: A Detailed Report on Fishery resources.* Appendix E. U.S. Fish and Wildlife Service, Washington, D.C.

Tiller, R.E. 1950. Greenwich Cove Survey. U.S. Fish Wildl. Serv., Clam Invest. Conf., *Clam Research.* 1:18-19.

Objective 2 - Introduction:

Fishery independent data are an important contributor to the development of a fishery management plan and a primary source of these data are research-based stock assessments (Gulland 1983, Cooper 2006). As a biological reference point, a shellfish stock assessment provides information on the spatial distribution of the existing biomass along with the age/size-class distribution and, when compared over time, an estimate of fishing mortality, changes to the age/size class distribution and recruitment in the stock (Cooper 2006). In total, stock assessments are critical to the proper management of the commercial fishery.

Referenced in the 2014 Sector Management Plan for the Shellfish Fishery (RIDEM 2013), the "RI Division of Fish and Wildlife (DFW) conducts a survey of quahogs in Narragansett Bay on an annual basis that commenced in 1993 (Ganz *et al*. 1999). Both fished and unfished sections of the bay are sampled. The sampling consists of towing a small hydraulic dredge (0.36 meter sweep, Figure 2-1) for a distance of 30.5 meters (100 ft) at each station. Pressurized water is delivered to the dredge manifold which dislodges shellfish from the substrate. The dredge is designed to retain legal-sized quahogs (>25.4mm thickness). All species retained in the dredge when hauled are identified and all shellfish are counted and measured. Based on the survey, the stratified mean density of quahogs in Narragansett Bay has been fairly constant through the duration of the survey typically around 2-3 quahogs per square meter."

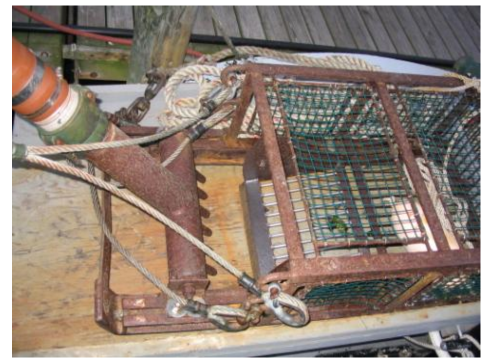


Figure 2-1: RIDEM hydraulic dredge used for quahog stock assessment

When utilizing a tool such as the hydraulic dredge for stock assessment, consideration must be paid to the catch efficiency of the equipment. Ganz *et al.* (1999) describe the methods used for measuring catch efficiency of the RIDEM hydraulic dredge employed for quahog stock assessment. Using diver surveys of the dredge track, they estimated that the dredge efficiency was 57.7% and this factor is applied consistently for all substrate types sampled (Ganz *et al.* 1999). However, the capacity of the dredge to sample all substrates consistently is questioned by the commercial quahog fishing fleet in RI. This question is supported to some degree by the variability in the data on catch efficiency on various substrates (Ganz *et al.* 1999). Furthermore, the commercial fleet is not trusting of the assessment data as it sometimes runs counter to their experience while fishing. Therefore, a mechanism that provides fishermen with the opportunity to participate in the stock assessment process would be an important factor in opening lines of communication and trust between the regulatory agency and the fishing fleet in addition to augmenting the annual stock assessment data currently collected by RIDEM.

In addition to assessing the stock structure, other important biological information can be derived from routine sampling of the population of target species. For example, determining reproductive status of the fished population can aid in predicting reproductive effort and provide insights into the environmental and/or physiological conditions experienced by the species. In RI, Marroquin-Mora and Rice (2008) utilized the condition index of quahogs to investigate the impact stock density may have on reproductive effort at selected sites in NBay. Condition index is a measurement that normalizes the soft tissue content of a bivalve to the size of the animal and is used as a proxy for overall reproductive condition, assuming the main source of soft tissue mass variability in the seasonal cycling of the animal is dependent on gonad development (Crosby and Gale 1990). Monitoring condition index as a proxy for reproductive condition will prove to be useful data when investigating the dynamics of larval dispersal and setting in NBay.

There are many instances where development of collaborative stock assessment programs have evolved between the commercial fishing fleet and the agencies tasked with managing the fishery. In the northeast, numerous examples can be found, such as those reported in the Northeast Regional Collaborative Research Conference, held in Portsmouth, NH in 2011 and the International

Collaborative Research Summit in 2013 in Narragansett, RI. Collaborative research constitutes the sharing of the intellectual development of a program and utilizes the intellect of both the scientist and the fisherman to develop the program (Wendt and Starr 2009). By conducting the survey work collaboratively, one can maintain the scientific robustness of the data while promoting the scientific credibility of the information among the fishing community because of their involvement in the design and implementation of the data collection and analysis (Wendt and Starr 2009).

Statement of research question or problem investigated:

In collaboration with the Rhode Island Shellfishermen's Association (RISA), we proposed to develop a means by which commercial quahoggers can participate in the stock assessment program currently managed by RIDEM Marine Fisheries. This involves developing a process by which the bullrake can be used as a stock assessment tool and calibrating the tool in the hands of individual fishermen as well as alongside the traditional stock assessment method used by RIDEM, the hydraulic dredge. As a subset of the data collected through the stock assessment process, we proposed to monitor the reproductive condition of the quahog population at various sites through collecting and measuring quahogs for condition index as a proxy for reproductive status.

Goals and Objectives of research project:

Develop a cooperative assessment of quahog standing stock and reproductive condition in the upper NBay with commercial fishermen through RISA.

Conduct side-by-side quahog stock assessments comparing the efficacy of the RI DEM's standard method (hydraulic dredge) with the commercial bullrake and diver quadrat sampling.

Methodology:

To measure the density and size/age class distribution of a stock of infaunal bivalves, a tool to quantitatively extract the bivalves from a known area of substrate must be developed. With the hydraulic dredge, the width is described as 0.36 m and it is towed a distance of 30.5 m, resulting in an area sampled of 10.98 m^2 (Gibson 2013). By counting and measuring the quahogs retrieved in the dredge, one can both calculate density (the number of quahogs per m^2) and size class distribution by measuring the individual quahogs caught. In addition to the retrieved catch, it is also necessary to know how many individuals the device missed as it fished, its "catch efficiency". This was done through diver assessment of the dredge track to survey for missed quahogs (Ganz *et al.* 1999). We propose to duplicate this methodology with a bullrake in the hands of a commercial quahogger.

Figure 2-2: a typical bullrake used to commercially harvest quahogs in Narragansett Bay.

The bullrake (Figure 2-2) is a basket-like device that has teeth across the bottom cutter bar that digs in and gathers quahogs that reside just below the sediment surface. The length of the teeth varies with the type of substrate at the fishing site. It is worked across the surface of the sediment by the fisherman in depths from 10 feet to 50 feet of water, by way of attaching the basket rake to the end of a series of interconnected aluminum poles (stales). To routinely measure the distance that the rake moves across the bottom, having already measured the rake width, we proposed to attach a handheld differential GPS (d-GPS) with remote antenna to the stale handle and measure the track followed by the stale, assuming it would duplicate the track of the bullrake across the bottom due to the rigid attachment between the rake and the stale handle. Upon retrieval of the catch following a raking event, we would then count and measure the quahogs retrieved in the rake. The quahogs were measured along the longest axis (length – anterior/posterior) to the nearest 0.1 mm with a Vernier caliper.

To evaluate the ability of the dGPS to measure the distance the rake travelled across the sediment surface, a diver was deployed to swim the track of the bull rake and to measure the actual distance covered. In addition, the diver picked up any quahogs that were missed and left deposited in the rake track.

Once the sampling protocol was developed and evaluated, the fishing efficiency of individual commercial bullrakers was measured. A minimum of three sampling tracks were monitored by diver on one of two substrate types for each bullraker tested. Hard bottom is described as a combination of sand and mud, often with shell fragments associated with it. Soft substrate was primarily soft mud. On average, the bull rake teeth normally selected by the fisherman were between 1 and 1.5 inches for hard substrate and up to 2.5 inches for mud. Other than tooth length, which was noted with each sample, the bullrakes employed by the fishermen had a standard gap between teeth of 1.0 inches, and the basket construction was the same with the distance between bars set at 1.0 inches.

In addition to the sampling completed with the bullrake, three 1 m^2 quadrats were sampled by diver adjacent to the length of each bullrake track, with all quahogs retrieved for measuring to develop an independent assessment of quahog density at the site. The diver sampled quadrats were raked twice over with a small garden-type hand rake that sampled to a sediment depth of approximately 3-4 inches. The direction of the second raking sample on a quadrat was oriented perpendicular to the first.

After "calibrating" the commercial quahogger, a field sampling process was developed that sampled locations that had previously been sampled by the RIDEM hydraulic dredge during their annual quahog survey. The locations (latitude/longitude) and catch were provided to us by Dennis Erkan and Jeff Mercer, on the Shellfish Team within RIDEM Marine Fisheries. A minimum of 5 bullrake transects were sampled at each location identified by RIDEM as a dredge sampling site. The density and size/age class distribution were measured at each site and compared with the data provided by the hydraulic dredge to test the comparability of the two techniques. In addition, one attempt at a simultaneous side-by-side sampling between the hydraulic dredge and a bullrake was undertaken in Greenwich Bay.

Site	Lat	Lon	Mean Density	SE	Fishing Status
Bissel Cove	41.54200	71.41940	0.7	0.4	Open
Greenwich Cove	41.66933	71.44215	69.0	6.1	Closed
Potowamut sanc.	41.66742	71.38981	6.2	1.1	Sanctuary
Rocky Pt.	41.69900	71.35185	12.3	0.8	Conditional
Providence River	41.76083	71.36716	72.0	2.7	Closed
Conditional Area B	41.67458	71.33950	1.0	0.4	Conditional
Prudence Island	41.63425	71.32703	24.5	6.9	Open
Hog Island	41.63560	71.27815	4.6	1.1	Open
Spawner Sanc. - Transplant	41.66433	71.40163	17.8	0.4	Sanctuary
Spawner Sanc. - Natural	41.66433	71.40163	1.5	0.7	Sanctuary

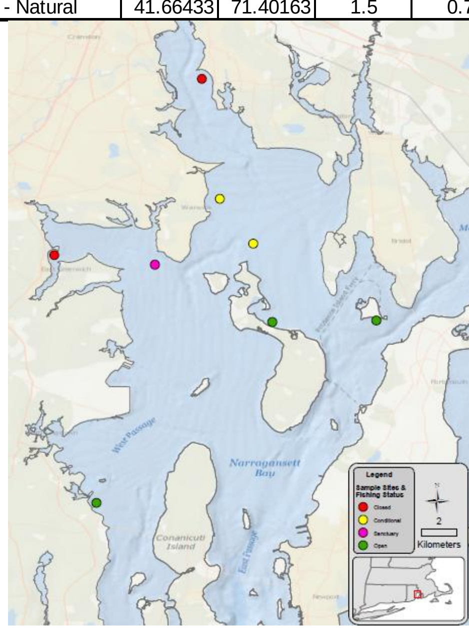


Table 2-1 and Figure 2-3: Locations of the ten Condition Index sampling sites.

During each of the bullrake sampling events, the distance traveled through the transect was measured by dGPS that was post-processed to obtain more accurate location information. In addition, the transect distance was also measured by using a recreational GPS mounted in the boat to compare the distance measured by conventional GPS to that measured by post-processed dGPS.

Initially, we proposed to conduct Condition Index (CI) measurements on quahogs sampled during the stock assessment collections. However, as we advanced in the program, we realized that by collecting repeated samples from the same location(s), it would afford us a better understanding of the reproductive effort and seasonal timing of quahogs in NBay. So we modified the protocol to conduct repeated sampling of quahogs from ten sites within NBay (Table 2-1 and Figure 2-3), including a mix of open and closed sites with varying levels of density associated with them. This study has become the basis for a Master's thesis for a student at URI (Matt Griffin) to be completed in 2014.

Twenty quahogs were collected by diver for CI measurement at each site (on an approximately three-week interval through the active season (April to November) and were returned to the laboratory where they were measured for morphometrics (length, width and depth) to the nearest 0.1 mm using Vernier calipers, weighed for live weight (to the nearest 0.1 g) then shucked to separate the soft tissue from the shell. The wet weight of the soft tissue and shell were measured to the nearest 0.1 mg and the tissues were then dried at 60^{o}C for 48 hours and reweighed.

Analysis techniques:

Catch efficiency for the bullrake was calculated as the number of live quahogs retrieved in the bullrake divided by the total number of live quahogs in the track (those retrieved by bullrake plus those retrieved by diver from the bullrake track after being missed by the bullrake). This efficiency value was used to adjust the number of retrieved quahogs from the bullrake transects to generate an estimate of total quahogs in the sampled track, similar to the adjustment used for the hydraulic dredge.

Comparison of the bullrake sampling method to the hydraulic dredge was completed by performing a paired T-test of the densities estimated by the two methods at each location (Zar 2010). The hydraulic dredge samples consisted of one transect while the bullrake sample was the average of five transects.

The quahog tissue/shell weight data were used to calculate CI using formula 1 (Crosby and Gale 1990).

$$\text{CI} = [\text{dry soft tissue (g)} * 1000] / [\text{live whole wt. (g)} - \text{wet shell wt. (g)}] \qquad (1)$$

Further analysis of condition index data will be forthcoming with the completion of Matt Griffin's Master's thesis.

Results:

Evaluation of the dGPS to measure linear distance (Table 2-2): Initially, we ran a series of land-based transects of known length with the dGPS to compare the post-processed distance measurement with the actual distance. Overall, the average difference between the two measurement techniques was 0.487 feet (0.15 m) with the largest difference being 1.5 feet (0.45 m).

Table 2-2: A comparison of measured land-based transect length to that calculated via post-processed dGPS.

		Measured Length (ft)	dGPS Length (ft)	Difference
Test 1 (7/19)	Trial 1	45.00	44.62	0.38
	Trial 2	45.00	44.48	0.52
	Trial 3	45.00	45.94	-0.94
	Trial 4	45.00	45.07	-0.07
	Trial 5	45.00	44.91	0.09
Test 2 (7/19)	Trial 1	90.00	88.96	1.04
	Trial 2	90.00	89.78	0.22
	Trial 3	90.00	88.94	1.06
	Trial 4	90.00	88.74	1.26
	Trial 5	90.00	89.99	0.01
Test 3 (8/2)	Trial 1	20.00	19.55	0.45
	Trial 2	20.00	19.48	0.52
	Trial 3	20.00	19.63	0.37
	Trial 4	20.00	19.47	0.53
	Trial 5	20.00	18.50	1.50
Test 4 (8/2)	Trial 1	70.00	69.92	0.08
	Trial 2	70.00	69.97	0.03
	Trial 3	70.00	70.22	-0.22
	Trial 4	70.00	70.22	-0.22
	Trial 5	70.00	70.05	-0.05
Test 5 (8/2)	Trial 1	30.00	29.41	0.59
	Trial 2	30.00	29.52	0.48
	Trial 3	30.00	29.62	0.38

		Measured Length (ft)	dGPS Length (ft)	Difference
Test 6 (8/2)	Trial 1	50.00	49.43	0.57
	Trial 2	50.00	48.72	1.28
	Trial 3	50.00	49.63	0.37
	Trial 4	50.00	49.33	0.67
	Trial 5	50.00	49.82	0.18
Test 7 (8/13)	Trial 1	30.00	28.99	1.01
	Trial 2	30.00	29.51	0.49
	Trial 3	30.00	29.07	0.93
	Trial 4	30.00	29.53	0.47
Test 8 (8/13)	Trial 1	60.00	58.81	1.19
	Trial 2	60.00	59.27	0.73
	Trial 3	60.00	58.89	1.11
	Trial 4	60.00	58.82	1.18
Test 9 (8/13)	Trial 1	90.00	89.39	0.61
	Trial 2	90.00	90.04	-0.04
	Trial 3	90.00	90.06	-0.06
	Trial 4	90.00	89.24	0.76

Mean	0.487
StDev	0.509
Max	1.50
Min	-0.94
N	40

Measuring bullrake transect length (Figure 2-4; Table 2-3): An initial attempt to measure overall transect length with the dGPS attached to the stale handle using a remote antenna resulted in a wavering track that included both the transect length and the swing of the boat as the bullraker maneuvered over the bottom (the irregular lines in Figure 2-4 lower). Calculating the total length of the track, including the movement of the boat, proved to be an inaccurate means to determine total transect length. To adjust for boat movement, the dGPS measurement was reduced to a start and finish point location and the overall distance between the post-processed start and finish points resulted in the straight line transect measurements (Figure 2-4 lower). The start-finish method was subsequently used to estimate each total track length and these were compared to actual diver-assisted measurements of track length (Table 2-2). After a few initial runs improving the adjusted measurement technique (Table 2-2: Transects 1 through 7), we were able to provide a dGPS transect measurement that only varied on average by 0.05 meters (SD = 0.60 m) from the actual distance sampled (Table 2-2: Transects 8 through 17) with the largest error being a difference of 0.79 m.

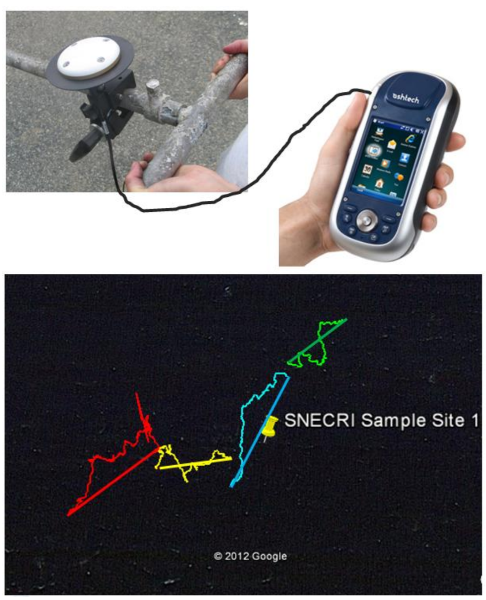


Figure 2-4: A plot of four test transects (lower figure) where the dGPS is attached to the bullrake stale via a remote antenna (upper figure)

Table 2-3: A comparison between the transect length of a bullrake sample measured using dGPS and the actual length of the transect measured using a diver and landscape measuring tape.

Transect	Transect	Quahogger	Diver Measured transect length (m)	Estimated transect length using dGPS (m)	Difference between measured and dGPS	% Difference between measured and dGPS
2-1	1	A	14.17	19.48	5.31	37.5%
2-2	2	A	15.54	14.52	-1.02	-6.6%
2-3	3	A	18.59	24.81	6.22	33.5%
2-4	4	A	15.54	14.61	-0.93	-6.0%
3-1	5	B	8.69	7.03	-1.66	-19.1%
4-1	6	C	13.41	15.75	2.34	17.4%
4-2	7	C	13.26	15.50	2.24	16.9%
4-3	8	C	12.68	12.62	-0.06	-0.5%
5-1	9	C	29.57	30.32	0.75	2.5%
5-2	10	C	29.26	29.16	-0.10	-0.3%
5-3	11	C	28.96	29.66	0.70	2.4%
5-4	12	C	27.58	28.25	0.67	2.4%
5-5	13	C	15.41	15.79	0.38	2.5%
6-1	14	D	21.03	20.40	-0.63	-3.0%
6-2	15	D	20.42	19.63	-0.79	-3.9%
6-3	16	D	28.96	28.51	-0.45	-1.6%
				average	0.05	0.1%
				stdev	0.60	2.5%

Comparison of dGPS measurement of transect length compared to conventional GPS (Table 2-4): Post-processed differential GPS measurements are accurate within 6 inches of the actual distance (Table 2-1); however, a dGPS unit costs thousands of dollars. So a comparison was made between the dGPS and a conventional GPS to measure the bullrake transect distance to determine whether a conventional GPS would suffice to measure start and stop points of the bullrake transect. Actual distance estimated by the conventional GPS was determined both with dedicated software (MobileMapper Field) and by plotting the tracks on Google Earth and calculating distances from that software. Overall, the difference in measurement of transect length averaged 0.39 m (SD $\pm$ 1.16) comparing dGPS to diver measured transect lengths (maximum difference 2.75 m) while the conventional GPS average difference from the measured length was 0.50 m (SD $\pm$ 1.41; maximum difference 3.35 m) when using dedicated software and 1.19 m (SD $\pm$ 1.45; maximum difference 2.91 m) when using Google Earth. None of the differences were different from each other when compared with one-way ANOVA.

Measure catch efficiency of the bullrake on different substrate types (Table 2-5): Using five different commercial quahoggers, we sampled hard and soft substrate types to measure the ability of the bullrake to catch quahogs (Table 2-5). All bullrake assessments were collected when the water temperature was above 12°C (between 1 May and 1 November). The overall average catch efficiency was 87.8% (SD ± 7.6%) of the total quahogs in the transect path, with the efficiency being no different when comparing harvest efficiency on soft substrate (87.4%) compared to hard substrate (88.3%). As we progressed into this aspect of the study, it became apparent the commercial quahoggers had an uncanny ability to recognize how the bullrake was fishing on the bottom. The quahogger could relate information about the fishing behavior of the bullrake such that they knew when the catch efficiency was being compromised due to some factor influencing the rake's fishing performance.

Table 2-4: A comparison between using the dGPS and a conventional GPS to estimate transect length covered by the bullrake.

Transect Length (m)				Difference		
(diver)	(GPS)	(dGPS)	(GE)	GPS - diver	dGPS - diver	GE - diver
22.26	23.48	22.78	22.79	1.23	0.52	0.53
16.16	16.08	15.81	15.81	-0.08	-0.35	-0.35
8.69	7.05	6.94	6.37	-1.64	-1.75	-2.32
21.03	19.26	20.07	21.90	-1.77	-0.96	0.87
20.42	19.26	19.82	21.69	-1.16	-0.60	1.27
28.96	30.25	28.66	30.31	1.30	-0.30	1.35
13.11	14.96	14.87	15.19	1.85	1.76	2.08
8.84	8.80	8.79	8.80	-0.05	-0.05	-0.04
10.37	10.31	9.81	9.81	-0.05	-0.56	-0.56
19.24	22.25	21.99	22.08	3.01	2.75	2.84
4.29	4.09	4.00	4.08	-0.21	-0.29	-0.21
13.65	14.15	14.15	14.10	0.51	0.50	0.45
29.57	31.39	30.32	32.04	1.83	0.76	2.47
29.26	28.96	29.16	30.86	-0.30	-0.10	1.60
28.96	29.26	29.58	31.30	0.30	0.63	2.34
28.96	28.35	29.66	31.76	-0.61	0.70	2.80
27.58	28.96	28.25	30.20	1.37	0.67	2.62
13.41	16.76	15.75	16.32	3.35	2.34	2.91
13.26	14.94	15.50	16.10	1.68	2.24	2.84
12.68	12.19	12.62	13.05	-0.49	-0.06	0.37

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*	*StDev*
GPS - diver	20	10.0689	0.5034	2.0088	1.4173
dGPS - diver	20	7.8656	0.3933	1.3413	1.1581
GE - diver	20	23.8868	1.1943	2.1038	1.4505

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	7.5411	2	3.7705	2.0740	0.1351	3.1588
Within Groups	103.6241	57	1.8180			
Total	111.1652	59				

Test the ability of a calibrated bullrake to quantitatively sample quahog density in the field (Table 2-6): Once we had worked with the fisherman on performing a stock assessment transect in the field and had measured their catch efficiency, we undertook a series of transects on two substrate types to gauge the fishermen/bullrake's ability to estimate quahog standing stock density. Using the diver-collected quadrat data as the baseline, we compared the density estimated by the bullrake, based on area sampled, number of quahogs collected in the rake and the catch efficiency, to that of the quadrats. The bullrake sample estimated the average density measured by five individual bullrakers to be 6.57 quahogs/m^2 (SD ± 5.89) compared to the diver quadrat estimate of 7.57 quahogs/m^2 (SD ± 5.12), resulting in a difference of 1 quahog/m^2. These density estimates were not significantly different ($p<0.05$) when compared using a paired T-test. There was an insignificant difference in the quahogger's ability to sample on different substrate types (mean difference of 2.07 quahogs/m^2 on hard substrate and 0.09 quahogs/m^2 on soft substrate when compared to the diver quadrats.

Table 2-5: Measurements of bullrake catch efficiency collected from four different bullrakers sampling on two substrate types.

Harvester	Soft	Hard
A	87.6%	73.9%
B	80.5%	96.3%
C	82.6%	
D	94.2%	88.3%
E	92.2%	94.8%
avg	87.4%	88.3%
StDev	5.9%	10.3%
	Grand Average	87.8%
	StDev	7.6%

Table 2-6: A comparison between quahog density measured by diver-collected 1-meter quadrat compared to density measured by bullrake.

Substrate	diver quadrat density (quahogs/m^2)	adjusted bullrake density (quahogs/m^2)
Mean - Soft	4.01	4.10
StDev	3.49	5.18
Mean - Hard	11.12	9.05
StDev	5.86	4.10
Grand Mean	7.57	6.57
Stdev	5.89	5.12

Conduct bullrake

surveys at sites sampled by the 2013 RIDEM hydraulic dredge survey (Figures 2-5, 6,7 and Table 2-7): RIDEM has adopted a stratified random sampling protocol for monitoring quahog stocks in NBay where the strata are focused on areas with high densities of quahogs that are frequently harvested (Figure 2-5, Gibson 2013). Through collaboration with RIDEM Marine Fisheries, the 2013 dredge sampling data were shared with this project to allow us to duplicate quahog transects at specific locations for comparing the bullrake sampling method to the hydraulic dredge. The sites sampled in the 2013 RIDEM quahog dredge survey are represented in Figure 2-6. We were able to sample ten of those sites, which had previously been sampled by the dredge, with a commercial quahogger who was familiar with the bullrake sampling protocol. The results of the comparisons are included in Table 2-5 and Figure 2-6. Following adjustment of the observed catch for catch efficiency, the average density across the ten sites as measured by the hydraulic dredge was 5.32 quahogs per m^2 (SD $\pm$ 6.59) compared to the density measured by the bullrake of 6.04 quahogs per m^2 (SD $\pm$ 4.95) (Table 2-7). When compared by a Paired T-test, the sampled densities are not different from each other ($p_{two\ tail}$ = 0.630).

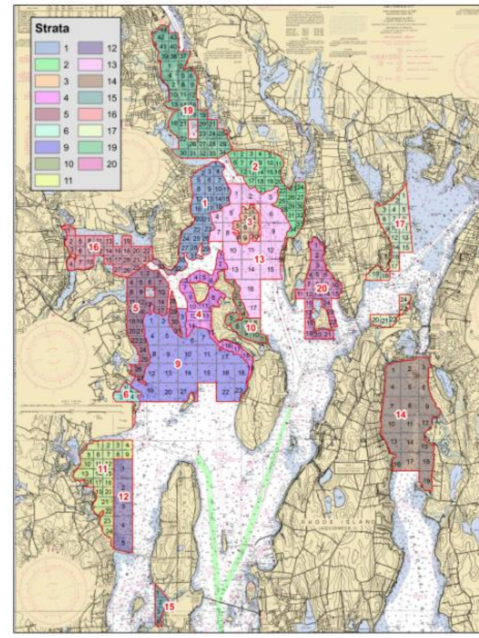
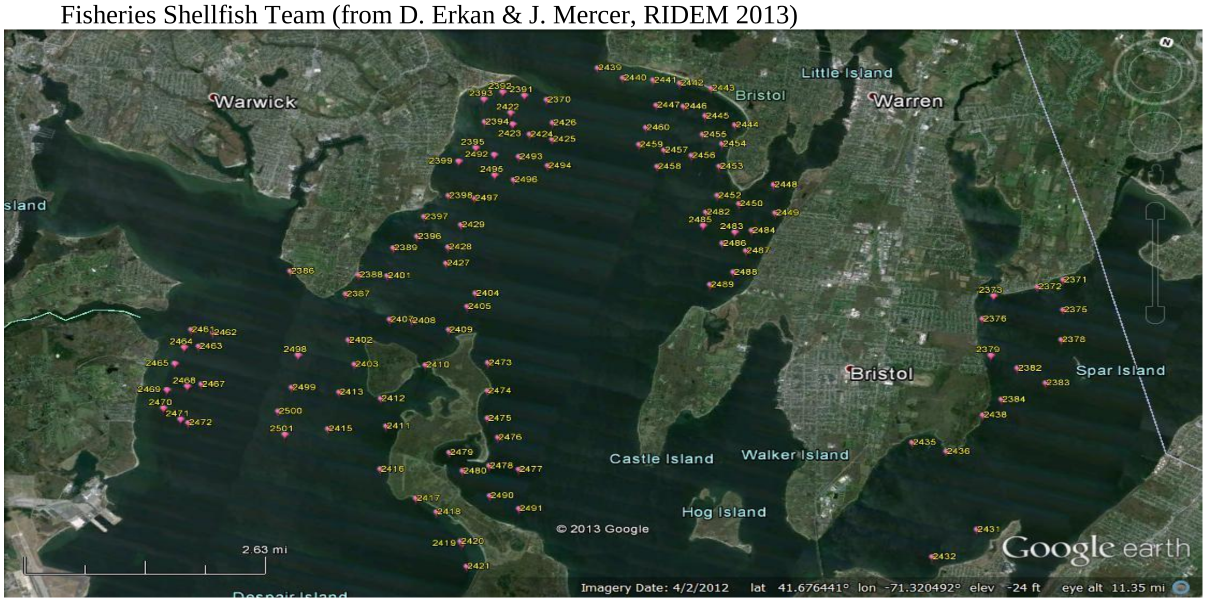


Figure 2-5: Strata identified for stock assessment in the RI quahog fishery (from J. Mercer RIDEM).

Figure 2-6: Locations of the sample sites for the 2013 quahogs stock survey completed by the RIDEM Marine Fisheries Shellfish Team (from D. Erkan & J. Mercer, RIDEM 2013)



On one occasion (4 October 2013), we were able to coordinate schedules between the commercial bullraker, the science/diver team and the RIDEM dredge team to allow a side-by-side comparison between the dredge and the bullrake. On very soft substrate (near Sally's Rock), the dredge measured an adjusted sample density of 1.11 quahogs per m^2, compared to the bullrake adjusted measured density of 1.99 quahogs per m^2 (SD $\pm$ 1.07) (Table 2-7).

Application of the bullrake sampling to stock assessment (Table 2-8): Following discussions with and recommendations from RI-DEM Marine Fisheries, the research team recruited the five calibrated bullrakers to participate in a stock assessment process to provide density information to the resource managers. RIDEM Marine Fisheries expressed an interest in the bullrakers sampling areas

RI-DEM Tow ID	Density as measured by Dredge	Dredge adjusted for 57.7% efficiency	Average Density as measured by Bull Rake	StDev	Substrate type
2389	8.86	15.36	9.37	2.22	hard bottom
2393	0.46	0.80	0.12	0.11	hard bottom
2424	11.65	20.19	13.73	6.87	very hard bottom
2429	1.90	3.29	8.05	4.60	moderate hard bottom
2445	0.25	0.43	0.77	0.70	soft mud
2448	3.69	6.40	6.63	3.99	soft sticky mud
2453	0.46	0.80	0.43	0.33	soft sticky mud
2484	0.27	0.47	3.21	2.13	soft sticky mud w/ shell
2485	2.96	5.13	11.80	6.41	hard w/ shells
2496	2.62	4.54	10.37	1.74	moderate hard bottom
GB adjacent	0.64	1.11	1.99	1.07	soft mud w/ shell
average	3.07	5.32	6.04		
stdev	3.80	6.59	4.95		

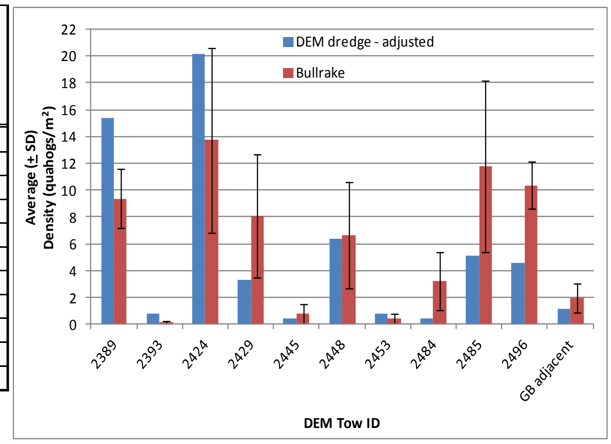


Table 2-7 and Figure 2-7: A comparison of quahog densities sampled by RIDEM hydraulic dredge and a bullrake.

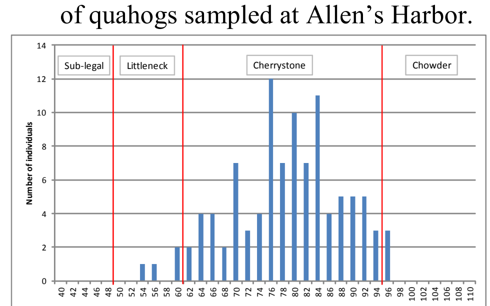
that were inaccessible to the hydraulic dredge, primarily in the shallow coves that lined the major body of the Bay. During June and July of 2014, the coves listed in Table 2-8 were sampled for standing stock of quahogs using commercial bullrakers. Densities of quahogs ranged from 0 in an area historically affected by seasonal hypoxia (Mary's Creek) to 50.11 quahogs per meter square in a highly productive site (Table 2-8).

	Quahog Density (Quahogs/m^2)	
	Mean	Stdev
Greens River (Potowomut Cove)	3.75	2.80
Greenwich Cove	10.69	3.90
Mary's Creek - Mouth	0.00	
Mary's Creek - Site 2	19.83	9.10
Mary's Creek - Site 3	13.91	9.20
Mary's Creek - Site 4	50.11	7.50
Warwick Cove - Mouth	32.62	10.20
Warwick Cove - Site 2	18.94	8.00
Warwick Cove - Site 3	22.77	13.70
Warwick Cove - Head	38.86	45.60
Warren River		

Table 2-8: A summary of the sampling completed by commercial bullrakers in support of the RIDEM Marine Fisheries Quahog Stock Assessment process.

Determine the size/age frequency distribution of quahogs sampled (Figure 2-8): At each site, it is possible to construct a size-frequency histogram that describes the population characteristics of that site. The data in Figure 2-8 represent the quahog population sampled at an Allen's Harbor location, where the size classes have been separated into the commonly used market designations of Littleneck (49-61 mm length), Cherrystone (61-95 mm), Chowder (>95 mm), and Sub-legal (<49 mm).

Figure 2-8: Size/age frequency distribution of quahogs sampled at Allen's Harbor.



Measure the condition index of quahogs collected in NBay to determine reproductive development and spawning times (Table 2-9, Figures 2-9 and 10): Quahog samples were collected by diver during two reproductive seasons (2012 and 2013; Table 2-9). The average condition index for each sample location and time are summarized in Figure 2-8. To simplify the analysis, we consolidated the site data into three general locations, open harvest areas, the spawner sanctuary at the entrance to Greenwich Bay, and areas that are closed to shellfish harvesting (Figure 2-9). The closed areas have a higher density of quahogs within their bounds (average 70.5 quahogs/m^2) than either the sanctuaries (average 6.4 quahogs/m^2) or the open areas (average 7.2 quahogs/m^2) (Table 2-1).

Condition Index			1-Jun-12	20-Jun-12	9-Jul-12	25-Jul-12	8-Aug-12	6-Sep-12	27-Sep-12	27-Oct-12
Sample Dates	10-Apr-13	10-May-13	4-Jun-13	19-Jun-13	1-Jul-13	17-Jul-13	29-Jul-13	15-Aug-13	16-Sep-13	11-Nov-13

Table 2-9: Dates for quahog collections to measure condition index.

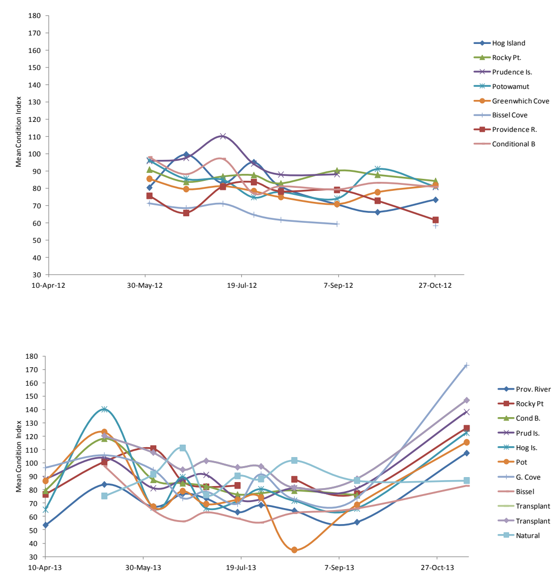


Figure 2-9: Average condition index of NBay sites monitored during 2012 (top) and 2013 (bottom).

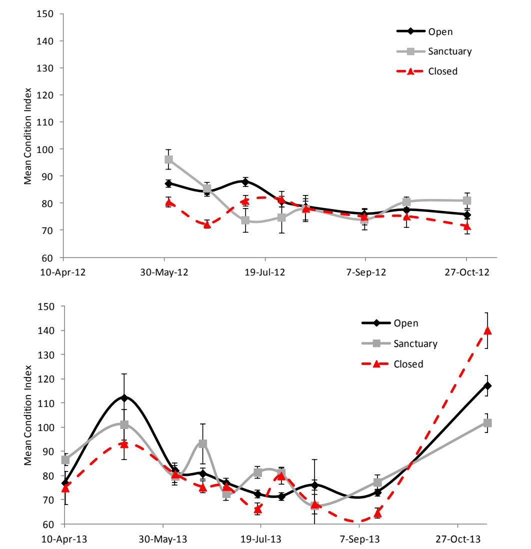


Figure 2-10: Average condition index (± SE) for three categories of habitat located in NBay over two years, 2012 (on top) and 2013 (on bottom).

Discussion:

Processed differential GPS location information is reported to have an accuracy of <1.0 foot (<0.3 m) under ideal conditions (Ashtech Mobile Mapper 100 specifications). When tested in an open space, the accuracy of the Mobile Mapper 100 dGPS unit utilized in this study, with post-processing by Mobile Mapper Office 4.0, averaged 0.487 feet (0.148 m; Table 2-2), providing better than the 1.5 foot (0.46 m) accuracy proposed as the tolerance value for unobstructed linear measurements in the field with this study. When the dGPS was applied under fishing conditions associated with bullrake sampling, the accuracy of measuring the distance that the bullrake had traveled across the bottom averaged a little less than 2 inches (0.05 m, Table 2-3) with the largest error measured at 2.6 feet (0.79 m). Again, this value is within tolerance levels acceptable for measuring the area sampled by a bullrake within the fishing grounds. However, to achieve this level (or better) of accuracy, there are details that must be addressed during sampling, as determined during the current study. The primary cause of inaccuracy during measurement of the distance traveled by the bullrake is that the boat and bullrake orientation are similar at the start and the end of the sampling interval. One must note the compass orientation of the stale at the start while marking the starting location with the dGPS, and ensure that the stale is in the same orientation when marking the finish point. Depending on the length of the stale (i.e. the depth of water where fishing), failure to do this can lead to significant error in measuring the distance the rake covered on the bottom, up to 4 m of the transect length under severe conditions (14 meter stale length deflected 60^{o}) (Figure 2-11).

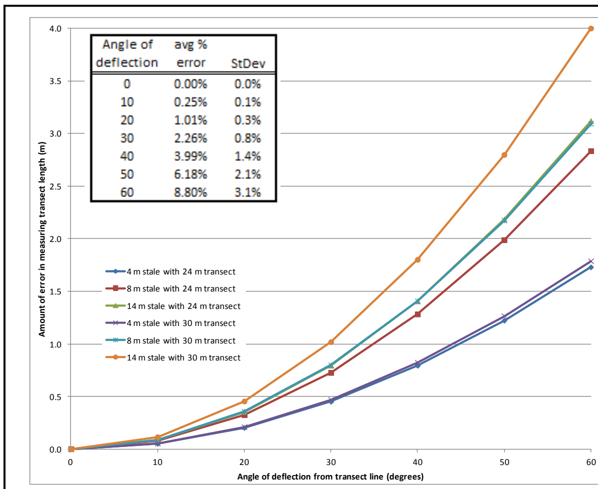


Figure 2-11: Potential errors in measuring transect lengths if stale angle is deflected from the direction of the transect.

Although it was initially suggested that using a dGPS would be important in achieving the level of accuracy required for sampling, subsequent preliminary evaluation of a conventional GPS unit proved to be nearly as accurate (0.39 m compared to 0.50 m average difference between the respective GPS measurements and the diver measurement; Table 2-4). While Wieh *et al.* (2009) reported a dGPS accuracy at approximately the same level as found in this study (0.79 m average versus 0.39 m), they suggested that some handheld recreational GPS units could come within a meter or less of matching the dGPS measurement. Therefore, it may not be necessary to invest in a high cost dGPS ($3-5,000 for a complete set-up) if a suitable recreational unit (estimated cost of $2-400) can be used.

Understanding catch efficiency of a harvest device is instrumental in using that device as a tool for stock assessment. Estimates of biomass are inversely related to the estimated catch efficiency of the hydraulic dredge so any inaccuracies in estimating catch efficiency can directly influence the biomass estimates used to determine harvest allowances (Thorarinsdo´ttir *et al.* 2009). The catch efficiency of the hydraulic dredge currently used by RIDEM to sample quahog populations in NBay was carefully measured when the device was first introduced to collect quahog samples in 1994 (Lazar *et al.* 1994, Ganz *et al* 1999). The value of 57.7 to 67.5% efficiency measured for the RIDEM dredge is significantly lower than some estimates of other hydraulic dredges used for harvesting infaunal clams (92% for an ocean quahog dredge in shallow water - Thorarinsdo´ttir *et al.* 2009; >90% for a Stimpson's surf clam dredge – Lambert & Goudreau 1995; 90.1% for dredging razor clams – Hauton 2007) but similar to estimates for American (66% - Rago *et al.* 2006) or Japanese (63% - Nashimoto 1994) surf clam dredges. Lazar *et al.* (1994) noted problems with replication of the dredge sampling in areas with densities higher than 5 quahogs per meter^2. RIDEM currently does not do replicate sampling as a component to their annual quahog stock survey. It has been 20 years since catch efficiency was last assessed on the RIDEM hydraulic dredge and there have been changes made to the dredge, suggesting that it should be recalibrated in the near future with a defined protocol for testing the catch efficiency on a regular basis in the future.

Catch efficiency for the bullrake is a less studied parameter. As measured in the current study, the average catch efficiency of the bullrake, in the hands of an experienced individual, was calculated to be 87.8% (SD $\pm$ 7.6%, Table 2-5) if the situations where something interfered with the rake are discounted. This value is somewhat lower than the 100% efficiency observed by Glude and Landers (1954) or Peterson *et al.* (1983) when fishing quahogs greater than 48 mm in length (23.6 mm depth) on sand bottom. Peterson *et al.* (1983) also investigated bullrake catch efficiency in eelgrass beds where he observed the catch efficiency drop to 83% for legal sized quahogs (>1 inch depth).

Using the bullrake to measure stock density is a reasonable means to gather that data. (Note: All densities reported for both bullrake and hydraulic dredge have been adjusted for catch efficiency prior to analysis, unless otherwise noted.) Although the density estimates provided by the bullrake are close to baseline (7.57 quahogs/m^2 measured by diver quadrat versus 6.57 quahogs/m^2 for the bullrake, Table 2-6), the difference may lie in the baseline measurement rather than the bullrake. The quahog is described as a having a clumped or superdispersed distribution pattern (Saila and Gaucher 1966, Lazar et al. 1994). This means that if you observe one quahog in a location then there is a higher probability that you will find another. One means to ensure the samples you collect better represent the actual quahog density of the area is to sample a larger amount of surface area. When sampling by diver, three replicate 1 m^2 quadrats are sampled adjacent to each transect whereas when sampling with the bullrake, we sampled between 6 and 16 m^2 of area per transect. Therefore, using the diver collected quadrat may not be the best baseline for comparison unless one samples as many quadrats as surface area covered by the bullrake. Often, this is not practical from a time and effort standpoint.

Following calibration of the commercial quahogger, we sampled ten sites that had previously been sampled by the RIDEM hydraulic dredge and we ran one simultaneous side-by-side measurement. The density measured by the commercial quahogger was similar to the density sampled by the dredge (5.32 quahogs/m^2 measured by the dredge and 6.04 quahogs/m^2 by the bullrake, Table 2-7 and Figure 2-7). A paired T-Test analysis of the density measurements demonstrated that there was no difference between the two sampling techniques. The largest variation in this relationship between sampling methods seemed to be when the quahog density was relatively high (Table 2-7 and Figure 2-7). As noted by Lazar *et al.* (1994), the RIDEM dredge had problems with quahog densities above 5 quahogs/m^2, where the variability of replicated dredge tows was exceedingly high and followed no discernible pattern.

Although not investigated in detail because we do not have the size distribution data from RIDEM from their sampling and also because of time constraints, the bullrake stock assessment provides the same capacity for characterizing the size/age class distribution at specific sites as the information generated by the dredge (Figure 2-8). These data provide a tool to look at the stock structure of local populations to measure impact of fishing pressure (e.g. Rice *et al.* 1989), to expand our knowledge of reproductive potential (Peterson 1983), to assign economic value to the resource (Kraeuter *et al.* 2008) or for a number of other applications.

The ultimate test of using a bullrake tool for stock assessment is the acceptability of the data by the resource managers. To that end, during the summer of 2014, we completed a survey of the coves of Greenwich and Narragansett Bays to augment the data currently collected by RIDEM (Table 2-8). Because the hydraulic dredge cannot be deployed in the shallow and spatially restrictive coves, these sites have not been assessed for standing stock for decades. Using calibrated commercial bullrakers, we succeeded in sampling a number of important coves for RIDEM and will provide that data to the managers for inclusion in their quahog stock assessment process. In addition, we will be participating in a large-scale, side-by-side assessment of the entire Greenwich Bay system during September/October of 2014, using commercial fishermen in conjunction with the standard hydraulic dredge.

As a proxy for reproductive effort, the condition index measurement offers insights into the level of gonadal development in quahogs as well as the seasonal timing of spawning events (Doall *et al.* 2008). The condition index data from 2012 and 2013 (Figures 2-9 and 2-10) suggest that the spawning cycle in NBay for those years resulted in larval releases from late May through the month of June. The timing observed in the present study reflects that reported by other shellfish researchers (Marroquin-Mora and Rice 2008)) and will be used to set the larval release times in the ROMS model developed under Objectives 3 and 4 of this study.

Wilson (1999) describes four different models of collaboration between fishermen, policy managers and scientists, with the "competing constructions" model being most relevant to the current effort in developing a collaborative stock assessment process. Wilson explains competing constructions as resulting from competition between different pictures of the resource that are constructed by interest groups that compete with each other in the fisheries policy arena. In RI, the RIDEM quahog stock assessment survey is routinely criticized by commercial quahoggers as not accurately representing the actual stocks as they are in the bay. The oft cited evidence of this revolves around dredge surveys that were conducted in Greenwich Bay just prior to an opening, where the shellfish biologist remarked that the dredge survey indicated no substantial catch of quahogs could be anticipated based on the survey while the fishermen were supported for an extended period of time thereafter on the extensive quahog beds that were available. This one situation has completely eroded the confidence of the quahogger in the state stock assessment process.

The goal of these experiments is to take advantage of the traditional fishermen's knowledge and their skill in catching quahogs to evolve collaborative efforts of the fishermen into the "community science" model described by Wilson (1999). With this collaboration, "fisheries science appears in the context of fisheries co-management and/or community development. These programs will often both defer to the knowledge of professional scientists and respect traditional ecological knowledge. They also take into account the competing constructions of various stakeholder groups and use collaborative science as a way to resolve and move beyond these disputes. They are characterized by an open discourse about all the aspects of the scientific problems." By including RISA and other fishermen in the stock assessment process, the level of data collection can be amplified, the data are available for all users, the trust and confidence of the fishermen about the data will be increased, and the management process becomes more transparent and collaborative.

Summary of conclusions:

- The bullrake, in the hands of an experienced fisherman with an appropriate protocol for measuring distance is a valid assessment tool that can deliver defensible data to be used for quahog fisheries management.
- Sampling quahog stock density with the bullrake is relatively simple to perform and can potentially be conducted with relatively inexpensive equipment.
- Developing a community science approach to quahog stock assessment could bring local fishermen into the quahog management process and allows for a more interactive and collaborative management strategy.

Future efforts:

- Long term goals, in collaboration with RIDEM, include
    - Developing a standard set of protocols for the fishermen to follow if they are sampling for stock assessment purposes.
    - Developing a means to integrate RISA and other commercial fishermen into the stock assessment process for RIDEM Marine Fisheries (i.e. a research fleet), starting with assigning areas that will be specifically surveyed by fishermen, primarily because of inaccessibility with the dredge and boat.
    - Look into mechanisms to compensate the quahoggers for their participation in a "research fleet" approach to stock assessment.
    - Expand on our understanding of the influence of water depth, sediment type and fishing style on catch efficiency of the bullrake and the hydraulic dredge.

References:

Cooper, A.B. 2006. A Guide to Fisheries Stock Assessment – From Data to Recommendations. NH Sea Grant College Program, Durham, NH. 44 pgs.

Crosby, M.P. and L.D. Gale. 1990. A review and evaluation of bivalve condition index methodologies with a suggested standard method. J Shellfish Res 91:233–237.

Doall, M.H., D.K. Padilla, C.P. Lobue, C. Clapp, A.R.Webb, and J. Hornstein. 2008. Evaluating northern quahog (=hard clam, *Mercenaria mercenaria* L.) restoration: Are transplanting clams spawning and reconditioning. J. Shellf. Res. 27(5):1069-1080.

Ganz, A., A. Valliere, M. Gibson, and N. Lazar. 1999. Narragansett Bay quahaug management plan. R.I. Dep. Environ. Manage., Div. Fish Wildl., Coastal Fish. Lab., Wakefield, pgs. 93.

Gibson, M. R. 1999. Assessment of quahaugs (*Mercenaria mercenaria*) in Narragansett Bay: Technical analyses in support of a bay wide quahaug management plan. Appendix 11.1 Stock Assessment of the Narragansett Bay Quahaug Population In: Ganz, A., A. Valliere, M. Gibson, and N. Lazar. 1999. Narragansett Bay quahaug management plan. A report to the Narragansett Bay Project and Rhode Island Marine Fisheries Management Council. Department of Environmental Management – Division of Fish and Wildlife. 158 pgs.

Gulland. J.A. 1983. Stock assessment: why? FAO Fisheries Circular No. 759. Food and Agriculture Organization of the United Nations. Rome, Italy. 18 pgs.

Glude, J.B. and W.S. Landers. 1953. Biological effects on hard clams of hand raking and power dredging. Special Scientific Report: Fisheries 110. Fish and Wildlife Service, U.S. Dept. of the Interior. 43 pgs.

Hauton, C., T.R.W. Howell, R.J.A. Atkinson, and P.G. Moore. 2007. Measures of hydraulic dredge efficiency and razor clam production, two aspects governing sustainability within the Scottish commercial fishery. J. Mar. Biol. Assoc. U.K. 87(4):869-877.

Kraeuter, J.N., J.M. Klinck, E.N. Powell, E.E. Hofmann, S.C. Buckner, R.E. Grizzle, and V.M. Bricelj. 2008. Effects of the fishery on the northern quahog (=hard clam, *Mercenaria mercenaria* L.) population in Great South Bay, New York: A modeling study. J. Shellf. Res. 27(4):653-666.

Lambert, J. and P. Goudreau. 1995. Stimpson's surf clams and razor clams on the Quebec coast. In: Savard, L.(ed.) 1995. Status Report on Invertebrates in 1994: Crustaceans and Molluscs on the Quebec Coast, Northern Shrimp and Zooplankton in the Estuary and Gulf of St Lawrence. Can Man. Rep. of Fish and Aquat .Sci. 2323:137 pgs.

Lazar, N., A. Ganz, and A. Valliere. 1994. Quahog stock assessment and an interim management plan in Greenwich Bay, RI. In: M.A. Rice and E. Gibbs (eds.) *Proceedings of the Third Rhode Island Shellfish Industry Conference.* Rhode Island Sea Grant, University of Rhode Island, Narragansett, RI. Pp. 5-30.

Marroquin-Mora, D.C., and M.A. Rice. 2008. Gonadal cycle of northern quahogs, *Mercenaria mercenaria* (Linne, 1758), from fished and non-fished subpopulations in Narragansett Bay. J. Shellf. Res. 27:643-652.

Nashimoto, K., K. Matsuyama, T. Hiraishi, and T. Takagi.1994. Catch efficiency of Japanese surf clam hydraulic jet dredge. Bull. Jap. Soc. Sci. Fish. 60(1):79-83.

Peterson, C.H. 1983. A concept of reproductive senility: application to the hard clam (*Mercenaria mercenaria*). Oecologia. 58:164-168.

Peterson, C.H., H.C. Summerson and S.R. Fegley. 1983. Relative efficiency of two clam rakes and their contrasting impacts on seagrass biomass. Fish. Bull. 81:429-434.

Rago, P. J.,Weinberg, J. R., and Weidman, C. 2006. A spatial model to estimate gear efficiency and animal density from depletion experiments. Canadian Journal of Fisheries and Aquatic Sciences, 63: 2377–2388.

Rice, M.A., C. Kickox, and I. Zehra. 1989. Effects of intensive fishing effort on the population structure of quahogs, *Mercenaria mercenaria* (Linnaeus 1758), in Narragansett Bay. *J. Shellf. Res.* 8:345-354.

RIDEM. 2013. 2014 sector management plan for the shellfish fishery. RI Department of Environmental Management, Division of Fish and Wildlife, Marine Fisheries, Providence, RI. 21 pgs.

Saila, S.B. and T.A. Gaucher. 1966. Estimation of the sampling distribution and numerical abundance of some mollusks in a Rhode Island salt pond. *Proc. Nat. Shellf. Assoc.* 56:73-80.

Thorarinsdo´ttir, G.G., L. Jacobson, S.A. Ragnarsson, E.G. Garcia, and K. Gunnarsson. 2009. Capture efficiency and size selectivity of hydraulic clam dredges used in fishing for ocean quahogs (*Arctica islandica*): simultaneous estimation in the SELECT model. ICES J. Mar. Sci. 67(2):345-354.

Wendt, D.E. and R.M. Starr. 2009. Collaborative research: an effective way to collect data for stock assessments and evaluate marine protected areas in California. Mar. Coast. Fish.: Dynamics, Management, and Ecosystem Sci. 1:315-324.

Wieh, R.C., M. Gilbert, J. Cross, and D. Freeman. 2009. Accuracy assessment of recreational and mapping grade GPS receivers. J. Arkansas Acad. Sci. 63:163-168.

Zar, J.H. 2010. Biostatistical Analysis, 5th Ed. Prentice-Hall. 960 pgs.

Appendices: To be collated in a CD that will be provided the CFRF.

Objective 3 – Introduction:

One method to characterize larval dispersal patterns in specific coastal embayments that has proved to be very successful is the use of hydrodynamic models to predict movement of larvae from their release point to their final settling destination. Movement of planktonic bivalve larvae results from a combination of hydrodynamic processes where they were spawned, the behavioral positioning of the larvae in the water column, and the duration of the larval period (Roegner 2000, North *et al.* 2008). The Regional Ocean Modeling System (ROMS) is an internationally recognized hydrodynamic model that has been applied to a number of different coastal embayments to investigate larval bivalve dispersal patterns (Chesapeake Bay, North *et al.* 2008; Delaware Bay, Narvaez *et al.* 2012; San Diego, CA, Rasmussen *et al*. 2006).

The ROMS is a 3-dimensional hydrodynamic model that was developed by the coastal modeling group at Rutgers University (Haidvogel *et al.* 2008). The model solves the set of primitive hydrodynamic equations under the hydrostatic and Boussinesq approximations. It is a free surface model with a terrain-following vertical coordinate and uses orthogonal curvilinear coordinates in the horizontal that allow for variable spatial resolution. The details of the model algorithms are described in Shchepetkin and McWilliams (2005). The model can be driven by imposed tidal forcing, surface momentum and heat fluxes, and by river runoff. In addition to the dynamically active temperature and salinity fields, the model can simulate an arbitrary number of passive (not influencing fluid density) tracers that can be used to estimate water property exchange (e.g. Kremer *et al.* 2010).

The ROMS model has been adapted for Narragansett Bay by the present University of Rhode Island Graduate School of Oceanography ROMS Group (comprised of Kincaid and Ullman) as well as several other present and former graduate students and has been used in a number of prior studies (Sullivan and Kincaid 2001, Bergondo 2004, Rogers 2008, Bergondo and Kincaid 2007, LaSota *et al.* 2007, Kremer *et al.* 2010). The implementation most relevant to this proposal was developed as part of a recent study investigating the processes influencing summertime hypoxia in the Bay where ROMS was used to provide estimates of the physical exchange of hydrographic and biological properties between the coarse elements of a two-layer ecological box model of the Bay (Kremer *et al.* 2010). A high-resolution model grid of the Bay, with horizontal spatial resolution of approximately 50-100 m in the upper Bay and 15 vertical levels, was nested within a coarser grid, which included the Bay and extended out onto the continental shelf south of the Bay mouth. At its open southern boundary, the coarse grid model was forced with tidal constituents from the Eastcoast Tidal Constituent Database (Mukai *et al.* 2002) and climatological temperature and salinity fields. The model was additionally forced by actual freshwater discharges from the eight rivers gauged by the United States Geological Survey (USGS) and from several sewage treatment facilities as well as by surface fluxes derived from meteorological measurements in the NBay region (see Kremer *et al*. 2010 for details). The output of the coarse resolution model was used to force the high-resolution model, using the same river and meteorological forcing, at its southern open boundary at the Bay mouth. Vertical mixing in both models was parameterized using the Generic Length Scale closure scheme (Umlauf and Burchard 2003, Warner *et al.* 2005). Model skill, as assessed using in situ current and hydrographic time series measurements, was generally high in the mid- to upper-Bay region (Balt *et al.* 2014 (in preparation)).

Statement of research question or problem investigated:

Taking advantage of the development of the ROMS for Narragansett Bay, we used our developing knowledge of quahog bivalve behavior and distribution in the bay, the ROMS characterization of the hydrodynamics of the bay, and measured observations of fecundity of specific populations in the upper Bay to predict the distribution of post-metamorphic quahog juveniles. There have been a few studies describing bivalve larval occurrence and distribution in portions of NBay (Landers 1954, Rice and Goncalo 1995, Butet 1997). But these data are very incomplete with respect to tracking quahog larval distributions because of their limited sampling and the degree of difficulty in separating *M. mercenaria* larvae from other bivalve larvae. Thus we performed a numerical study of the dispersion of quahog larvae from several sites within the middle and upper Bay that are known to harbor large populations of adult quahogs. The objective was to compare the effectiveness of the different sites in potentially seeding the Bay with juveniles.

Goals and Objectives of research project:

Through the application of the ROMS Hydrodynamic Model for Narragansett Bay, simulate specific quahog larval release points (spawning areas) based on stock assessments (derived from fishermen interviews and Objective 2) and predict sites of juvenile recruitment resulting from these releases.

Table 3-1. Release sites for numerical particles representing quahog larvae and the percentage of released particles that reach the mouth of the Bay and are lost to the Bay for each of the two years simulated.

Site #	Site Name	Latitude (deg. N)	Longitude (deg. W)	% lost, 2006	% lost 2007
1	Providence River	41.761	71.367	34	20
2	Spawner Sanctuary	41.668	71.394	51	45
3	Greenwich Cove	41.669	71.442	21	11
4	Rome Point	41.542	71.42	95	96
5	Hog Island	41.633	71.28	46	35
6	Rocky Point	41.697	71.359	43	34

Methodology:

To simulate the trajectories of quahog larvae, we used the Lagrangian TRANSport (LTRANS) model (North *et al.* 2008), which is a particle-tracking model designed for use with velocity fields that are output from the ROMS circulation model. We used ROMS simulations of the Bay for the years 2006 and 2007 forced with actual environmental parameters (tides, rivers, surface fluxes) to provide hourly maps of currents and vertical mixing in the Bay. These fields were used in LTRANS to compute the trajectories of particles representing quahog larvae. Vertical motion of particles in LTRANS results from a superposition of vertical velocities and random-walk motions that are based on the turbulent vertical diffusivities from the ROMS simulation. Additional vertical motion due to larval behavior can optionally be imposed as well.

Particles were released from six sites within the Bay that were considered to be potential larval sources (Table 3-1 and Figure 3-1). The sites were selected based on discussions with commercial quahoggers to identify potential sites with high densities of quahogs that would be contributing to the larval pool. Clusters of 65 particles were released from each of the six sites every 2 h over a one-month period during the quahog spawning period (May-June, Figures 2-9 and 2-10) and were tracked for 10 days (the approximate duration of the quahog larval stage). The rationale for this strategy is that particles are released during various stages of the tidal cycle and under a wide range of meteorological forcing conditions such that the results should be representative of real conditions in the Bay (at least for the years 2006 and 2007).

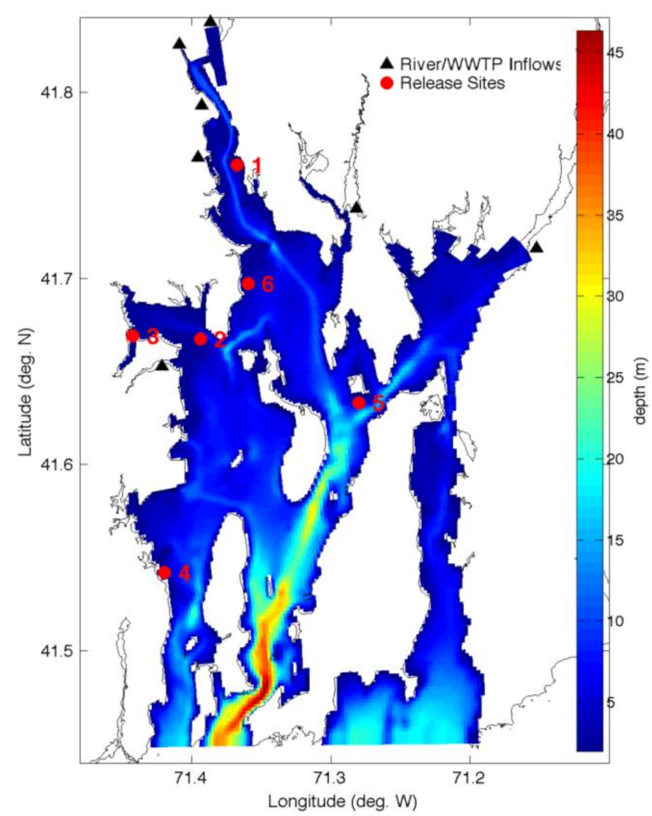


Figure 3-1. Narragansett Bay ROMS model domain showing water depth. The locations of the 6 proposed larval sources, where model particles were released, are denoted by the red dots. The site names are (1) Providence River, (2) Spawner Sanctuary, (3) Greenwich Cove, (4) Rome Point, (5) Hog Island, and (6) Rocky Point.

Figure 3-2 shows the environmental conditions during the particle release period (May 15 - June 15) of each of the two years simulated (2006 and 2007). Particles that reached the southern boundary of the model domain, the mouth of Narragansett Bay, were assumed to be lost to the system and were not tracked further.

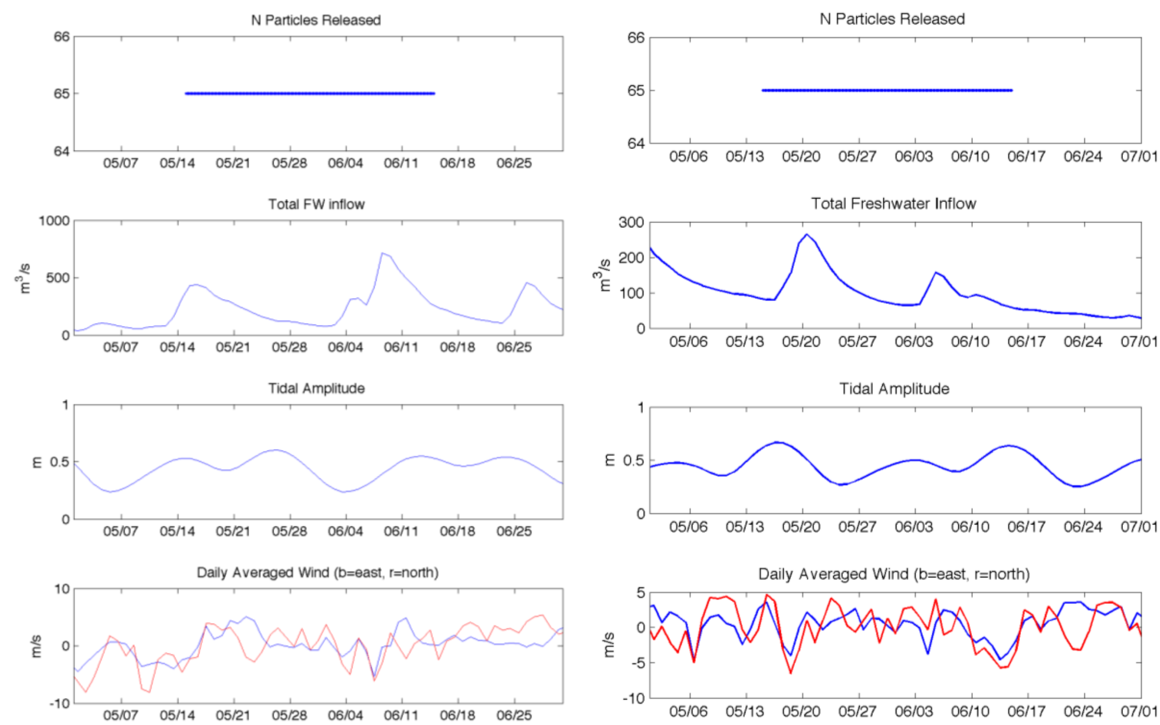


Figure 3-2: Number of particles released and environmental conditions during particle release periods during 2006 (left) and 2007 (right). The plots in each panel show, from top to bottom, number of particles released at each site (every 2 hours), total freshwater inflow to Narragansett Bay, tidal amplitude at Newport, and wind speed in eastward (blue) and northward (red) directions.

The LTRANS model can account for larval behavior, for example vertical swimming. In the initial runs, larvae were assumed to be passive, with their vertical position in the water column governed solely by physical advection and vertical mixing. In these experiments, larvae were released near the surface (1 m below the surface), consistent with the observational evidence that newly spawned larvae tend to be found near the surface (Andrews 1983, Baker 2003). Subsequently, we performed simulations whereby larvae had vertical swimming behavior, with a tendency for upward swimming early in the larval stage and downward swimming late in the larval stage (North *et al.* 2008). This simple behavior, where larval swimming speed varied linearly from 5 mm/s upward to 5 mm/s downward over 14 days is shown graphically in Figure 3-3.

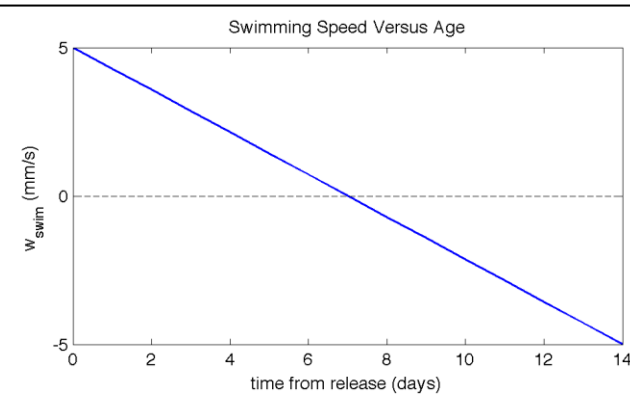


Figure 3-3: Vertical swimming speed of quahog larvae as a function of larval lifetime (time since larvae were released) for the experiment including larval behavior.

Analysis techniques:

The trajectories of all particles released were analyzed to obtain a statistical characterization of the fate of larvae released from each of the six sites. Although particles were released at different times (every 2 h for a month), the analysis was carried out using particles of a given age (time since release). A grid composed of square cells 400 m on a side was superimposed on the Bay model grid. The grid cell corresponding to the location of each larval particle at an age of 5, 10, and 15 days was determined and the number of particles within each cell was then computed. The total number of particles reaching the southern boundary of the Bay, which were assumed to be lost from the Bay, was also determined. We prepared maps showing the number of particles as a function of spatial location within the Bay for particle ages of 5, 10, and 15 days (only the 10 day results are shown here).

Results:

Maps showing the number of particles 10 days after release as a function of location for the experiments with passive larvae are shown for the two years simulated in Figures 3-4 - 3-9. The percentage of particles released from each site that are lost to Narragansett Bay is given in Table 3-1. This percentage can be viewed as a measure of the effectiveness of the particular site as a spawning sanctuary for the Bay.

Particles released from the Providence River location, the northernmost site considered, are distributed widely throughout the Bay after 10 days of drift. There are somewhat more particles in the West Passage than in the East Passage. Due to its location in the northern part of the Bay, relatively few particles are lost to the coastal ocean (34% and 20% in 2006 and 2007, respectively).

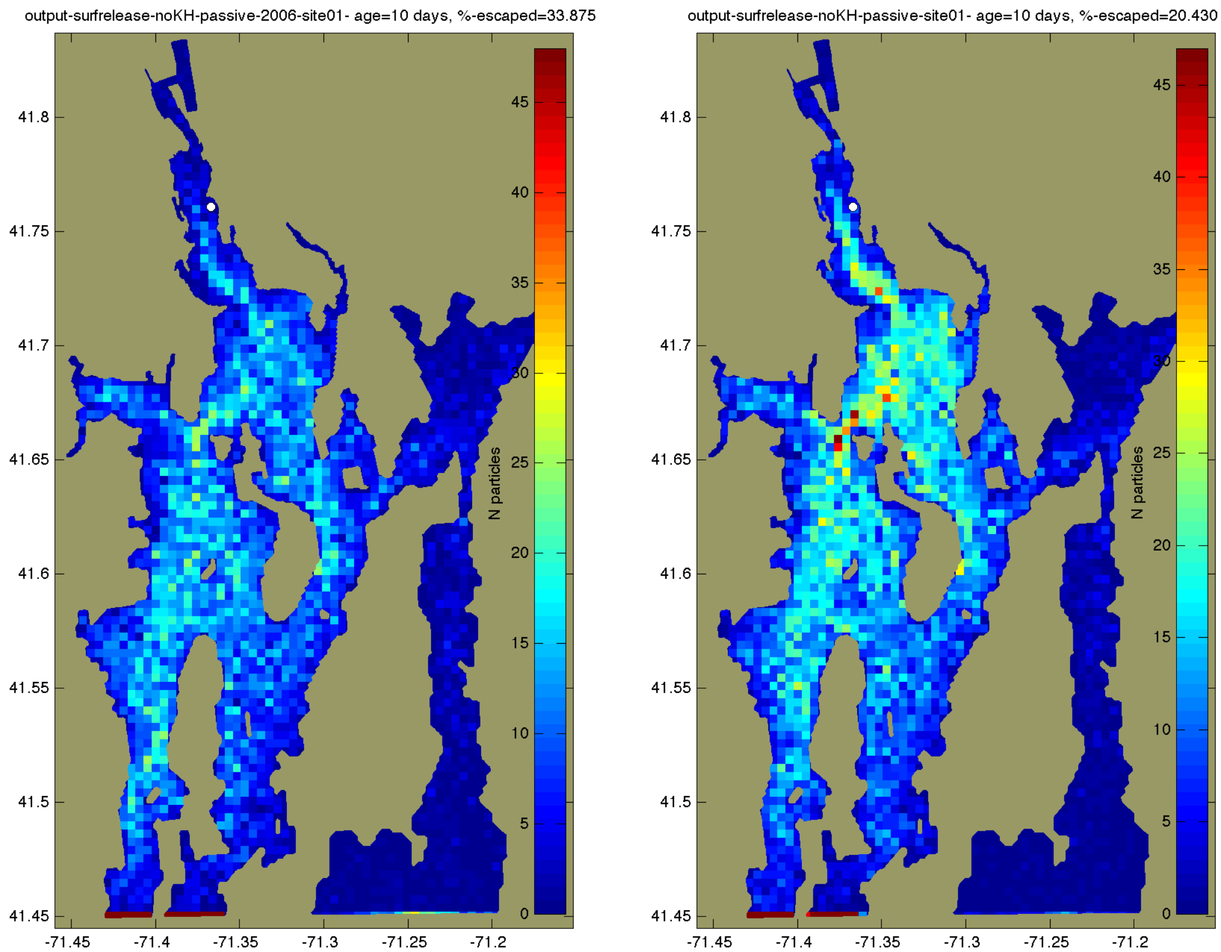


Figure 3-4. Number of particles as a function of position within the Bay 10 days after release from the Providence River site for 2006 (left) and 2007 (right). The white dot indicates the release location.

Numerical larvae released at the Spawner Sanctuary site, located just inside Greenwich Bay, are retained in large numbers within upper Greenwich Bay, with significant numbers of particles ending up in the West Passage, but with few making it to the East Passage. Nearly half of the particles released at this location are lost from the Bay (51% and 45% in 2006 and 2007 respectively).

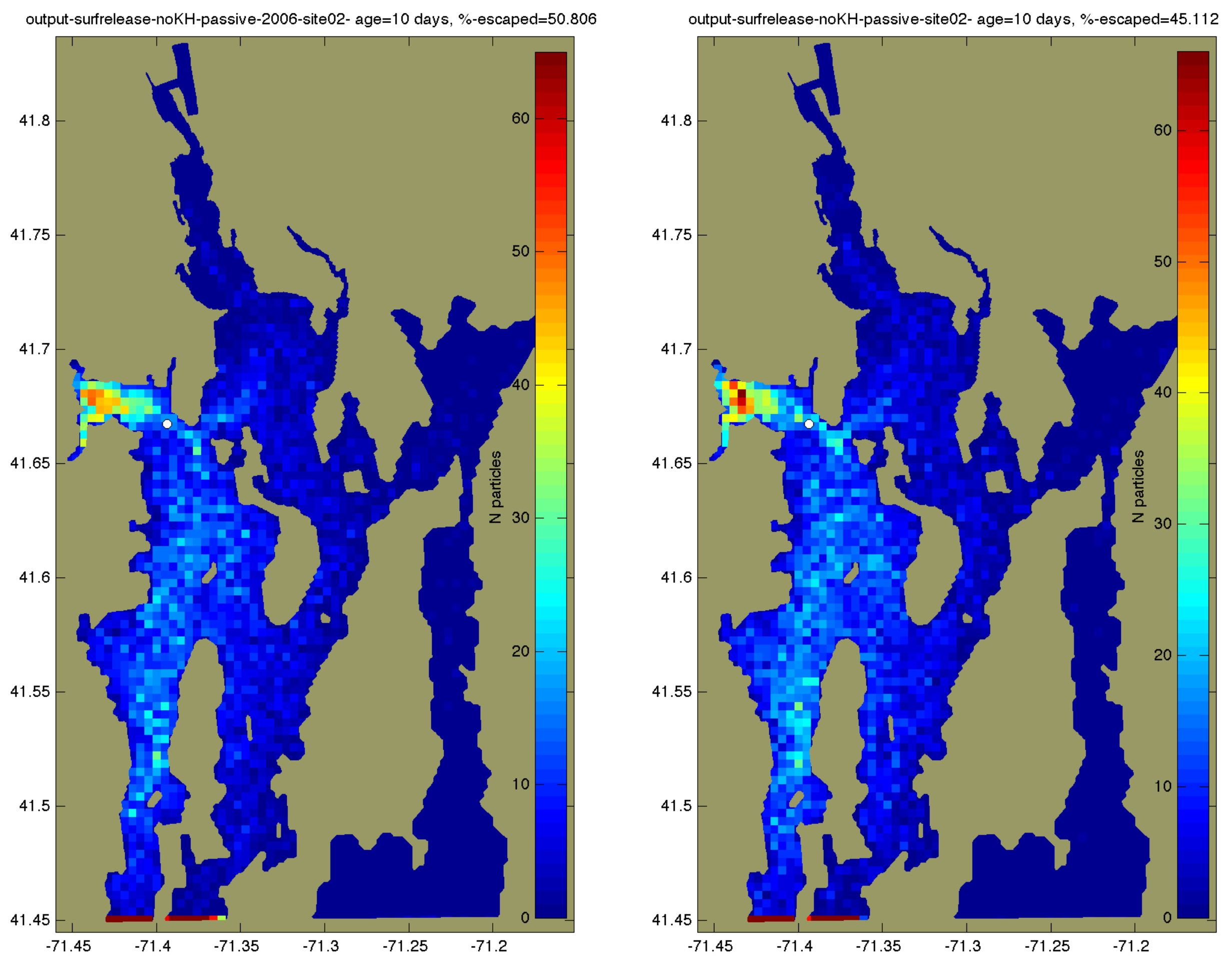


Figure 3-5. Number of particles as a function of position within the Bay 10 days after release from the Spawner Sanctuary site for 2006 (left) and 2007 (right). The white dot indicates the release location.

Particles released from the Greenwich Cove site in western Greenwich Bay are mostly retained within the Bay. After 10 days, the highest concentration of particles is within Greenwich Bay, with significant numbers present in the West Passage. Loss rates are generally low, with only 21% and 11% of released particles escaping the Bay in 2006 and 2007 respectively.

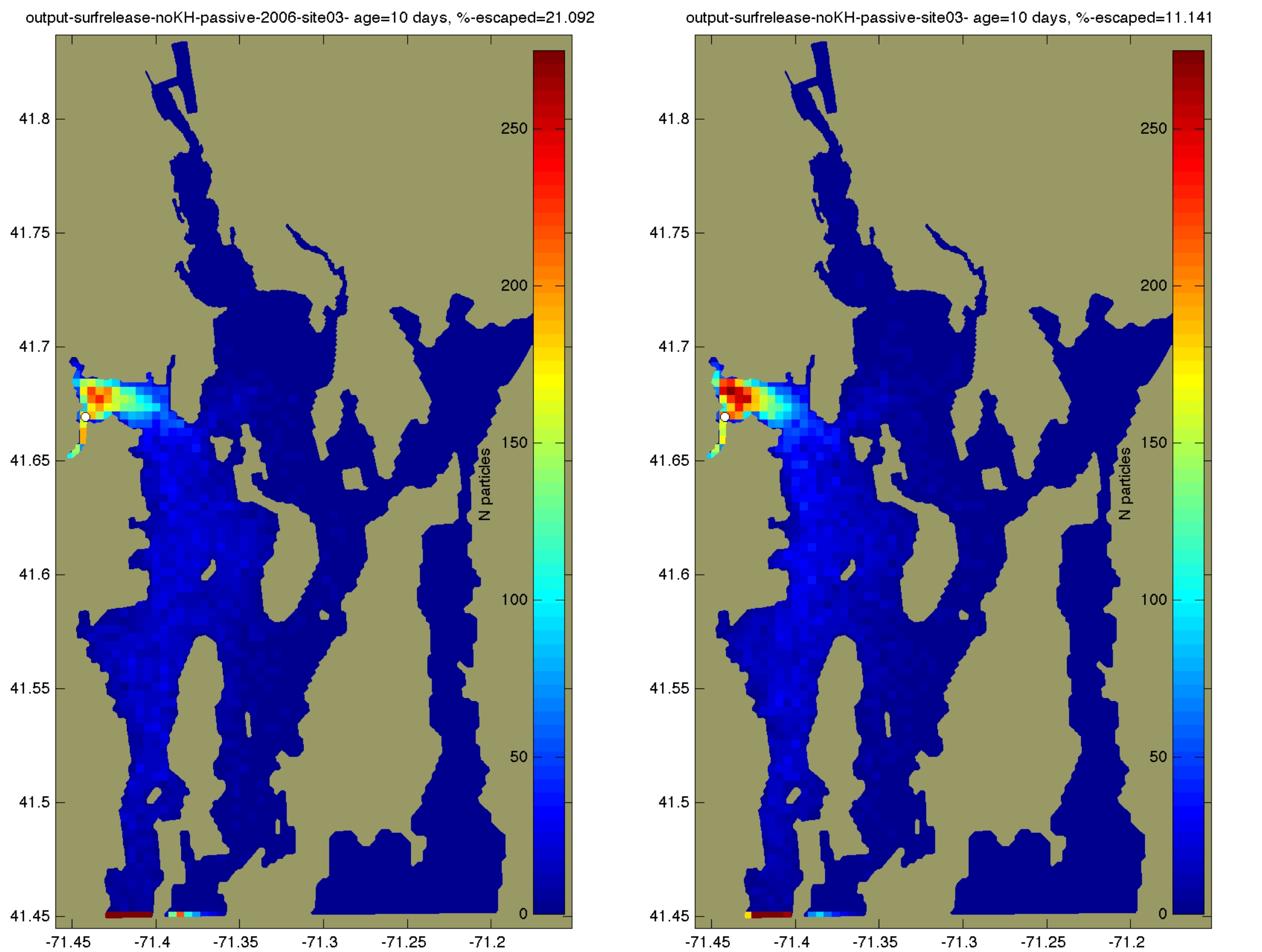


Figure 3-6. Number of particles as a function of position within the Bay 10 days after release from the Greenwich Cove site for 2006 (left) and 2007 (right). The white dot indicates the release location.

Rome Point, the release site closest to the Bay mouth, is not surprisingly a poor site from the standpoint of larval retention. A small number of particles remain within the lower East and West Passages after 10 days, but most particles escape the Bay. The percentage of particles lost to the coastal ocean is 95% in 2006 and 96% in 2007.

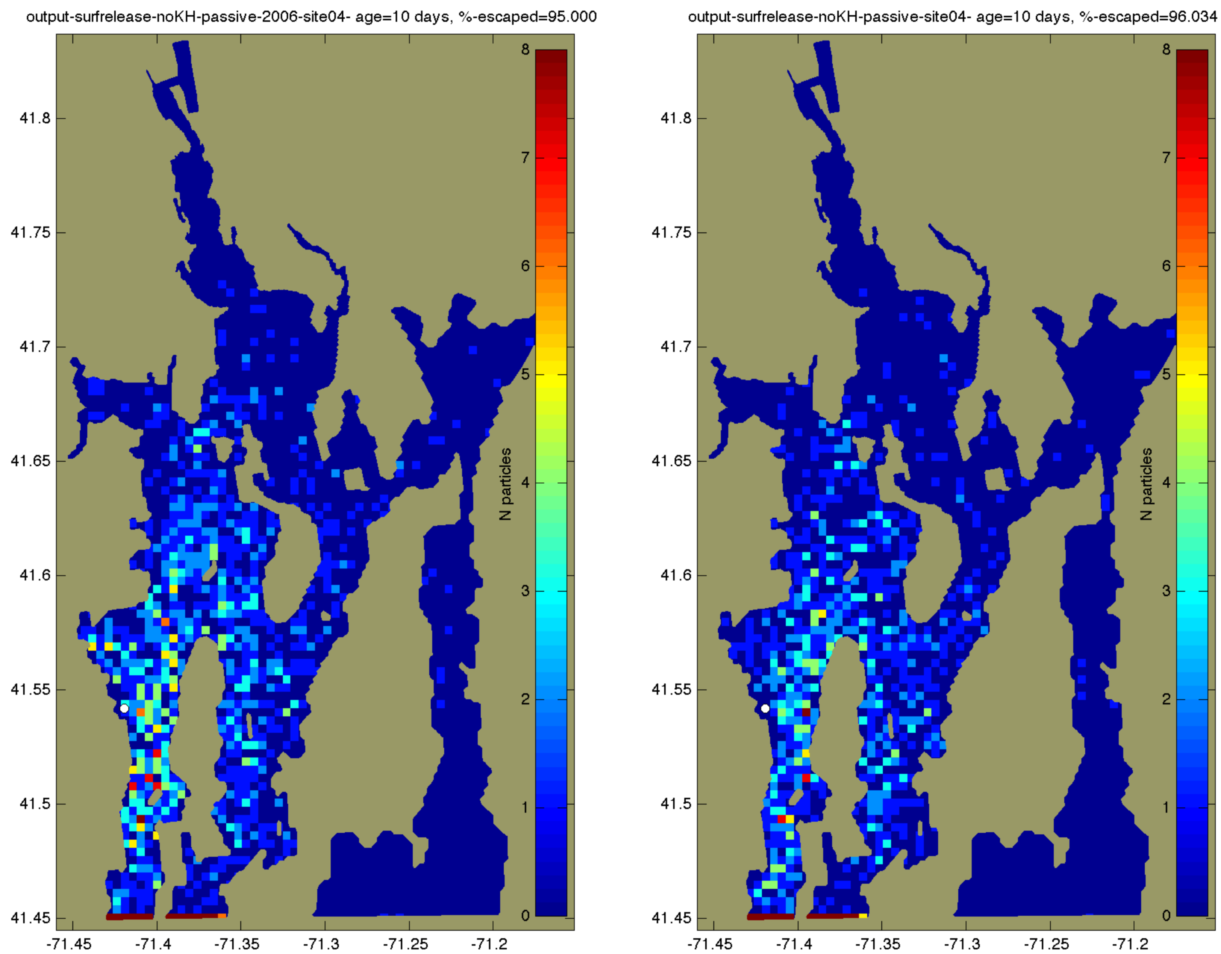


Figure 3-7. Number of particles as a function of position within the Bay 10 days after release from the Rome Point site for 2006 (left) and 2007 (right). The white dot indicates the release location.

Particles released from the Hog Island site end up distributed widely throughout the Bay after 10 days drifting. Highest numbers are found in the East Passage and Mount Hope Bay, but significant numbers of particles are found in the Upper Bay and West Passage as well. Total percentage losses are 46% and 35% for 2006 and 2007 respectively.

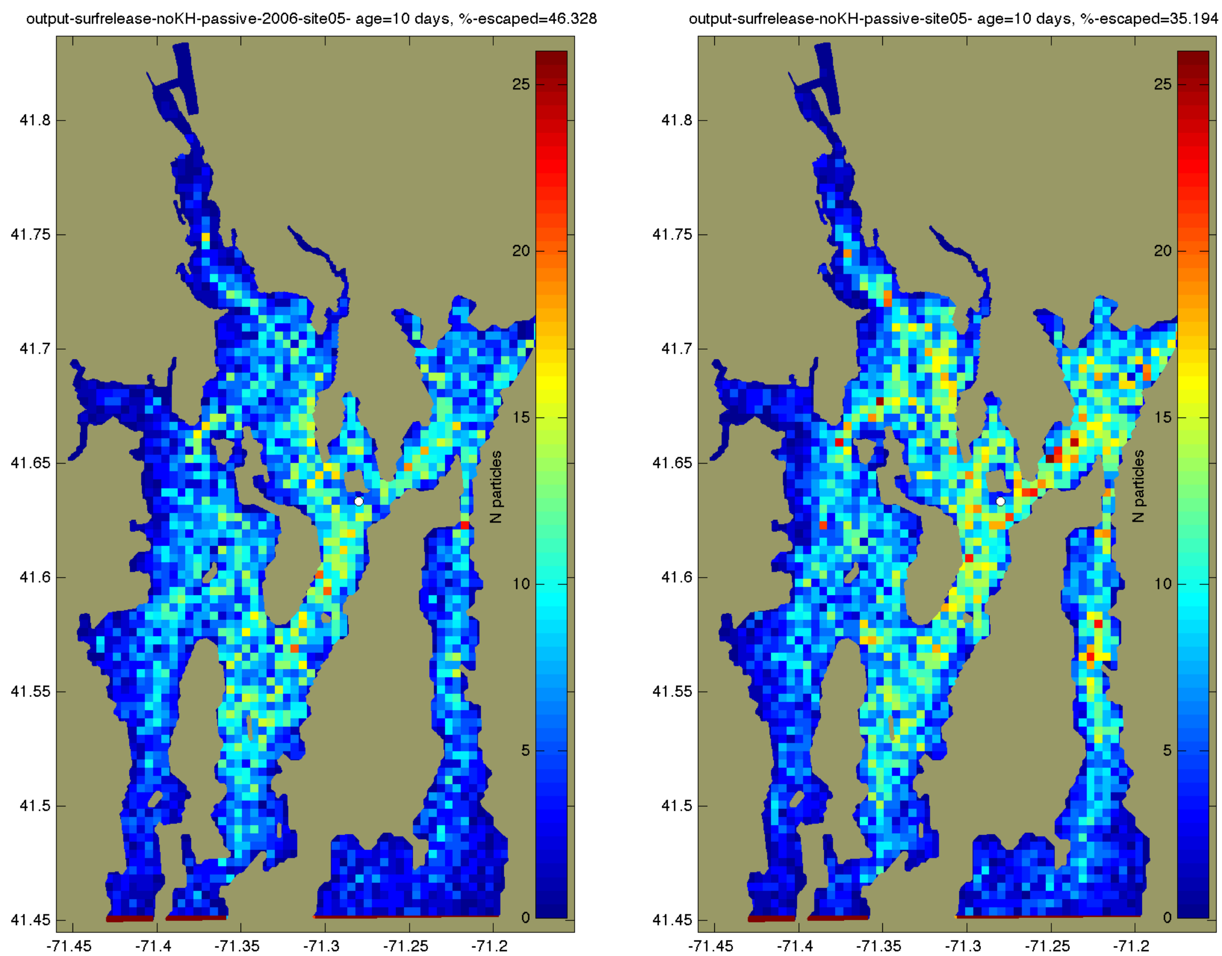


Figure 3-8. Number of particles as a function of position within the Bay 10 days after release from the Hog Island site for 2006 (left) and 2007 (right). The white dot indicates the release location.

After 10 days, numerical larvae released at the Rocky Point site are predominantly found in the West Passage, with smaller numbers found in a band along the western side of the East Passage. This site is fairly effective from the standpoint of larval retention with 43% lost in 2006 and 34% lost in 2007.

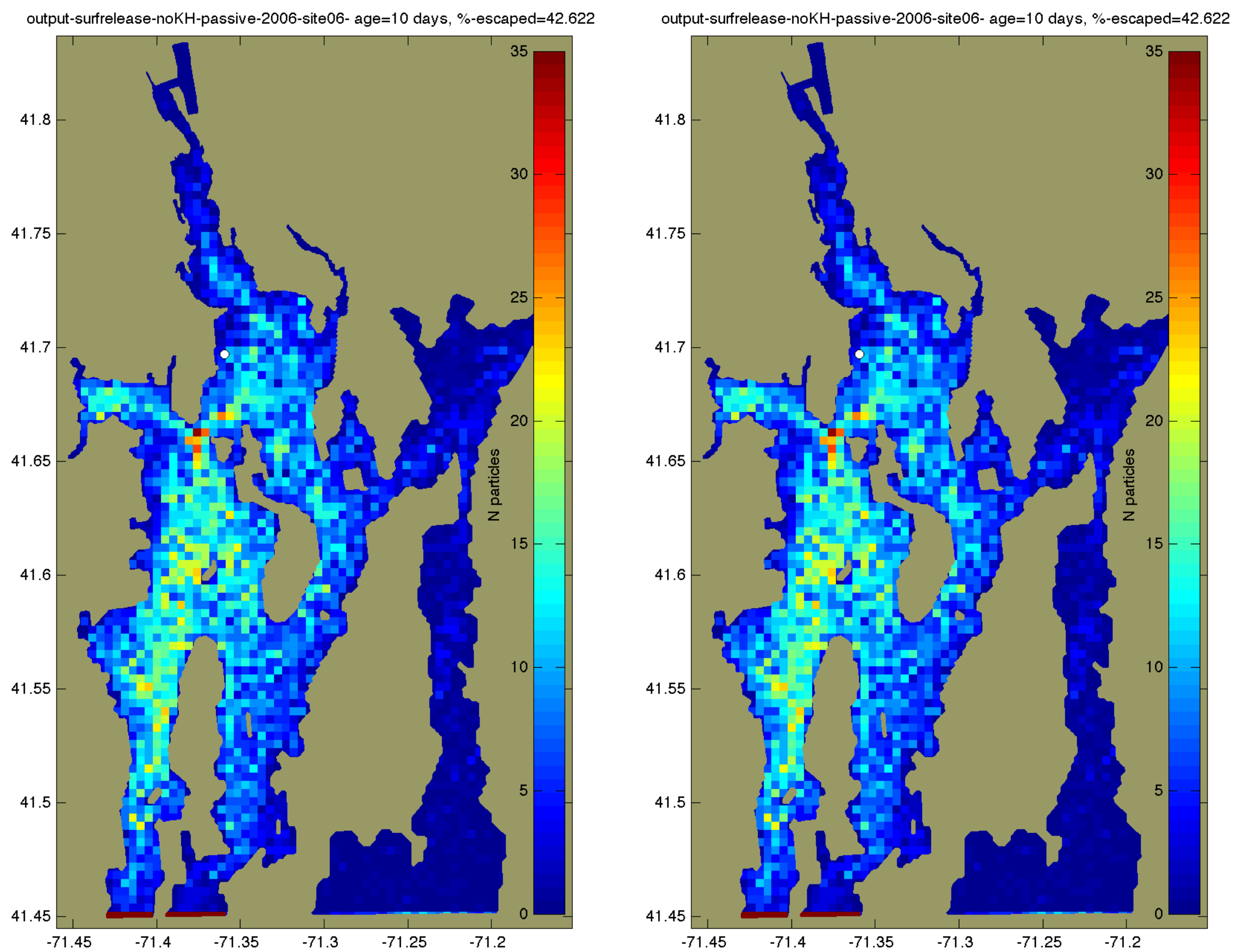


Figure 3-9. Number of particles as a function of position within the Bay 10 days after release from the Rocky Point site for 2006 (left) and 2007 (right). The white dot indicates the release location.

Examination of Table 3-1 indicates that larval retention within the Bay was significantly different in 2007 than in 2006. In fact the Bay circulation in 2006 seems to have been more conducive to the flushing of larvae out of the Bay. All sites, with the exception of Rome Point, exhibited higher loss rates in 2006. Loss rates at Rome Point, which is closest to the Bay mouth, were essentially constant over the 2 years simulated. The reason for higher larval loss in 2006 is still under investigation, but we hypothesize that the typical estuarine circulation pattern in the Bay (outflow at surface, inflow at bottom) was stronger in 2006. Particles initialized at the surface tend to travel southwards under this circulation and the stronger the circulation, the more effectively are particles swept out of the Bay. Preliminary support for the idea that the estuarine circulation was stronger in 2006 is found by examination of the environmental forcing (Figure 3-2). Peak freshwater inflow to the Bay in 2006 (~700 m^3/s) was higher than in 2007 (~300 m^3/s). As the estuarine circulation is driven by freshwater inflow at the head of an estuary, increased flow is expected with higher inflow.

The experiment in which larval particles exhibited vertical swimming behavior of the form shown in Figure 3-3 illustrates the importance of larval behavior on the retention of larvae within the Bay. During the first half of a 15-day larval stage, model larvae tend to swim upwards and the swimming speed decreases linearly with time, becoming downwards during the second half of the larval period. Figure 3-10 shows a comparison of the 10-day larval distribution for larvae released from the Providence River site with and without swimming behavior. The distributions are very different, with many more larvae escaping the Bay when behavior is included (53% lost as compared to 20% loss with no behavior). There is also an odd aggregation of particles near shorelines, which is under investigation at this time. To understand the increased loss of larvae when upward swimming behavior occurs early in the larval stage, Figure 3-11 shows the mean (and 1 standard deviation about the mean) depth and height above bottom for larvae in the two cases. When larvae exhibit swimming behavior, they tend to be found closer to the surface than when larvae are passive (even though the larvae are released at the surface, with no behavior they tend to be mixed downwards by turbulent diffusion). Larvae near the surface tend to be advected southwards in the estuarine circulation, thus more larvae near the surface results in greater export of larvae from the Bay.

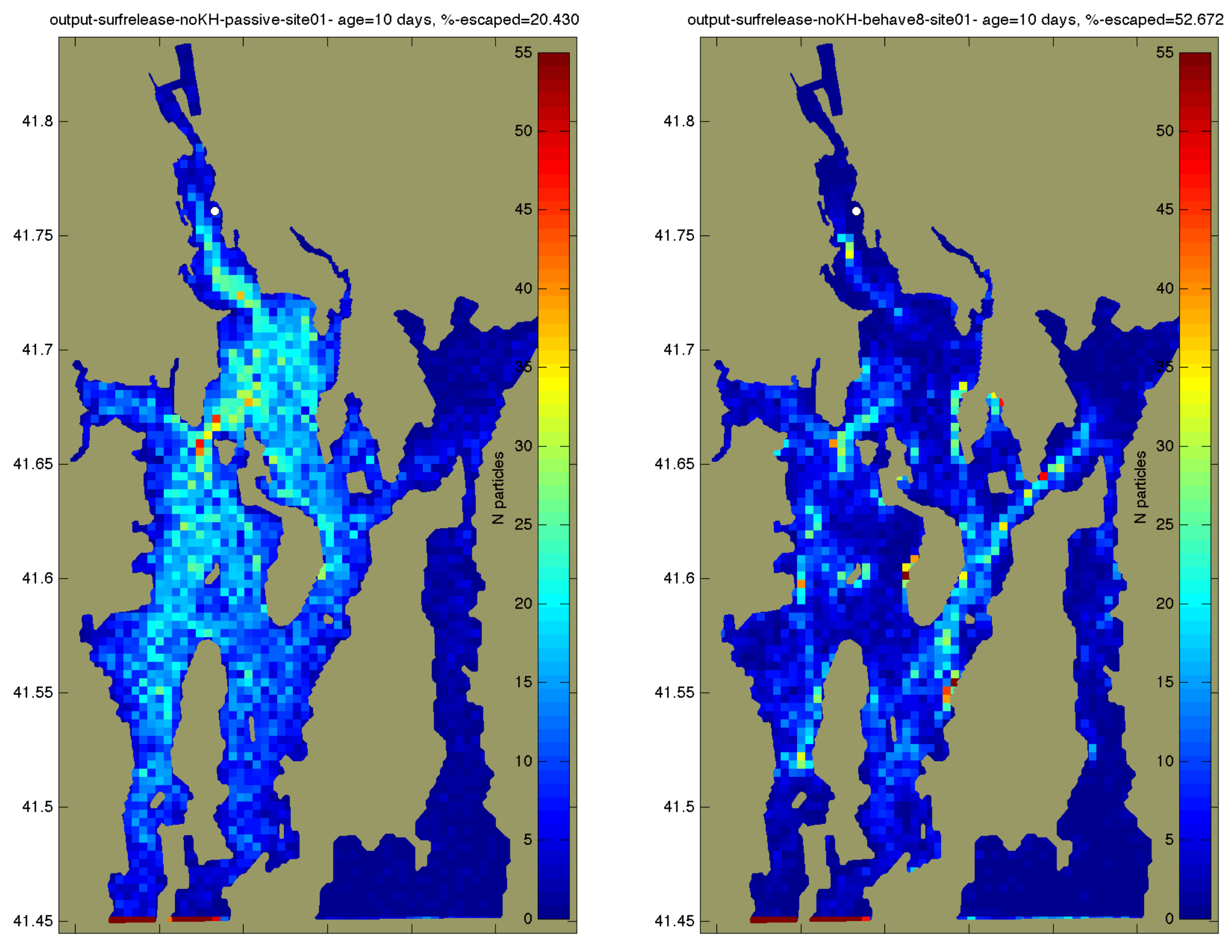


Figure 3-10. Comparison of the number of particles as a function of position within the Bay for particles released at the Providence River site (white dot) during 2007 for larvae with no swimming behavior (left) and larvae with the swimming behavior shown in Figure 3-3 (right). The percentage lost is 20% for the case of passive larvae and 53% for the case of swimming larvae.

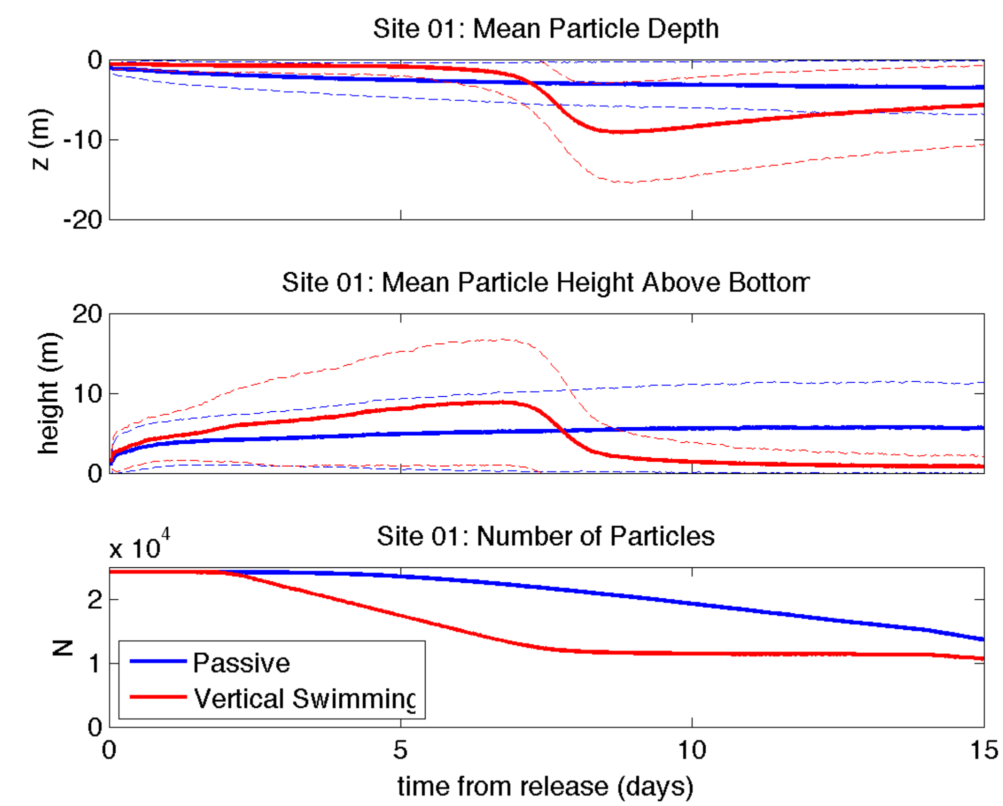


Figure 3-11. Comparison of the depth of particles (top), the height of particles above the bottom (middle), and the number of particles remaining within the Bay as a function of time after release for the case of passive larvae (blue) and the case where larvae swim vertically as shown in Figure 3-3. The solid curves show the mean depth/height and the dashed lines are the mean $\pm$ 1 standard deviation.

Discussion:

The simulations of larval dispersal from potential spawning sanctuaries in Narragansett Bay indicate that the effectiveness of a spawning sanctuary is strongly dependent on its location. The proposed location at Rome Point is a poor location as most larvae released there were exported from the Bay within the assumed 10-day duration of the quahog larval stage. The most effective location, from the standpoint of minimizing export from the Bay is the Greenwich Cove site, although most larvae from that site remain in the Greenwich Bay region, with little dispersion to other parts of the Bay. If dispersal of larvae within the Bay is considered, then the Providence River site appears to be quite effective, with larvae dispersed throughout the East and West Passages. Larval losses are relatively low from this site as well, although not as low as from the Greenwich Cove site.

Comparison of larval tracking simulations from two different years suggests that larval dispersal in the Bay is likely to be highly variable on a year-to-year basis. The strategy of periodic releases of larval particles over an entire month allows averaging over releases made during different environmental conditions and is expected to be effective in accounting for variation in parameters that vary rapidly relative to the 1-month period considered here (e.g. stage of tide, wind speed and direction). However, river discharge to the Bay varies more slowly and in fact freshwater inflow to the Bay was larger in 2006 than 2007. This appears to account for the increased larval export in 2006 as compared to 2007. Clearly, the timing of the annual spring peak in freshwater discharge to the Bay in relation to the quahog spawning period will be a critical factor in determining the number of larvae lost from the Bay.

The effect of behavior on the dispersion of pelagic larvae appears to be significant for Narragansett Bay quahogs. The upward swimming behavior early in the larval stage that we simulated resulted in increased larval loss from the Bay as well as a different 10-day distribution pattern within the Bay. This appears to have resulted from the increased exposure of the larvae to southward near-surface estuarine circulation. This conclusion is dependent on the specifics of larval behavior. Lacking better information on quahog larval behavior, we chose a simple model of behavior with a rather high swimming speed. Clearly, further investigation of larval behavior is warranted.

We presented larval dispersal results assuming a 10-day larval duration period. Not surprisingly, we find that in general the dispersion of particles is dependent on the larval stage duration. Distribution maps after 5 days (not shown) exhibit less dispersion and lower export from the Bay than is seen in the 10-day maps shown above. The results for 15-day trajectories indicate increased export. If the duration of the larval stage is inversely related to the temperature experienced by the larvae then higher temperatures under a global warming scenario should result in shorter larval stage duration and thus lower export of larvae from the Bay. Future work will examine the dispersal of larvae with variable, temperature dependent larval stage duration.

Summary of conclusions:

- Simulations of particles representing larvae that are passive (no behavior) indicate that potential spawning sanctuaries in the Providence River and Greenwich Cove are the most effective in maximizing larval retention, while Rome Point is a very poor site.
- Year-to-year variability in larval dispersal due to variability in environmental forcing is likely to be significant in Narragansett Bay.
- Simple larval behavior, upward swimming early in larval period and downward swimming late, results in increased larval export from the Bay.
- Better information on larval behavior and duration of the larval stage are needed to improve our capability to model and predict larval dispersal within the Bay.

References:

Andrews, J.D. 1983. Transport of bivalve larvae in James River, Virginia. J Shellfish Res 3:29–40

Baker, P. 2003. Two species of oyster larvae show different depth distributions in a shallow, well-mixed estuary. J Shellfish Res 22:733–736

Bergondo, D.L. 2004. Examining the processes controlling water column variability in Narragansett Bay: Time series data and numerical modeling. *Doctoral dissertation,* Graduate School of Oceanography, University of Rhode Island, 136 pp.

Bergondo, D. and Kincaid, C. 2007. Development and Calibration of a Model for Tracking Dispersion of Water from Narragansett Bay Commission Facilities. *Narragansett Bay Commission Annual Report*.

Butet, N.A. 1997. Distribution of quahog larvae along a north-south transect in Narragansett Bay. *M.Sc. Thesis*, University of Rhode Island, South Kingston, RI. 85 pp.

Haidvogel, D.B., H. Arango, W.P. Budgell, B.D. Cornuelle, E. Curchitser, E. Di Lorenzo, K. Fennel, W.R. Geyer, A.J. Hermann, L. Lanerolle, J. Levin, J.C. McWilliams, A.J. Miller, A.M. Moore, T.M. Powell, A.F. Shchepetkin, C.R. Sherwood, R.P. Signell, J.C. Warner, J. Wilkin, 2008, Ocean forecasting in terrain-following coordinates: Formulation and skill assessment of the Regional Ocean Modeling System. *Journal of Computational Physics.* 227:3595–3624.

Kremer, J. N., J. M. P. Vaudrey, D. S. Ullman, D. L. Bergondo, N. LaSota, C. Kincaid, D. L. Codiga, and M. J. Brush, 2010. Simulating property exchange in estuarine ecosystem models at ecologically appropriate scales, *Ecological Modelling,* 221: 1080-1088.

Landers, W.S. 1954. Seasonal abundance of clam larvae in Rhode Island waters 1950-1952. *U.S. Fish and Wildlife Service Special Science Reports in Fisheries.* 117:1-29.

LaSota, N., D. Bergondo, and C. Kincaid. 2007. Observational and numerical experiments on the flushing of nutrients in the Providence River estuary. *ERF* Annual Meeting, Providence, Rhode Island.

Mukai, A. Y., J. J. Westerink, R. A. Luettich Jr., and D. Mark. 2002. *Eastcoast 2001: A tidal constituent database for the western North Atlantic, Gulf of Mexico and Caribbean Sea,* U. S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Technical Report, ERDC/CHL TR-02-24, September 2002, 201 pp.

Narvaez, D. A., J. M. Klinck, E. N. Powell, E. E. Hofmann, J. Wilkin, and D. B. Haidvogel, 2012. Modeling the dispersal of eastern oyster (*Crassostrea virginica*) larvae in Delaware Bay, *Journal of Marine Research,* 70:381-409.

North, E. W., Z. Schlag, R. R. Hood, M. Li, L. Zhong, T. Gross, and V. S. Kennedy, 2008. Vertical swimming behavior influences the dispersal of simulated oyster larvae in a coupled particle-tracking and hydrodynamic model of Chesapeake Bay, *Mar. Ecol. Prog. Ser.* 359: 99-115.

Rasmussen, L.L., B.D. Cornuelle, E. Di Lorenzo, J.L. Largier, L.A. Levin, and B.J. Becker. 2006. Modeling circulation and transport pathways of larval bivalve populations on a regional scale. *EOS Trans. Am. Geophys. Union.* 87:suppl.

Rice, M.A. and J. Goncalo. 1995. Results of a study of bivalve larval abundance in Greenwich Bay, Rhode Island. In; M.A. Rice and E. Gibbs (eds.) *Proceedings of the Third Rhode Island Shellfisheries Conference.* Rhode Island Sea Grant, Narragansett, RI. Pp. 31-40.

Roegner, G.C. 2000. Transport of molluscan larvae through a shallow estuary. *J. Plankton Res.* 22:1779-1800.

Rogers, J.M. 2008. Circulation and transport in the heart of Narragansett Bay. *M.Sc. Thesis*, University of Rhode Island. Graduate School of Oceanography, 95 pp.

Shchepetkin, A.F. and J.C. McWilliams, 2005: The Regional Ocean Modeling System: A split-explicit, free-surface, topography-following coordinates ocean model. *Ocean Modeling*, 9:347-404.

Sullivan, B., and C. Kincaid (2001), Modeling circulation and transport in Narragansett Bay, *EOS Trans. Amer. Geophys. Union*, *82*:S51.

Umlauf, L. and H. Burchard. 2003. A generic length-scale equation for geophysical turbulence models, *J. Mar. Res.*, 61:235-265.

Warner, J. C., C. R. Sherwood, H. G. Arango, and R. P. Signell. 2005. Performance of four turbulence closure models implemented using a generic length scale method, *Ocean Modelling*, 8:81-113.

Appendices: To be collated in a CD that will be provided the CFRF.

Objective 4 –Introduction:

Taking advantage of the development of the ROMS for NBay, we propose to utilize our developing knowledge of quahog bivalve behavior and distribution in the bay, ROMS characterization of the hydrodynamics of the bay, and measured observations of reproductive activity of specific populations in the upper Bay to predict the distribution of post-metamorphic quahog juveniles. There have been a few studies describing bivalve larval occurrence and distribution in portions of NBay (Landers 1954, Rice and Goncalo 1995, Butet 1997) but these data are very incomplete with respect to tracking quahog larval distributions because of their limited sampling and the degree of difficulty in separating *M. mercenaria* larvae from other bivalve larvae. Nevertheless, it will be constructive to compare the results of the ROMS simulations with the published information on larval distributions in the Bay.

As a means to evaluate the capacity of the ROMS model to predict larval distribution, we simulated larval releases from adult quahog populations *in situ*. Simulations of pelagic larval releases to investigate dispersal patterns have been employed using a variety of materials for larval replacement, including neutrally buoyant drogues (Williams 2006), surface drifters (Hitchcock *et al.* 2008), fluorescamine dye (Erskine *et al.* 2005), sulfur hexafluoride dye (Hitchcock *et al*. 2006), Rhodamine WT dye (Parker 1973), and design-buoyancy particles (Ruddick *et al.* 2006). The results of a subset of these studies were used with varying success to evaluate quahog spawner sanctuary siting (Becker 1978) or to predict quahog larval recruitment locations (Hitchcock *et al.* 2006, 2008). We propose to use and to compare the results from the field studies with those predicted by the ROMS model, with similar parameters of location and depth of release.

Whatever methodology is used, it is imperative that the ROMS model results be validated through field observation. We propose to utilize two specific methods to evaluate the output of the ROMS model, namely, surface drifter drogues and *in situ* sampling for quahog larvae.

Standard Davis-style surface drifters (Davis 1985) have been successfully used to track large-scale larval quahog releases when compared with modeling results in the Indian River Lagoon in Florida (Arnold *et al.* 2005, Hitchcock *et al.* 2008). In both cases, the drifters reflected the advection-influenced movement of quahog larvae within a coastal embayment system. The field verification of both drifter and larval movements indicated that a simple diffusion (tracer) model was inadequate for predicting larval movements and one needed to utilize a particle tracer approach that accounted for advective forces on the movement of the larvae, i.e. a ROMS-type of model system.

The identification of larval bivalves to species has long been a goal of mollusk researchers and has proven to be a very problematic undertaking. Identification of bivalve larvae based on shell morphometrics is time consuming and difficult to undertake (Lutz 1985). As mentioned above, numerous techniques have been employed to facilitate bivalve larval identification with varying degrees of success and efficiency. One method that is relatively quick (2-3 minutes per sample) and reliable (80% correct identification) (Andrew Jacobs - personal communication) is the Larval Identification and Hydrographic Data Telemetry package (LIHDaT). LIHDaT is a system that employs a polarized laser light source to generate a reflected birefringence pattern displayed by the larval bivalve shell. The interpretation of the birefringence pattern is based on custom computer software. It has been demonstrated that with proper computer training, the application of this technology allows for species-specific identification of individual bivalve larvae (Figure 4-1, Tiwari & Gallager 2003).

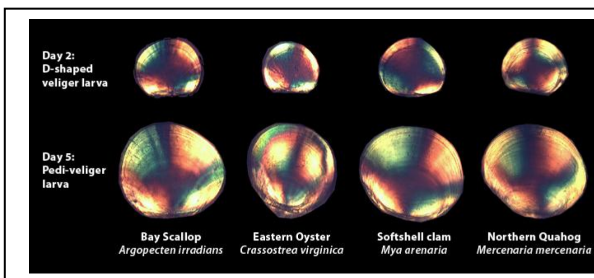


Figure 4-1: A sample of the differences in birefringence patterns of various bivalve species, as generated by the LIHDaT system (Mingione 2008).

Statement of research question or problem investigated:

As noted above and based on projections from the ROMS model (Objective 3), there are areas within NBay where quahog larvae may be aggregated prior to settlement due to prevailing wind and water movement. To verify the projected model simulations, we will ground truth the model forecasts using a combination of surface drifters, to physically track the movement of passive particles in the bay, and surveying for late-stage competent quahog larvae in the near-bottom environment.

Goals and Objectives of research project:

Using the results of the model, validate predicted larval settlement sites through a combined effort of surface drifter deployments and monitoring for the occurrence of quahog larvae, identified with a polarized laser video plankton sampler (LIHDaT).

Methodology:

Drifters

There are several existing designs for low-cost drifters (e.g. http://gisweb.wh.whoi.edu/ioos/drift/driftdesign.html) and we initially chose a design ("Roger", Figure 4-2) that proved unsatisfactory after it frequently ran aground within 12 hours of deployment. We modified the design repeatedly, concluding with one designed to track water movement one-meter below the surface and with minimal windage (Figure 4-3). These routinely would remain adrift for up to seven days before either running aground or leaving the Bay. The final design is easily adapted to track currents at deeper depths by using a taller mast and we successfully deployed several three-meter versions of the drifter during the summer of 2013.

Figure 4-2: A photo of the original "Roger" drifter design.

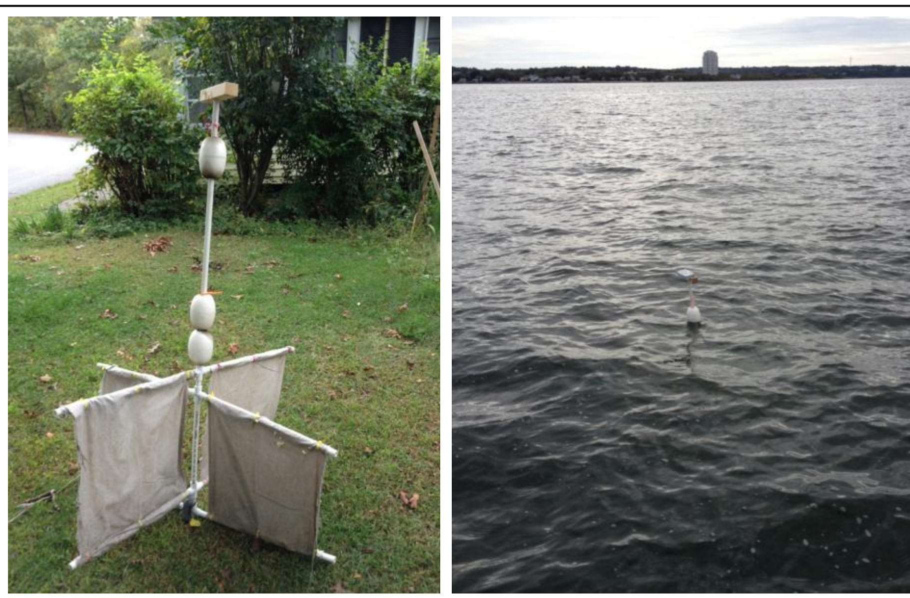


Figure 4-3: Final "Roger" drifter design on land (left) and while deployed (right). The center of the canvas sail is approximately one meter below the upper-most white float. When deployed, only the top of the drifter is emergent. Mounted at the top of the mast is a GPS/cell phone unit for data collection and transmission.

Drifters were equipped above the water surface with a FoxTrax GPS Equipment Tracker (Spider AT 3010) programmed to transmit its location and speed *via* cell service once every hour. The drifter tracks were displayed on the FoxTrax website (http://foxtraxgps.com/) and were available to download for analysis. Depending on exact ballasting of the drifter and the sea state (the GPS cannot get a fix if it is submerged by a wave crest when the fix is attempted), some hourly transmissions failed resulting in small gaps in the drifter track records.

Typically, we deployed multiple drifters at the same location and time to get a sense of the effect of small-scale variation in initial conditions. Six potential larval source areas identified based on discussions with commercial quahoggers served as drifter release points: High Banks, Hog Island, Rocky Point, Rome Point, Sabin Point/Providence River, and the current Spawner Sanctuary (Table 4-1). The High Banks location was a late addition to our original sites and only a few drifters were released here.

Table 4-1: Sites selected for deploying drifters to test model predictions.

Location	Lat	Long
Sabin Point	41.7608	-71.3672
Rocky Point	41.6969	-71.3600
Spawning Sanctuary	41.6670	-71.3913
High Banks	41.6397	-71.3955
Rome Point	41.5471	-71.4220
Hog Island	41.6333	-71.2801

As the drifters were moved by hydrographic forces (current), drifter tracks provided insight into the dispersal of larvae from prospective source areas and can be compared to numerical model results that use passive particle tracers, such as the ROMs predictions outlined in Objective 3.

Table 4-2: Sites selected for sampling late-stage quahog larvae.

Name	Lat	Long	Anticipated larval supply
Greenwich Cove	41.661637	-71.442319	High
Chepiwanoxet	41.676307	-71.442443	High
Sandy Point	41.664646	-71.405473	Low
Spawning Sanctuary	41.669821	-71.389343	Low
Sugar Mountain	41.655645	-71.370999	High
Warwick Neck	41.663884	-71.368550	High
Hope Island	41.377688	-71.377688	Low

<u>Quahog Larval Sampling:</u>

As bivalve larvae develop they become more negatively buoyant (Dekshenieks *et al.* 1996) and they undergo behavioral changes (more photonegative) resulting in them swimming deeper in the water column (Manning and Whaley 1954, Bayne 1965). As they approach competency, it is theorized that the larva approach the bottom and effectively bounce along the substrate as they seek out an appropriate spot for settlement (Keough and Downes 1982, Butman 1986, Butman *et al.* 1988). Therefore, we proposed to sample for competent larvae at a depth of 0.5 m off the substrate, using sites predicted by the ROMS model as either having a projected high density of larvae (at 10-15 days post fertilization) or a low density. Based on ROMS predictions (see Objective 3), we selected the sites depicted in Table 4-2 and Figure 4-4 for larval sampling.

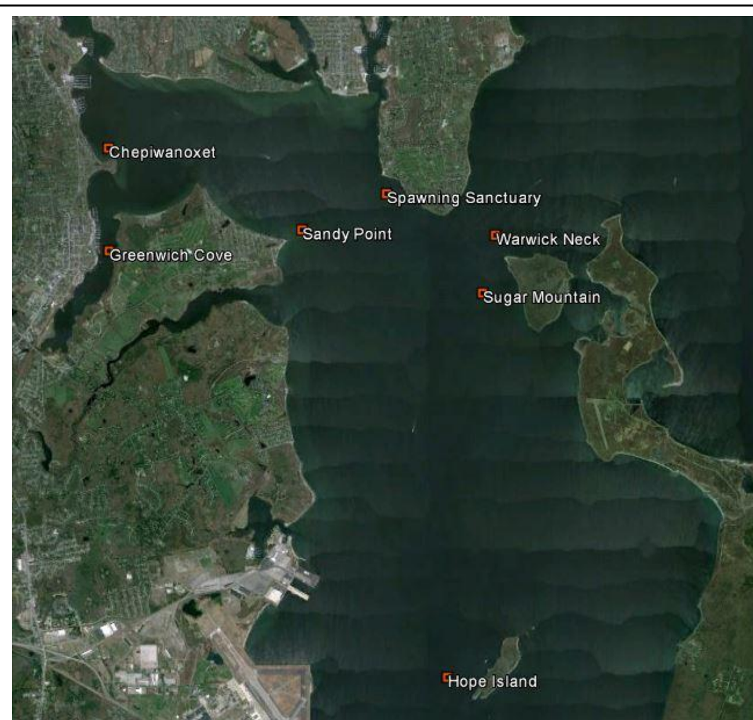


Figure 4-4: The sites sampled for late-stage swimming quahog larvae as predicted by the ROMs model simulation of larval distribution.

Sampling was achieved by lowering a 12VDC pump suspended in a PVC frame that was weighted at the base and held the pump 0.5 meters off the bottom (Figure 4-5). To sample, the pump frame was lowered to the bottom on site and the pump output was brought to the surface through a length of 1" diameter Tygon tubing. At the boat side, the pump effluent ran through an inline flowmeter (GPI Turbine flowmeter) then discharged into a 150 μm plankton net. 100 gallons of seawater was sampled at each location and sampling event. The volume was measured by an inline flowmeter (TPI Turbine Water Flow Meter, Model TM075) installed just before the discharge outlet of the pumped line. The material retained on the plankton net was placed in a capped bottle, placed on ice and returned to the laboratory. Upon return to the laboratory, the plankton sample was concentrated on a 100 μm screen and transferred to a 100 ml plastic bottle, where it was preserved in 1% buffered formalin with a small amount of Borax to buffer the overall solution (LIHDaT preservation protocol). At this time, the samples were preliminarily inspected for bivalve larvae with a dissecting microscope to ensure the presence of larvae.

Figure 4-5: The bottom tending plankton pump for sampling at an elevation of 0.5 m off the bottom.

Identification and enumeration of bivalve larvae in the sample would be completed by the LIHDaT instrumentation in collaboration with the Aquinnah Wampanoag Water Quality Laboratory in Aquinnah, MA. The preserved samples were to be shipped to the lab where they would be processed and analyzed.

Analysis techniques:

Drifter:

Drifter tracks were downloaded from the FoxTrax website and compiled at RWU using the Generic Mapping Tools (GMT) software. The completed tracks were plotted on a map of NBay and the patterns were evaluated visually for comparison to the projected larval transport patterns predicted by the ROMS model. Similarities and dissimilarities were noted with the feedback going to the modeling team for analysis and discussion on methods to refine any inconsistencies between model projections and drifter tracks.

Quahog Larval Sampling:

The total number of quahog larvae collected with each sample were to be compared over time and between sites using a two-way ANOVA with time and location being the two independent factors.

Results:

Drifters

After several design modifications and refinements, we implemented a low-cost version of the Davis-style drifters to investigate the near-surface current movements in Narragansett Bay with regard to potential larval source locations. Dubbed the "Roger", the drifters were deployed on 49 different occasions during the late spring, summer and fall of 2012 and 2013 (Table 4-3).

Over the course of the two years of deployments, several units were lost to sea as we were unable to recover them before they were swept out of the Bay (although two units that left the bay were recovered on beaches in East Hampton, NY). Two units displayed evidence of being hit by vessels and were only partially recovered. Several units were lost without explanation and may have also been struck by vessels or suffered electronic or physical failure.

Table 4-3: Timeline for drifter deployments.

2012		2013	
Release Date	Location (number drifters released)	Release Date	Location (number drifters released)
31-May-12	Hog Island (2)	20-May-13	Hog Island (1)
5-Jun-12	Hog Island (2)	24-May-13	Hog Island (1)
11-Jun-12	Greenwich Cove (2)	26-May-13	Hog Island (1)
11-Jun-12	Hog Island (1)	4-Jun-13	Hog Island (2)
11-Jun-12	Spawner Sanc. (3)	11-Jun-13	Hog Island (3)
18-Jun-12	Hog Island (1)	17-Jun-13	Spawner Sanc. (4)
18-Jun-12	Spawner Sanc. (2)	17-Jun-13	High Banks (1)
19-Jun-12	Hog Island (2)	24-Jun-13	High Banks (2)
19-Jun-12	Spawner Sanc. (1)	24-Jun-13	Spawner Sanc. (2)
11-Jul-12	Rocky Point (1)	1-Jul-13	Rocky Point (4)
11-Jul-12	Sabin Point (2)	2-Jul-13	Spawner Sanc. (1)
25-Jul-12	Sabin Point (1)	3-Jul-13	High Banks (1)
25-Jul-12	Rocky Point (2)	9-Jul-13	Rocky Point (4)
1-Aug-12	Rocky Point (2)	9-Jul-13	High Banks (1)
7-Aug-12	Rome Point (1)	15-Jul-13	Sabin Point (2)
10-Sep-12	Rome Point (2)	15-Jul-13	Spawner Sanc. (1)
29-Sep-12	Spawner Sanc. (2)	15-Jul-13	Rocky Point (2)
1-Oct-12	Spawner Sanc. (2)	18-Jul-13	Sabin Point (1)
2-Oct-12	Hog Island (2)	22-Jul-13	Hog Island (1)
3-Oct-12	Rome Point (2)	24-Jul-13	Hog Island (2)
4-Oct-12	Hog Island (1)	24-Jul-13	Rocky Point (2)
5-Oct-12	Rome Point (2)	7-Aug-13	Spawner Sanc. (2)
7-Oct-12	Hog Island (1)		
10-Oct-12	Rome Point (3)		
10-Oct-12	Spawner Sanc. (1)		
23-Oct-12	Rome Point (1)		
23-Oct-12	Spawner Sanc. (1)		

The individual track data from each deployment at each site was compiled and the compilations of tracks were plotted on a chart of NBay. The compiled tracks are included in the following charts (Figure 4-6).

Although High Banks releases were limited (Figure 4-6A), these drifters stayed on the west side of the Bay (West Passage) reaching as far north as Ohio Ledge and as far south as Rhode Island Sound *via* the West Passage. We would expect that some drifters that reached the Ohio Ledge area would move to the East Passage given the appropriate wind and tide conditions.

Drifters released on the south side of Hog Island (Figure 4-6B) predominantly stayed in the East Passage with one making its way into the Sakonnet River. Depending on the wind and tide, several drifters moved northward into lower Mount Hope Bay only to leave on the outgoing tide and travel down the East Passage (excepting the single Sakonnet River case). Two drifters traveled into the West Passage where they ran aground, and four exited the Bay *via* the West Passage. Curiously, no drifters were able to travel to the northwest between Prudence Island and Popasquash Point.

Drifters released from Rocky Point (Figure 4-6C) traveled to nearly all parts of Narragansett Bay, excepting Greenwich and Mount Hope Bays, as far north as Conimicut Point and as far south as the Bay mouth via both the east and west passages. The track shown in dark olive illustrates a case where several data transmissions failed resulting in gaps in the track.

Most drifters released from Rome Point traveled north and south along the west side of the west passage (Figure 4-6D). Two released at the same time crossed into the east passage and were recovered near Newport. Strong sea breezes pushed many drifters northward, contrary to the prevailing large-scale surface flow, which must be southward out of the bay.

The Sabin Point/Providence River release site (Figure 4-6E) proved to be a difficult area for the drifters as they frequently ran aground. That said, the overall pattern is one of nearly complete coverage north of Conimicut Point. Unfortunately these results do not provide any information on potential bay-wide distribution of larvae emanating from Sabin Point.

Drifters were released in Greenwich Cove, but the shallow, narrow, cove lined on the west side with marinas resulted in drifters rapidly running aground or being trapped in marina docks. This site was subsequently abandoned as a drifter release location.

Evaluating the current Spawner Sanctuary with regard to larval distribution was one of our primary goals. Thus, that location was the site of 12 out of 49 drifter releases (Figure 4-6F). The resulting drifter tracks cover much of the northern half of the Bay west of Prudence Island with three drifters making it to the east of Prudence Island and one into Mount Hope Bay. The tidal state at the time of the release appears to have significant impact on whether a drifter enters Greenwich Bay and stays there, or ultimately leaves Greenwich Bay. As a side note for completeness, the drifter shown in dark blue extending southward down the west passage was adrift during hurricane Sandy when winds were from the northeast at 30-40kts and is not representative of normal conditions.

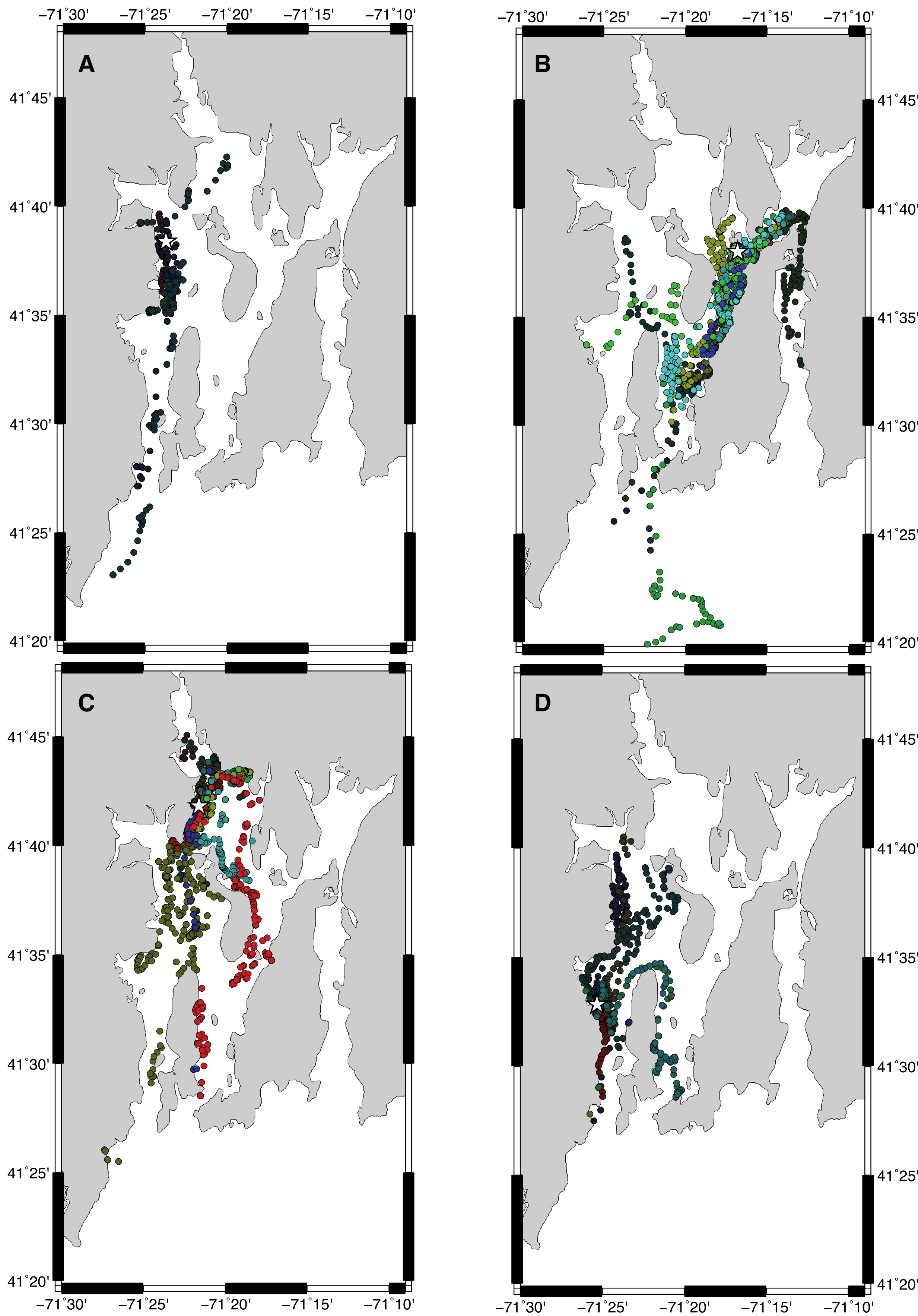


Figure 4-6. Maps showing tracks for all drifters release from High Banks (A), Hog Island (B), Rocky Point (C), and Rome Point (D). Each color represents an individual drifter track and the white star denotes the release location.

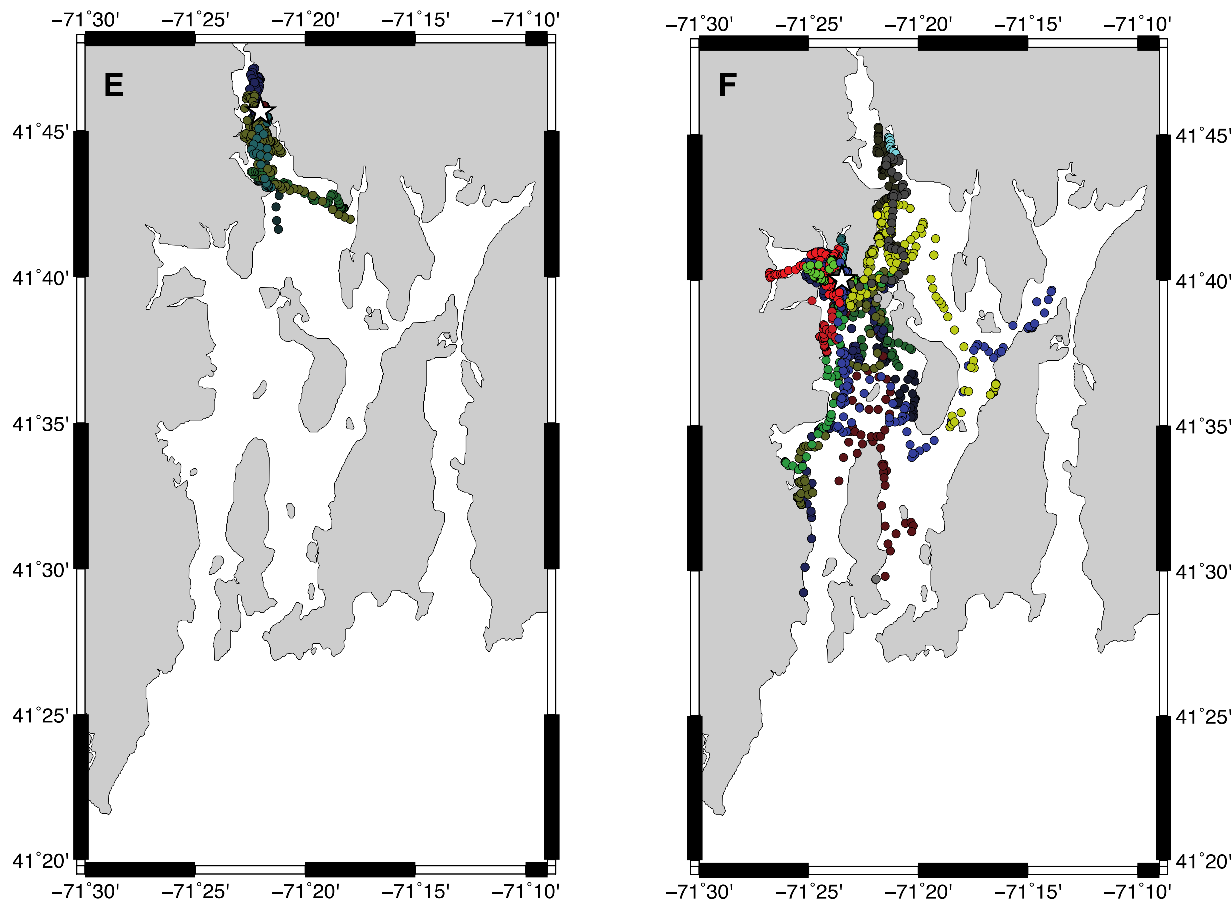


Figure 4-6 (continued). Maps showing tracks for all drifters release from Sabin Point (E) and the Spawner Sanctuary (F). Each color represents an individual drifter track and the white star denotes the release location.

Quahog Larval Sampling:

The larval sampling program initiated on 31 July 2013, after a few false starts due to pump failure and apparatus problems. Samples were collected every two - three days for a little more than a week (Table 4-4) and were inspected quickly following each sampling interval. The sampling program was abandoned after one week due to a lack of bivalve larvae in any of the samples collected up to that point.

Table 4-4: Sampling frequency for plankton pumping.

Location:	31-Jul-13	2-Aug-13	5-Aug-13	7-Aug-13
Greenwich Cove	2	1	1	1
Chepiwanoxet	2	1	1	1
Sandy Point	2	1	1	1
Spawning Sanctuary	2	1	1	1
Sugar Mountain	2	1	1	1
Warwick Neck	2	1	1	1
Hope Island	2		1	1

Discussion:

Drifters

We can compare the drifter tracks (Objective 4) to the locations of passive particles released in the ROMS simulations (Objective 3) as a means to validate the ROMS results. This is not a direct comparison because the drifters were released from late spring through early fall 2012 and 2013, whereas the model results are based on forcing (e.g. wind and freshwater) during the late spring of 2006 and 2007. Thus the conditions experienced by the particles in the model and the drifters can be quite different. In addition, particles were released in the model at all stages of the tidal cycle, across two precipitation events (2007) and observed wind conditions in May and June of 2006/2007. The advantage of the model is that the particle locations depict an integrated result across a wide range of wind and tidal conditions, something that cannot be done with physical drifters. Finally, drifters often run aground prior to the 10-day results obtained in the model. Unfortunately, the drifters do not perfectly mimic microscopic larvae. On the other hand, the spatial resolution of the model does not approach that of the real world. Nonetheless, the drifter-model comparison is instructive with regard to the general trends.

Generally, the model results and drifter results are very similar, strikingly so in some cases. One example is the results from Rocky Point releases (Figure 4-7). Here, the northward extent of the particles/drifters in the Providence River, the dominantly southward movement between Patience Island and Warwick Point, and the movement along the eastern edge of Prudence Island area all in excellent agreement. That said, the model results show a significant percentage of particles entering Greenwich Bay whereas the drifters were unable to fully enter Greenwich Bay, although some ran aground at the mouth just inside Warwick Point.

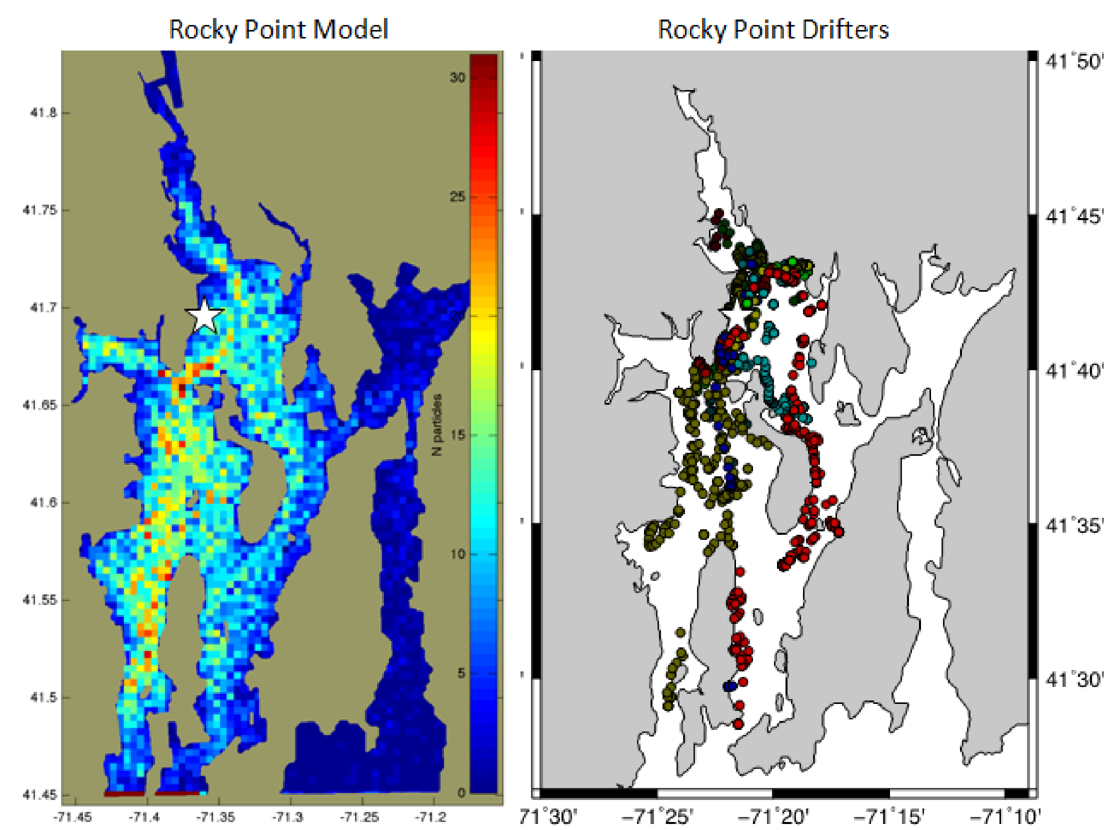


Figure 4-7: A comparison between the ROMs model projections and the drifter tracks when the release occurs at Rocky Point.

The Spawner Sanctuary is one release location where the model and drifter results seem quite different (Figure 4-8). Drifters released here traveled widely throughout the bay whereas modeled particles were mainly either trapped in Greenwich Bay or lost to Rhode Island Sound after 10 days. Part of the discrepancy may be due to the drifters running aground before 10 days time. Perhaps if they had stayed adrift longer, they would have exited the Bay.

The Hog Island drifter/model data show some similarities and important differences as well (Figure 4-9). Drifters and modeled particles traveled both south along the east passage and into the Sakonnet River. The model shows particles traveling far up in to Mount Hope Bay, which was not observed with the drifters. It should be noted, however, that the spatial resolution of the model in Mount Hope Bay is relatively low compared to the rest of the upper Bay. In addition, a significant percentage of modeled particles traveled northeastward from Hog Island into the vicinity of Ohio Ledge, a pattern not seen with the drifters.

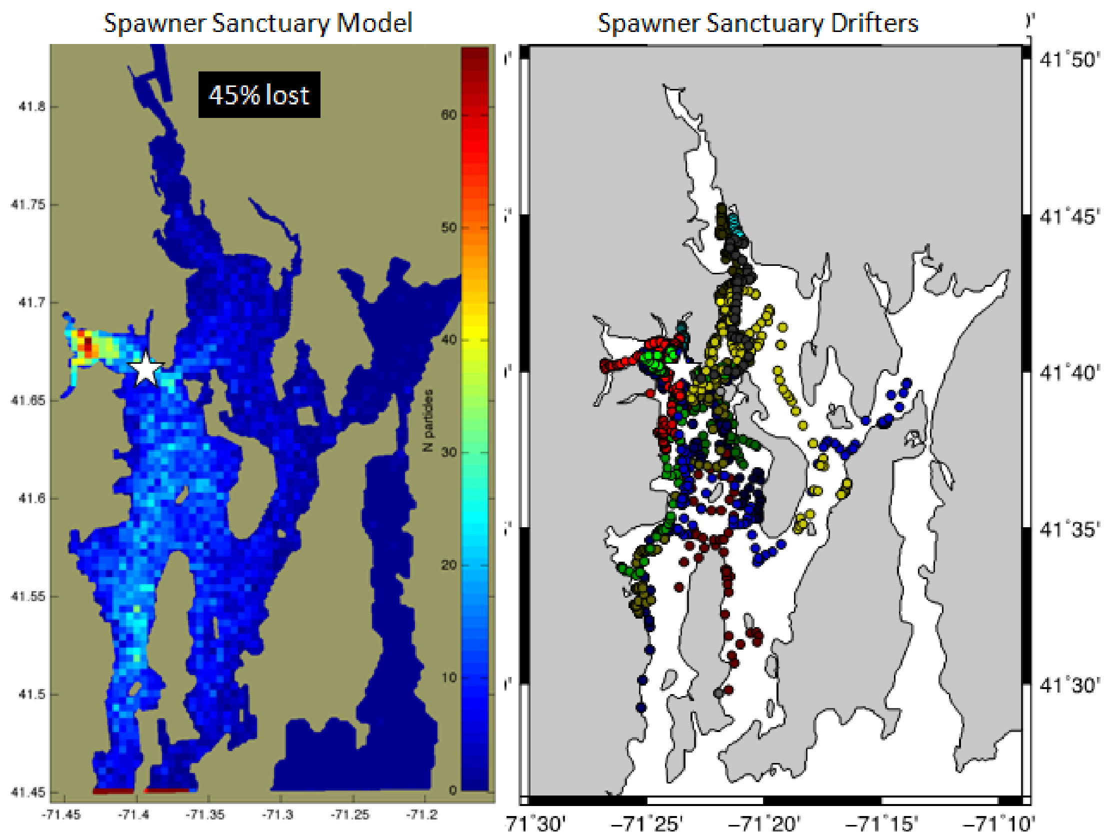


Figure 4-8: A comparison between the ROMs model projections and the drifter tracks when the release occurs at the Spawner Sanctuary.

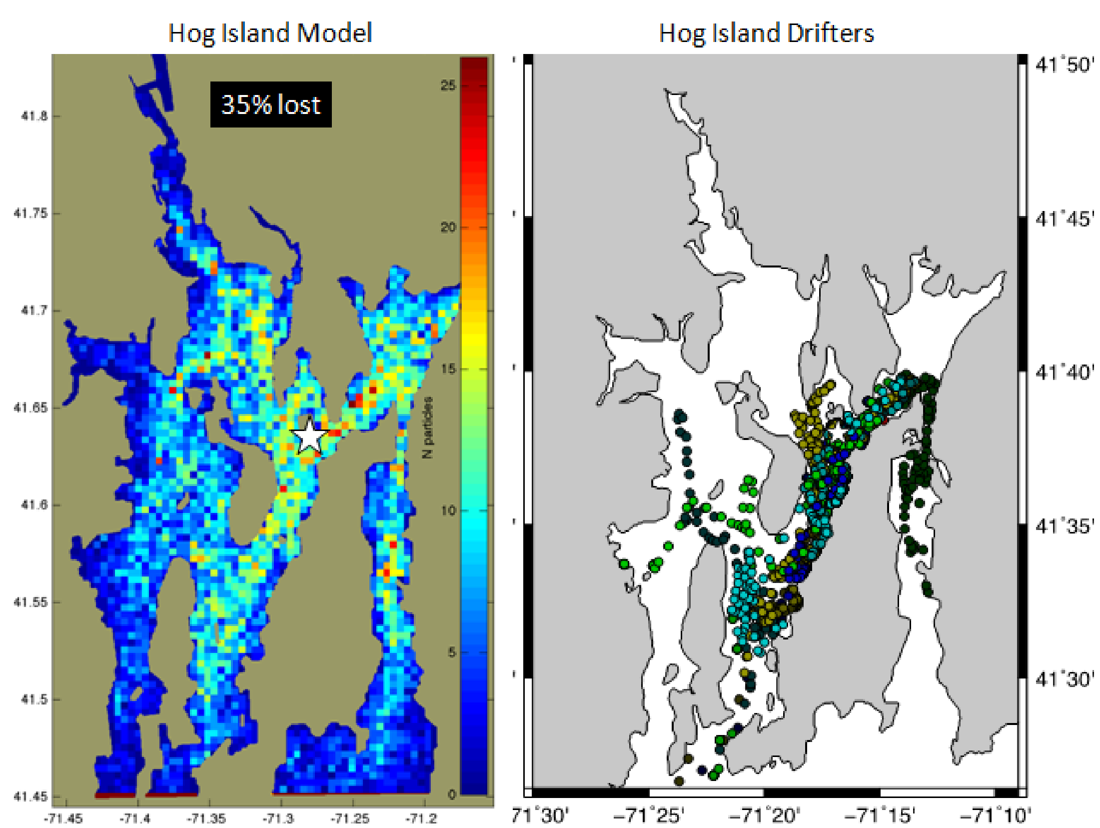


Figure 4-9: A comparison between the ROMs model projections and the drifter tracks when the release occurs at Hog Island.

In summary, the model and drifter results are in strong agreement given the caveats discussed above (i.e. environmental conditions in different time periods). Thus, in general, we have considerable faith in the model to accurately portray the movement of passive particles in Narragansett Bay. However, some attention may need to be paid to the model predictions for hydrodynamics in the vicinity of Greenwich Bay.

Quahog Larval Sampling:

Our inability to capture bivalve larvae in the plankton pump sampling we conducted was a surprising result. Microscopic analysis of the plankton samples revealed a wide variety of larval stages of other marine invertebrates, indicating that the dearth of bivalve larvae was a real phenomenon rather than a failure of the equipment or protocol to collect larvae. In addition, bivalve larvae were assumed present in the system. Based on previous work by Jeff Mercer (RIDEM personal communication), he indicated that bivalve larvae could be retrieved by plankton net tows within the water column at almost any time during the summer months at many locations in NBay, including spots close to our designated sampling sites. Mercer's observations are supported by three reports of quahog larval distribution in NBay that report larvae present in the bay during the interval sampled in this study (Landers 1954, Rice and Goncalo 1995, Butet 1997). However, all three studies sampled larvae either much higher in the water column (1.6 m deep) or at the surface (0.3 m deep).

Two sampling factors most likely contributed to the lack of bivalve larvae in the bottom plankton samples. These are the plankton net mesh size (150 μm) and/or the location of the pump (0.5 m off the bottom). Quahog larvae approach a size of 170 to 240 μm in length as they approach competency while they start their development as trochophores between 50 to 90 μm (Loosanoff and Davis 1950, Landers 1954). Therefore, the plankton net used in the current study was selected to target only those individual larvae that were large and therefore assumed to be near metamorphosis. Other studies sampling quahog larvae in NBay used much smaller mesh nets (60 to 90 μm; Landers 1954, Rice and Goncalo 1995, Butet 1997) allowing them to sample the entire range of quahog larval stages. With mortality estimates approaching 95% over the course of quahog larval development (Butet 1997), the absolute numbers of competent quahog pediveligers is much less than the numbers of earlier stage larvae captured in the field. Therefore, by only selecting the larger pediveligers in the quahog larval population, we are sampling a much smaller proportion of the larval population than the previous researchers. Nevertheless, one would anticipate collecting reasonable levels of competent larvae, as all three previous studies were able to collect late stage quahog veligers in the same area we sampled during the sampling interval that we covered (Julian days 212 to 219), albeit that they were sampling higher in the water column. This is particularly reasonable, considering that we sampled 4 times as much water (or more) as the previous studies.

By focusing our samples to the level of 0.5 m from the bottom, we were working from the assumption that late developing bivalve larvae tend to swim at or near the substrate as they become competent to metamorphose (Bayne 1965). It is often stated that as bivalve larvae become competent, their swimming behavior, as well as their overall buoyancy, tends them to swimming at the substrate water interface, especially under flow conditions (Johnsson 1991). It is reported that they proceed to "bounce" along the substrate as they are seeking appropriate habitat within which to settle (Keough and Downes 1982, Butman 1986, Butman *et al.* 1988). Under some circumstances, when water flow exceeds certain thresholds, they become incorporated in the substrate hugging boundary layer flow (Pawlik *et al.* 1991, Johnsson 1991). Although the direct evidence is not available, the results from this exercise suggest that the competent bivalve larvae are not located in the depth profile of 0.5 m above the sediment surface. Therefore, they are either swimming higher in the water column or are more closely associated with the sediment surface as they explore their future habitat. Other explanations for a lack of larvae in the sampling include that the larvae were not there for some other reason or we were not able to sample the targeted larvae with the plankton pump that we developed. Further studies are required to address this question.

Summary of conclusions:

- Drifter
  - We designed a drifter that, when deployed in Narragansett Bay, was able to collect data and not run aground for 5-10 days post-deployment.
  - Drifter tracks (49) were collected from six release points that corresponded to particle release points utilized in the ROM model for tracking quahog larval distributions in NBay.
  - On the whole, the results of the drifter deployment supported the particle distribution patterns generated by the ROMS.
  - There may be areas in the ROMS model (i.e. Greenwich Bay) where work is needed to improve the ability of the model to forecast particle transport from hydrodynamic forces.
- Quahog Larval Sampling
  - A plankton pump was developed to sample plankton at the level of 0.5 m from the substrate surface.
  - The pump was utilized at 7 sampling sites on 5 sampling days that corresponded to a time interval when late-stage quahog larvae should be present in the water column and where model projections indicated that the locations would either have high or low concentrations of larvae in the vicinity.
  - No bivalve larvae were collected at any of the locations during any of the sampling attempts.
  - The results of a lack of competent quahog larvae in the sample might suggest that the late-stage pre-metamorphic larvae are more closely associated with the substrate than previously thought or may be because of a failure to capture larvae with the existing sampling equipment.

References:

Arnold, W.S., G.L. Hitchcock, M.E. Frischer, R. Wanninkhof and Y.P. Sheng, 2005. Dispersal of an introduced larval cohort in a coastal lagoon. Limnol. Oceanogr. 50: 587-597.

Bayne, B. L. 1965. Growth and the delay of metamorphosis of the larvae of *Mytilus edulis* (L.). Ophelia 2(1): 1-47

Becker, D.S. 1978. Evaluation of a hard clam spawner transplant site using a dye tracer technique. *Special Report New York State University (SUNY)*, Feb. 1978. Stony Brook, NY. 42 pgs.

Bergondo, D.L. 2004. Examining the processes controlling water column variability in Narragansett Bay: Time series data and numerical modeling. *Doctoral dissertation*, Graduate School of Oceanography, University of Rhode Island, 136 pp.

Bergondo, D. and Kincaid, C. 2007. Development and Calibration of a Model for Tracking Dispersion of Water from Narragansett Bay Commission Facilities. *Narragansett Bay Commission Annual Report*.

Butet, N.A. 1997. Distribution of quahog larvae along a north-south transect in Narragansett Bay. *M.Sc. Thesis*, University of Rhode Island, South Kingston, RI. 85 pgs.

Butman, C.A. 1986. Larval settlement of soft-sediment invertebrates: some predictions based on an analysis of near-bottom velocity profiles. In: Nihoul, J.C.J. (ed.) Marine Interface Ecohydrodynamics. Elsevier, Amsterdam, 487-513

Butman, C.A., J.P. Grassle, and C.M. Webb. 1988. Substrate choices made by marine larvae settling in still water and in a flume flow. Nature, Lond. 333:771-773.

Davis, R. 1985. Drifter Observations of Coastal Surface Currents During CODE: The Method and Descriptive View. J.Geophys.Res.,90,4756-72.

Deshieneks, M.E., E.E. Hofmann, J.M. Klinck, And E.N. Powell. 1996. Modeling the vertical distribution of oyster larvae in response to environmental conditions. Mar. Ecol. Prog. Ser. 136:97-110.
Erskine, A.J., S. Snyder, M. Southworth, K. Hudson, J. Shen, and R. Mann. 2005. So how far do oyster larvae disperse? A dye study simulation. *J. Shellf. Res.* 24[2]:647.
Hitchcock, G.L., W.S. Arnold, M.E. Frischer, C. Kelble, and R.K. Cowen. 2008. Short-term dispersal of an intentionally-released patch of larval *Mercenaria* spp. in the Indian River Lagoon, Florida, USA. *Bull. Mar. Sci.* 82:41-57.
Hitchcock, G.L., W.S. Arnold, R, Wanninkhopf, M.E. Frischer, and P. Sheng. 2006. Lagrangian tracer studies of larval dispersal. *EOS Trans. Am. Geophys. Union.* 87(36):suppl.
Johnsson, P.R., C. Andre, and M. Lindegarth. 1991. Swimming behavior of marine bivalve larvae in a flume boundary-layer flow: evidence for near-bottom confinement. Mar. Ecol. Prog. Ser. 79:67-76.
Keough, M. J , Downes, B. J. (1982). Recruitment of marine invertebrates: the role of active larval choices and early mortality. Oecologia 54: 348-352
Kremer, J. N., J. M. P. Vaudrey, D. S. Ullman, D. L. Bergondo, N. LaSota, C. Kincaid, D. L. Codiga, and M. J. Brush, 2010. Simulating property exchange in estuarine ecosystem models at ecologically appropriate scales, *Ecological Modelling,* 221: 1080-1088.
Landers, W.S. 1954. Seasonal abundance of clam larvae in Rhode Island waters 1950-1952. *U.S. Fish and Wildlife Service Special Science Reports in Fisheries.* 117:1-29.
LaSota, N., D. Bergondo, and C. Kincaid. 2007. Observational and numerical experiments on the flushing of nutrients in the Providence River estuary. *ERF* Annual Meeting, Providence, Rhode Island.
Loosanoff, V. L., and H.C. Davis. 1950. Conditioning *Venus mercenaria* for spawning in winter and breeding its larvae in the laboratory. Biol. Bull. 93(1):60-65.
Lutz, R.A. 1985. Identification of bivalve larvae and postlarvae: a review of recent advances. *Am. Malacol. Bull.* 1:59-78.
Manning, J.H. and H.H. Whaley. 1954. Distribution of oyster larvae and spat in relation to some environmental factors in a tidal estuary. Proc. Nat. Shellf. Assoc. 45:56-65.
Mukai, A. Y., J. J. Westerink, R. A. Luettich Jr., and D. Mark. 2002. *Eastcoast 2001: A tidal constituent database for the western North Atlantic, Gulf of Mexico and Caribbean Sea,* U. S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Technical Report, ERDC/CHL TR-02-24, September 2002, 201 pp.
Parker, G.G., Jr. 1973. Tests of Rhodamine WT for toxicity to oysters and fish. J. *Res. U.S. Geol. Surv.* 1(4):499.
Pawlik, J.R., C.A. Butman, and V.R. Starczak. 1991. Hydrodynamic facilitation of gregarious settlement of a reefbuilding tube worm. Science 251: 421-424
Rice, M.A. and J. Goncalo. 1995. Results of a study of bivalve larval abundance in Greenwich Bay, Rhode Island. In; M.A. Rice and E. Gibbs (eds.) *Proceedings of the Third Rhode Island Shellfisheries Conference.* Rhode Island Sea Grant, Narragansett, RI. Pp. 31-40.
Rogers, J.M. 2008. Circulation and transport in the heart of Narragansett Bay. *M.Sc. Thesis*, University of Rhode Island. Graduate School of Oceanography, 95 pp.
Ruddick, B.R., C.T. Taggart, J. Feitcher, A.M. Szmant, and R.F. Whitehead. 2006. Particles are better than dye: Direct measurement of Lagrangian connectivity of coral larvae. *EOS Trans. Am. Geophys. Union.* 87(36):suppl.
Sullivan, B., and C. Kincaid (2001), Modeling circulation and transport in Narragansett Bay, *EOS Trans. Amer. Geophys. Union, 82*:S51.
Tiwari, S. *and S. Gallager.* 2003 *Machine learning and multiscale methods in the identification of bivalve larvae. In:* Proceedings of the Ninth IEEE International Conference on Computer Vision. *Vol. 2. IEEE Computer Society Press, Los Alamitos. pp.* 1–*8.*

Umlauf, L. and H. Burchard. 2003. A generic length-scale equation for geophysical turbulence models, *J. Mar. Res.*, 61:235-265.
Warner, J. C., C. R. Sherwood, H. G. Arango, and R. P. Signell. 2005. Performance of four turbulence closure models implemented using a generic length scale method, *Ocean Modelling,* 8:81-113.
Williams, S.M. 2006. The early larval dispersal of the long-spined sea urchin *Diadema antillarum* in La Parguera, Puerto Rico. *EOS Trans. Am. Geophys. Union.* 87(36):suppl.

Appendices: To be collated in a CD that will be provided the CFRF.

Objective 5 –Introduction:

In January 2013, Rhode Island Sea Grant and the URI Coastal Resources Center announced a collaborative program with RI Department of Environmental Management and the RI Coastal Resources Management Council to develop a state-wide Shellfish Management Plan (SMP). The overall purpose of the planning process is best described in the Vision Statement and Goals developed for the plan.

<u>SMP Vision</u>

The shellfish that inhabit our waters are part of the social fabric of Rhode Island and are integral components of the marine ecosystem that provide food, recreation, income, employment, and other environmental, economic, social, and cultural benefits. In order to ensure the health and proper ecological functioning of the marine ecosystem and realize the socio-economic benefits associated with healthy shellfish populations, we shall seek to preserve, protect, manage, and when necessary, restore shellfish resources and essential habitats using the best available information and science. We shall also strive to employ sound governance to achieve fair, equitable, and safe access to shellfish resources and support the interests of those who harvest for personal use and enjoyment; those who participate in the commercial wild harvest fishery; those who engage in the aquaculture of shellfish species; those who rely upon the shellfish industry as a source of food, and those who recognize the importance of shellfish in our marine ecosystems.

<u>SMP Goals</u>

1) Honor, promote and enhance the existing shellfish resource and uses. Shellfish offer a myriad of ecological services to Rhode Island state waters, jobs and business opportunities to its residents, and recreation for all. As such, actions should strive to maintain healthy populations of shellfish while honoring the current uses of Rhode Island's natural resources and promoting Rhode Island shellfish as a source of local, sustainable seafood.
2) Contribute to a properly functioning ecosystem that is both ecologically sound and economically beneficial. The prosperity of the shellfish industry depends on the health of our marine environment and the quality of the water that shellfish inhabit. It is therefore necessary to evaluate the current status and potential future changes to the natural resources, ecosystem conditions, and anthropogenic impacts on the marine environment and recommend actions to protect and, where necessary, restore our marine waters.
3) Manage marine and shellfish resources for equitable and sustainable use. Through both scientific research and practical knowledge, better understand the existing activities taking place in Rhode Island waters. Identify best management practices to support all shellfish activities for long-term sustainability while supporting compatible uses and minimizing user conflicts to ensure the equitable harvest of these marine resources.
4) Enhance communication and improve upon the established framework for coordinated decision making between state and federal management agencies, industry, and other interested parties. Engage management agencies, industry and other interested parties in the development of the shellfish management plan and implementation of recommendations to ensure that all concerns and appropriate legal requirements are integrated into the process. Coordination will allow for the sharing of information across all sectors, improve management, clearly establish roles and responsibilities of all parties and streamline the licensing and permitting process where appropriate.

As the SMP process has developed, stakeholder inputs along with agency concerns are being integrated into action items to be outlined in the plan. While not a "quahog-centric plan", a number of issues identified in the stakeholder process are directly relevant to the work being completed with this SNECRI Project. For example, some bulleted issues and comments collected during stakeholder meetings:

- Identify spawner sanctuaries based on environmental characteristics
    - Hydrodynamics – part of siting spawner sanctuaries
    - Incorporation of hydrodynamic information
- Stock assessments:
    - Shellfish stock assessment at a reasonable scalar level (research)
    - Industry-based surveys (stock assessments)
    - In 1990's, DEM made 3 different dredges, tested these, and did efficiency calculations. With opening of GB, turns out the CPUE was same as the total pounds calculated from the stock assessment/dredge work.
    - Have to show/explain the science continually
    - Feels that if fishermen report from small areas, this could give us enough resolution to manage – should run the independent and dependent data together and might find the same as in the 90's.
- Communication
    - Have to explain over and over throughout time why there are certain rules, i.e. direct marketing, harvest size, etc.
    - Our quahog fishery as an excellent example of co-management, an artisanal fishery, and a model for co-management; stakeholder input has always been at the forefront

Statement of research question or problem investigated:

As this project finishes, the information gained through this work can have a significant impact on the issues identified by stakeholders as well as by the resource managers of RI. We need to communicate the results of this project to the appropriate management agencies as well as the stakeholders and develop ways by which the details of this effort can be implemented into the on-going management strategy of the state.

Goals and Objectives of research project:

Apply the prediction of quahog larval sources and sinks to the development of a bay-wide quahog management plan currently under discussion within RI-DEM Marine Fisheries Division. (Note: While the integration of this information within RIDEM Marine Fisheries management program, as originally proposed, is the primary means to "use" the information generated by this research, it equally is important that the results of this work be included in the SMP process currently underway.)

Methodology:

With the validation of the ROMS model and a realistic estimate of the accuracy and precision of the model to predict quahog larval sinks based on observed or proposed larval sources, we will have the capability of performing a series of "what if" simulations to explore bay-wide quahog management. In collaboration with M. Gibson, J. Mercer and D. Erkan from RI-DEM Marine Fisheries and the Rhode Island Shellfishermen's Association (RISA), we have the capacity to investigate the impact of various management scenarios that may result in differing target densities and standing stocks of adult quahogs in specific sub-populations across the upper bay. Application of this information can significantly contribute to such management decisions as siting of spawning sanctuaries; optimal locations for the placement of relayed adult quahogs; appropriate placement of quahog seed from the RISA quahog enhancement project; harvest management strategies to control standing stock and spawning density, such as rotational closures; and other management decision scenarios as suggested by Marine Fisheries.

Stock assessment has repeatedly been identified by SMP stakeholders along with managers and researchers as a critical tool for shellfish resource management. At the present time, quahog stock assessment is limited by economics (time and effort from RIDEM) and technology (access to locations and equipment reliability). With the proof that a bullrake in the hands of a commercial quahogger is an effective stock assessment tool, we have expanded the capacity of the industry to work with the resource managers to gain better coverage of RI's quahog areas in terms of measuring standing stock and quantifying fishing impacts on stocks. In the short-term we have proposed to RIDEM Marine Fisheries that commercial quahoggers be allowed to participate in the annual quahog stock assessment process, potentially assaying areas that are inaccessible to the RIDEM hydraulic dredge. In the long-term, we foresee the development of a research fleet of commercial quahoggers who will be responsible for significant portions of the annual stock assessment program in RI.

Analysis techniques:

Results:

The application of the ROMS model for predicting sources and sinks of quahog larvae has provided some interesting information regarding the efficacy of spawning sanctuaries and the role of prohibited areas in provided quahog seed to NBay, (this study as well as the URI PhD Dissertation of Jeff Mercer). These data are currently being shared with RIDEM Marine Fisheries and will provide information to justify recommendations in the upcoming RI SMP. To continue the development of the ROMS model and its application in investigating quahog larval dynamics in NBay, RWU, URI and RIDEM Marine Fisheries have partnered to undertake a RI Sea Grant Project (funded to start in March 2014) that will collect more data for refining the ROMs model and to develop more year-specific data sets (2013/2014) for running the model simulations. These will then be used to broaden our understanding of the role that environmental conditions as well as sources of quahog larvae play in supplying NBay with this important resource.

In preliminary discussions with RIDEM Marine Fisheries, there is a willingness to use commercial bullrakers for augmenting their stock assessment program during the summer of 2014. Discussions and activities are under way for continuing to validate the bullrake assessment program and to explore ways to integrate the commercial quahoggers into the state program. We anticipate a limited interaction this summer (2014) to permit RIDEM to become comfortable with the process and to demonstrate the value of this highly skilled work fleet to assist in generating data for quahog management.

Discussion:

Two specific and significant outcomes were generated by this research. The first was the development of a predictive model of quahog sources and sinks in the upper NBay that will provide valuable information to the development of a bay-wide quahog management strategy currently being considered by RI-DEM Marine Fisheries. These benefits from the proposed research are clearly articulated in the narrative above.

The second outcome is more subtle but, possibly, more important than the first and that is the development of a higher level of communication of and involvement in quahog management by the commercial fishing sector in NBay. The commercial fishing sector will be participating in this project by performing stock assessments of quahog sub-populations, validated through an assessment intercalibration between the standard Marine Fisheries method and techniques commonly employed by commercial fishermen. We anticipate that by demonstrating the validity and comparability of using common shellfish harvest methods to conduct a fishing independent assessment, RI-DEM will look to expand their annual stock assessment efforts by recruiting fishermen to assist. We envision the potential for the development of a collaborative assessment program, designed annually by Marine Fisheries biologists while being managed and completed by commercial shellfishermen, either as a fee for service relationship or possibly linked with the licensing process as a community service requirement.

The fishermen will also be a part of the research effort through their involvement in the field collection of information for the project. We will use them to monitor the integrity of the surface drifters as they travel across the bay and to assist in the collection of samples to detect the presence of quahog larvae. They will be continually updated on the progress of the project through Leavitt's attendance at RISA meetings as well as through their active participation. We intend for this project to provide the commercial shellfishing sector with an additional voice in the development of a bay-wide management through their participation in this project.

Summary of conclusions:

- The current information generated by the ROMS model on sources and sinks of quahog larvae is being utilized by RIDEM to improve on their quahog management strategies.
- Funding has been secured to continue improvement of the model with direct application to management of quahog fisheries in the state.
- Discussions currently are underway with RIDEM Marine Fisheries as to how and when a commercial quahogger research fleet can be utilized to assist in the annual quahog stock assessment program.
- The information generated by this study is being integrated in to the RI Shellfish Management Plan through the actions of all of the PIs on the project.

References:

Appendices: To be collated in a CD that will be provided the CFRF.

Responses to Reviewer's Comments:

The authors thank the two reviewers who offered insightful comments for improving the Final Report. Specific comments that required clarification in the body of the text have been incorporated into the text as suggested. In addition, there were a number of comments that could not be easily addressed in the body of the report and these comments have been summarized and responded to in the following addendum. Where possible, specific comments that addressed a similar issue were grouped to facilitate responding to those comments.

Introduction:

Page 8: Following the decline from 1979 to 1995, due to overfishing, the implementation of "precautionary management" by the RI-DEM Marine Fisheries Division resulted in the stabilization of the standing biomass at a level substantially below that needed to provide a sustainable yield (BMSY). (*Reviewer 2 comment*: This may not be a good metric for hard clam populations because the most valuable individuals are not the largest. With this price structure in place, biomass can remain high while smaller size classes are depleted and thus population replacement can be substantially reduced while biomass remains high. In addition, there is evidence that the largest sizes (greatest biomass) do not necessarily yield the greatest numbers of gametes. Is there any information on the numbers of individuals by the major market sizes (littleneck, cherrystone and chowder) being landed?)
Response: The authors agree that information on the size frequency distribution of the quahog population in NarBay is an important consideration from both an economic and a fecundity standpoint. The recent work of Mercer (2013) has started to compile the size class information that has been routinely collected through DEM-Marine Fisheries surveys but this information has not been entered into management considerations at this point in time (to my knowledge).

Page 8: The recent increase in landings may originate from management restrictions, including implementation of possession limits and seasons, reduction of fishable areas due to pollution closures, limited number of licenses available and reduction in the number of participants (RIDEM 2009). (*Reviewer 2 comment:* If this is "may" then there is a need to make some analysis (collect data?) on which if any of these is responsible for the recovery. Perhaps a portion could be ascribed to each.)
Response: We agree that trying to identify what factors are responsible for the ups and downs of quahog populations in NarBay is an important analysis but that is beyond the scope of the current study to address this statement.

Objective 1: Compile past and current quahog standing stock resource assessments from published and grey literature and from surveys by RI-DEM Marine Fisheries for upper Narragansett Bay (NBay) to indicate potential areas for spawning activity

(*Reviewer 1 comment:* Objective 1 was carried out by project partner RIDEM, instead of the lead PI. This seems like a minor detail as the work was still completed and results integrated into subsequent objectives.)
Page 10: As this project was launching in 2011, RI-DEM Marine Fisheries restructured their Shellfish Team and added a new staff member, Jeff Mercer. One of Mr. Mercer's primary responsibilities was to oversee the operations of the shellfish stock assessment program. Mr. Mercer also understood the necessity of compiling the existing stock assessment data as his logical starting point to managing the quahog fishery, as we had proposed. With that in mind, Mr. Mercer undertook the same series of analyses that we suggested. Some of his information was included in the introduction to this section of the report and was presented as a component to the 12th Annual Baird Symposium on "The Future of

Shellfish in Rhode Island" held on 14-15 November 2013. Rather than duplicate Mr. Mercer's efforts, we selected to defer this aspect of the project to his work such that we could focus our efforts on expanding the data collection aspects to the proposed research.
(*Reviewer 2 comment:* Compilation of past information was to be a significant part of the analysis. Without this information it is hard to place the current data in a context. This is a significant omission from the report and efforts should be undertaken to have RIDEM or another group finish this work within the year). Judging from the list above, one has the impression that there is no one time when the entire bay was surveyed. How the distribution of the stock plays into the assessment of the larval distribution data is therefore difficult to assess. If the adult distribution was substantially different, would the spawning time, recruit per adult, or other parameters be different?)
Response: While compilation of the existing data was proposed in the current project to provide a historical context to the work to be completed, it was not necessary to complete the objectives as presented (other than Objective 1). In the long-term, these data will aid in the overall management planning by RIDEM Marine Fisheries, which is why the RIDEM Biologist (Mercer) initiated this work within the management infrastructure. It was unnecessary for the SNECRI Project to duplicate Mercer's efforts to compile the stock assessment information that exists. Our selection of study sites was assisted by the fishermen themselves, who had a much more complete understanding of the current distribution of quahogs in NarBay than anyone else at the time of initiation of the study. Finally, yes, distribution of adults will significantly affect the reproductive efforts of the population and we are continuing the work of Marroquin-Mora and Rice. (2008) to investigate some of those effects through the Master's research of Griffin, to be completed in fall of 2014 and partially supported by this SNECRI Project.

Objective 2: Develop a cooperative assessment of quahog standing stock and reproductive condition in the upper NBay with commercial fishermen, including conduct side-by-side quahog stock assessments comparing the efficacy of the RI DEM's standard method (hydraulic dredge) with the commercial bullrake and diver quadrat sampling

NOTE: Objective 2 in this study will not be completed until 1 July 2014. Therefore, many of the questions generated by the reviewers of this interim Final Report cannot be answered at this point but will be addressed when the final version is submitted to CFRF in July.

Page 13: Fishery independent data are an important contributor to the development of a fishery management plan and a primary source of these data are research-based stock assessments (Gulland 1983, Cooper 2006). As a biological reference point, a shellfish stock assessment provides information on the spatial distribution of the existing biomass along with the age/size-class distribution and, when compared over time, an estimate of fishing mortality, changes to the age/size class distribution and recruitment in the stock (Cooper 2006). In total, stock assessments are critical to the proper management of the commercial fishery.
(*Reviewer 2 comment:* It is equally important to monitor size specific natural mortality rates (at least of the adults) – this is often the weak point in establishing the dynamics of the population.)
(Reviewer 2 comment: It looks like no consideration was given to compiling data on the numbers of double valve dead clams (boxes) to calibrate the dredge against the bullrake. Calibration should also be done to compare the "catchability" of boxes and live clams, because these may not be the same. While no studies of what boxes of clams actually mean relative to mortality (information is needed on how long they last in various types of sediment and under different temperature conditions), they do provide a measure of mortality. This can be more important than recruitment if mortality rates are high.
(*Reviewer 2 comment:* In addition, any information on numbers and sizes of dead paired valves should be included.)

Response: We agree that natural mortality is an important factor in describing the dynamics of a population; however, that was beyond the scope of the current study.
Response: While measuring boxes has been utilized to look at natural mortality in oyster populations, the mechanics of clam harvesting precludes the use of boxes as a tool to describe *in situ* mortality. Through the mechanical action of the bullrake or the hydraulic dredge, quahog boxes are often disarticulated as they are extracted from the substrate with the half valves potentially falling through the grates of the bullrake or dredge basket. Therefore, boxes are not a reliable means to describe *in situ* mortality in quahogs retrieved by fishing activity.

Page 13: Therefore, a mechanism that provides fishermen with the opportunity to participate in the stock assessment process would be an important factor in opening lines of communication and trust between the regulatory agency and the fishing fleet in addition to augmenting the annual stock assessment data currently collected by RIDEM.
(*Reviewer 2 comment:* There should be a basic survey that is conducted annually – special studies can be incorporated as time and $ permit. The basic survey should provide the minimal information about the stock (numbers of individuals by size, a measure of recruitment, a measure of size specific natural mortality, a measure of the size specific removals by the fishery) in various areas of the bay. Without this information on a regular basis, the extra funds expended on special studies have much less value
(*Reviewer 2 comment:* An alternative would be to have an independent third party do the survey. That way both RIDEM and the industry could criticize and suggest improvements.)
Response: The reviewer is correct in concluding (based on earlier introductory comments) that there has not been a bay-wide quahog survey completed in a long time (if ever). However, based on a stratified sampling protocol, RIDEM annually has been surveying the most important quahog areas in NarBay since 1984. These yearly surveys have been inconsistent in recent years due to equipment failures. Also, the surveys only target market-size quahogs and do not take into consideration any measure of recruitment into the population or natural mortality.
Response: Agreed that a third party would provide an impartial assessment (i.e. no vested interests); however, the cost of running such a program needs to be carefully considered. Also, this may result in neither group accepting the results of the assessment, whereas having both RIDEM and the fishermen involved with all aspects of the assessment process provides a more secure footing for both parties to accept the results of the efforts.

Page 14: To measure the density and size/age class distribution of a stock of infaunal bivalves, a tool to quantitatively extract the bivalves from a known area of substrate must be developed. With the hydraulic dredge, the width is described as 0.36 m and it is towed a distance of 30.5 m, resulting in an area sampled of 10.98 m^2 (Gibson 2013).
(Reviewer 2 comments: tooth or blade length?, bar or mesh size in the collecting bag?)
Response: Information on the details of the RIDEM hydraulic dredge will be provided in the updated Final report in July 2014.

Page 15: Initially, we proposed to conduct Condition Index (CI) measurements on quahogs sampled during the stock assessment collections. However, as we advanced in the program, we realized that by collecting repeated samples from the same location(s), it would afford us a better understanding of the reproductive effort and seasonal timing of quahogs in NBay.
(*Reviewer 2 comment:* Does this mean there is a lot of variability in the gonadal development from site to site?)
Response: Based on the work of Marroquin-Mora and Rice. (2008) there does appear to be a large amount of variability in reproductive effort of quahogs from different areas of the bay. This is currently being investigated more closely by Griffin with his Master's thesis, where he is looking at

stage of gonad development alongside condition index to describe the variability in both reproductive and condition index cycling within NarBay.

Page 15: Table 2-1 and Figure 2-3: Locations of the ten Condition Index sampling sites.
(*Reviewer 2 comment:* for this table it would be nice to have the number of samples, Also the units need to be included on the table or in the legend.)
Response: This information will be included in the table when submitted with the upgraded Final Report in July 2014.

Page 16: The wet weight of the soft tissue and shell were measured to the nearest 0.1 mg and the tissues were then dried at 60^{o}C for 48 hours and reweighed.
(*Reviewer 2 comment:* are they sure that 48 hours is enough to completely dry the tissue of the largest clams?)
Response: A few references for using 60^{o}C for 48 hours for drying bivalve soft tissue when calculating condition indices:

Ansell, A.D., F.A. Loosmore and K.F.Lander. 1964. Studies on the hard-shell clam, *Venus mercenaria*, in British waters. II. Seasonal cycle in condition and biochemical composition. J. Appl. Ecol. 1(1):83-95. (60^{o}C for 48 hours)

Lawrence, D.R. and G.I Scott. 1982, The determination and use of condition index of oysters. Estuaries. 5(1):23-27. (68^{o}C for 48 hours)

Steele, S. and M.F. Mulcahey. 2001. Impact of the copepod *Mytilicola orientalis* on the Pacific oyster *Crassostrea gigas* in Ireland. Dis. Aquat. Org. 47:145-149. (60^{o}C for 48 hours)

Mercado-Silva. N. 2005. Condition index of the Eastern Oyster, *Crassostrea virginica* (Gmelin, 1791) in Sapelo Island Georgia--effects of site, position on bed and pea crab parasitism. J Shellf. Res. 24(1):121-126. (60^{o}C for 48 hours)

Page 18: Using four different commercial quahoggers, we sampled hard and soft substrate types to measure the ability of the bullrake to catch quahogs (Table 2-5). **All bullrake assessments were collected when the water temperature was above 12^{o}C (between 1 May and 1 November).** The overall average catch efficiency (minus the disrupted sampling events, noted in comments section) was 90.8% (SD $\pm$ 7.9%) of the total quahogs in the transect path, with the efficiency being a little higher on mud substrate (93.5%) compared to sand substrate (89.3%).
(*Reviewer 2 comment:* It would be nice to know the dates of the samples. I presume these were done in warmer months when the bay bottom is appreciably softer than in the late winter. Water temperature – if available would also be nice to have.)
Response: The report text was modified to provide the range of dates and the minimum temperature under which samples were collected (highlighted in bold). I have bottom water temperature for a monitoring buoy in the upper NarBay that could be included if requested and this can be added during the July 2014 report resubmission.

Page 18: Test the ability of a calibrated bullrake to quantitatively sample quahog density in the field (Table 2-6).
(*Reviewer 2 comment:* What size clam was retained (not retained)?)
Response: The average minimum sized clam caught with the bullrake was 48.0 mm ($\pm$9.2 - SD) valve length while the smallest quahog caught in the bullrake was 29.9 mm. The average minimum size quahog missed by the bullrake was 51.1 mm ($\pm$16.7) with the smallest missed being 21.0 mm. In the diver-sampled quadrat, the average minimum size was 41.4 mm ($\pm$15.9) with the smallest recovered being 16.3 mm.

Page 18: The bullrake sample estimated the average density measured at thirteen sites to be 7.22 quahogs/m^2 (SD $\pm$ 4.45) compared to the diver quadrat estimate of 6.63 quahogs/m^2 (SD $\pm$ 2.58). Resulting in a difference of 0.59 quahogs/m^2 (SD $\pm$ 2.99). There was a small and insignificant difference in the quahogger's ability to sample on different substrate types (mean difference of 1.91 quahogs/m^2 (SD $\pm$ 2.97) on sand and -0.95 quahogs/m^2 (SD $\pm$ 2.38) compared to the diver quadrats.
(*Reviewer 2 comment:* Are any of these significantly different?)
Page 20: On very soft substrate (near Sally's Rock), the dredge measured an adjusted sample density of 1.11 quahogs per m^2, compared to the bullrake adjusted measured density of 1.99 quahogs per m^2 (SD $\pm$ 1.07) (Table 2-7).
(*Reviewer 2 comment:* so are these different?)
Response: These data and more will be statistically analyzed at the end of the project in July 2014.

Reviewer 2: Page 22: It has been 20 years since catch efficiency was last assessed on the RIDEM hydraulic dredge and there have been changes made to the dredge, suggesting that it should be recalibrated in the near future with a defined protocol for testing the catch efficiency on a regular basis in the future.
(*Reviewer 2 comment:* I agree with this statement – and it should be tested on different bottom types in different areas of the bay. This is expensive, but doing a little each year or every other year would mitigate the costs.)
Response: No response necessary other than this recommendation will be included in the upcoming RI Shellfish Management Plan, to be published in November 2014.

Page 23: Therefore, using the diver collected quadrat may not be the best baseline for comparison unless one samples as many quadrats as surface area covered by the bullrake. Often, this is not practical from a time and effort standpoint.
(*Reviewer 2 comment:* Another possible calibration would be with a hydraulic patent tong).
Response: Agreed, the hydraulic patent tong has been used in the past to survey quahog populations in NarBay. However, chartering a boat that is large enough to handle patent tongs may be cost prohibitive. If RIDEM should consider contracting the annual quahog dredge survey to a third party then this may be an option for efficient sampling of the population.

Page 20: Determine the size/age frequency distribution of quahogs sampled (Figure 2-8): At each site, it is possible to construct a size-frequency histogram that describes the population characteristics of that site. The data in Figure 2-8 represent the quahog population sampled at an Allen's Harbor location, where the size classes have been separated into the commonly used market designations of Littleneck (49-61 mm length), Cherrystone (61-95 mm), Chowder (>95 mm), and Sub-legal (<49 mm).
(*Reviewer 2 comment:* Are all the data going to be appended to the report?)
Page 23: Although not investigated in detail because we do not have the size distribution data from RIDEM from their sampling and also because of time constraints, the bullrake stock assessment provides the same capacity for characterizing the size/age class distribution at specific sites as the information generated by the dredge. These data provide a tool to look at the stock structure of local populations to measure impact of fishing pressure (e.g. Rice *et al.* 1989), to expand our knowledge of reproductive potential (Peterson 1983), to assign economic value to the resource (Kraeuter *et al.* 2008) or for a number of other applications.
(*Reviewer 2 comment:* The data should be included in an appendix.)
Response: All data collected during this research project will be provided to CFRF at the end of the project, in July 2014.

Reviewer 2: Page 22: As a component to the conclusion of this study, this spring we propose to test a suite of handheld GPS units available to the investigators to see if they can approach the level of

accuracy demonstrated with the dGPS, following a protocol similar to what has been employed in the current study.
(*Reviewer 2 comment:* The authors should provide a written protocol so any subsequent use of GPS and bullrakes is standardized)
(*Reviewer 2 comment:* If the bullrake technique is to be used the authors should develop a sheet describing how to do the calibrations, what information is required etc.)
Response: A final report on Objective 2 will be completed in July 2014, as this portion of the study has been extended to that point. This will include a detailed manual on how to conduct a bullrake stock assessment for future training of fishermen for participation.

Objective 3: Through the application of the Regional Ocean Modeling System (ROMS) Hydrodynamic Model for NBay, simulate specific quahog larval release points (spawning areas) based on stock assessments (derived from Objectives 1 & 2) and predict sites of juvenile recruitment resulting from these releases

Page 35: Figure 3-4. Number of particles as a function of position within the Bay 10 days after release from the Providence River site for 2006 (left) and 2007 (right). The white dot indicates the release location.
(*reviewer 2 comment:* On the figure below you provide an estimate of the % lost from the bay. Why not for this figure as well?)
Response: The figure will be corrected with % lost from the bay with the revised final report available in July 2014.

Objective 4: Using the results of the model, validate predicted larval settlement sites through a combined effort of surface drifter deployments and monitoring for the occurrence of quahog larvae, identified with a polarized laser video plankton sampler (LIHDaT),

(*Reviewer 1 comment:* Objective 4 failed to produce expected results. No larvae were collected during field sampling, despite deployment a plankton pump sampler. Pump failure and apparatus problems were experienced in the beginning and then the sampling effort was abandoned after one weak due to lack of larvae collected. The pump was utilized during a time when larvae should be present in high concentration from model predictions. The PI suggests that larvae may be more closely associated with the substrate than previously thought. This failure to produce actual observations of larvae has implications for the utility of the drifter and particle model predictions. Further confidence would be gained in using the ROMs model for management if larvae had been observed in the same tracks or pathways as the model predicted. However, scientific failures often lead to next steps. The PIs have identified a future research objective in their failure to capture larvae where expected.)
(*Reviewer 1 comment:* As mentioned earlier, one improvement would have been to attempt other larvae sampling methods instead of abandoning sampling altogether. I also understand the project limitations (money, resources, time) may have prevented the team from finding an alternative solution and perhaps this task warrants additional funding in the future.)
Page 45-46: The larval sampling program initiated on 31 July 2013, after a few false starts due to pump failure and apparatus problems. Samples were collected every two - three days for a little more than a week (Table 4-4) and were inspected quickly following each sampling interval. The sampling program was abandoned after one week due to a lack of bivalve larvae in any of the samples collected up to that point.
(Reviewer 2 comment: Why wasn't a plankton net attempted to see if it was an equipment issue or simply a timing issue?)

Page 50: Microscopic analysis of the plankton samples revealed a wide variety of larval stages of other marine invertebrates, indicating that the dearth of bivalve larvae was a real phenomenon rather than a failure of the equipment or protocol to collect larvae.
(*Reviewer 2 comment:* See note above about the plankton net.
Response: Both reviewers are correct in that we should have been more diligent in completing this objective. A plankton net sampling protocol in addition to the plankton pump would have contributed much valuable information as to why no bivalve larvae were retrieved 0.5 meters above the sediment surface with the plankton pump. Unfortunately, at the time, we did not consider this option and therefore missed the opportunity to further understand the failure of the pump to collect larvae.

Page 34: Rome Point, the release site closest to the Bay mouth, is not surprisingly a poor site from the standpoint of larval retention. A small number of particles remain within the lower East and West Passages after 10 days, but most particles escape the Bay. The percentage of particles lost to the coastal ocean is 95% in 2006 and 96% in 2007.
(*Reviewer 2 comment:* so for this site the timing of spawning relative to the flood and ebb cycle and the spring and neap cycle could be important in increasing or decreasing the retention.)
Response: This reviewer is correct in suggesting that the tidal cycling will play an important role in affecting larval dispersal and retention in the bay. Their suggestion has been corroborated to some degree by the drifter releases in the Spawning Sanctuary at the entrance to Greenwich Bay, where drifter (i.e. larval) retention in Greenwich Bay was highly dependent on the tidal stage when the release was implemented. While further exploration of this phenomenon was not possible with the current CFRF study, the PIs have acquired additional funding to continue this aspect of the study through the RI Sea Grant Program.

Page 37: When larvae exhibit swimming behavior, they tend to be found closer to the surface than when larvae are passive (even though the larvae are released at the surface, with no behavior they tend to be mixed downwards by turbulent diffusion). Larvae near the surface tend to be advected southwards in the estuarine circulation, thus more larvae near the surface results in greater export of larvae from the Bay.
(*Reviewer 2 comment:* What would happen if the larvae are swimming upward only a portion of the time (i.e. – no preference at night?)
Response: While we have not had the opportunity to incorporate extensive larval swimming behavior in the ROMS modeling effort during this study, these and other larval behaviors will be tested with the upcoming extension of the study through the recently funded RI Sea Grant Project.

Objective 5: Apply the prediction of quahog larval sources and sinks to the development of a bay-wide quahog management plan currently under discussion within RI-DEM Marine Fisheries Division.

No comments were provided.