Remote sensing of marine animals has lagged behind that of physical parameters. Satellites routinely monitor sea surface temperature, sea surface state, currents, and chlorophyll. Moored instrument arrays record and relay subsurface nutrient profiles, temperature, salinity, and currents in real time for immediate application to navigation and environmental health data, e.g., the Long-term Ecosystem Observatory (LEO-15) in New Jersey (Glenn et al. 2000) and the NOAA-Physical Oceanographic Real-Time System (PORTS, http://co-ops.nos.noaa.gov/d_ports.html) coast-wide in the United States. However, routine telemetry of marine animals is in its infancy. Marine macrofauna, especially highly mobile marine fishes in their natural habitat, are difficult to monitor. They are usually hidden from sensors in the visible and radio wavelengths, and unlike mammals, do not surface for regular contact with satellite receivers. The few exceptions, such as visual surveys of surface-swimming tuna and sharks (e.g., Chen et al. 1995; Lutcavage et al. 1997), are limited by water and weather conditions and by the fact that individuals cannot be identified, making calibration between numbers and sightings difficult (Brill et al. 2002). Archival tags on large fish may detach and float for satellite download or may be downloaded upon recapture (Boustany et al. 2001), but resolution of movement from such tags is best suited for basin-scale studies. Yet, the ability to monitor fish distribution and movement at the level of the individual on smaller spatial scales is desirable for understanding population structure and habitat use (Beck et al. 2001; Gillanders et al. 2003). Acoustics are a monitoring
option being developed to include improvements to the echogram (returns from active sonar, e.g., Fabi and Sala 2002; Petitgas et al. 2003) and individually coded transmitters fitted to fishes. Individual acoustic telemetry is not new, but serious challenges remain in fulfilling its potential as a routine process.

Acoustic tags have been used since at least the 1970s to track individual fish (Stasko and Pincock 1977; Coutant and Caroll 1980; Farquhar and Gutreuter 1989), and simple arrays have been used sporadically to address specific short-term questions, such as behavior of migrating fish at barriers (Thorstad et al. 2000) and home range delineation in Marine Protected Areas (see review by O’Dor et al. 1998). Heupel and Heuter (2001) used a more extensive array (14 hydrophones) to track 18 juvenile blacktip sharks (Carcharhinus limbatus) with near-complete coverage of a small semi-enclosed bay (Terra Ceia Bay, Florida) for up to 159 d. In another example, three separate hydrophones independently monitored the presence of 10 goliath groupers (Epinephelus itajara) among widely separated spawning aggregation sites over several months (Eklund and Schull 2001). Wider arrays are becoming more common due to considerable private sector technical support for telemetry studies. However, routine telemetry remains financially risky from a local perspective. Highly mobile marine animals often simply leave the monitored area.

The risk of marine animals carrying transmitters out of a study area decreases if the listening array covers widely spaced strategic areas (such as in Eklund and Schull 2001), or can be established regionally and cooperatively over a period long enough to monitor revisitation. The advent of estuary-wide and cross-shelf, coast-wide, multiple-hydrophone arrays, such as those used for salmon by Voegeli et al. (1998) or the Pacific Ocean Salmon Tracking Project (POST) (Welch et al. 2003), addresses the need for wide-area synoptic telemetry. These large projects substantially lower the risk of movement out of the study area compared with small arrays. We call our instrument array an observatory because it is amenable in its infrastructure to use by various scientists interested in a range of species and questions, including exploratory science. In our version, an observatory is deployed in habitat used by a number of species and over a time and size range suitable for the observation of short-term (episodic) movements to interannual trends.

Observatories for physical/chemical oceanography and estuarine and riverine limnology exist within the boundary of the Jacques Cousteau National Estuarine Research Reserve (JCNER) in southern New Jersey (USA). These were recognized as complementary to the establishment of an observatory to study striped bass (Morone saxatilis) movement and population structure (migratory contingents), and that of other macrofauna within the tidal Mullica River, Great Bay, and coastal ocean. These observatories are LEO-15 of the Institute of Marine and Coastal Sciences (von Alt and Grassle 1992) and the System-Wide Monitoring Program under the local custodial oversight of JCNER (Kennish and O’Donnell 2002).

We describe in this paper the implementation of an observatory for studying macrofauna in a semi-enclosed system, the Mullica River/Great Bay estuary. Private-sector vendors provide proven equipment for such studies, but equipment choice, deployment, and proper application needs to be discussed to avoid costly mistakes. This paper is meant to encourage the establishment of similar observatories by shortening the empirical learning curve. Our intent is not only to describe the system configuration and functional efficiency in detail, but also to provide for a discussion of the logic of the observatory design including constraints of instrument function, placement, performance, mooring design, system health monitoring, data stream management, and integration with public outreach in order to enhance future efforts in the implementation of other such systems. We compare the observatory with other designs in place to facilitate industry understanding and response to the needs of biologists. We also provide a brief description of two studies currently underway using this observatory.

Materials and procedures

Study area—The Mullica River/Great Bay estuary is one of the few remaining relatively undisturbed estuaries in the northeastern United States (Good and Good 1984; Psuty et al. 1993). The Mullica River is joined by several tributaries, the Batsto, Wading, and Bass rivers in draining the Pinelands National Reserve through Great Bay over an area of about 400,000 ha (Fig. 1). Much of the 280 km shoreline consists of cordgrass ( Spartina alterniflora)–dominated salt marsh, with a tidal range between 0.7 m (in Little Egg Harbor) and 1.1 m (near the mouth of Great Bay). Mean salinity of 29 extends 10 km up river, but drops sharply to about 8 within 30 km upriver. The salinity inflection point also corresponds to a steep decrease in pH from 8 to 6 (Martino and Able 2003). The majority of water flows to the ocean through the narrow but deep (17 m) Little Egg Inlet and a lesser amount through the Main Marsh Thorofare, a dredged intra-estuarine connection with Absecon Bay that is itself open to the ocean (Chant et al. 1996). The Mullica, Wading, and Bass rivers potentially serve as spawning habitats for anadromous fishes such as striped bass and river herring ( Alosa spp.) (Zich 1977).

The study area is located in the JCNER, which provides useful infrastructure for routine environmental monitoring. Permanent JCNER instrumentation includes dataloggers for salinity, temperature, pH, tide level, turbidity, and nutrient profiles (Kennish and O’Donnell 2002). The JCNER also facilitates outreach. In addition, instruments of the Rutgers University LEO-15 and the Coastal Ocean Observation Laboratory monitor much of the study area and adjacent coastal ocean for meteorological parameters and surface and sub-surface water currents (Glenn et al. 2000).

Study examples—Striped bass ( Morone saxatilis), summer flounder (Paralichthys dentatus), bluefish ( Pomatomus saltatrix), horseshoe crab ( Limulus polyphemus), and blue crab ( Callinectes sapidus) are currently under study in the observatory, the later
three in preliminary stages. Striped bass are anadromous moronids ranging on the U.S. east coast from Florida to the Gulf of St. Lawrence. They apparently occur as populations of coastal migrants and fresh water or estuarine residents even in open systems. The integration and fluidity of these populations is not well understood, nor is the role of estuaries in providing resources to coastal contingents.

Summer flounder (Paralichthyidae) migrate offshore to spawn in fall and winter, but spend warmer months near shore and in estuaries. Cues to the timing of migration onset require study. Bluefish (Pomatomidae) range along the entire eastern seaboard of the USA, where coastal migrants use estuarine and oceanic habitat. Bluefish stocks may be comprised of separate migrating contingents with different patterns of estuarine habitat use. These studies benefit from information on frequency, duration, and seasonality of estuarine visitation and on the large-scale use of estuarine and riverine versus coastal habitat use. The current observatory requirement is thus for high-fidelity monitoring of passage between bay, river, and ocean habitats. It complements but does not require fine-scale positioning.

Wireless hydrophone system function—Macrofauna fitted with individually coded acoustic-transmitters (76.8 KHz, 210 possible codes) are detected when they come within range of moored wireless hydrophones (WHS_1100, Lotek Wireless, Inc., St. Johns, Newfoundland, Canada). Wireless hydrophones are suspended at an instrument depth of 3.2 m on galvanized chain and steel rope hydrophone bridle between a pyramid anchor (25-37 kg, Dor-Mor, Inc.) and surface buoy (CC-3, Polyform Inc.). A transmitting radio antenna cable secured to the riser extends through the center of the buoy on a steel axis. Total water depth at mooring locations varies from 2.5 to 10 m (Table 1). Several moorings are at the edge of drop-offs to water as deep as 16 m. Wireless hydrophone units convert received sound to a VHF radio frequency unique to the unit. Radio signals are received by a master antenna assembly and interpreted by a receiver/datalogger/processor (SRX_400 with Code Log software, Lotek Wireless, Inc.). These “receivers” log decipher-
able acoustic codes by their identification number along with the sending hydrophone identity, date and time stamp, receiving antenna, signal power, and number of occurrences of that code within a specified time. Receivers are also able to decode second and third channels for transmission data (e.g., pressure, temperature) collected by tags with sensors, although no such tags are currently deployed in the observatory. The receivers may also be used to track radio tags, or as receivers for hard-wired hydrophones. Details of an early version of the wireless system hardware in a pilot project are given in Lembo et al. (2002), but we deploy the equipment differently with attendant changes to data handling.

Receivers listen to one wireless hydrophone for a user-specified period or “listening window,” then switch to the next in a task list. The fact that receivers are scanned in sequence has two major implications to observatory structure. The first is that signals from different hydrophones cannot be used to triangulate exact location based on signal arrival time as is the case for Vemco’s wireless RAPT system (O’Dor et al. 1998) or from Lotek’s wired MAP system (Niezgoda et al. 2002). It is, however, possible to determine “activity centers” following Simpfendorfer et al. (2002) in their application of autonomous Vemco VR1 dataloggers. The other implication is that the number of hydrophones tasked to a particular receiver increases the total time elapsed between monitoring of a particular hydrophone. This elapsed time may be extended through an optional routine to scan any slave antennas independently. Therefore, it is useful to calculate the total time between scans in conjunction with the pulse intervals of tags in deciding how many hydrophones to task to a single receiver.

Receiving antennas for each receiver are configured as a master (group) of directional slaves. Gain is set individually for each directional slave and is determined empirically during an observation period. Gain settings vary with the distance between the

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### Table 1. Configuration of SRX receiver elements of the acoustic-telemetry array monitoring fishes in the Mullica River/Great Bay estuary

<table>
<thead>
<tr>
<th>SRX</th>
<th>Location and antennae mount</th>
<th>Power supply</th>
<th>Slave antennae and (Gain)</th>
<th>Hydrophones monitored and distance (km)</th>
<th>Minimum scan interval, T (s)</th>
<th>Maximum scan interval, T (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RumfsA</td>
<td>RU Marine Field Station meteorological tower</td>
<td>110 V AC</td>
<td>1 (60)</td>
<td>1 (2.5), 2 (1.7), 3 (0.25)</td>
<td>18</td>
<td>36</td>
</tr>
<tr>
<td>RumfsB</td>
<td>RU Marine Field Station meteorological tower</td>
<td>110 V AC</td>
<td>2 (75,50)</td>
<td>4 (2.5), 5 (2.0), 13 (6)</td>
<td>18</td>
<td>54</td>
</tr>
<tr>
<td>Pkwy</td>
<td>Garden State Parkway Bridge pylon platform</td>
<td>12 V DC</td>
<td>2 (60,60)</td>
<td>6 (0.4), 7 (0.2), 8 (0.2), 9 (1.7)</td>
<td>18</td>
<td>54</td>
</tr>
<tr>
<td>LBB</td>
<td>Lower Bank Bridge Dock, no antenna</td>
<td>12 V DC</td>
<td>none, hardwired (10)</td>
<td>10 (attached)</td>
<td>Continuous</td>
<td>Continuous</td>
</tr>
<tr>
<td>SWC</td>
<td>Sweetwater Casino Dock, no antenna</td>
<td>110 V AC</td>
<td>none, hardwired (7)</td>
<td>11 (attached)</td>
<td>Continuous</td>
<td>Continuous</td>
</tr>
</tbody>
</table>

Total scan interval of the receiver increases as a function of the number of slave antennae linked to it and of the number of hydrophones hearing transmitters, but may increase the number of contacts made if a wireless hydrophone signal is captured on both antennae.

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### Table 2. Location, configuration, and details of wireless hydrophone (WHS_1100) moorings monitoring the Mullica River/Great Bay estuary

<table>
<thead>
<tr>
<th>Buoy</th>
<th>Site</th>
<th>Channel frequency</th>
<th>SRX</th>
<th>Mean signal strength</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Water depth (m)</th>
<th>Date moored</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Little Egg Harbor Inlet</td>
<td>148.160</td>
<td>RUMFS</td>
<td>162</td>
<td>3930.541</td>
<td>7418.306</td>
<td>9</td>
<td>18 Oct 02</td>
</tr>
<tr>
<td>2</td>
<td>Little Egg Harbor Inlet</td>
<td>148.440</td>
<td>RUMFS</td>
<td>190</td>
<td>3930.387</td>
<td>7418.393</td>
<td>10</td>
<td>20 Oct 02</td>
</tr>
<tr>
<td>3</td>
<td>Shooting Thorofare</td>
<td>150.580</td>
<td>RUMFS</td>
<td>232</td>
<td>3930.353</td>
<td>7419.393</td>
<td>9</td>
<td>23 Oct 02</td>
</tr>
<tr>
<td>4</td>
<td>Grassy Channel</td>
<td>148.020</td>
<td>Bay</td>
<td>179</td>
<td>3930.959</td>
<td>7419.774</td>
<td>7</td>
<td>18 Oct 02</td>
</tr>
<tr>
<td>5</td>
<td>Newmans Thorofare</td>
<td>151.840</td>
<td>Bay</td>
<td>117</td>
<td>3930.958</td>
<td>7420.135</td>
<td>8</td>
<td>10 Oct 02</td>
</tr>
<tr>
<td>6</td>
<td>Ditch</td>
<td>150.240</td>
<td>PKWY</td>
<td>161</td>
<td>3933.002</td>
<td>7427.283</td>
<td>6</td>
<td>20 Oct 02</td>
</tr>
<tr>
<td>7</td>
<td>Chestnut Neck</td>
<td>149.790</td>
<td>PKWY</td>
<td>226</td>
<td>3933.214</td>
<td>7427.620</td>
<td>9</td>
<td>20 Oct 02</td>
</tr>
<tr>
<td>8</td>
<td>Collins Hole</td>
<td>150.280</td>
<td>PKWY</td>
<td>211</td>
<td>3933.435</td>
<td>7427.976</td>
<td>9</td>
<td>20 Oct 02</td>
</tr>
<tr>
<td>9</td>
<td>Wading River</td>
<td>150.440</td>
<td>PKWY</td>
<td>106</td>
<td>3933.461</td>
<td>7427.797</td>
<td>9</td>
<td>12 Mar 03</td>
</tr>
<tr>
<td>10</td>
<td>Lower Bank</td>
<td>Hardwired</td>
<td>LBB</td>
<td>No VHF</td>
<td>3935.616</td>
<td>7432.992</td>
<td>4</td>
<td>15 Apr 03</td>
</tr>
<tr>
<td>11</td>
<td>Sweetwater</td>
<td>Hardwired</td>
<td>SWC</td>
<td>No VHF</td>
<td>3937.215</td>
<td>7437.630</td>
<td>4</td>
<td>9 Apr 04</td>
</tr>
<tr>
<td>13</td>
<td>Great Bay</td>
<td>150.280</td>
<td>Bay</td>
<td>84</td>
<td>3928.925</td>
<td>7420.137</td>
<td>8</td>
<td>25 Jun 03</td>
</tr>
</tbody>
</table>

Hydrophone numbering roughly reflects a shore-to-headwater sequence but is not continuous so that the sequence may be preserved if additional planned hydrophones are placed at designated points of interest.
receiver and the wireless hydrophones and the ambient radio noise on the frequencies being monitored. Antennas are placed as high as possible using existing structures while minimizing antenna cable length (Tables 1, 2, Fig. 2). The use of an existing bridge support saved money and increased array performance but required planning for approval by authorities. The task assigned to various receiver units monitoring the hydrophone array differs with location (Table 2). Incoming signals may be viewed at the receiver or on a nearby computer via serial cable. Cell modems can link remote receivers to a computer, but cell service is unreliable in the largely undeveloped Pinelands National Reserve; hence remote receivers are downloaded to a computer at least weekly. In choosing specific locations, equipment, and tasks for this observatory, we learned of distinct advantages and disadvantages to the use of wireless hydrophones with shore-side receiving in comparison to autonomous hydrophones. Among the most important advantages is the real-time and local (in the laboratory) data collection and related system health monitoring and calibration outlined below.

1) Real-time data acquisition allows for reactive sampling and optimized mobile tracking. A researcher wishing to track fine-scale movement of a particular animal may narrow the search area based on incoming or recent observatory data.

2) Catastrophic loss of a hydrophone does not mean the loss of data accrued since the last download because data are stored in the shore-side receiver. In our system, four hydrophones were lost when mooring chains prematurely corroded. However, all data collected by these hydrophones prior to their loss was preserved. This advantage is balanced against the potential for catastrophic loss or power failure of a receiver with concomitant loss of data from several hydrophones at once. The potential for such a loss is less than that for submerged equipment and is mitigated by frequent downloading or streaming of data to a computer. Downloading receivers does not require boat time as does downloading autonomous hydrophones.

3) Real-time data acquisition allows for instantaneous system health monitoring. Wireless hydrophones broadcast several power status transmissions every hour. These transmissions alert investigators to the continued presence of the hydrophones.
Thus, hydrophone loss or malfunction can be detected and responded to within the hour. Several hydrophone losses to ice rafting and damaged moorings were prevented by diligent status monitoring when changes in signal strength indicated displacement. Analysis of the long-term record, which includes not only the frequency of received transmissions but also their signal strength, could potentially be used to statistically weight the value of data from various hydrophones.

4) Real-time acquisition, particularly via radio link, allowed us to calibrate and diagnose system performance reactively. In the simplest example, we tested acoustic transmission by towing an active tag away from a wireless hydrophone while watching the data stream on a receiver in the boat. Then, by mooring a reference tag at a static location and increasing the distance between the hydrophone (radio retransmitter) and the receiver (in the boat), we examined the propagation of the radio signal. Because the instruments did not need to be downloaded to view data, the efficiency of sound capture in several locations was checked quickly before selecting a final mooring position.

5) Real-time data collection allows frequent posting to a Web site without the boat time required for frequent downloads from independently recording hydrophone/logger units. In our experience, WHS_1100 wireless hydrophones or their moorings need service every 4 to 5 months, a much longer interval than would be desirable for data posting to an educational or research Web site. Service includes battery change and cleaning and inspection/replacement of mooring chain links and takes about 10 min per hydrophone. Two people can perform such service from a small boat.

There are several disadvantages to using a wireless system. One is the loss of information regarding the position or distance of an acoustic transmitter relative to the hydrophone. This is a consequence of the retransmission of the acoustic signal as a radio signal, the strength of which is unrelated to the acoustic signal strength.

A second disadvantage is that hydrophone location is limited not only to environments that are quiescent in the long term, but also to those free of episodic high turbulence. Completely submersible and independent hydrophone/dataloggers may be secured to the bottom in areas that periodically experience high-breaking waves without being broken (although acoustic signals will also be periodically attenuated for these as well). However, a hydrophone suspended from a surface buoy with antenna risks displacement or loss from cable breakage. Furthermore, the weight of mooring and suspension cable limits the moorings to relatively shallow water (12 m) using our current buoys (1.5 m diameter). In very shallow water with episodic storm swells, such as around bars that form near estuarine inlets, heave may still cause impact of a suspended hydrophone on the bottom. Different mooring designs may
lessen this problem. For example, fixing the hydrophone in an armored, benthic base will allow an associated antenna buoy to be periodically tossed with little risk to the instrument.

A third disadvantage is that limitation of wireless hydrophones must be within VHF communication range. Thus, the current hydrophones are not amenable to use far offshore. Increased radio power can alleviate this but would then be regulated by Federal Communications Commission in the United States and battery life would decrease from the current 4 to 6 months. Adjustment of antenna gain can mitigate distance limitation but must be balanced against the potential negative impacts related to radio noise, particularly false signal acquisition. Some of these concerns are thus common to those of radio-only telemetry arrays used in fresh water (David and Closs 2001; Moser et al. 2002). A treatment of additional considerations for use in radiotelemetry, but applicable to wireless hydrophones, is given by Sisak and Lotimer (1998). Thus, the current wireless system provided some benefits over wired and independent remote systems but also challenged us with different constraints.

Study constraints—Hydrophone placement strategy was dictated by the need to detect passage of migrants between habitats, especially along the estuarine salinity gradient. The concept of perimeter hydrophones as “gates” (as in a gated estuary) allows for data handling that captures presence or absence in the entire study area or its gated sections, unlike the case for an unbounded hydrophone configuration. Gate passage indicates presence of a tagged animal within the perimeter of a large area even for times during which it was not being detected. This concept is routinely used to determine the number of tagged fish in a reservoir by tallying Passive Integrated Transponders (PIT)-tagged anadromous fish passage past dams. However, in a wide estuary mouth, a hydrophone can detect even an animal’s approach, and detection does not indicate presence inside a perimeter until the same tag is detected at a farther hydrophone.

Critical bottlenecks in the estuary were chosen and instrumented to detect passage of fish even with weak transmitters. Suitable hydrophone sites include narrow coastal inlets, natural or artificial geographical constraints such as bridge abutments, or those areas for which even brief visits have important implications (e.g., spawning sites). Biological constraints such as body size (as it relates to tag size and related sound pressure) and swimming speed dictate the overlap of detection radius among hydrophones to provide that a passing animal is in hydrophone range long enough even for intermittent listening. A size and swimming speed constraint can be addressed in a wireless array by increasing the number of hydrophones or by decreasing the scan cycle by adding receivers. For wireless and autonomous logging hydrophones, the appropriate configuration is addressed empirically, as below.

Physical constraints—To perform well, hydrophones must be reasonably shielded from noise (see Thorstad et al. 2000). Thus, a preliminary survey of the acoustical properties and bathymetry of a study area together is essential. Chief noise sources are surface turbulence such as breaking waves, wind and rain, and moving substrate. Aside from noise, entrained air bubbles or suspended materials attenuate acoustic signals. Deep hydrophone positioning minimizes both problems, a consideration potentially complicated by biology and instrument mooring capabilities. Our study area, as for other estuaries, has a soft bottom that is bounded by clay and marsh peat banks, and so is both acoustically quiet and relatively free of reflection. However, the mostly shoal inlet is periodically subject to large (2 m) breaking waves. We conducted both acoustic and bathymetric surveys at potential bottlenecks prior to deploying hydrophones and setting hydrophone gain. Finally, wireless hydrophones must be in radio range of receivers. Radio acquisition should be considered to allow the use of existing infrastructure for mounting antennae and providing power and accessibility to the receivers. In this respect, we also surveyed the ambient radio environment to optimize operating frequency choice.

Acoustic survey—Following bathymetric survey in likely deployment areas, we surveyed acoustic noise and propagation in areas deemed suitable based upon the biological and bathymetric considerations. To survey ambient acoustic noise we deployed a hardwired hydrophone at various sites and incrementally increased acoustic gain until the receiver’s processor was induced to recognize a false signal. The manufacturer then set hydrophone gain just below this “acoustic noise floor.” To survey acoustic propagation, we deployed a tag below a surface float, and the distance between the transmitter and hydrophone was increased until the signal could no longer be reliably decoded.

Radio survey—Because detected sound must be retransmitted as VHF, we surveyed ambient radio noise prior to hydrophone fabrication. We used a receiver with an omnidirectional antenna to incrementally (0.002 MHz) increase radio frequency from 148.000 to 152.000 MHz while listening for interference. This was repeated 2 to 3 times in succession on several dates, day and night. From a list of quiet channels, the vendor chose 25 candidates. A more rigorous survey of these candidate channels entailed incremental gain increase on each until the “radio noise floor” could be determined as for acoustic noise. We ranked candidate frequencies by their average and maximum gain at false signal recognition and chose those with the highest achievable gain. This maximized the useful gain range that could be employed for listening to wireless hydrophones while minimizing the interference and false signals from ambient radio noise.

Hydrophone array configuration—Based on acoustic noise and bathymetry we separately instrumented the interior inlets to Great Bay and Little Egg Harbor (Fig. 1). The entrance to Little Egg Harbor is deep (17 m) and sufficiently narrow for a single hydrophone (Hydrophone 1) situated near the entrance center to detect transmitters across either side. A ridge centered inside the inlet provides a suitable mooring depth and also diverts
boat traffic away from the surface float. The entrance to Great Bay is similarly deep (to 16 m) but split by a long and occasionally emergent bar into the narrow but deep Shooting Thoroughfare on the landward (western) side, and shallower Grassy Channel to the east. A hydrophone was moored in each channel (Hydrophone 3 and 4, respectively). A hydrophone (Hydrophone 2) was placed on a clay shelf near the central part of the main Little Egg Inlet, thus protecting the buoy from boats. Hydrophone 2 was placed to document fish use of the main inlet area and, as the first hydrophone encountered by immigrating fish, to provide directionality through subsequent detection at hydrophones 1, 3, or 4. All four of these hydrophones are well within range of a single receiver (designated “RumfsA”) mounted at the Rutgers University Marine Field Station (RUMFS), but the monitoring load was set at three hydrophones to reduce total scan time. Therefore, Hydrophone 4 is monitored together with Hydrophones 5 and 13 on another receiver (designated “RumfsB”) also located at RUMFS. Hydrophone 13 monitors the Main Marsh Thoroughfare, the only other significant exit to Great Bay, but was not added until spring of 2003. Hydrophone 5 monitors Newmans Thoroughfare, a narrow navigable channel on the eastern side of the bay. This hydrophone also monitors the entrance to Little Sheepshead Creek, a shallow tidal creek that bisects the Sheepshead Mounds land mass and could potentially be used by fish to cross into Little Egg Harbor without coming first through the Little Egg Inlet. There is no hydrophone monitoring passage around the broad southwestern portion of the bay, much of which is very shallow and occasionally emergent. Use of that portion of the bay is deduced from passage of fish between an inlet and the Mullica River without interception by Hydrophone 5, and is often confirmed by contacts with Hydrophone 13.

Another series of wireless hydrophones in the Mullica River upstream of Great Bay is positioned to discern differences in use of upstream portions of the estuary as spawning sites and as a potential mechanism of population segregation among contingents (see Secor 1999). These wireless hydrophones, labeled 7 and 9 (previously also Hydrophones 6 and 8), are monitored by a receiver (designated “Pkwy”) mounted to the support structure of the Garden State Parkway Rt. 9 Bridge (Fig. 1 and 3). Based on towed test transmitters, each of these hydrophones could detect fish moving past them, but in series they indicated direction and rate of movement and allowed for a test of the array efficiency in tracking macrofauna at liberty. Hydrophone 8 was discontinued late in spring 2003 and Hydrophone 6 in early 2004. Hydrophone 9 is located at the junction of the Wading and Mullica rivers. Hydrophone 10 is hard-wired to a receiver at the Lower Bank Bridge about 10 km north of Hydrophone 9. This hydrophone is at the salt front in some years and detects arrival into oligohaline or fresh water. Based on early confirmation of such movement, a second wired hydrophone (Hydrophone 11, Fig. 1) was deployed in April 2004 at Sweetwater, 0.25 km below the confluence of the Batsto and Mullica River, 12 km upstream from Hydrophone 10 and well into fresh water. Reception power on the two hydrophones cabled directly to their receiver (Lower Bank Bridge and Sweetwater) does give an indication of transmitter proximity, and listening is continuous on the single channel.

Data processing—Data collected by the receivers are downloaded as plain text files to a computer using the supplied software WINHOST (Lotek Wireless, Inc.). Data dump files are read, processed, merged with physical/chemical data, and graphed using MATLAB (The Mathworks, Inc.) script files written by the senior author. The product of initial processing is a file for each animal (a history of all acoustic contacts by hydrophone and time) and a file for each hydrophone individually (a history of all animals heard by time). Records of individual acoustic contacts are compressed into user-defined intervals (day, hour, half-hour, or quarter-hour) while retaining the number of contacts per interval. This type of handling is appropriate for use with physical data collected by other dataloggers at similar time intervals. Compression also facilitates flexible definition of a temporal filter (contacts-per-interval) to exclude spurious code detection from either acoustic or radio noise and could be independently set for different hydrophones dependent on their receiver scan load. Each fish is thus logged at a hydrophone within a given sample interval by a single corresponding data line. Such summary interval logging can be accomplished within Code Log itself, which is useful to reduce necessary data storage capacity in the receiver. However, running this operation after collection allows greater flexibility in data handling for different tasks and allows data to be structured in multiple files as a database. Computation tasks are optimized because a single flat file does not need to be searched for tasks on single or defined groups of animals or hydrophones. Original dump files are never affected or overwritten. MATLAB scripts are available with documentation upon request from the first author.

Hydrophone array performance assessment—Successful detection of animals fitted with acoustic transmitters in a wireless hydrophone array depends on three operational steps. The first is transmission of the ultrasonic code through the water to its reception by the hydrophone. This depends on distance between the transmitter and hydrophone and on acoustic path quality. The second step is radio retransmission of the signal by the wireless hydrophone to the receiver. This depends on the number of hydrophones being monitored and the number of signals from them, and on ambient radio conditions. The third is discrimination of the code by the receiver’s processor, which is dependent on both the acoustic and radio environment. The first step has been tested by the manufacturer (Lotek Wireless Inc.) for each transmitter model. Thus, advertised sound pressure decibels (dB) coupled with acoustic survey information for each site predicted detection distances under normal conditions and formed a first basis for determining the number of hydrophones necessary to gate a bottleneck. Operation at the second and third steps is independently verified hourly by the reception of battery status codes from the hydrophones.
Recorded status calls provide a simple means of judging relative performance of the radio operational environment among hours, days, seasons, years, and among individual hydrophones (Fig. 4). Regular inspection of the incoming transmissions allows for problems to be corrected as they develop, for instance by adjusting antenna gain or noise blanking (setting a higher criteria for logging on the basis of signal reception power). Performance of the array at the first operational level, acoustic reception, must be judged using reference transmitters. Because a record of their reception indicates successful operation at all three levels, reference transmitters provide calibration of the detection efficiency of each hydrophone.

Testing detection in the riverine locations (Hydrophones 6-10) consisted of lowering a working transmitter into the water at either riverbank abreast of the wireless hydrophone and noting detection at every scan cycle. Recording the transmitter while lowering it from a boat drifting at distances greater than the distance to the riverbank (up or down the river main axis) indicated that, if detection efficiency on the cross and long river axes are similar, the detection radius would be well beyond the limits of river width. This greater detection radius lengthens the chord that is a fish’s path through the circular detection cell even when a fish passes close to the riverbank. Occasionally, synoptic detections of transmitters in fish at liberty by multiple hydrophones (some many kilometers apart) within a single receiver scan cycle demonstrate that the detection radius is, at times, far greater than the width of some of the river-width bottlenecks. Even so, there are times when

Fig. 4. A record of the hourly occurrence (presence/absence) of battery status signals from all wireless hydrophones in the array between March and December 31, 2003. This represent the period during which tag signals may be received from any one hydrophone. Gaps in the record reflect when hydrophones were removed prior to heavy ice cover or were otherwise inoperable.
expected battery status transmissions are undetected, i.e., are missed by the receiver for a given hour but are detected in the next hour (Figs. 3, 4). The most likely reason for intermittent missed status calls is numerous transmissions on other channels so that the scan interval is lengthened in a flexible scan routine. Antenna obstruction or unusually high ambient radio noise can also mask wireless hydrophone transmissions. Status transmissions are set by us at five per hour, all within 1 min from a given hydrophone. Thus, they are more easily missed than fish carrying tags within the detection cell and are, thus, conservative estimators of the transmitter function.

We performed a further evaluation of the entire code reception process over the long term by mooring reference tags near several of the hydrophones. Initially, these were suspended together from a single mooring 100 m distant from Hydrophone 5. These were detected at an equal rate (100%), so they were placed below floats and suspended at distances of 125 m and 250 m for durations of at least 24 hours at three of the hydrophones (1, 2, and 5). In addition one tag was suspended at 125 m from riverine hydrophones 6, 7, and 9 (Table 3). Data from reference tags were treated, as they would be for fish, with a temporal filter criterion of at least two contacts per 15 min, and summing contacts within 15-min time bins. The mean number of contacts was similar among the two reference tags despite their separation. However, the number of contacts for either reference tag within a 15-min time period did vary considerably, ranging between 2 and 66 on a cyclical basis, and the cycle of contacts for both tags was similar (Table 3). Data from reference tags were treated, as they would be for fish, with a temporal filter criterion of at least two contacts per 15 min, and summing contacts within 15-min time bins. The mean number of contacts was similar among the two reference tags despite their separation. However, the number of contacts for either reference tag within a 15-min time period did vary considerably, ranging between 2 and 66 on a cyclical basis, and the cycle of contacts for both tags was similar (Table 3). These cycles were most likely the effect of tides on depression of the reference tag moorings, which were fouled by floating algae (Ulva lactuca) and pulled to the bottom, rather than on the radio reception of the wireless hydrophone retransmission. The rate of contacts was higher in the river (Hydrophones 6, 7, and 9) than in the bay or inlet.

It is possible and likely that noise (acoustic or radio) will at some time imitate transmitter codes resulting in spurious code logging. The application of a temporal filter helps mitigate this. The chance of a code being spuriously reproduced twice or more at the same hydrophone within a given time period becomes very small as that time period becomes small. Even a fairly loose temporal filter (allowing two contacts of any one code at a given hydrophone within a 15-min period) was highly successful at limiting data to real transmitter contacts as revealed by a simple test. Using the MATLAB script files, we scanned the data record of all hydrophones from March 1, 2002, through December 31, 2003, for contacts with any of 204 possible codes. The tested codes excluded five that had been deployed previous to March 1, 2003, and one that was used as a reference transmitter. For codes that had been deployed after March 1, 2003, we searched only those dates prior to the fishes’ release date (see Web Appendix 1, Table 1). Any such contacts must be spurious. With the exception of Code 1, few spurious contacts were recorded, regardless of the time a particular code was free; i.e., a coded transmitter released into the system later could be expected to accrue more spurious contacts under this criterion. However, we did note that code 2 (deployed previous to the search window and not tested) occurred often within the database as a spurious signal. Evidence for spurious logging of Code 2 is that it occurred at multiple widely spaced hydrophones within time periods that cannot be achieved by a swimming fish. It is apparent that these contacts are caused by radio rather than acoustic imitation as evidenced by signal strength. Because

<table>
<thead>
<tr>
<th>Hydrophone</th>
<th>Tag</th>
<th>Distance (km)</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
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<tr>
<td>1</td>
<td>163</td>
<td>0.25</td>
<td>2</td>
<td>50</td>
<td>17.52</td>
</tr>
<tr>
<td>1</td>
<td>107</td>
<td>0.12</td>
<td>2</td>
<td>49</td>
<td>21.7</td>
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<tr>
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<td>163</td>
<td>0.25</td>
<td>2</td>
<td>52</td>
<td>28.8</td>
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<tr>
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<td>107</td>
<td>0.12</td>
<td>6</td>
<td>55</td>
<td>31.5</td>
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<tr>
<td>5</td>
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<td>0.25</td>
<td>2</td>
<td>66</td>
<td>7.3</td>
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<tr>
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<td>33</td>
<td>5.4</td>
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<tr>
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<td>0.12</td>
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<td>57.4</td>
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<tr>
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<td>107</td>
<td>0.12</td>
<td>6</td>
<td>91</td>
<td>64.4</td>
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<tr>
<td>9</td>
<td>107</td>
<td>0.11</td>
<td>2</td>
<td>67</td>
<td>37.8</td>
</tr>
</tbody>
</table>

Table 3. Number of detection events of reference tags within 15-min time bins post-processing with a filter passing 2 contacts 15 min⁻¹

<table>
<thead>
<tr>
<th>Fish</th>
<th>Time elapsed (Min)</th>
<th>Contacts</th>
<th>Hydrophones</th>
<th>Contacts/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flounder_202</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>0.2046</td>
</tr>
<tr>
<td>Flounder_189</td>
<td>151</td>
<td>1</td>
<td>1</td>
<td>0.6307</td>
</tr>
<tr>
<td>Bass_128</td>
<td>1523</td>
<td>1</td>
<td>1</td>
<td>1.8</td>
</tr>
<tr>
<td>Flounder_176</td>
<td>23</td>
<td>2</td>
<td>1.2</td>
<td>0.6307</td>
</tr>
<tr>
<td>Flounder_104</td>
<td>190</td>
<td>2.3</td>
<td>0.2385</td>
<td></td>
</tr>
</tbody>
</table>

Table 4. Differences in the unfiltered detection pattern of coded acoustic signals from tagged striped bass and summer flounder
signal strength recorded by the receiver is the strength of the radio transmission (not the strength of the acoustic signal), and because the distance to the hydrophones remains constant, “real” retransmissions, including status signals, have a characteristic strength (Table 2). Spurious contacts originating as radio interference (typically with a very weak signal strength) can thus be easily filtered by the receiver or in post processing. Because the accumulation of spurious signals is obviously code-specific, we recommend a test period in a potential study area previous to the deployment of any coded transmitters to look for the frequent logging of codes with reception power similar to “real” wireless hydrophone retransmissions (as determined from either reference tags or battery status signals). Filter criteria may then be applied on a code-specific basis, or use of particular codes can be avoided.

**Performance in real studies**—Striped bass (n = 68) were surgically implanted with intraperitoneal CAFT16_3 transmitters (16 × 97 mm, 5-s pulse interval, 723 day duration, 20.5 g in water, 162 dB, Lotek Wireless Inc.). In a concurrent study, 70 summer flounder carrying external CAFT16_1 (16 × 54 mm, 5-s pulse interval, 717 day duration, 18.9 g in water, 156 dB, Lotek Wireless Inc.) transmitters are providing information on the rates and environmental cues associated with habitat use (Rowles et al. unpubl. data unref.). Transmitters on striped bass at liberty produced over 300,000 acoustic contacts in the first 2 years. Many springtime (2003) contacts came from fish passing hydrophones 6, 7, 8, 9, and 10 during rapid upriver and return movements suggestive of spawning runs, but also showed localizing or staging of fish near these hydrophones. Summertime contacts came predominantly from fish spending time in the ocean inlet. Three striped bass were detected after being tagged and leaving a similar observatory in the Saco River, Maine, and one fish tagged in New Jersey entered after being tagged and leaving a similar observatory in the Saco River, Maine, and one fish tagged in New Jersey entered

Although transmitters on both striped bass and summer flounder produce pulses at 5-s intervals at similar sound pressure levels, transmission recordings from the two species differed during extended periods in the array (Table 4, Fig. 6). The differences probably relate to residence or swimming behavior of the fish while within continuous range of the hydrophone, i.e., rapid or leisurely swimming, linear or meandering swimming, burying in the substrate (summer flounder), or aggregation (striped bass). Aggregation may promote the partial or complete occlusion of one code transmission by another (i.e., code collision). It is prudent, therefore, to be flexible to species-specific considerations when constructing temporal filters, such as decreasing the number of contacts min⁻¹ while increasing the allowed time. These rules are best determined from an initial data set of real fish at liberty in an array or under mobile telemetry. Detailed investigation into biological effects of internal transmitters on feeding, behavior, and gonad development is reported elsewhere (e.g., Lagardère et al. 1998).

**Public education and outreach**—The attributes of this estuarine observatory are available for education outreach and use by other scientists. With a mission to improve management of coastal environments through science, public education, and outreach, JCNERR developed a web page (www.StriperTracker.org) for the general public and professional development programs for K-16 educators to apply the observatory data to classroom projects (McDonnell and Hotaling 2003). JCNERR also facilitates use of the research for informal education programs with partner institutions such as the New York Aquarium. A public fish-adoption program promoted through these avenues generates program revenue beyond grant funds and vests supporting classrooms with an interest in marine science. A profile of the adopted fish is posted to the program’s Web site along with the sponsor’s name. A running history of an individual fish’s visits to individual hydrophones can be accessed through interactive graphics. Likewise, the history of a particular hydrophone, in terms of all tagged fishes that passed it, is accessed through an interactive map. These histories will soon be joined with those of physical parameters (temperature, salinity, pH) provided by JCNERR (Kennish and O’Donnell 2002). The accessibility of these real data are integrated with lesson plans for classroom use and supporting electronic publications.

The project is expected to benefit K-16 education as an attractive source of authentic material for inquiry-based learning on the environment. Findings of the National Assessment of Educational Progress Science 2000 revealed a statistically significant increase in standardized test scores of those students who downloaded and analyzed data. Thus, there exists compelling evidence that approaches to science instruction that include the use of real-time and near real-time data can improve standardized test scores (National Center for Education Statistics 2001, see http://nces.ed.gov/nationsreportcard/pdf/main2000/2002452.pdf).

**Assessment Summary**—In 2000, the Sloan Foundation challenged marine biologists to count all marine organisms by funding several high-risk telemetry projects through the Census of Marine Life program (Malakoff 2000). These pilot studies included the temporary deployment of hydrophones in several long cross-shelf transects to track estuarine emigration and dispersal of salmon smolt with small, relatively short-lived transmitters. Independent of Census of Marine Life program, researchers have applied multiple hydrophones in complement to physical/chemical sensors. One design is such as that by Heupel and Hueter (2001) where omni-directional hydrophones are placed in overlapping detection zones to provide relatively fine-scale resolution of habitat use. Even in open systems, hydrophones have been employed in overlap-
ping detection zones seeking complete coverage of limited but well-delineated fish habitat such as a coral reef (Lembo et al. 2002) or along depth contour lines (Starr et al. 2002) over periods of several months.

Intermediate to the need for short-term hydrophone telemetry of parochial species and satellite tracking of ultra-mobile species is the need for observatories that can be sustained with fairly little labor or ship time for durations of years, and that have the capability for real-time observation (implicitly, without instrument recovery). In addition to fishes, fauna in this category include seals (e.g., *Phoca vitulina*), horseshoe crabs (*Limulus polyphemus*), and portunid crabs (e.g., *Callinectes sapidus*), all of which migrate through estuaries during an important life stage.

In the case presented here, deployment of 10 wireless hydrophones and two hard-wired hydrophones provides synoptic real-time or near-real-time data on fish movements through an estuarine observatory with existing infrastructure to sample abiotic variables. The design is based on the concept of gating, rather than positioning, but this allows for confident gauging of movement among extensive habitat reaches at a coarse scale, such as for migration and stock structure studies, and multiple hydrophones allow direction to be determined in hydrophone clusters. Hydrophone placement considered the biology of potential study species, geography, bathymetry, acoustic and radio environment, existing infrastructure such as towers, and the need for real-time capability. Beyond the specific illustrative study questions above, however, an observa-
tory should also be useful for purely explorative work, which
often begins on the broad scale. For example, the subsurface
habitat (including tidal creeks) use of tagged horseshoe crabs is
currently being explored in the observatory (J. Quinlan et al.,
Rutgers University, unpubl. data unref.). The gross scale nar-
rows the task of searching numerous creeks with a mobile
hydrophone. For such an application, hydrophone placement
can be based on geophysical constraints and convenience.

The type of gear used in this observatory, i.e., wireless
hydrophones with a radio relay to shore-side dataloggers, fills a
specific niche among several scenarios of interest to biologists
working on migratory macrofauna. It is highly efficient at log-
ging the presence of both test transmitters and free-moving
fish, and because of system status signaling, allows quick
response to incidents requiring equipment service and the pre-
vention of data loss from catastrophic equipment loss. The
observatory serves both as a complement to mobile tracking
and independently as a tool for coarse-scale telemetry of move-
ment and fish habitat use. The array is easily serviced and data
are collected without boat time, a cost savings that outweighs
the savings from less-expensive independent submerged sys-
tems. The wireless system is less suitable for applications where
a float cannot be used to bear the hydrophone antenna, such as
in very deep water (owing to antennae cable length con-
straints), sites prone to periodic high sea state, or where floats
are not permitted. The wireless system in its current form is also

Fig. 6. Differences in the unfiltered reception of coded signals from similar tags on striped bass (internal placement) and summer flounder (external
tethering) when five fish were simultaneously being monitored by a single receiver (RumfsA, Hydrophone 1-3). Each circle represents a single contact.
Codes from striped bass are received at higher density (contacts min⁻¹) than those from summer flounder even during transition between reception cells
of hydrophones 1 and 2.
less suitable than autonomous loggers where long-term monitored sites are far from shore or are in an urban high-radio-noise environment. However, regional floating receivers with satellite communication could conceivably support clusters of offshore wireless hydrophones. Alternately, hydrophones might themselves be engineered to support satellite or cell communication. In addition to extending wireless range, this would allow for centralizing the receivers or even eliminating them in favor of real-time software hosted on a desktop computer.

Our experience in applying wireless hydrophones in this observatory has stimulated our understanding of how they might be applied in other, novel ways. For example, a drifting wireless design would be suitable for use in the deep open ocean to synoptically track multiple members of schooling pelagic fish, currently tracked individually. A ship with receivers could monitor a field of drifting hydrophones (~10 km radius), and small boats could deploy new hydrophones ahead of observed advances as the ship follows aggregations. Hydrophones without moorings, but with global positioning reporting capability, for such a study would be expected to last only on the order of hours or days and might then be expendable relative to recovery cost. Such a reactive, progressive monitoring design requires real-time feedback and emulate the U.S. Navy’s practice of deploying expendable sonobuoys by helicopter to focus searches for hostile submarines. Designs that we have considered for other observatory applications include modifications to the mooring and suspension tackle, which has proven to be the limiting factor in wireless hydrophone placement and maintenance. This includes staking armored hydrophones and their antennas on pilings, jetties, or fixed channel markers rather than suspending them, especially in shallow, episodically turbulent water. Alternately, hydrophones might be fixed on the bottom, with a much smaller float supporting only the antenna.

We hope this paper provides a broader understanding of the potential application and constraints of real-time instrumentation for telemetry observatories of similar spatial scale. Such estuary-wide studies are of the scale that would be useful for joining into a coast-wide effort. Estuaries may be of such value to migrant macrofauna as to form bottlenecks to their reliable interception, yet retain the ability to provide useful information independently. Further, the described instrumentation strategy is useful for the potential expansion to linked coastal observatories that support cable transmission of what would otherwise be a radio link (Schofield et al. in press). Because the low-source level acoustic signal is already up-modulated by these instruments for radio transmission, they can potentially be transformed for transmission over long distances via fiber-optic cable and can thus be integrated with a growing number of offshore physical observational platforms, such as those modeled on the LEO-15. Both goals respond to a growing demand for increased study areas to support multi-agency/multi-animal research using a common tracking system infrastructure (House Bill S.1400, see http://thomas.loc.gov/cgi-bin/bdquery/z?d108:S.1400:).

References


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