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Retention of Winter Flounder Larvae within a Rhode Island Salt Pond[1]

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ABSTRACT: Two winter flounder, *Pseudopleuronectes americanus*, spawning sites in a 630 hectare Rhode Island lagoon were located by collecting eggs with a modified epibenthic sled towed by boat. A two-dimensional vertically-averaged hydrodynamic model predicted that larvae hatched at these spawning sites would be minimally displaced by tidal movement. Ichthyoplankton samples taken hourly during the day at six locations on March 27 and April 27, 1981 reflected the larval distribution predicted by the model. Larval retention within this lagoon appeared to be strongly influenced by the hydrodynamics of this system. It is suggested that the hydrodynamic features of lagoons are exploited in the reproductive strategies of estuarine species and that the relationship between hydrodynamics and the quality of nursery habitat must be considered before making hydraulic modifications to these systems.

Introduction

The winter flounder, *Pseudopleuronectes americanus,* is an unusual flatfish in that it lays demersal eggs rather than the buoyant type produced by most pleuronectids. Pearcy (1962b) postulated on the adaptive significance of demersal winter flounder eggs. Noting that since the inshore population of this species spawns in brackish, estuarine shallows, demersal eggs would be advantageous in an environment where nearshore currents would quickly disperse more buoyant eggs. He also noted that winter flounder spawn in the winter when these shallows are often frozen and demersal eggs are less likely to be damaged by ice. The bottom water during this time is also well oxygenated and less subject to changes in salinity.

However, for an animal which spawns in a system with net seaward transport and which depends on long estuarine residence time for larval development, winter flounder larvae appear vulnerable indeed. They are negatively buoyant and swim feebly for the first week or more depending on the temperature (MacPhee, personal communication). Unlike herring larvae which have been demonstrated to orient toward and successfully swim against a current (Bishai 1959) and have been observed to use their swimming ability to maintain their presence within an estuary (Graham 1972), young winter flounder larvae are only able to adjust their position vertically in the water column. In a two-layered density current system typical of deeper estuaries, this behavior may exploit the diminished seaward transport of the deeper saline layer since these larvae spend an increasing amount of time near the bottom as they grow (Pearcy 1962a). Development of this species to metamorphosis may take more than six

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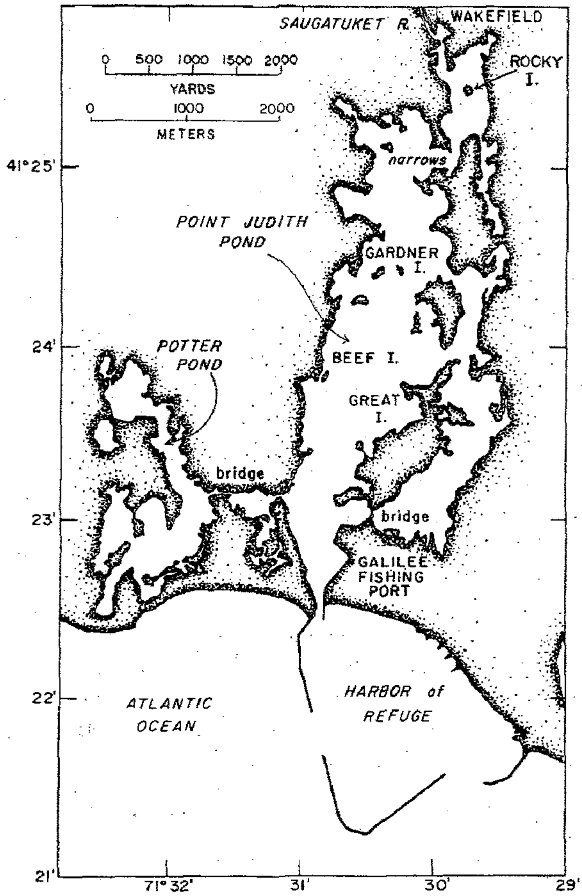

Fig. 1. Point Judith Pond, Rhode Island lagoon study site.

weeks and Pearcy has suggested this larval behavior contributes to the long estuarine residence time of these animals. In this paper we present evidence that the hydrodynamics of an estuary may also play an important role in retaining these larvae in a lagoon.

Winter flounder is the most abundant demersal fish in Rhode Island coastal waters (Jeffries and Johnson 1974) and sustains important fisheries in Narragansett Bay and several lagoons or salt ponds along the southwestern shore. This species has been the subject of various local investigations (Berry et al. 1965; Grove 1982; Worobec 1982; Mulkana 1966; Oviatt and Nixon 1973; Perlmutter 1947; Rogers 1976; Rogers et al. 1979; Saila 1961, 1962a, 1962b; Saila et al 1965; Stolgitis et al. 1976; and others) and was a focus of attention during a recently concluded four-year multidisciplinary study of five salt ponds by the University of Rhode Island.

During the course of this larger study, plankton tows in March of each year revealed a high abundance of winter flounder larvae near the narrows of Point Judith Pond (Fig. 1). By April, large numbers of the moon jelly, *Aurelia aurata,* would often be seen throughout the basin immediately below the Narrows, sometimes so dense that the water appeared "milky" from the color of their protoplasm. It was difficult to collect fish larvae when medusae were so abundant. Above the Narrows, jellies were also common but less numerous. However, the salinity in this northern-most basin was apparently less favorable since the manubrium of jellies there was often torn and fragmented and carcasses were common. Winter flounder larvae and moon jellies were never as abundant in the lower portions of Point Judith Pond.

Although a systematic plankton survey was not carried out during this time, repeated observations of the jellyfish distribution gradient begged the question as to what mechanism led to the retention of such large numbers of plankters in a basin which had tidal flow sufficient to create small wakes from anchored navigation buoys. These jellies, like winter flounder larvae, are not strong swimmers although they too can adjust their position in the water column. We surmised that the mechanism retaining such large numbers of jellies near the Narrows may also act to retain winter flounder larvae.

A two-dimensional vertically-averaged hydrodynamic model of Point Judith Pond had been developed as part of the larger multidisciplinary study (Licata 1981; Isaji et al. 1985). This model suggested that retention of plankters may be explained by a decrease in current velocity along a transect away from the inlet. This hypothesis was tested by modelling the effects of water movements on batches of non-swimming "particles" affected by diffusion and river transport near identified winter flounder spawning grounds. We then compared the results of the computer simulation with field observations of larvae abundance patterns. Our interpretation of the distribution of lar-

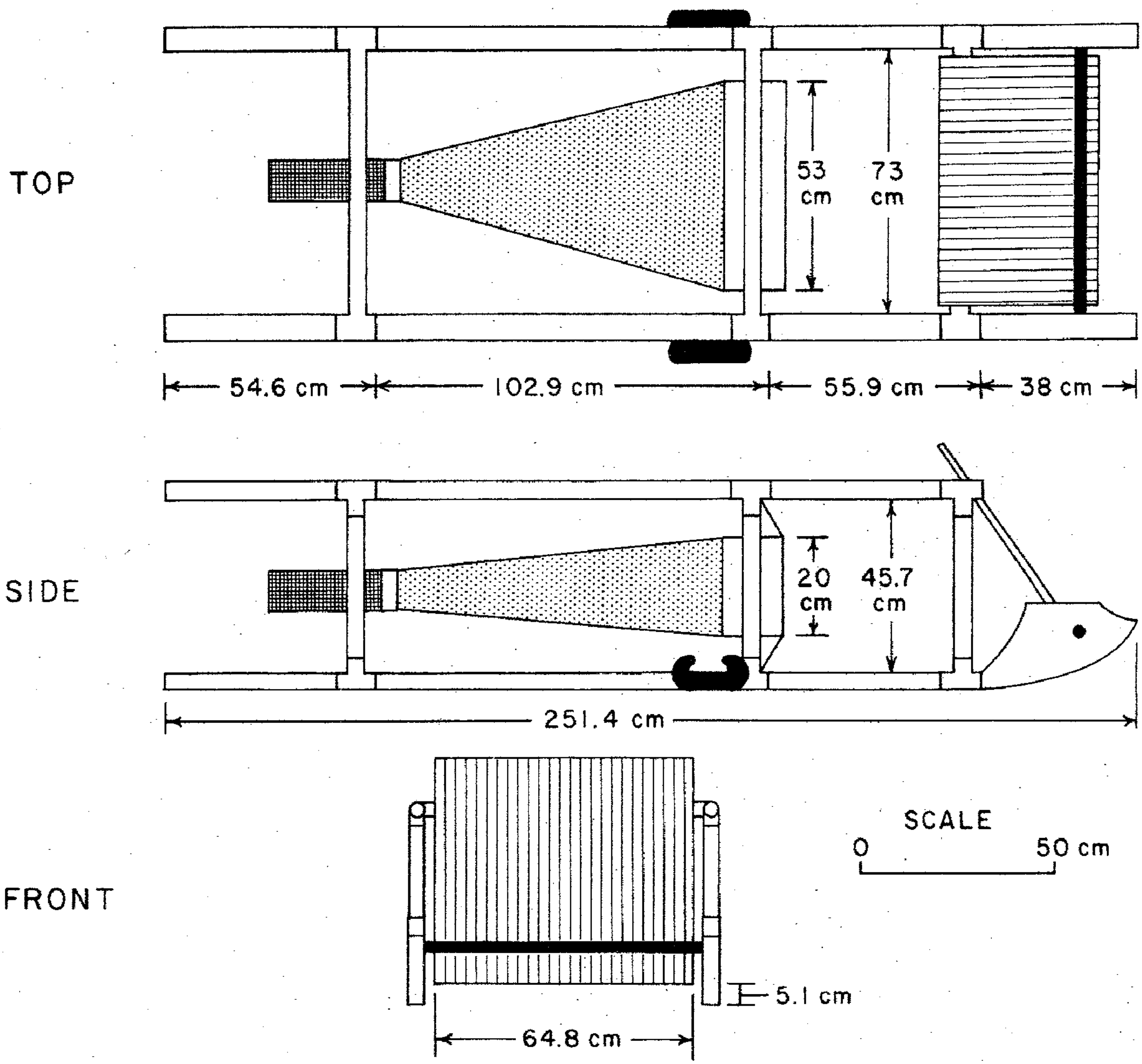

Fig. 2. Epibenthic sled with 505 micron plankton net mounted for collecting demersal fish eggs. Sled depicted was constructed of PVC pipe and fittings. A second generation sled of 37 mm aluminum angle is superior.

vae during a tidal cycle is presented and the role hydrodynamics may play on the retention of larvae within this coastal pond is discussed.

Materials and Methods

Identification of Spawning Grounds

An epibenthic sled for collecting demersal fish eggs was adapted from the design of Yocum and Tesar (1980). Our sled (Fig. 2) differed in that we added a depressor vane to the front and provided for 5 cm clearance between it and the substrate. As the sled was towed through the water, turbulence behind the depressor vane swept eggs off the bottom up to the level of the sampling net. This allowed us to survey many different bottom types including soft, fine sediments without quickly clogging the 0.505 mm mesh net.

During earlier work in this estuary we became familiar with the distribution of the various types of bottom. The sled was towed in various areas, especially where firm substrate and pelagic algae were known to occur (Fig. 3) since these are characteristic of winter flounder spawning habitats (Bigelow and Schroeder 1953). Sampling was conducted weekly throughout the month of March. Each time an area was sampled approxi-

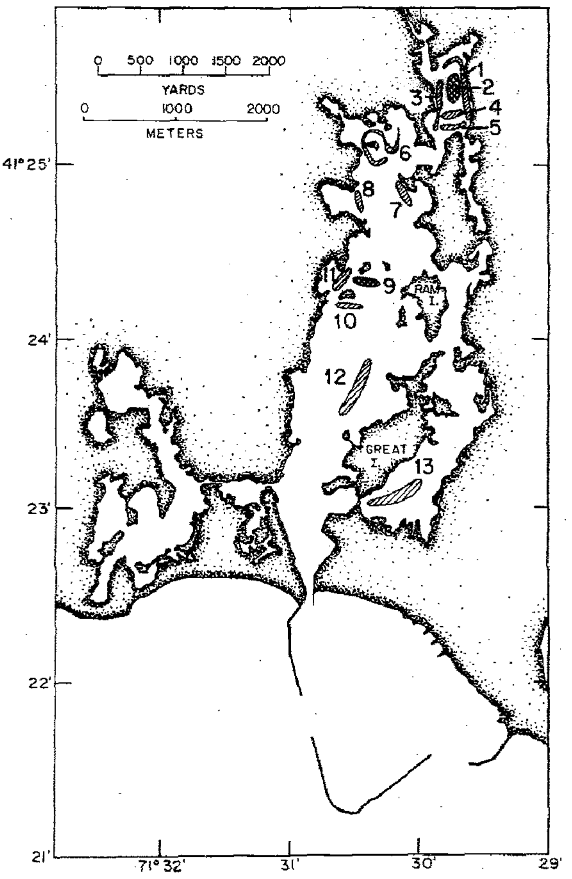

Fig. 3. Sites sampled in Point Judith Pond lagoon for winter flounder eggs. Eggs were found at areas 2 and 9.

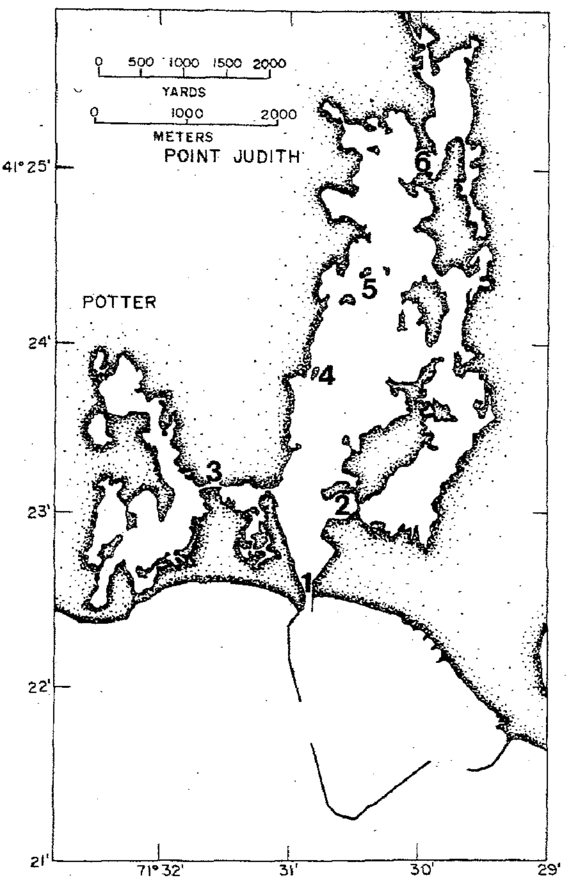

Fig. 4. Locations within Point Judith Pond lagoon where winter flounder larvae were sampled. Refer to text for details.

mately five tows were made. Water temperature at the commencement of sampling was approximately 3 °C, suitable for initiating spawning (Rogers 1976). Tow duration was typically 5 to 10 min at approximately one knot tow speed. Contents of the net were rinsed into the cod end, fixed in 5% formalin and sea water buffered with sodium tetraborate (Richards and Berry 1973), and returned to the laboratory for examination. When eggs were found, that area was subsequently more intensively sampled for further verification.

Sampling Larvae

Six sampling stations were occupied during the daylight hours of 27 March and 27 April 1981 (Fig. 4). Station 1, at the mouth of the inlet, was occupied by a boat towing a 0.5 m^2 plankton trawl. Stations 2 and 3 were each occupied by separate teams who operated 0.35 m^2 trawls from bridges at the respective sites. Stations 4, 5, and 6 were sampled by a skiff towing a 0.35 m^2 trawl and travelled between the three stations at the designated sampling times. All plankton nets were 0.425 mm mesh of the bridleless Tucker-type trawl design and flow meters were mounted in the mouth of each net to provide for quantification of the samples. Extrusion and escapement of flounder larvae through this size mesh was considered negligible (T. McKenny, personal communication).

Sampling commenced at dawn, which was near the time of low tide at station 1 on each date, and continued hourly so that a complete flood and ebb cycle during daylight hours was sampled. At stations 1, 2, and 3, duplicate oblique samples were taken and larvae were fixed in buffered formalin. At stations 4, 5, and 6 single oblique samples were taken. Salinity and temperature were also recorded hourly at each station.

Sampling was limited to daylight hours due to constraints imposed by available equipment.

In the laboratory winter flounder larvae were counted, measured, and their stage of development categorized according to Laroche (1981) as follows:

Stage 1—yolk sac larva = prior to absorption of yolk material (2.4–3.8 mm)
Stage 2—preflexion larva = prior to notochord flexion and gut beginning to loop (3.9–4.9 mm)
Stage 3—flexion larva = notochord undergoing flexion and urostyle beginning to slant upwards, caudal fin forming (5.0–7.4 mm)
Stage 4—transforming larva = onset of migration of left eye to right side, caudal, dorsal, and anal fin development, benthic habit (6.8–9.8 mm)

Flow meter readings were used to determine the number of larvae per 100 m^3 for each sample. Average or single hourly values were plotted over time to examine the distribution of winter flounder larvae in Point Judith Pond during two separate tidal cycles.

Hydrodynamic Considerations and Simulation

Point Judith Pond (630 hectares) is oriented perpendicular to the coast on a north–south axis, is approximately 9 km long and averages about 1.85 km in width (Fig. 1). The Saugatucket River discharges into the upper basin of the pond, a 50 hectare arm of the estuary separated from the lower portion of the pond by a constricted passage known as the Narrows. The upper basin averages 1.3 m in depth while the main body of the pond north of the dredged out fishing port has a maximum depth of 2.3 m (Licata 1981). Potter Pond is smaller (137 hectares) and connects to the west side of Point Judith Pond by a dredged channel. There has been no direct connection from Potter Pond to the sea since the early 1900's when the narrow channel to Potter Pond and the larger permanent inlet to Point Judith Pond were constructed (Lee 1980). On the seaward side of the latter inlet a large breakwater was also constructed at that time to form the 251 hectare Point Judith Harbor of Refuge. There are two openings in this granite boulder breakwater through which vessels have access to the sea.

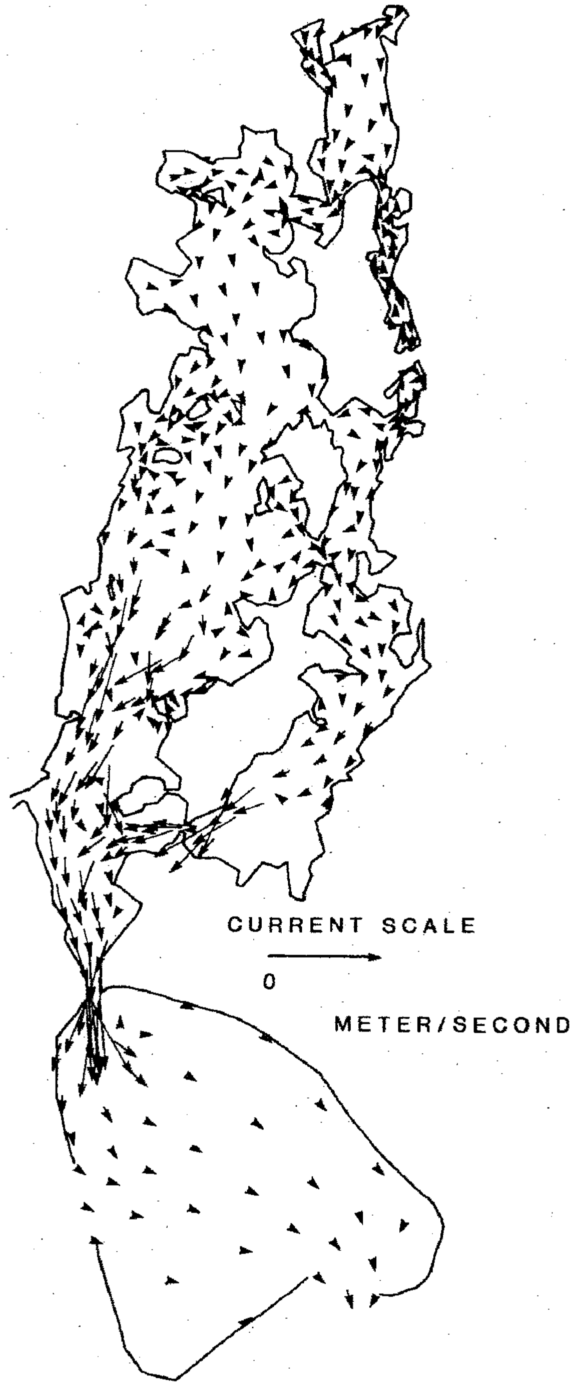

Fig. 5. Predicted tidal currents four hours after high water at the inlet to Point Judith Pond (Source: Licata 1981.)

The southern portion of Point Judith Pond has the characteristics of a well mixed, open estuary (Licata 1981). The dimensions of the lower pond and inlet as well as a typical tidal range of one meter result in high current velocities (Fig. 5) and the water is well mixed. There is also a phase lag in the tides along a north–south transect from the inlet up toward the middle of the pond.

Characteristics of the northern portion of the pond, on the other hand, approximate a two-layered, closed system. Current velocities are low (Fig. 5) and there is little tidal phase lag. A halocline is often present in this portion of the pond, especially after episodes of large freshwater input. However, a shallow halocline can also be observed in the upper ten centimeters of the water column as far south as station 6 during breezy, dry summer days (R. Crawford, personal observation). The main forces influencing planktonic drift in the upper portion of the pond are diffusion, which is proportional to the weak tidal currents, and the net seaward transport of surface fresh water input to the pond.

Based on these considerations we simulated twenty tidal cycles with a two-dimensional vertically-averaged hydrodynamic model to determine the fate of batches of 100 "particles" with the mathematical characteristics of nonswimming fish larvae injected at various locations on the pond. The numerical values of the diffusion coefficients for these "particles" were found by using formulae proposed by Taylor (1954) and later transformed by Harleman (1966) to give:

$$Dx = 20g^{1/2}UH/Cc$$

and

$$Dy = 20g^{1/2}VH/Cc$$

where

$$Cc = \frac{H^{1/6} \times 1.49}{0.03}$$

= Chezy's friction constant

H = depth (feet)

g = gravitational acceleration

U/V = velocity (feet/sec)

The diffusion coefficients were recalculated at all grids of the model at each time step.

Freshwater input from the Saugatucket River averages 33×10^3 m^3 per tidal cycle (Friedrich 1982) although it was observed to peak at 96×10^3 m^3 during observations in 1980 and 1981 (S. Granger, personal communication). For our purposes a freshwater input parameter of 60×10^3 m^3 per tidal cycle was selected since our period of concern was February through April when higher than average runoff figures would be expected. The hydrodynamic model was developed by Licata (1981) but was modified and run for this simulation by Tatsusaburo Isaji.

Results and Discussion

During the first week of March, many winter flounder eggs were found in the vicinity of a tidally submerged gravel bar once called Rocky Island which lies adjacent to the dredged navigation channel in the small northern basin near the mouth of the Saugatucket River (Fig. 3, Area 2). Most eggs were clumped on the gravel substrate or attached to fronds of algae. Three weeks later eggs were found in area 9 near Gardner Island, the boundary region of the open/closed hydrodynamic system in this lagoon. The Rocky Island site appeared to be a larger spawning area and we believe this location is of major importance to the winter flounder in Point Judith Pond.

Routine plankton samples taken in the Narrows during the last week of February contained a few young winter flounder larvae. None were found elsewhere in the pond. In mid-February there had been a pulse of warm weather which had apparently stimulated spawning near the Narrows. Because of the shallowness of the small northern basin and the proximity of the Saugatucket River, these waters would be expected to warm sooner than the deeper water of the main body of the pond and spawning in this portion of the estuary would be expected to occur first.

During this year, after the water had reached 3 °C in mid-February, water temperature decreased and remained near 1 °C for almost two weeks. We suspect this interrupted the spawning of the fish near Rocky

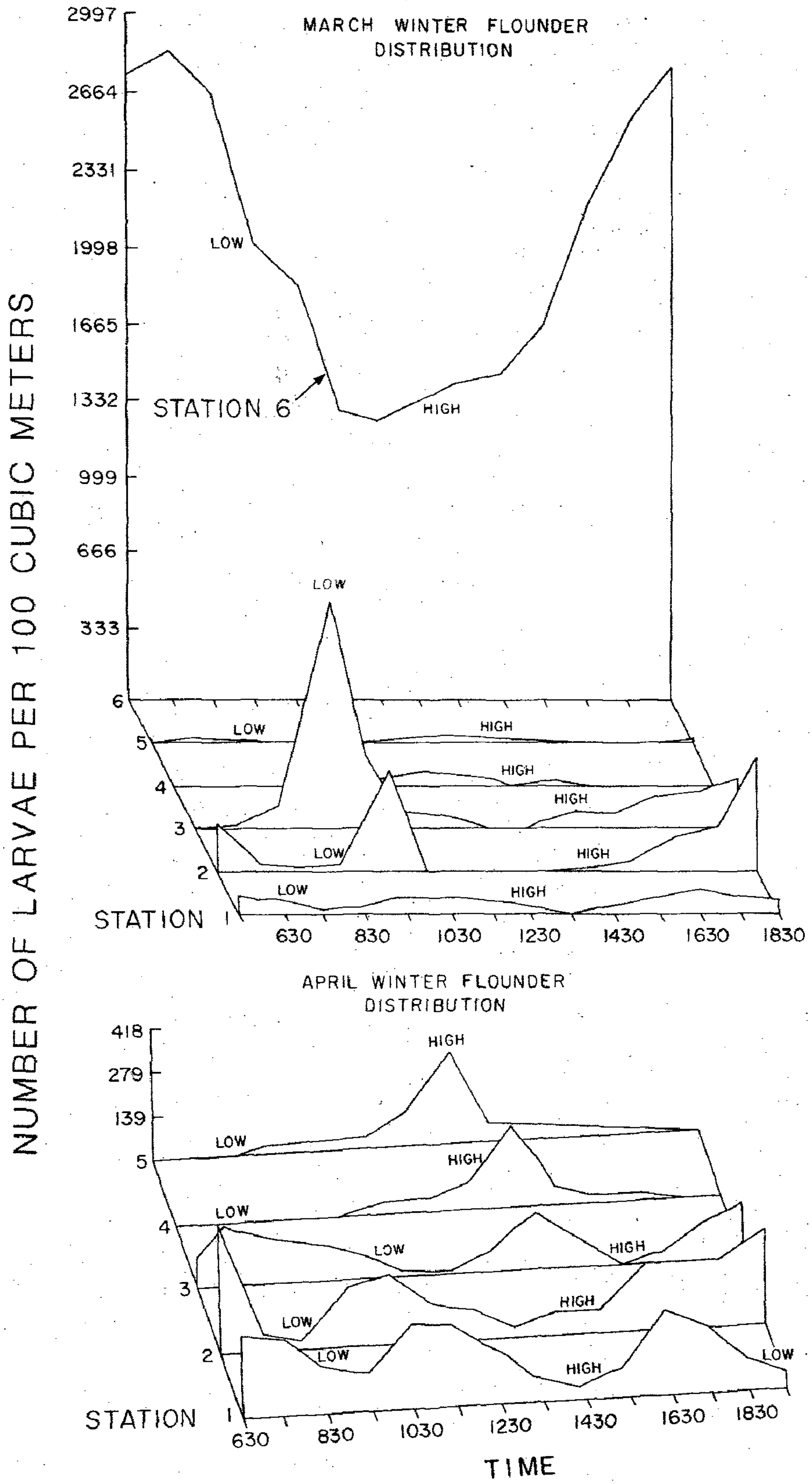

Fig. 6. Density of water flounder larvae in Point Judith Pond lagoon during daylight hours on 27 March and 27 April 1981. Approximate time of high and low tide is indicated. Refer to Fig. 4 for station location. Note different axes.

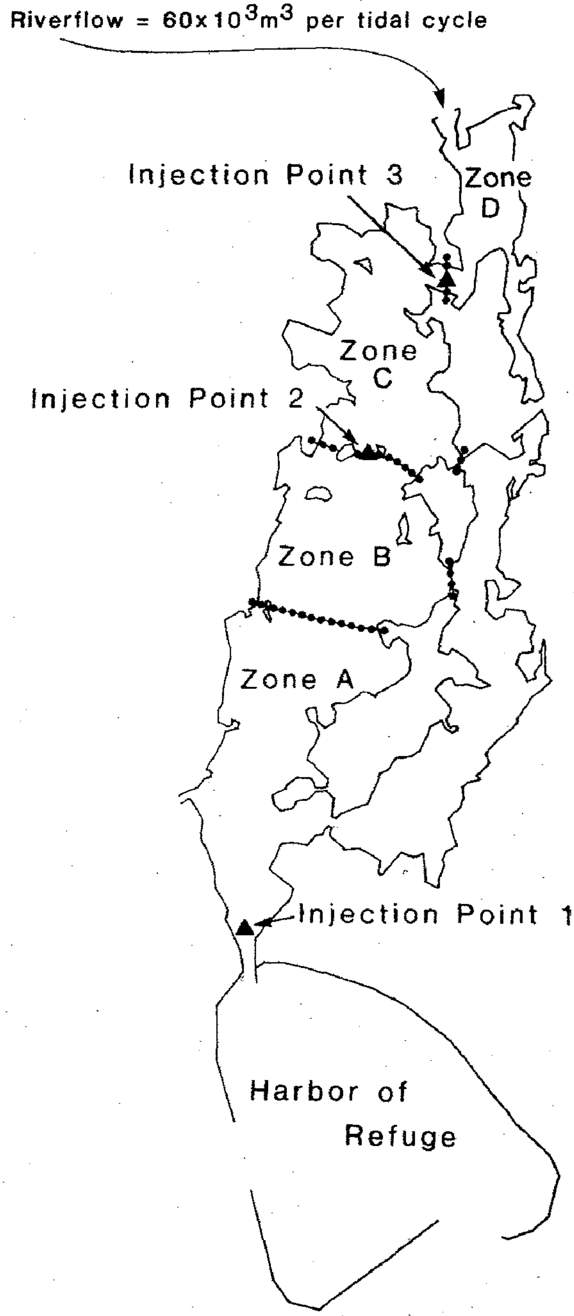

Fig. 7. Location of sites where particles were theoretically injected on a grid of a vertically-averaged two-dimensional hydrodynamic model of Point Judith Pond (Licata 1981). Particles were defined as non-swimming and were affected only by diffusion and fresh water input from river flow. Time of insertion was high tide at the inlet to the Harbor of Refuge. Tidal phase lag between this point and the upper pond resulted in an initial net northward drift of particles during the first few tidal cycles.

Island and delayed the time the fish at the more southern site spawned, exaggerating the observed difference in larval distribution recorded during our two coordinated winter flounder larvae surveys.

March 27 Larvae Distribution

Young winter flounder larvae were extremely abundant in the Narrows (Station 6, Fig. 6) near the Rocky Island spawning site. The hydrodynamic model predicted that after ten tidal cycles and with a freshwater input of 60×10^3 m^3 per tidal cycle into the system, winter flounder larvae would not be expected to be flushed from the Narrows (Fig. 7). Our observations during one tidal cycle confirm that larvae do not get displaced long distances in this region of the pond.

However, on this date there were also significant numbers of young larvae in the channel under the bridge to Great Island (Station 2, Fig. 4) and in the Potter Pond channel (Station 3, Fig. 4). Larvae in the Potter Pond samples did not appear at the sampling site in any quantity until well into ebb tide. Since it took approximately four hours of tidal flow for them to reach the channel, this suggests that they may have traveled from the back waters of Potter Pond. Although we did not sample this pond for eggs, we did learn that freshwater springs and suitable spawning habitat are plentiful along its northern shoreline. Furthermore, when one compares the bathymetry and shape of Potter with Point Judith, it is reasonable to surmise that the tidal currents of Potter Pond would retain larvae in the northern basin in a manner similar to what occurs in the northern portion of Point Judith Pond (Spaulding, personal communication). Also, the densest concentrations of jellyfish in Potter Pond are known to occur in the northern basin, another characteristic similar to Point Judith Pond. While circumstantial evidence suggests the existence of a winter flounder spawning site in the northern basin of Potter Pond, further work is needed to verify its location.

We also could detect a conservative nature of the Harbor of Refuge outside the inlet. We sampled many larvae passing out the inlet on an ebb flow only to sample similar masses passing through the inlet back into the pond on the flood. Rapid currents and tidal phase lags in the southern portion of the pond obscure their sites of origin, although undetected spawning grounds in Potter Pond or eastern Point Judith Pond are possible candidates. Very few larvae are collected outside of the Harbor of Refuge.

Larvae collected at all stations on this date were young and the length distributions were fairly uniform (Fig. 8) indicating that hatching had commenced in the spawning areas within a week or so of each other.

April 27 Larvae Distribution

The distribution of larvae on April 27 was very distinct from the earlier collection. One sample taken in the Narrows yielded an extremely large quantity of the moon jelly, *Aurelia aurata* (approx. 6,480 per m^3). There were too many moon jellies to effectively sample this area but repeated attempts revealed flounder larvae were rare in these waters. The moon jelly was very dense throughout much of the northern half of the estuary and it was only as we approached station 5 (Fig. 4) that our nets would not quickly clog. The moon jelly is a predator of winter flounder larvae for we have often observed partially digested larvae in the gut of this jellyfish. In our opinion, predation of winter flounder larvae in the upper portion of the pond would have been very significant at this time, if larvae were still planktonic in the surface waters of that area of the lagoon.

In the central portion of the estuary large masses of larvae were being swept up and down the channels by the tides and the bulk of the population was now in the southern half of the pond. An occasional moon jelly was also captured in this portion of the pond at this time and we believe they represented plankters which were slowly flushed out of the northern basin. Length distributions of April 27 larvae (Fig. 9) revealed a mixture of larvae sizes throughout the southern portion of the estuary which suggests that spawning had been continuous during the preceding several weeks. The youngest animals found were those collected at station 5, likely hatched from eggs deposited at the nearby spawning site detected earlier.

The gradient we observed in the distribution of larvae between our two sampling

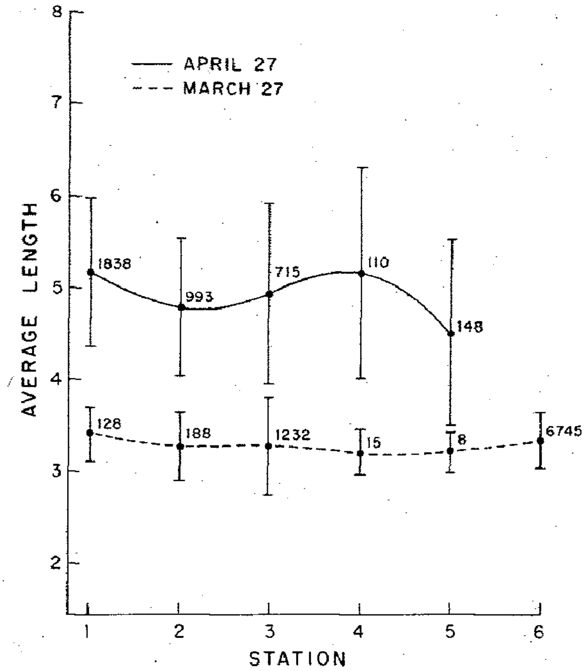

Fig. 8. Average lengths of winter flounder larvae collected in Point Judith Pond lagoon by station number. Refer to Fig. 4. Sample size ± standard deviation about the mean indicated. Differences among means are not significantly different for each date.

dates are very similar to those observed by Pearcy (1962b) in the Mystic River estuary. Larval densities there were initially highest in the upper portion of the estuary. A few weeks later density became greater in the lower portion of the estuary and the sizes of the larvae were more mixed. He postulated that larvae were able to maintain their position in the upper estuary by sinking toward the bottom to take advantage of the density current system. Our observations of flounder larvae distribution could also be explained by Pearcy's proposed mechanism of larval retention. However, a hydrodynamic model of Point Judith Pond reveals that hydrodynamics may play a similar role in the retention of young larvae in small estuaries. That we found a major winter flounder spawning site well within the portion of this estuary where larvae would be least likely to be flushed out to sea suggests that winter flounder exploit this characteristic of small, narrow estuaries in their reproductive scheme.

Hydrodynamic conservation may not be unique to winter flounder. The distribution

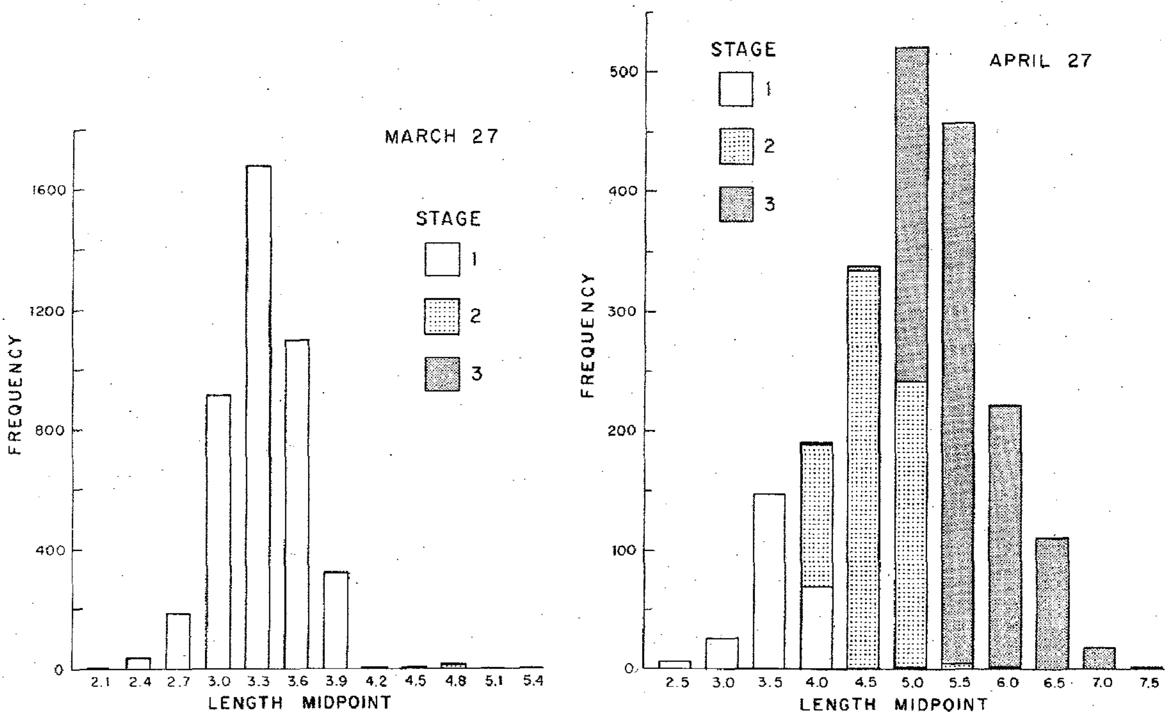

Fig. 9. Distribution of larval stages [according to Laroche (1981)] collected in Point Judith Pond lagoon. Hourly samples from six locations are combined. Note differences in axes.

of the highly visible moon jelly in Point Judith Pond also reflects the separation of this estuary into two hydrodynamic zones. Observations of this species reveal it reaches its peak abundance a few weeks after the peak in abundance of winter flounder larvae and they are also most dense in the northern portion of the pond. In the southern portion, a few moon jellies can be easily observed drifting in the navigation channel and passing in and out the inlet on both tides, reflecting our observations of winter flounder larvae. Moon jellies are not known to utilize the density current system as Pearcy suggested winter flounder do, and we believe the retention of these jellyfish in the upper portion of Point Judith Pond is a function of the hydrodynamics of this estuary.

The likely importance of hydrodynamics in determining the quality of an estuary as fish nursery habitat has significant resource management implications (Olsen et al. 1983). Hydraulic modifications are frequently made to the tidal flushing of lagoons but the impact of increased flushing on such parameters as planktonic residence time within the estuary have rarely been considered (Crawford 1983). Our findings suggest that the maintenance of conservative hydrodynamic patterns can be extremely important in maintaining the quality of estuarine areas as a fisheries nursery habitat.

Acknowledgments

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