Proceedings
of the
Third Biennial
Long Island Sound Research Conference

The University of Connecticut
at Avery Point
October 18, 1996
Groton, Connecticut
Third Biennial

Long Island Sound Research Conference

Proceedings

Margaret Stewart Van Patten, editor

October 18, 1996
The University of Connecticut
Avery Point Campus
Groton, Connecticut
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Preface

The Long Island Sound Research Conference from which this proceedings springs is the third in an ongoing series that began in 1992. The conference was intended as a bi-state collaboration, with the venue alternating between the states of Connecticut and New York. The conference serves as an open forum for the presentation of any research pertaining to Long Island Sound, as thus serves as a multidisciplinary vehicle for researchers and students to realize a holistic view of Long Island Sound, an estuary of national importance.

The first conference was held at Southern Connecticut State University in New Haven, CT in 1992, chaired by the late Professor Harry O. Haakonsen of the same institution. The second, with the theme "Is the Sound Getting Better or Worse?" was held at the State University of New York at Stony Brook in September, 1994, chaired by Dr. Anne McElroy, then Director of the New York Sea Grant Institute.

This third conference was chaired by Dr. Edward C. Monahan, Director of the Connecticut Sea Grant College Program and Professor of Marine Sciences at the University of Connecticut. The conference was held at the University’s Avery Point campus.

Presenters were given the opportunity to submit extended abstracts or manuscripts at the time of the conference. Rather than being clustered by topic, the papers presented in this volume are grouped in the order in which they were presented, under the broad categories of "Estuaries," "Benthic Habitats," "Open Water," "Watersheds," and "Posters." In addition, there are summaries of two panel discussions of timely and critical topics, dredging and hypoxia.

I have taken a few liberties with the manuscripts and figures, for the sake of consistency, and note that any errors or omissions are my responsibility.

The conference organizers wish to thank the speakers, panelists, and attendees for their support to the Sound, and we further wish to convey gratitude to Sue McNamara and The Long Island Sound Foundation for organizing the conference and providing supplementary funding for the printing of the proceedings.

The conference organizers and chair hope that this volume will contribute significantly to the growing body of knowledge about Long Island Sound, and generate new ideas and collaborations. Plans are already underway for the fourth conference, to be held in New York in the fall of 1998.

[Signature]

Margaret Stewart Van Patten
Connecticut Sea Grant
Editor
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Panel Discussion

Dredging
Dredging and Dredged Material Disposal:  
State of the Practice 1996

Panel Discussion of the Issues

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Summary

Dredging, or the mechanical displacement of sediment for the purposes of creating, maintaining or extending ports and navigational waterways, represents one of the oldest ocean engineering activities, dating back to at least the tenth century BC. Historical data suggest that some of the earliest dredging activity occurred within the eastern Mediterranean Sea, where, by the end of the Bronze Age, the combination of developing maritime trade and sedimentation induced closure or depth restrictions in the major rivers leading to the construction of engineered harbors. With the spread of the Roman empire beyond the Mediterranean, northward along the western European coastline, the establishment and maintenance of ports became increasingly important and more difficult. The procedures developed to deal with the higher sediment loads and increased tidal ranges and transport energies represented a significant engineering advance and contributed directly to the continuing commercial viability of many of the European nations.

In the United States dredging to support port facilities began in the early 19th century. Prior to this period coastal ports generally displayed natural depths sufficient to accommodate the prevailing draft vessels and there was only limited interest in commercial use of inland waterways. By the early 1800's however, interest in these latter routes increased sufficiently to cause Congress in 1824 to direct the U.S. Army Corps of Engineers to “remove the snags and bars” on the Ohio and Mississippi Rivers. Intermittent dredging of coastal ports began during this same period but it was not until after 1850 that the combination of increased sedimentation caused by wide-spread “clear-cutting” of forests and increasing vessel draft lead to the general use of mechanical techniques to maintain required channel depths in coastal
harbors. In New York, for example, it was not until after 1860 and the arrival of the vessel “Great Eastern” having a 30 ft draft that continued dredging was considered necessary. Since the initiation of this dredging in the 1880’s more than $2 \times 10^9$ cubic yards of sediment have been moved to maintain the port.

Despite its long history, the environmental impact of dredging on the adjoining waterway and associated ecosystem has only recently received consideration. In the United States, the majority of studies intended to detail dredge related environmental effects first date from approximately 1970 coincident with the passage of the National Environmental Policy Act (NEPA). Initially, concerns focused on acute, short-term, effects induced by dredging and/or dredged material disposal. These studies placed particular emphasis on such items as mass mortality of selected benthic or pelagic organisms, reductions of regional dissolved oxygen levels, and impairment of coastal recreational habitat. With few exceptions these concerns proved to be unfounded. Impacts, if any, tended to be subtle, sub-lethal, and long-term. These characteristics make it difficult to establish simple “cause and effect” relationships in coastal waters due to confounding influences resulting from multiple types and sources of contaminants. This “signal-to-noise” problem represents a particular challenge to the study of dredge-induced environmental effects.

In Long Island Sound detailed studies of the effects of dredging and dredged material disposal began in the early 1970’s within and adjacent to New Haven Harbor. These studies followed the closing of the majority of the historical disposal areas, by the newly established EPA, and as a result involved both project specific studies and surveys to assist in the designation of new open water disposal sites. The matter of site designation was of particular concern first in the eastern Sound where plans to dredge the navigational channel to accommodate deeper draft submarines were delayed due to the absence of a reasonably proximate and/or acceptable disposal site. Litigation associated with these efforts lead in 1978 to the establishment by the New England Division, Corps of Engineers of DAMOS - the Disposal Area Monitoring System - a continuing monitoring program intended to facilitate evaluations of both local and regional impacts of dredging and dredged material disposal. This program built on knowledge developed by the earlier Corps sponsored Dredged Material Research Program (DMRP) and provided support essential to the subsequent Field Verification Program (FVP), a joint EPA/Corps research effort complementing the establishment of scientifically based regulatory criteria. DAMOS continues today and has resulted in a substantial list of publications and reports contributing significantly to our understanding of the environmental effects of dredging.

Each of the panel’s speakers built on this historical background using it as justification for present practices and protocols and a basis for required future work. Tom Fredette, DAMOS Program Manager, began by summarizing 20 years of DAMOS monitoring and the extensive list of resulting reports and publications. This work and the fact that no acceptable alternative to open water disposal has been found has resulted in the development of capping procedures in which any moderately contaminated dredged material placed at one of the Long Island Sound disposal sites is covered, or capped, by relatively clean sediments. Studies have shown such capping is possible and results in a stable deposit offering effective isolation of the contaminated materials. Touching briefly on the “signal-to-noise” issue, Dr. Fredette asked the audience to consider the leading management question “Have we learned enough?” or alternatively “How will we know when we have learned enough?”

The capping procedures in general use in Long Island Sound, introduced by Dr. Fredette, were discussed in more detail by Armand Silva with an emphasis on settlement of the disposal mound and pore water migration. Summarizing a variety of field observations and laboratory analyses he showed excellent agreement between measured and predicted settlement and migration rates. Although the results were not simply generalizable, showing evident material and site dependence, they nicely complement evaluations of contaminant transport and the overall effectiveness of capping as an isolator. Recognizing no sediment
deposit is absolutely stable. Dr. Silva briefly introduced the Geogrid mattress, a synthetic textile retainer filled with crushed stone or similar high density aggregate, as a means to effectively armor a placed deposit. Such a system used in combination with advanced placement or sediment delivery techniques has the potential to significantly reduce surface erodibility and any associated contaminant transport. This engineered armoring may represent the next level of capping to be used selectively as a function of contaminant characteristics, transport potential, and ecosystem sensitivity.

The acceptability of open water disposal and required extent of capping or armoring is at present based on a combination of sediment bulk chemistry and bioassays. These numeric criteria are said to be risk based although these relationships are often less than clear. The need for clearer and more accurate risk assessments as an essential component of future evaluations of the effect of dredged material disposal was discussed briefly by John Scott. He described a three step process, driven by the tiered approach to dredge material management, in which risk estimates are developed from an understanding of contaminant release, biological exposure, and species effects. Some of these areas, particularly effects, clearly need additional research prior to operational use.

The question of just how to most effectively and accurately resolve biological effects induced by dredging was taken up by Joe Crivello beginning with the matter of a meaningful endpoint. Two related candidates were mentioned, decreased fecundity and genetic diversity. Contaminant effects on both are, in themselves, expected to be subtle before any consideration of the confounding influence of multiple contaminants and contaminant sources. Resolution requires long term controlled experiments, with a minimum two-year duration, emphasizing genetic effects including stress impacts on individual cells. Such investigations are ambitious but clearly warranted if any long-term chronic effects of dredged material in coastal waters are to be resolved.

The issues discussed by each of the panelists highlighted the need for initiation of the “next generation” of monitoring and effects assessment. These activities would be science rather than management and/or protocol driven and be designed to answer carefully formulated questions. Primary concerns include quantitative measurements of contaminant migration and the associated biotic exposure and effects. Such issues are best addressed within a series of controlled experiments by a multidisciplinary team of scientists and engineers. There appears to be general agreement that acute effects, beyond the obvious, are generally not a concern at the low to moderate levels of sediment contamination characteristic of most areas in Long Island Sound. Long-term chronic effects may be a different matter and require careful consideration. The form of this consideration represents a substantial challenge to future investigators and the project management community.
Tidally-Driven Residual Circulation in Estuaries with Lateral Depth Variation, with application to the Connecticut River and LIS

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Tidally-driven residual circulation in estuaries with a lateral bottom slope has been studied analytically with a horizontally two-dimensional depth-integrated model. Exchange flow is found to be correlated with topography. The magnitude of this exchange flow mainly depends on four parameters: the ratio between the minimum depth on the shoal and the maximum depth in the channel, the ratio between the length of the estuary and the tidal amplitude at the mouth and the minimum depth, the ratio between the length of the estuary and the tidal wave-length, and the ratio between the tidal time scale and the decay time scale due to friction. The maximum residual velocity is only weakly dependent on the width-length ratio. Generally, a net landward flow occurs over the shoals and is balanced by a return flow in the channel. The exchange decreases monotonically towards the head of the estuary. The along-channel residual velocity changes nearly linearly from a maximum positive value (into the estuary) on the shoal to a minimum negative value (out of the estuary) in the center of the channel. The transverse residual velocity is convergent at the center of the channel. The mean elevation shows a setup at the head. This drives the outward residual flow in the channel. The maximum longitudinal residual velocity is highly dependent on the length of the estuary. When the length of the estuary is about a quarter of the wave length, the magnitude of the residual velocity reaches its maximum. The model is applied to the Connecticut River and Long Island Sound estuaries to obtain tidally induced residual flow components.
A Field Investigation of the Turbidity Maximum in the Connecticut River Estuary

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Introduction

The transport of fine-grained sediments and associated nutrients and contaminants to and through the Connecticut River Estuary is affected by a variety of interactions between the water column density and the local velocity field. These interactions vary over a range of spatial and temporal scales, producing a suspended material field characterized by a high degree of variability with concentrations varying over several orders of magnitude. A significant portion of the temporal variability is the result of the monthly spring-neap tidal cycle and longer term seasonal fluctuations in streamflow. The remainder is dominated by the passage of short-term high energy storm events with the potential to induce both local and far-field effects modifying tidal conditions, stream discharge and the surface wind-wave field.

The factors affecting the spatial distributions of suspended material are less well understood. Of particular initial interest is the character of the turbidity maximum (TM), a local peak in suspended material concentrations with values typically higher than those observed upstream or downstream of the feature. Such distributions have the potential to affect particulate residence time within the estuary and associated contaminant reaction or biotic exposure times. For the Connecticut River, one must begin with the fundamental question “Is there a turbidity maxima in this system?”, to be followed by “Where is it?” and “What are the governing factors?”. Comparisons of the primary characteristics of the Connecticut River to those of other estuarine systems where turbidity maxima have been observed (Table 1) suggest that there should be a TM in the Connecticut, most probably in the vicinity of the limits of salt intrusion. Given these similarities, a field investigation intended to determine if a TM is present in the Connecticut River, and if so, to detail its response to tidal and streamflow conditions, was initiated in 1992. The following summarizes some of the principal findings of this investigation.

Methods and Procedures

Time series characteristics of the spatial distribution of suspended materials in the Connecticut River Estuary were detailed using a combination of shipboard hydrographic surveys and long-term deployments of three bottom mounted instrument arrays. Twelve hydrographic surveys were conducted during the period August 25, 1992 to August 8, 1994 covering a range of seasonal, streamflow, and tidal conditions (Table 2). Surveys began in the vicinity of the mouth of the river with sampling conducted at 15 stations distributed along the navigational channel (Figure 1). Each survey required approximately 1.5 hours to complete, providing a reasonably synoptic view of the suspended material field characteristics. Sampling at each station included CTD profiling of the vertical density structure using a Sea-Bird Electronics
SBE 19 Seacat conductivity, temperature, depth (CTD) system. Concurrent suspended material concentrations were detailed using a D&A Instrument Co. optical backscatterance (OBS) probe mounted directly on the CTD. Water samples collected at alternate stations, using 3 to 5 liter Niskin bottles, provided continuing checks on instrument accuracy and stability and provided a basis for the calibration of the optical backscatter probes.

The bottom mounted instrument arrays were deployed at the stations A1, A2, & A3 (Figure 1) for two extended periods, the first in January-February, 1993 (38 days) and the second in April-May, 1993. The first deployment period was characterized by less than average streamflows. Discharge during the second progressively decreased from a maximum of approximately 1700 m³/sec at the start to nearly 250 m³/sec at the end of the deployment period. Each array contained a two axis electromagnetic current meter, temperature and conductivity sensors and a combination of optical backscatterance and/or optical transmission sensors pre-calibrated to monitor suspended material concentrations. Each array was self-contained and programmed to burst sample the sensors four times each hour. The instruments sampled conditions approximately 1 meter above the sediment-water interface.

Results and Conclusions

The variety of hydrographic and array data provide clear indication of the presence of a turbidity maximum in the Connecticut River under most tidal and streamflow conditions. Longitudinal position within the navigational channel appears to be primarily a function of streamflow. Examination of representative survey data indicate that during periods of low flow (i.e., discharge below annual average of 550 m³/sec) the TM appeared during the flood tide as a well defined feature centered in the area approximately 12 km upstream in the vicinity of the 5-10 psu isohaline (Figure 2). Peak suspended material concentrations reached approximately 35 mg/l, significantly exceeding those observed in areas both upstream and down of the TM. The onset of the ebb during low streamflows effectively dispersed the TM resulting in a poorly defined feature and several secondary “pockets” of high near-bottom concentration (Figure 3). These features in combination with the general increase in background suspended material concentration appear representative of a substantial alteration in vertical mixing associated with the ebbing tide.

Increasing streamflows to values slightly in excess of the annual average results in a downstream migration of the TM with the feature centered near 9 km during the ebb and 4 km on the flood (Figures 4-5). Peak concentrations during the flood are similar to those during the ebb and differ little from those observed during the low flow periods (Figures 2-3). The feature definition is essentially similar during both the ebb and flood, and there is little indication of the dispersion observed during low flow-ebb conditions (Figure 3).

The position of the TM with respect to the density field and the associated isohalines at higher flows is only slightly different than that observed during low flow conditions. In both cases the TM was positioned within the intruding tongue of high salinity waters. During low flows the feature was centered near the 10 psu isohaline. With increasing flow the center of the feature was shifted to higher values in the vicinity of the 25 psu isohaline. This shift appears to be primarily the result of the increase in stratification and the decreasing slope of the density surfaces.

A substantial change in the positioning of the TM relative to the density field was observed during the ebb of May 6, 1993. Here, with a streamflow of approximately 640 m³/sec, the TM was
centered immediately upstream of the limit of salt intrusion largely within the fresh river water (Figure 5). This appears to be primarily the result of interactions between the outgoing river water and the intruding density front. These interactions favor the development of lower near bottom velocities enhancing the aggregation and settlement of particles advected downstream by the river waters. A survey conducted during the slack water period immediately preceding this ebb showed the flood tide TM in the process of breaking up, with a portion remaining intact within the density front separated from a second larger piece by approximately 1 km. The onset of the ebb reunited these fragments resulting in a developing TM upstream of the high salinity waters. This feature appears to have been further enhanced by continuing particulate settlement. A summary of the TM characteristics observed during each of the hydrographic surveys is provided in Table 3.

The time series array data also provide clear indication of the presence of turbidity maxima in the Connecticut River. Comparison of conditions at Stations A1 and A2 during the intermediate flow conditions of early May, 1993, for example, show that as the flood begins near the end of the day on May 4th (Figure 6), the salinity at the downstream station (A1) progressively increases. The passage of this front past the instrument array produces an abrupt increase in suspended material concentrations followed by an equally abrupt decrease with the arrival of generally high salinity water. This pattern is repeated during the following ebb.

A similar response to the migration of the salinity intrusion is observed at the upstream station (A2). Here however, the pattern is less distinct with the advancing front producing an abrupt increase in material concentrations as it arrives, but, only a slight decrease following passage. This response suggests that the TM in this area is substantially larger longstream than that observed at A1. In addition to the spatial differences, the time series data show the ebb response to be less distinct than the flood it representative of the complexity of interactions between the ebbing river waters and the salinity intrusion suggested by the hydrographic data and discussed above.

Discussion

Initial analysis of the variety of field data obtained over the project period provides clear indication of the presence of a turbidity maximum in the Connecticut River under most tidal and streamflow conditions. The fundamental characteristics of this feature are similar to those displayed by the TM's previously observed in other dynamically and sedimentologically equivalent systems such as the Weser River in Germany (Grabemann and Krause, 1994) or the Tamar in England (Uncles, et.al., 1991). In common with the majority of these systems, the Connecticut River TM displays moderate variability with an evident fundamental dependence on streamflow. Additional factors contributing to variability including tidal phase, surficial sediment characteristics, and the presence or absence of bordering shallows. The role of this latter factor, including consideration of the three-dimensional character of the flow within the estuary, is difficult to resolve, at present, due to the two-dimensional nature of the data obtained in the surveys conducted as part of this project. Additional measurements to supplement the along-channel sampling with detailed cross-channel observations must be obtained to properly evaluate the extent to which sediments transported to, or eroded from, bordering shallows contribute to the TM observed within the navigational channel. Such observations and continuing analysis of the data provided by this study will allow evaluation of the specific processes responsible for the formation of the Connecticut River turbidity maximum.
References


Table 1. A Comparison of the Three Major European Estuaries and the Connecticut River.

<table>
<thead>
<tr>
<th>Estuary Name</th>
<th>Estuarine Classification</th>
<th>Mean Annual Discharge</th>
<th>Tidal Range</th>
<th>Peak Tidal Currents</th>
<th>SMC Range</th>
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</thead>
<tbody>
<tr>
<td>Gironde (Allen et al., 1977)</td>
<td>Partially Mixed to Salt Wedge</td>
<td>725 m$^3$ s$^{-1}$</td>
<td>5 m</td>
<td>3 m s$^{-1}$</td>
<td>0.2-10 g l$^{-1}$</td>
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<td>Tamar (Uncles et al., 1990)</td>
<td>Partially Mixed</td>
<td>40 m$^3$ s$^{-1}$</td>
<td>3.3 m</td>
<td>0.9 m s$^{-1}$</td>
<td>0.02-1 g l$^{-1}$</td>
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<tr>
<td>Weser (Riethmuller, 1988)</td>
<td>Partially Mixed</td>
<td>300 m$^3$ s$^{-1}$</td>
<td>3.8 m</td>
<td>1.2 m s$^{-1}$</td>
<td>0.03-1.5 g l$^{-1}$</td>
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<tr>
<td>Connecticut River</td>
<td>Partially Mixed to Salt Wedge</td>
<td>560 m$^3$ s$^{-1}$</td>
<td>1 m</td>
<td>1 m s$^{-1}$</td>
<td>.0005-0.1 g l$^{-1}$</td>
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Table 2. Longitudinal Hydrographic Survey Dates, Riverflow and Tide Conditions

<table>
<thead>
<tr>
<th>SURVEY DATE</th>
<th>STREAM FLOW (M³/S)</th>
<th>TIDE STAGE</th>
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<tr>
<td>25-AUG-92</td>
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<td>09-NOV-92</td>
<td>402.1</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>16-NOV-92</td>
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<td>•</td>
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<td>555.1</td>
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<td>•</td>
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<tr>
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<td>•</td>
<td>•</td>
</tr>
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<td>23-MAR-94</td>
<td>603.2</td>
<td>•</td>
<td>•</td>
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<td>03-AUG-94</td>
<td>271.0</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>08-AUG-94</td>
<td>213.8</td>
<td>•</td>
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</tr>
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Table 3. Summary of Longitudinal Transects in the Connecticut River.

<table>
<thead>
<tr>
<th>Date</th>
<th>Tide Stage</th>
<th>TM Present</th>
<th>TM Position (upstream from mouth)</th>
<th>Range of SMC in TM (mg/l)</th>
<th>Salinity Range at TM (PSU)</th>
<th>River Flow (m^3/s)</th>
<th>Lunar Phase</th>
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<tr>
<td>10/01/92</td>
<td>Flood</td>
<td>Yes</td>
<td>10-14 km</td>
<td>20-70</td>
<td>5-20</td>
<td>244.6</td>
<td>Neap</td>
</tr>
<tr>
<td></td>
<td>SBE</td>
<td>No</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>Neap</td>
</tr>
<tr>
<td>10/02/92</td>
<td>Ebb</td>
<td>Yes</td>
<td>9-11 km</td>
<td>10-30</td>
<td>8-15</td>
<td>226.1</td>
<td>Neap</td>
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<tr>
<td></td>
<td>SBF</td>
<td>No</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>Neap</td>
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<tr>
<td>11/16/92</td>
<td>Flood</td>
<td>Yes</td>
<td>3-5 km</td>
<td>20-60</td>
<td>20-28</td>
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<td>Yes</td>
<td>5-9 km</td>
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<td>1-20</td>
<td>555.1</td>
<td>Neap</td>
</tr>
<tr>
<td>04/06/93</td>
<td>Ebb</td>
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<td>--</td>
<td>--</td>
<td>--</td>
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<td>Spring</td>
</tr>
<tr>
<td>05/06/93</td>
<td>SBE</td>
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<td>--</td>
<td>--</td>
<td>--</td>
<td>640.0</td>
<td>Spring</td>
</tr>
<tr>
<td></td>
<td>Ebb</td>
<td>Yes</td>
<td>6-12 km</td>
<td>20-40</td>
<td>&lt;1-10</td>
<td>--</td>
<td>Spring</td>
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<td>SBF</td>
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<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>Spring</td>
</tr>
<tr>
<td></td>
<td>Flood</td>
<td>Yes</td>
<td>3-5 km</td>
<td>10-30</td>
<td>10-26</td>
<td>--</td>
<td>Spring</td>
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<tr>
<td>03/23/94</td>
<td>Ebb</td>
<td>Yes</td>
<td>1-4 km</td>
<td>20-50</td>
<td>1-20</td>
<td>603.2</td>
<td>Spring</td>
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<tr>
<td>08/03/94</td>
<td>Ebb</td>
<td>Yes</td>
<td>9-14 km</td>
<td>10-30</td>
<td>1-15</td>
<td>271.0</td>
<td>Spring</td>
</tr>
<tr>
<td>08/08/94</td>
<td>Ebb</td>
<td>Yes</td>
<td>10-11 km</td>
<td>10-30</td>
<td>10-25</td>
<td>213.8</td>
<td>Spring</td>
</tr>
<tr>
<td></td>
<td>SBF</td>
<td>No</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>Spring</td>
</tr>
</tbody>
</table>
Figure 1. Station locations within the Connecticut River.
Figure 2. Suspended material concentration profile for the October 1, 1992 axial survey. Line contours represent the salinity in units of the practical salinity scale.
Figure 3. Suspended material concentration profile for the August 3, 1994 axial survey. Line contours represent the salinity, in units of the practical salinity scale.
Figure 4. Suspended material concentration profile for the November 16, 1992 axial survey. Line contours represent the salinity in units of the practical salinity scale.
Figure 5. Suspended material concentration profile for the May 6, 1993 axial survey. Line contours represent the salinity in units of the practical salinity scale.
Figure 6. Comparison of Station A1 and A2 time series showing movement of density front and TM. The backscatter data has been normalized for plotting purposes.
Relative Sea Level Rise along the Eastern USA Coast over the last 1000 Years

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Abstract

Future rates of sea level rise are of importance because of their impact on coastal development. We studied the "fossil record" of relative sea level rise in coastal salt marsh sequences from the US east coast from the last 1000-1500 years, and determined small fluctuations in the rate of sea level rise over that period. We found about local average rates during the period from AD 500-1200, whereas very slow rates were common from AD 1250-1650. The period from AD 1650 until recent had much faster rates, synchronous with a general warming trend. Many "wiggles" in the sea level rise curves are not associated with trends in the climate curve, and, most notably, the strong acceleration in temperature rise during the 20th century is not associated with a strong increase in the rate of sea level rise.

Introduction

Sea level has risen about 120 meters since the last deglaciation at rates of up to several cm years, which have slowed over the last 3000 years to about 1 mm/a (Belknap and Kraft, 1977; Patton and Horne. 1992; van de Plassche et al., 1989). Tide gauge data from Long Island Sound indicate modern rates between 2-3 mm/a (Gornitz, 1992), raising the questions: 1. When did these higher rates of sea level rise start? and 2. Is there possibly a relation with the modern global warming of the last 100 years? We studied variations in the rates of relative sea level rise (RSLR) over the last 1000-1500 years and possible relations with climate fluctuations. We outline the methods that we have developed to extract detailed RSLR data from coastal salt marsh sequences and present data on the onset of the recent RSLR acceleration.

Coastal Salt Marsh Deposits

Coastal salt marshes are depo-centers of organic-rich, fine-grained muds and peats. Overall, marsh accretion keeps up with the rate of RSLR, but when studied in detail, marsh sequences show evidence of periods of relative drowning and emergence. Apparently, marsh accretion is in dynamic equilibrium with RSLR (Allen, 1990) and the periods of marsh drowning and emergence can be used as evidence for variations in the rates of RSLR (Thomas and Varekamp, 1991; van de Plassche, 1991; Varekamp et al., 1992). Mudflat and marsh environments extend over a vertical distance of about 1 meter and may form plains many miles wide. Cross sections from sea to land over a marsh complex show a distinct floral zonation (Niering et al., 1977) as well as changes in sediment characteristics and faunal contents. These changes are probably a complex function of food web structure, inundation characteristics and atmospheric exposure time frequencies. Physical changes in sediment are largely expressed in contents of organic matter or mud, whereas chemical changes also involve sulfur diagenesis. Sea water sulfate is reduced in the pore waters of salt marsh deposits by decay of organic matter and subsequently fixed as
Fe-sulfides. The extent of sulfide fixation can be a function of sulfate supply, contents of labile organic matter, or availability of reactive iron. Our studies suggest that the mud-poor high marsh deposits (between mean high water and highest high water) have relatively low S abundances and the S-fixation is limited by iron availability (Varekamp, 1991; Nydick et al., 1995). In mud-rich low marshes, the presence of labile organic matter is the limiting parameter in S fixation, but S contents are higher. We use combined Fe-S-C_org data as a qualitative indicator for paleo marsh environment. A more quantitative indicator of distance of paleomarsh surface from paleo mean high water can be derived from the vertical zonation of agglutinated salt marsh foraminifera (unicellular benthic organisms). These benthic faunal assemblage zones have been mapped in several modern marshes (Scott and Medioli, 1980) and show a pattern of decreasing species diversity with increasing distance from mean sea level, no foraminiferal species occur above the highest high water line.

Techniques and Study Sites

The vertical zonations in marsh facies can be applied to fossil marsh deposits (Thomas and Varekamp, 1991), which can be obtained by coring. Cores of 2-3 meter provide a record on the order of 2000 years and can give detailed RSLR information. The cores are divided into 2-5 cm intervals and the whole core is sliced up, providing a continuous record with several decades as the theoretical limit in absolute age resolution. Faunal data from marsh sequences can be applied towards a zonal chart for a specific marsh or tidal regime and these data are then summarized in marsh paleo environmental (MPE) curves (Thomas and Varekamp, 1991). The sediments are leached and chemically analyzed for pollutants (for dating purposes) and S, Fe and Loss on Ignition, the latter a proxy for organic carbon. The core samples are dated by radiocarbon, ^{210}Pb, and with the onset of metal pollution (anthropogenic marker). The radiocarbon dates are calibrated in calendar years after Stuiver and Pearson (1993), and ages between marker points are interpolated, assuming a continuous record. The data are then presented as mean sea level rise curves, showing the level of paleo-mean sea level below modern mean sea level versus calendar year. The slope fluctuations of these curves show variations in the rate of RSLR, but the absolute values are strongly influenced by marsh location, e.g., specific crustal rebound characteristics and marsh compaction rates. We therefore provide a technique to compare these variations in the rates of RSLR over a larger region: the slopes of the RSLR curves in 50 year time slices are normalized by the average rate over the last 1000 years ("rate-ratio" curves), which show periods of anomalous rates of RSLR with respect to the local average.

We studied the marshes of Barn Island, the Patuquott River, the Guilford marshes and the Clinton marshes (all in Connecticut), as well as marshes along Delaware Bay (Dennis Creek, NJ). Each site was surveyed through extensive coring for its local stratigraphy and 2-3 cores from each marsh were studied in detail. Each core is individually dated and presents an independent sea level rise record. Compaction of marsh sequences in the upper 1-2 meter is very limited, but deeper sections of the marsh series are probably dewatering, taking the top part "along for the ride" (Pizzuto and Schwendt, 1996). Rates of accretion and RSLR thus may vary strongly within a single marsh and between marshes, so studies that integrate age/depth points from separate cores in a single RSLR graph may create artifacts in apparent rates of RSLR.

Results

Marsh paleoenvironmental curves (Figure 1) show that the marshes undergo periods of drowning and emergence as a result of the subtle interplay between marsh accretion and rate of RSLR. Some of the fluctuations are the result of local geomorphic changes in the marsh systems, whereas others show up in
Figure 1. Marsh paleo environmental curves for cores GA, GD, GK (Guilford), cores F, E (Clinton), and core DCA (Dennis Creek).
Figure 2. A. Relative sea level rise curves for Guilford (cores GA, GD, GK), Clinton (cores F, E) and Dennis Creek (core DCA). Vertical axis is depth of mean sea level (MSL) below modern mean sea level (MMSL); the time scale is in calendar years calibrated from $^{14}$C ages.

B. "Rate ratio" plot for the Guilford and Dennis Creek marshes with the annual $^{18}$O record from the GISP2 ice core. Note the close correlation between the curves after AD 1650, but the strong increase in temperature since AD 1850 is not accompanied by a strong acceleration in the rate of sea level rise.
many different cores throughout the marsh. The age data are transformed into age-depth curves, which are then recast into mean sea level rise curves (Figure 2A). The data show that strong variations in the rate of RSLR occur, and many curves show evidence for increased rates of RSLR in the core top sections. The MPE curves also show in a qualitative way the "drowning tendencies" in the tops of many cores. The data from Guilford marsh can be summarized as follows: the period from AD 500 to 1200 is characterized by relatively slow-to-average rates of RSLR (about 1 mm/a), the period from AD 1500 to 1600 by very slow rates (<0.5 mm/a) and the period from AD 1600 - 1996 by very rapid rates (2.5 mm/a). The records for the last 300 years show also abundant variation, with possibly a slight deceleration during the 18th century. The RSLR record from Clinton marsh (Vanekamp et al., 1992), about 15 miles east of Guilford, is shown for comparison and is very similar to that of the GK core in Guilford (Nydick et al., 1995). The RSLR record from a core with excellent time resolution from Dennis Creek (NJ) shows a slow rate of RSLR from AD 1000-1600, followed by a sudden increase to >6 mm/a. This is typical for the whole marsh, where both deduced rates of RSLR and marsh accretion rates seem to have increased dramatically about 350-400 years ago.

The records from Dennis Creek marsh and from along Long Island Sound can not be easily compared when plotted directly in the same graph because of the large differences in the rates of RSLR. We have plotted the data in "rate ratio" plots (Fig. 2B), which indicate periods when the rates are anomalous compared to the local average rate. When >1, the rates are relatively fast, when <1, they are relatively slow. The data show that for most of the last 1000 years, rates were slightly below average, but since about AD 1600-1650, rates both along Delaware Bay and in Guilford marsh have doubled and tripled. Interestingly, there is no evidence for an acceleration during the last 150 years, conform observations from tide gauge records (Douglas, 1992).

Conclusions

Rates of RSLR have varied by factors of up to 3 over the last 1000-1500 years, with the fastest rates occurring during the last 300-400 years. These observations are in agreement with a varied set of data from other sources, e.g., land loss and archeological studies (Kearney and Stevenson, 1991). The high rates started around AD 1600, which precedes the time that is generally considered to be the onset of modern global warming (e.g., the end of the last century). No acceleration is found associated with the rise in temperatures of this century, making the link between rates of sea level rise and small climate wiggles tenuous. On a larger scale, climate started to warm up from about AD 1600 on (Bradley and Jones, 1993; Stuiver et al., 1995), and this is also the time that the rates of RSLR started to increase. Predictions on future rates of RSLR (Watson et al., 1996; Baltuck et al., 1996) should keep in mind that it is possible that the climate and sea level systems fluctuate around an equilibrium value. When the systems are forced too strongly, they may generate a new equilibrium at a different level, which may explain the sudden jumps in the rate of sea level rise in the past. It is not yet clear what these forcings exactly are, but given the record of the past, it is possible that sudden changes in rate of sea level rise may occur again. It is also possible that this new high rate since the last 300 years will be stable for some centuries, and remain constant despite further temperature rise.

Acknowledgments

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LP0267. We thank many sea level researchers for their support and/or inspiration, especially Orson van de Plassche, Jim Pizzuto, John Kraft, and John Allen.

References


Varekamp, J. C., Thomas, E., and van de Plassche, O., 1992. Relative sea-level rise and climate change over the last 1500 years (Clinton, CT, USA). *Terra Nova*, v. 4, p. 293-304.

Impact of Flow Restrictions on Salt Marsh Chemistry and Long Island Sound Water Quality

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The Connecticut coast of Long Island Sound (LIS) is a region of intensive human development. One of the consequences of growth has been the alteration of the tidal flow regime in many coastal marshes. The construction of transportation arteries along the coast has resulted in reduced tidal flow into marshes through narrow gaps beneath bridges and through embankments. In addition, dikes or tide gates have been installed at the mouths of many Connecticut marshes for the purpose of reducing water levels within the marshes. Tide gates, which are used for flood and mosquito control and to allow salt-hay mowing, are simple flap valves which close against a frame to prevent the incoming tide from flooding the marsh, but which open on the ebb tide to allow the marsh to drain. In many cases, the tide gates are operated on a seasonal basis, being left open in the winter months to allow a period of “normal” tidal flushing.

The reduction of tidal flow may lead to two types of changes in marsh chemistry: increased oxidation of marsh sediments due to the lower water table; and a reduction in tidal exchange of material (organic matter, nutrients, sediments, metals) between the marsh and LIS. These chemical changes may result in significant water quality problems both for the marsh and for LIS:

1. The oxidation of previously accumulated sulfide and sulfide-containing minerals (e.g., pyrite) may result in acidification (see Gosling and Baker 1980; DeLaune and Smith 1985; Soukup and Portney 1986; Vranken et al. 1990; de Jong et al. 1994; Evangelou and Zhang 1995).

2. Trace metals may be mobilized by oxidation of sulfide-bound metals and/or by the low pH (see Boulegue et al. 1982; Davies-Colley et al. 1985; DeLaune and Smith 1985; Gambrell and Patrick 1988; Moore et al. 1988; Sacki et al. 1993; Gambrell 1994).

3. Release of soluble, partly decomposed organic matter may result in increased oxygen demand in the water column, resulting in low dissolved oxygen (DO) levels (Portney 1991).

4. The combination of increased organic matter decomposition and reduced tidal subsidy of mineral sediment may lead to lower sedimentation rates within the marsh, or even to subsidence (Armentano and Menges 1986; Cahoon and Turner 1989).

5. Lower sedimentation rates may result in a reduction in the amount of N and C which are removed from the system (and hence do not reach LIS) through burial in the marsh.
Lower sedimentation rates also affect the ability of the system to be restored through re-establishment of tidal flushing (Roman et al. 1995).

For at least one tide-gated marsh, there is evidence that subsidence has resulted in a marsh surface which is ~1 m lower in elevation than comparable unrestricted marshes (US Army Corps of Engineers 1994), implying that restoration of tidal flow may result in inundation of the marsh surface and conversion to open water.

We have examined the effects of flow restrictions on salt marsh chemistry and water quality using several restricted and unrestricted marshes in Branford and Guilford, Connecticut, along the coast of LIS. Two marshes (restricted and reference) were the sites for a study of surface and pore waters from August 1994 to November 1995 (Anisfeld and Benoit 1996). In addition, fifteen sediment cores were collected from 6 restricted, reference, and restored marshes during 1994 and 1995, in order to determine accretion rates and assess whether the impact of flow restriction could be seen in the marsh sediments (Anisfeld et al. 1997). Results from these two investigations are discussed below.

**Surface and pore waters.** Summertime operation of the tide gate in the restricted marsh (Sluice Creek) during 1995 led to dessication of the marsh surface, with aerobic conditions prevailing in the top several cm of the sediments. As a result, dissolved oxygen concentrations in surface waters were generally higher in the restricted marsh than in the reference marsh (Hoadley Creek). This is in contrast to results in other flow-restricted systems, where leaching of organic matter and/or reduced Fe and S lead to high chemical oxygen demand and low DO (Portnoy 1991). Another consequence of the flow restriction was a disconnection between the main channel, the small drainage ditches, and the sediments: these separate environments were no longer frequently connected by high-tide flushing. This allowed oxidative processes to dominate in the sediments, with the buildup of high nutrient concentrations and low alkalinity during the summer. In fall 1995, there was a month-long period of high nutrient levels and acidic conditions in surface waters within the tide-gated marsh (pH as low as 3.6). Based on pore-water and surface water H₂S, SO₄²⁻, Cl⁻, and alkalinity measurements, this episode appears to be linked to oxidation of reduced sulfur, which occurs as a result of air entry into previously anoxic sediments due to restricted flow (Figure 1). Clean-technique trace metal measurements showed that the acidic conditions led to mobilization of Pb, Cu, Ag, and Cd, with extremely high levels observed in the dissolved phase (>2000 ng/L dissolved Pb).

**Sediment cores.** High bulk densities and low C and N concentrations were found at depth in 6 sediment cores from 3 restricted marshes, which we attribute to a period of organic matter oxidation, sediment compaction, and subsidence upon installation of flow restrictions. Nonetheless, recent sedimentation rates (as determined by ¹³C and ²¹⁰Pb dating) do not differ greatly between restricted and reference marshes; the restricted marshes have apparently reached a new equilibrium at a lower elevation. A marsh which has been "restored" by removal of flow restrictions has a much higher sedimentation rate; it appears to be "catching up" to higher water levels. The differences in sedimentation rates between restricted, reference, and restored marshes are due primarily to differences in organic matter and pore space accumulation, while mineral supply is not correlated with flow restriction, perhaps because of the seasonal operation of the tide gates (Table 1). C and N burial are similar in the restricted and reference marshes, while the restored marsh removes significantly greater amounts of both C and N (Table 1).
Figure 1. Excess sulfate plotted against acid-neutralizing capacity (ANC) for pore waters from the reference and restricted marshes, sampled in fall 1995. Excess sulfate is defined as \([\text{SO}_4^{2-}] - ([\text{Cl}] / 19.3)\), where 19.3 is the \([\text{Cl}] : [\text{SO}_4^{2-}]\) ratio in seawater. Alkalinity generation at the reference marsh is linked to sulfate depletion, while the low-ANC pore waters of the restricted marsh are high in sulfate as a result of oxidation of reduced sulfur.

Table 1.

Accretion rates (based on \(^{137}\text{Cs}\) dating), contribution of IM (inorganic matter), OM (organic matter), and pore space to accretion, and N and C burial rates. Different letters in a column indicate statistically different values.

<table>
<thead>
<tr>
<th>Core name</th>
<th>Accretion rate (cm yr(^{-1}))</th>
<th>Burial rate (g m(^{-2}) yr(^{-1}))</th>
</tr>
</thead>
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<tr>
<td></td>
<td>overall</td>
<td>IM</td>
</tr>
<tr>
<td>Restricted marsh</td>
<td>0.29 ± 0.08</td>
<td>0.039 ± 0.022</td>
</tr>
<tr>
<td>(average of 6 cores)</td>
<td>a</td>
<td>a</td>
</tr>
<tr>
<td>Reference marsh</td>
<td>0.37 ± 0.07</td>
<td>0.029 ± 0.013</td>
</tr>
<tr>
<td>(average of 6 cores)</td>
<td>a</td>
<td>a</td>
</tr>
<tr>
<td>Restored marsh</td>
<td>0.66 ± 0.04</td>
<td>0.041 ± 0.011</td>
</tr>
<tr>
<td>(average of 2 cores)</td>
<td>b</td>
<td>a</td>
</tr>
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References


Observations on the Hydrography of the Connecticut River During High and Low River Discharges

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Introduction

The Connecticut River is the largest river in the New England region. Running due south for a distance of 660 km, from the Canadian border to the Connecticut shore, the river drains an area of 29,000 km². The river then discharges into the largest estuary in New England, Long Island Sound. Both the river and the sound are vital economic and recreational resources for the region. Yet, despite the significance of these systems, the hydrodynamics and interaction of the river with the sound has only been infrequently studied and is still poorly understood.

We do know that the Connecticut River, at one time or another, has been classified in each of the four classic circulation modes: salt-wedge, partially mixed, well-mixed, and sectionally homogenious (Garvine, 1975; Horne and Patton, 1989, Szabados, 1975). During low flow salt has been detected as far as 25 km upstream; during high flow the river is completely flushed, surface to bottom, of salt. Garvine (1974) documented the extent and shape of the riverine ebb plume during high discharge and found that the buoyant freshwater can be mixed across the sound and transported out the eastern end. Horne and Patton (1989) conducted several hydrographic longitudinal sections of the river at various flow and tide stages and concluded that the position of the saltwater/freshwater interface was determined by the spring/neap cycle. Only two studies (Szabados, 1975; Horne and Patton, 1989) have directly measured current speed and direction. Both studies were short-term and showed that except in the deeper parts of the channel and during extremely low river discharge (< 75 m³/s⁻¹), net flow was downstream. The effect of the wind on riverine hydrodynamics is unclear; Meade (1966) interpreted some observed circulation patterns as wind-driven, whereas Garvine (1975) found meteorological effects to be inconsequential.

Objectives

Our objectives were to assess, using long term hydrographic measurements over a broad range of conditions, the relative importance of wind, tide, and freshwater runoff, as well as to determine the residual, or non-tidal, circulation.

Methods and Procedures

Hydrographic Transects

A Seabird Seacat 19 conductivity, temperature and depth (CTD) profiler was used to sample 15 stations along the axis of the river (Figure 1). The first station was located approximately 0.5 km south of the entrance breakwaters, in Long Island Sound; the last station was just off the southern tip of Eustasia Island, near Deep River, CT. The tide takes approximately 1 hour to propagate upstream from Saybrook Point to Deep River; the surveys averaged 1.5 hours to complete, thus we were able to obtain a nearly synoptic picture of the river hydrography. The stages of the tide and the fortnightly cycle were noted for each survey, with the overall intent of sampling as many different conditions as possible. Water samples, from both the surface and bottom, were collected at every other station and transported back to the laboratory for salinity analysis and determination of the suspended material concentration.
Figure 1. Location of the 15 sampling stations and current meter arrays.
Moored Instrument Arrays

Three bottom-mounted arrays were deployed along the length of the river during a period of low river
discharge (Winter 1992-1993) and high river discharge (April-May 1993). For each deployment period,
one array was placed at the mouth of the river, a second was positioned 3 km upstream in a region where
the full range of salinity conditions were expected, and the final array approximately 14 km upstream –
behind the reach of the saltier Long Island Sound water. The arrays could not be positioned within the
channel due to navigation concerns, and therefore were placed just to the west of the main river channel.
Each array was equipped with a temperature probe, a conductivity cell, optical sensors, and a two-axis
electromagnetic current meter. All instruments were positioned to sample conditions at a point
approximately 1 meter above the sediment-water interface. A datalogger was programmed to burst
sample each sensor four times each hour at a rate of 0.5 Hz for a period of one minute, then average and
store the burst data. Data were downloaded from the logger’s RAM during servicing to a shipboard
portable computer. Water samples were taken during servicings near the sensors and at the surface by
divers. These samples were returned to the laboratory and analyzed for salinity and suspended sediment
concentration.

Results

A total of 21 surveys were completed over a two year period from August, 1992 through August,
1994. River flow during these surveys ranged from a low of 175.6 m³s⁻¹ to a high of 1645.4 m³s⁻¹. The
irregularly spaced raw hydrographic data measured by the CTD were contoured to create regularly spaced
data grids and plotted versus depth and position to create longitudinal plots, or sections, showing the
distribution of a parameter with distance upstream. An example of the salinity distribution during the ebb
for low river flow and high river flow is shown in Figure 2. From these longitudinal sections, the
intersection of the position of the front of the salt wedge (defined as the 2 isohaline) with the bottom was
determined. This distance of the penetration of the salt wedge was plotted against the river flow (Figure
3). It can be clearly observed that the principle determinate of the position of the salt wedge is the
magnitude of the river flow. Secondary to the river flow is the phase of the moon (spring or neap). When
the flow is below ~500 m³s⁻¹, the minimum penetration of the salt wedge is 10 km. Once the flow
increases beyond ~500 m³s⁻¹, the maximum penetration of the wedge becomes approximately 10 km, with
the minimum near 3 km. Within these bounds determined by the river discharge, is a range which is
dependent on the moon phase. Only one data point was collected during high river discharge, during
which the salt wedge was able to travel almost 7 km upstream.

The instrument arrays provided 38 days of data during the low flow period (mean discharge = 376
m³s⁻¹) and 27 days of data during high flow (mean discharge = 829 m³s⁻¹). During the low flow
deployment, however, only Stations 1 and 3 yielded data. Heavy fouling by leaves and seagrasses
rendered the Station 2 data unusable. Figure 4 shows time series plots of the salinity data for Stations 1
and 3 and the river flow data during low discharge. Even during this low flow period freshwater makes it
downstream to Station 1 (the mouth) at the beginning of the deployment. When the river flow drops
below 300 m³s⁻¹, salty sound water is able to reach Station 3 (at the head) during flood tide, mixing with
the bottom freshwater increasing the salinity to a brackish 18 psu. Simple correlation analysis shows that
nearly two thirds of the variations observed in the subtidal residual salinity field can be attributed to
changes in the river flow (62% for Station 1 and 60% for Station 3). Time series of the salinity and river
flow during high discharge is shown in Figure 5. During the early part of the deployment, when the flow
is the highest (> 500 m³s⁻¹), the salinity ranges from 0 to 28 psu at both Stations 1 and 2. During the
extreme of the river flow observed (April 29, ~ 1500 m³s⁻¹), salt water is unable to penetrate to Station 2.
It is only when the river flow falls below 500 m³s⁻¹ that bottom salt water is observed at Station 3, which
reaches a maximum of 4 psu by the end of the deployment. Results of correlation analysis for the high
A) August 8, 1994: $Q=213.8$ cms, ebbing spring tide

B) April 6, 1993: $Q=1645.4$ cms, ebbing spring tide

Figure 2. Two of the resulting salinity longitudinal sections from the hydrographic surveys; A) shows a profile during low flow and B) a high flow profile.
Figure 3. Intersection of the 2 psu isohaline with the bottom plotted against river discharge. When the flow falls below approximately 500 cms the position of the freshwater/saltwater interface (FSI) is located at least 10 km upstream; conversely, when the flow exceeds 500 cms, the FSI is pushed below the 10 km mark. The tidal cycle sets the upstream and downstream limits, with the extreme excursions occurring during spring tides and minimal excursions during the neap. Data from Horne and Patton's 1989 study is also shown for comparison.
Figure 4. Time series of salinity data and river discharge (mean Q=376 cms), solid thin line is the residual salinity after low-pass filtering to remove the tidal signal.
Figure 5. Time series of the salinity data and river discharge (mean Q=829 cms). Solid thin line is the residual salinity after low pass filtering to remove the tidal signal.
flow data reveals that almost all of the residual subtidal salinity variations can be explained by the river flow for Station 1 (97%) and Station 2 (98%).

The current meter data, for all stations and both deployments, is summarized in Table 1. The ebb dominates during both deployments for all stations. The mean ebb is higher during the low flow phase at Station 3, but is the same at Station 1. The magnitude of the mean flood tide, for each station, does not differ significantly from the low flow to the high flow deployments. The residual, or non-tidal, transport was calculated using a low-pass filter with a 48 hour cutoff frequency. The resulting vectors showing magnitude and direction for each station are presented in Figure 6. For all stations, the transport is downstream for both low and high river phases. The magnitude of the residual transport is always highest upstream at Station 3.

**Table 1. Summary of Current Meter Data From Moored Arrays**

<table>
<thead>
<tr>
<th></th>
<th>Station 1</th>
<th></th>
<th>Station 2</th>
<th></th>
<th>Station 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low Discharge</td>
<td>High Discharge</td>
<td>Low Discharge</td>
<td>High Discharge</td>
<td>Low Discharge</td>
</tr>
<tr>
<td>Ebb mean ± std dev (cm·s⁻¹)</td>
<td>34.7 ± 21.3</td>
<td>35.5 ± 20.0</td>
<td>31.0 ± 18.1</td>
<td>43.4 ± 21.3</td>
<td>36.8 ± 21.3</td>
</tr>
<tr>
<td>min-max (cm·s⁻¹)</td>
<td>0.2 - 101.8</td>
<td>0.2 - 109.1</td>
<td>3.5 - 79.0</td>
<td>0.8 - 116.8</td>
<td>0.2 - 85.3</td>
</tr>
<tr>
<td>Flood mean ± std dev (cm·s⁻¹)</td>
<td>22.8 ± 11.2</td>
<td>22.0 ± 11.1</td>
<td>19.2 ± 8.5</td>
<td>15.6 ± 9.2</td>
<td>13.7 ± 7.3</td>
</tr>
<tr>
<td>min-max (cm·s⁻¹)</td>
<td>0.0 - 69.5</td>
<td>0.4 - 63.1</td>
<td>1.6 - 42.8</td>
<td>0.4 - 52.0</td>
<td>0.2 - 39.3</td>
</tr>
<tr>
<td>Residual u (cm·s⁻¹)</td>
<td>-2.3</td>
<td>-6.8</td>
<td>-5.6</td>
<td>-5.9</td>
<td>-5.28</td>
</tr>
<tr>
<td>v (cm·s⁻¹)</td>
<td>-6.8</td>
<td>-14.9</td>
<td>-9.9</td>
<td>-25.2</td>
<td>-23.6</td>
</tr>
</tbody>
</table>

Wind data, obtained from the Northeast Utilities Power Plant in Waterford, CT, was also compared with the hydrologic data. During the high flow period, wind energy was low, and analysis showed no significant coherence between either wind component and the velocity components for any of the three stations. There were several wind events during the low flow period which coincided with short duration perturbations in the velocity, however, these wind events also coincided with variations in the river discharge confounding the effect of the wind stress.

**Summary**

This set of data represents one of the most extensive, both spatially and temporally, ever collected from the Connecticut River. From the hydrographic survey data we are able to show that the position of the freshwater/saltwater interface is primarily a function of the river flow. The river flow rate acts as the principle control, from which we can predict the approximate location of the FSI. The tidal cycle sets the upstream and downstream limits of the FSI within that approximate location, with the extreme excursions occurring during spring tides and minimal excursions during neaps.

The moored current meter data analysis revealed subtidal transport downstream for all stations during both river flow phases, implying that the river is indeed a major source of dissolved nutrients, suspended
Figure 6. Residual transport vectors for the A) low river discharge deployment period (38 days, mean Q = 376 cms) and B) high river flow deployment period (27 days, mean Q = 829 cms).
sediments and pollutants to the Sound. However, salt is being transported upstream suggesting that the mechanism by which this is occurring is more complicated than those described by the traditional modes of estuarine transport. We are unable to address the significance of lateral currents induced by velocity shears and pressure gradients at the channel boundaries, or trapping of salty water in bathymetric lows during ebbs and the “pumping” of that trapped water further upstream during the following flood.

References


Benthic habitat
Long-Term Management of the Subaqueous Disposal of Contaminated Dredged Material: A Study of the Central Long Island Sound Disposal Site

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Abstract

The Central Long Island Sound Disposal Site (CLIS) is one of the most active sites within the New England Division of the US Army Corps of Engineers. Covering a 6.86 km² (2 mile) area in Long Island Sound, the disposal site receives sediments dredged from the industrialized harbors of New Haven, Stamford, and Norwalk, as well as many smaller harbors along the Connecticut coast. Sediment deposits at CLIS have been monitored annually since 1977 as part of the Disposal Area Monitoring System (DAMOS) Program.

Since 1984, the management strategy at CLIS has been to form a basin-like bottom feature by creating a ring of disposal mounds. During the 1993/94 disposal season, approximately 590,000 m³ of sediment classified as unacceptably contaminated dredged material (UDM) was deposited within this basin and capped with approximately 569,000 m³ of capping dredged material (CDM) to a thickness of 0.5 m to 1.0 m. The lateral containment provided by the basin feature and the coordinated efforts of NED, SAIC, and the dredging contractor resulted in the successful construction of the confined aquatic disposal (CAD) mound known as NHAV 93, with a CDM to UDM ratio of 0.96 to 1.0.

As part of the environmental monitoring effort, SAIC collected time series data of mound height and composition during the development and subsequent consolidation of the NHAV 93 mound. This data set, consisting of precision bathymetry, sediment-profile photography, geotechnical, and subbottom profiling data, has allowed SAIC and NED to document the evolution of the NHAV 93 mound. The results suggest this long-term management strategy facilitated the subaqueous disposal of a large volume of contaminated sediment while minimizing the economic and environmental impacts.

Introduction

The managed disposal of dredged material was introduced to the central Long Island Sound region in October 1973 with the development of the New Haven 1974 (NAV 74) mound in the center of the newly designated New Haven Disposal Site. An estimated 1,150,000 m³ of material dredged from the New Haven Harbor was deposited at this site from October 1973 through March 1977. In 1977, the US Army Corps of Engineers, New England Division (NED), instituted the Disposal Area Monitoring System (DAMOS) Program in response to the recognized need for long-term management and environmental monitoring of the New Haven Disposal Site, as well as 10 other disposal sites in New England waters (NUSC 1979). Since 1977, advances in dredged material disposal, precision navigation, and environmental monitoring technologies have continually improved the tools used in disposal site management.
In 1979, the designation of the New Haven Disposal Site was modified, expanding the boundaries of the site and changing its name to Central Long Island Sound Disposal Site (CLIS; SAI 1979). The new disposal site boundaries encompassed a 6.86 km (2 nmi) area located approximately 10.39 km (5.6 nmi) south of South End Point, East Haven, Connecticut. For the past seventeen years, CLIS has been one of the most active disposal sites in the New England region. The disposal site receives sediments dredged from New Haven, Bridgeport, Stamford, and Norwalk Harbors, as well as adjacent coastal areas. The abundance of disposal activity within the boundaries of the of the disposal site allowed NED to develop and refine a variety of dredged material management strategies. During the 1978/79 disposal season, subaqueous capping was introduced as a new dredged material management approach with the formation of the Stamford-New Haven mounds (SAIC 1995).

Capping is a containment method which uses sediments determined to be suitable for unconfined open water disposal, or capping dredged material (CDM), to overlay and isolate deposits of unacceptably contaminated dredged material (UDM) from the environment (Fredette 1994). As a result of the operational success of the 1979 capping project, many additional capped mounds have been formed. From 1977 through 1983 the site management strategy at CLIS entailed the formation of many independent mounds over the given area of the disposal site. Each mound was monitored individually, assessing mound stability, cap thickness, benthic recolonization status, etc. Although this practice was highly successful, the overall capacity of the disposal site was compromised due to the unusable area between discrete sediment mounds.

In 1984, a new management strategy was instituted at CLIS. Past experience had shown that large scale dredging of New Haven Harbor was required every ten years to maintain adequate passage for commercial, deep draft vessels. Using this ten year dredging cycle, NED managed the deposition of small to moderate volumes of dredged material at CLIS to form a disposal mound ring. By 1992, this network of disposal mounds had formed a basin-like feature, or artificial containment cell, on the CLIS seafloor. This feature could accept a large volume of UDM, limit the lateral spread of the deposit, and facilitate efficient capping operations.

The development of a capped disposal mound within this containment cell would result in a confined aquatic disposal (CAD) mound. A CAD mound is a capped dredged material deposit developed in conjunction with artificial or natural containment measures, that limits the lateral spread of the UDM apron and facilitating efficient capping operations. The ring of disposal mounds on the CLIS seafloor provided sufficient lateral containment for use during the 1993/94 disposal season as part of the New Haven Capping Project.

Project Description

The New Haven Capping Project entailed the maintenance dredging of the federal channel to navigable depths. Sediments were to be excavated from the mouths of the Quinnipiac and Mill Rivers south to the entrance of New Haven Harbor in order to maintain adequate navigational access. Permits were also granted to remove the accumulated sediments from five area marine terminals to improve their operations efficiency and accommodate deeper draft vessels. As part of the Dredged Material Management Plan, formulated by the New England Division (NED) of the US Army Corps of Engineers (USACE), the federal channel and marine terminal sediments were sampled and subjected to a variety of tests to determine their physical and chemical properties before dredging operations commenced.

The results of chemical analysis and standard 28-day *Amphilestes* bioassay tests indicated that the sediments to be dredged from inner federal channel and portions of the marine terminal projects were classified as UDM and required capping. A supply of CDM was identified in the outer New Haven
Harbor sediments. The material to be dredged from the federal channel south of City Point was found to be suitable for unconfined open water disposal and should provide an adequate volume of CDM.

In September 1993, a disposal buoy marked "NAV" was placed at CLIS in the center of a ring of seven historic disposal mounds in preparation for the deposition of a large volume of dredged material (Figure 1). From October 1993 to February 1994, the New Haven Harbor was dredged and an estimated barge volume of 590,000 m$^3$ of UDM (500,000 m$^3$ federal channel; 90,000 m$^3$ private marine terminals) followed by 569,000 of CDM (506,000 m$^3$ federal channel; 63,000 m$^3$ private marine terminals) was deposited in close proximity to the NAV buoy.

SAIC has conducted a total of eight monitoring surveys over NAV 93 from September 1993 to July 1996 as part of the DAMOS Program. This comprehensive time-series data set consists of precision bathymetry, Remote Ecological Monitoring of the Seafloor (REMOTS®) sediment-profile photography, geotechnical coring, acoustic subbottom profiling, as well as physical and chemical sediment classification. The results of NED/SAIC monitoring efforts document the development, recolonization, and subsequent consolidation of this CAD mound.

**CAD Mound Development**

In September 1993, SAIC conducted a baseline survey over the artificial containment cell developed during the previous nine disposal seasons. A 1600 m X 1600 m precision bathymetric survey was conducted over the 2.56 km$^2$ area to assess the overall bottom topography and identify possible routes of material movement between the historic disposal mounds (Figure 1). In addition, the bathymetric survey would provide a baseline against which all future surveys would be compared.

REMOTS® camera transects across the independent mounds of the containment cell determined the benthic recolonization status and characterized the grain size and relative shear strength of the sediments. Five geotechnical cores were collected within the containment cell to analyze the geotechnical properties of the historic disposal mound aprons, thin layers of dredged material produced by the lateral spread of a mound, and the underlying ambient Long Island Sound sediments.

From 3 October to 23 October 1993, an estimated 324,000 m$^3$, more than 54% of the total UDM volume, was deposited at the NAV buoy. A second, interim disposal bathymetric survey was conducted on 24 October 1993 to determine the size and shape of the disposal mound. The UDM deposit was approximately 510 m wide, 3.25 m high, nearly conical in shape, and residing within the confines of the containment cell. Sediment grab samples were also collected for grain size analysis to compare with the pre-dredging survey results.

An additional barge volume of 136,000 m$^3$ UDM was placed at the NAV buoy from 23 October to 31 October 1993. The clamshell dredge completed the excavation of UDM from the northern reaches of the federal channel and began removing pockets of CDM from the outer New Haven Harbor. The NAV 93 mound received approximately 460,000 m$^3$ of UDM, as well as the first 76,000 m$^3$ of CDM deposited on the northwest flank of the mound, before the completion of a precap survey at CLIS.

A third bathymetric survey was completed over the active disposal area at CLIS in early November 1993 at the precap stage of development to document the changes in mound morphology and ensure containment within the disposal mound ring. The overall width of the NAV 93 mound expanded to 620 m, but a significant reduction in mound height was detected during the precap survey (Figure 1). The apex (2.75 m high) of the disposal mound shifted to the northwest as a result of the recent CDM deposition, and a pocket of central mound consolidation 1.25 m deep was formed despite the disposal of
212,000 m$^3$ of additional dredged material. Furthermore, the 76,000 m$^3$ of CDM placed north and northwest of the NHAV buoy could not be differentiated from the NHAV 93 UDM mound by standard hydrographic techniques due to its deposition before the completion of the precap bathymetric survey.

A second set of gravity cores were collected to define the geotechnical properties of the UDM deposit and attempt to better define the consolidation of the disposal mound through examination of the subsurface sediment strata. REMOTS® sediment-profile photography was used to track the fresh dredged material deposited within the mound apron in layers too thin to be detected acoustically. Eight, four-station transects were occupied in areas of likely dredged material movement, the valley features between individual disposal mounds. From this data set, a series of twenty-eight capping points were identified to aid in the development of an adequate cap over the entire UDM deposit.

Small volumes of UDM (400 m$^3$ to 26,000 m$^3$) from the five private marine terminals and the adjacent sections of the federal channel continued to be deposited southwest of the NHAV buoy at Disposal Point I from early-November 1993 through early-January 1994. Larger volumes of CDM generated by the federal channel maintenance dredging were being deposited to the northeast and southeast of the disposal buoy. An interim cap survey was completed in late-November 1993 to verify the cap placement and examine the grain size of the CDM. At the interim cap stage of development, the NHAV 93 mound expanded to a width of 720 m along the southwest-northeast axis and retained the mound height of 2.75 m.

Capping operations over the NHAV 93 mound were completed in February 1994 with a final estimated barge volume of 569,000 m$^3$ of CDM placed over the initial UDM deposit. Capping Points I through U on the western side of the NHAV 93 mound were the last to be covered by CDM, completely capping the smaller volumes of UDM released at Disposal Point I through early-January 1994. A postcap survey, consisting of a fifth bathymetric survey and the collection of a third set of geotechnical cores, was conducted in mid-March 1994.

Depth difference calculations based on comparisons between the March 1994 and September 1993 baseline bathymetric surveys displayed the completed NHAV 93 mound as a wide and relatively flat CAD mound. The NHAV 93 mound was found to be approximately 820 m wide, with a maximum mound height of 2.75 m at an apex skewed 75 m east of center (Figure 1). A wide projection of CDM was visible spreading southwest between the historic CLIS 88 and NORTWALK disposal mounds. A total barge volume of 298,000 m$^3$ of CDM was released over the western and southwestern flanks of the NHAV 93 mound, providing an abundance of capping material and prompting some movement down the gradual slope.

As expected, depth difference calculations based on the March 1994 postcap and November 1993 precap bathymetric surveys detected an apparent lack of capping material over the north and northwest quadrants of the NHAV 93 mound (Figure 2). The geotechnical cores obtained on the northeast and northwest flanks of the mound verified the presence of at least 0.5 m of cap material. However, other means would be required to quantify the cap thickness over the northern region of the CAD mound.

During the sixth survey over NHAV 93 in July 1994, an X-Star Digital Subbottom Profiler was able to differentiate between the UDM and CDM layers over the northern portions of the mound. Density differences between the layers were measured, gridded, and contoured, an average cap thickness of 0.75 m to 1.0 m was detected over the northern half of the CAD mound (Figure 2). Geotechnical cores confirmed the subbottom data, showing a sharp increase in water content and corresponding decrease in density at the UDM/CDM interface. The bathymetric data collected over the NHAV 93 mound displayed little change in overall size or shape at four months post-completion, with the exception of a few small pockets of consolidation 0.25 m deep.
The detection of the cap material on the northern flanks of NHAV 93 confirmed the success of the New Haven Capping Project. In the past, a typical capped mound would require a 2:1 to 6:1 CDM to UDM ratio when initiating capping operations on a flat or gently sloping area of seafloor. The completed CAD mound was found to be broad, stable, adequately capped, and exhibiting a 0.96:1.0 CDM to UDM ratio.

Additional survey operations have been conducted over the 2.56 km NHAV 93 project area in September 1995 (1.5 years post-completion) and July 1996 (2.25 years post-completion). Both surveys have detected moderate consolidation (0.25 m) over the entire surface of the disposal mound with deeper pockets (0.5 m to 0.75 m) near the CAD mound center. REMOTS® photographs obtained over the surface of NHAV 93 show the sediments are supporting a stable benthic infaunal population with mature assemblages (head-down deposit feeding and errant polychaete worms).

Outlook

As with other capped dredged material disposal mounds at CLIS, the NHAV 93 mound is expected to gradually consolidate over the next ten to fifteen years (Poin Dexter-Rollings 1990). The average cap thickness of 0.75 m should fully isolate the contaminated sediments in spite of the burrowing activities of some benthic macrofauna (i.e., lobster, mud anemones). The increased organic load of the New Haven Harbor CDM will promote the development of a denser infaunal population, relative to ambient central Long Island Sound sediments.

Dredging operations in urbanized and industrialized areas may not produce an abundance of CDM for use in capping operations. However, the perfection of this disposal and management technique allows NED to deposit large volumes of UDM, while requiring a minimum investment of CDM. The NHAV 93 capping project was the first in New England region to utilize an artificial containment cell to control the spread of UDM. The use of the disposal mound ring at CLIS significantly reduced the outward migration of the UDM mound apron. As a result, cap material was distributed over a much smaller area, decreasing the total volume of CDM required to cap the inner New Haven Harbor sediments.

The operational success of the New Haven Capping Project has led NED to continue developing containment cells at CLIS as well as adopt this management strategy at other DAMOS disposal sites along the New England coast. The strategic placement of a disposal buoy and subsequent deposition of small to moderate volume of material in preparation for large scale CAD mound construction is currently being used at the New London Disposal Site (NLDS) and Massachusetts Bay Disposal Site (MBDS). Natural containment measures (bedrock outcrops, glacial deposits, etc.) are being utilized at the Portland Disposal Site (PDS), and Western Long Island Sound Disposal Site (WLIS).

Each disposal site has a finite amount of space available to accept the deposition of dredged material. The long-term use of this management strategy will improve the efficiency of disposal operations at the respective sites by concentrating deposition into predetermined networks of mounds to form interlinked containment cells. Over time, the development and use of containment cells for large scale dredging and disposal projects will minimize the surface area occupied by each high volume dredged material deposit and therefore maximize the overall capacity of the disposal sites.
Figure 1 Location of the NHAV 93 buoy over the basin created by a ring of seven historic disposal mounds, September 1993 baseline bathymetric survey.
Central Long Island Sound
Disposal Site
Detectable Cap Thickness over the NHAV 93 Mound
1600 m X 1600 m Survey Area
North American Datum of 1927
Depth in meters

Figure 2  Contour plot of the detectable mound margin (0.25 m), overlaid by subbottom layer 1 (cap material thickness over the northern NHAV 93 mound) and March 1994 cap material footprint.
References


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Abstract

Winter flounder, *Pleuronectes americanus*, are bottom-dwelling fish which are important residents of the Sound. Juveniles use nearshore habitats, including bays and harbors, as nursery and feeding areas. These habitats are most frequently affected by anthropogenic inputs and may become hypoxic during the summer months. Yet little is known about the reactions of juvenile flounder to hypoxia, nor the consequences for habitat utilization by juveniles. Juvenile winter flounder were exposed to progressive increases in hypoxia, from 5 to 0.5 mg O₂/L, in aquaria. Observations of their behavior found that swimming activities showed little change between normoxia down to 4 mg O₂/L. At 3 mg O₂/L and lower, a sequence of response was initiated: at 3 mg O₂/L the amount of swimming activity increased, at 2 mg O₂/L fish started to gulp air, and at 1 mg O₂/L the flounder had become pale, were ventilating heavily, and had become quiescent. The possible adaptive significance is discussed in relation to the respiratory needs and survival of small flounder in nearshore habitats of the Sound.

Introduction

Winter flounder are bottom-dwelling fish which are important residents of Long Island Sound. The shallow bays and wetlands serve as nurseries where the juveniles may grow rapidly. In summer these waters commonly become depleted of oxygen, hypoxic. We investigated the responses of juvenile (YOY) winter flounder to progressive hypoxia. We observed effects of activity levels, in both vertical and horizontal planes, and found changes which may represent “escape” responses to declining oxygen concentration.

There have been occasional newspaper reports of flounder “gasing at the surface” but the ecophysiological significance of such behavior is not known. We made laboratory investigations of this behavior. Our results suggest that such unusual behavior is probably a response to severe oxygen-deficiency in nearshore waters. Alternative modes of respiration at the water surface have been found to occur in a variety of teleost fishes. These include aquatic surface respiration (ASR), or utilization of the relatively oxygen-rich surface layer of the water column for respiration, and air breathing. Although these alternative modes of respiration are best documented for tropical freshwater fishes, they may also be used by temperate fishes in hypoxia-prone habitats (Kramer, 1987; Graham, 1994; Gee, 1978; McEnroe and Allen, 1994). Such respiratory adaptations may confer advantages which allow fish to explore and
exploit marginal habitats, and particularly to survive periodic hypoxia. In the harbors and embayments of Long Island Sound dissolved oxygen concentrations fluctuate with the diel cycle reaching minima late in the night.

We measured behavioral and respiratory responses of juvenile winter flounder to declining oxygen concentrations, to determine if flounder used alternative modes of respiration to withstand periodic hypoxia, such as occurs during the diel cycle in many nearshore areas which serve as nursery habitats for this species.

Materials and Methods

Young-of-the-year (<12 cm) winter flounder were collected from West Meadow Beach, Stony Brook, NY in the central Sound, using a 25' seine with 1/2" mesh. They were transported to the laboratory in coolers with Sound water. They were held in aquaria for two weeks at temperatures of 20-23°C and salinity of 26 ppt, typical of summer conditions in the nearshore areas of the Sound. The aquaria were fitted with undergravel filters and aerated (dissolved oxygen concentrations were maintained at 6-7 mg O₂/l), water was renewed periodically. During the winter months artificial sea water of the same salinity was made up using Instant Ocean. Fish were fed Artemia and Tubifex several times/day.

Six experiments were made, for each 5 fish were placed in a 25 liter glass experimental tank and acclimated for at least one day before beginning experiments. Before initiating each experiment the temperature, salinity and DO levels were measured. Dissolved oxygen concentration (DO, mg O₂/l) and temperature were measured using a YSI Model 58B Dissolved Oxygen meter fitted with a water stirrer, salinity was measured using a Riechert-Jung refractometer. During experiments DO concentration was continuously recorded and nitrogen flow was adjusted to decrease DO concentrations at a rate of about 1 mg O₂/hr, from normoxic levels down to 1 mg O₂/l. Measurements were made at normoxia, then at 5, 4, 3, 2, and 1 mg O₂/l. In one experiment measurements were also made at 0.5 mg O₂/l. At each DO concentration tested steady conditions were maintained for at least 30 min before observations were made. Control observations were made by under similar conditions, but with air bubbling into tank instead of nitrogen.

Three measurements of behavior were made:

a) To measure activity levels a grid, which divided the tank into 3 vertical and 3 horizontal sections, was placed behind the tank. Activity was measured by counting the number of times fish crossed the vertical (or horizontal) lines during the 10 min. observation period.

b) Fish were considered to be using ASR when they swam just below the water surface and used the relatively-oxygen rich surface layer for aquatic respiration. During the 10 min. observation period the total number of ASR events for 5 fish were counted.

c) At low DO concentrations fish broke the surface film with open mouths, apparently taking in air. This behavior, which was quite distinct, it was easily differentiated from ASR, and was termed air gulping. In each experiment the total number of air gulping events for the 5 fish were counted during the 10 min observation period.
Results

Activity was measured in horizontal and vertical planes, and the sum of these was termed total activity. Total activity (Figure 1) was steady as oxygen levels were decreased from normoxic values (7 to 8 mg O$_2$/l) down to 3.0 mg O$_2$/l. At 2 mg O$_2$/l, total activity increased about three-fold, this increase was significant (p < 0.001). However, at 1 mg O$_2$/l activity fell sharply. Horizontal swimming (Figure 2) showed a fairly similar pattern: in normoxia flounder showed rather little horizontal movement, and this was maintained as DO levels were decreased to about 4 mg O$_2$/l. Between 4.0 and 2.0 mg O$_2$/l flounder quickly increased their swimming activities in this plane. At 1.0 mg O$_2$/l, horizontal swimming varied between individuals, but tended to decline. Vertical swimming behavior was clearly distinguishable, the flounder swam straight up towards the surface, then rapidly returned to the bottom (Figure 3). At each DO level from normoxia down to 4.0 mg O$_2$/l vertical swimming events were more frequent than horizontal swimming, they were a relatively steady component of behavior, although varying in extent between individuals. At DO concentrations between 3.0 and 2.0 mg O$_2$/l, an increase in vertical swimming (about two-fold) was observed in all flounders (Figure 3). However, although the same pattern of activity occurred, there was variability between individuals in the degree of this response. At 1.0 mg O$_2$/l vertical activity declined sharply.

Flounder were exposed to progressive levels of hypoxia, and when DO concentrations fell below 2.0 mg O$_2$/l they appeared to gulp air at the surface during their vertical swimming migrations. Air gulping was only observed after DO fell below 2.0 mg O$_2$/l, but occurred frequently as oxygen declined toward 1 mg/l. Although overall activity was generally suppressed at about 1.0 mg O$_2$/l, flounders continues to make occasional forays to gulp at the surface. Flounder were able to survive the 4 to 8 hours experimental exposure to increasingly severe levels of hypoxia, including 1 to 2 hours at 1.0 mg O$_2$/l.

Discussion

Juvenile winter flounder increased their swimming activity at dissolved oxygen concentrations of 3.0 - 2.0 mg O$_2$/l. In the Sound this might enable the fish to leave hypoxic areas and seek better oxygenated waters. Field studies in the Sound suggest that winter flounder may leave hypoxic areas. Simpson et al. (1995, 1996) found the biomass of demersal finfish to be reduced at oxygen concentrations <3.7 mg/l, and no demersal finfish were found below 1.0 mg/l. Howell and Molnar (1996) calculated that habitat utilization by demersal finfish was diminished (4.6% - 12.6%) as a result of hypoxia during summers between 1991 and 1995.

Juvenile winter flounder were not observed to utilize the relatively oxygen-rich surface layer of water by swimming horizontally at the surface, that is, ASR. This is unlike Fundulus heteroclitus, which readily employ ASR in similar hypoxic conditions (McEnroe and Allen, 1994). Winter flounder lack a swimbladder and without neutral buoyancy it may be difficult to perform ASR. However, at very low DO (2 mg O$_2$/l and below) winter flounder were observed to periodically protrude their heads from the water, they appeared to gulp air. This behavior may represent a “last-chance effort” to survive severe hypoxia when normal respiratory methods are unable to extract sufficient oxygen for these water breathing fishes. Air bubbles obtained by gulping may be held in the buccal cavity and used to oxygenate water flowing through it, thereby increasing oxygen content before it passes over the gills.
Figure 1. Total activity, or the amount of movement in both vertical and horizontal planes, during 6 experiments in which juvenile winter flounder were exposed to progressive hypoxia. Each symbol represents the mean activity of 5 fish during the 10 minute observation period at the indicated dissolved oxygen concentration.
Figure 2. Measurements of horizontal activity in juvenile winter flounder during progressive hypoxia. Each symbol represents the mean activity of 5 fish during the 10 minute observation period at the indicated dissolved oxygen concentration.

Figure 3. Measurements of vertical activity in juvenile winter flounder during progressive hypoxia. Each symbol represents the mean activity of 5 fish during the 10 minute observation period at the indicated dissolved oxygen concentration.
Our results suggest that the critical DO for juvenile winter flounder (e.g., the DO level at which behavioral responses begin) is about 3 mg O$_2$/l at summertime temperatures (20-23°C). Juvenile flounder exhibit a sequence of adaptive behaviors in response to increasingly severe environmental hypoxia. At 3.0 mg O$_2$/l the amount of swimming activity increased, at 2.0 mg O$_2$/l fish started to gulp air, and at 1.0 mg O$_2$/l the flounder had become pale, were ventilating heavily, and had become quiescent. These sequential components of behavior may have somewhat different functions. By increased swimming activity the fish will move around more and may secure access to greater oxygen concentrations. If this is not attained, local air-gulping augments oxygen availability, but the behavior is energetically costly. At 1.0 mg O$_2$/l and below, activity is reduced to minimize oxygen demand, the flounder only occasionally swim up to gulp surface air.

There have been occasional newspaper reports of flounder seen “gasping at the surface”. Our experiential results suggest that such behavior may occur only in severe hypoxia of 2 mg O$_2$ and below, it may be a "last-chance behavior" by the fish to survive periodic hypoxia. However, surface respiration can expose fish to increased predation in shallow water, particularly from birds. The are reports of increased predation under such circumstances (Kramer, 1987) and we have observed gulls, herons and egrets feeding on winter flounder at the water surface in Norwalk Harbor, CT and Milton Harbor, NY; similar observation of birds preying on flounder at the surface in summer have been made in Milford, CT.

References


Juvenile Winter Flounder Distribution by Habitat Type

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Connecticut’s inshore estuaries provide vital spawning and nursery grounds for the state’s fisheries resources, and their health directly affects the long-term abundance of these resources. Among the many species dependent on inshore embayments is winter flounder, one of the most heavily harvested fish species in Connecticut. This study was designed to determine if there are habitat types which consistently provide preferred nursery grounds for winter flounder in Long Island Sound so that these areas can be identified and protected from degradation. Information describing the relative abundance of flounder in these embayments is used to guide provisions placed on DEP permits for in-water activities that have adverse effects on young flounder. Increased understanding of the relationship between production of winter flounder and preferred nursery habitat area will also make design of enhancement projects possible.

Sites Examined

Five sites were sampled for juvenile fish as part of a larger DEP Inshore Finfish Survey (Howell and Molnar 1995, 1996). Fish were sampled seasonally, June (spring), July-August (summer) and October-November (fall) in 1990-93 in the Thames River, Connecticut River, Clinton Harbor, New Haven Harbor, and Housatonic River (Figure 1). In the final year of sampling, 1994, new sites-Niantic River/Bay and Milford Harbor- were sampled spring and fall to test the general applicability of the distributional pattern developed from the original site data. During the same years (1990-94), Harbor Watch volunteers sampled the Saugatuck and Norwalk Rivers providing additional data with which to test the applicability of the DEP database (Harbor Watch 1995). All Harbor Watch samples were taken weekly from July-September.

Figure 1: Sites sampled for young-of-year winter flounder.
Each sampled embayment was bounded landward by average spring bottom salinities greater than 5 ppt and seaward headland to headland approximately along the 5.5 M (18 ft.) depth contour. These boundaries delineate waters protected from the open Sound which are above the lethal minimum salinity for winter flounder embryos (Rogers 1976).

Sampling Methods

Each sampled area was divided into 0.11-0.25 sq. km sampling grids, depending on the year and site. For sites sampled by DEP, every other grid was sampled each season; for sites sampled by Harbor Watch, three grids were sampled each week one each in the upper, middle and lower river. All samples were taken using a 1-meter-beam trawl with 6.4 mm (0.25 in.) bar mesh. Finfish taken in each sample were identified to species and counted. Winter flounder were measured to total length (mm), and classified as young-of-year if less than 10 cm in spring, less than 11 cm in summer, and less than 12 cm in fall. The age of flounder falling near these boundaries was verified by examination of the sagittal otolith.

Physical data recorded for each sample included water depth (+0.5 ft), sediment type and overlying litter type (by visual inspection), bottom temperature (+0.5°C), bottom salinity (+0.5 ppt), and water column turbidity (Secchi disc depth, -0.25 ft). Other variables recorded for each sample were the relative volume of sea lettuce (Ulva lactuca) taken in the net, and whether the tow was taken in a navigational channel or not.

Results

Of 1346 tows taken by DEP in 1990-93, young-of-year winter flounder were present in 67%, however only 18% of the samples caught 10 or more. This distribution indicates that this species is wide spread but not uniform in distribution. Catch frequencies, transformed to the log scale to normalize the data, were then used to define preferred flounder nursery areas. Initial examination of all the physical measurements taken, by chi square analyses and linear regression, showed that only sediment type was a reliable predictor of abundance. Catch data showed no consistent pattern in relation to salinity, seasonal temperature, or water column turbidity. Depth interval, channel/ off-channel, and presence of Ulva showed some pattern but none that was consistently statistically significant. In general, young flounder were present in higher densities in shallower, off-channel sites where Ulva was present.

The stronger relationship between flounder densities and sediment type was then examined by classifying the DEP 1990-93 catch data by five habitat types which were defined by a combination of sediment and overlying litter in each sampled grid: (1) mud covered by any live bivalves or shell, (2) mud covered by woody debris or leaves, (3) mud with no litter cover, (4) sand covered by shell or any other litter, (5) sand with no litter cover. Statistically significant differences (alpha=0.05) in catch rate among habitat types were then determined by analysis of variance (ANOVA). The ANOVA model showed that mean catch was significantly different (p<0.01) among four of the five habitat types, with the paired comparison of types 4 and 5 nearly significant (p=0.064, Table 1). This five-habitat model explained more of the variance in abundance, and showed greater statistical separation, than models based on more or less
Table 1: Young-of-year winter flounder abundance by habitat in five embayments sampled by beam trawl. Mean catches (retransformed from the log scale) among habitats are significantly different except between types 4 and 5. Differences among years are not significant. Sample size (N) is the number of tows taken in each habitat.

<table>
<thead>
<tr>
<th>Habitat Type</th>
<th>Mean (N)</th>
<th>95% Confidence Interval</th>
<th>Proportional Abundance</th>
<th>1990</th>
<th>1991</th>
<th>1992</th>
<th>1993</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.05 (408)</td>
<td>4.4 - 5.8</td>
<td>39%</td>
<td>40</td>
<td>30</td>
<td>39</td>
<td>42</td>
</tr>
<tr>
<td>2</td>
<td>2.39 (209)</td>
<td>1.9 - 3.0</td>
<td>19%</td>
<td>9</td>
<td>21</td>
<td>14</td>
<td>31</td>
</tr>
<tr>
<td>3</td>
<td>3.57 (236)</td>
<td>2.9 - 4.3</td>
<td>27%</td>
<td>34</td>
<td>27</td>
<td>37</td>
<td>14</td>
</tr>
<tr>
<td>4</td>
<td>1.20 (245)</td>
<td>0.9 - 1.5</td>
<td>9%</td>
<td>9</td>
<td>13</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>5</td>
<td>0.81 (248)</td>
<td>0.6 - 1.1</td>
<td>6%</td>
<td>9</td>
<td>9</td>
<td>3</td>
<td>6</td>
</tr>
</tbody>
</table>

Habitat Type: 1 = mud with live bivalve or shell cover 2 = mud with wood or leaf debris 3 = mud with no litter cover 4 = sand with shell or any litter cover 5 = sand with no litter cover

Numerous divisions of sediment and litter type. Areas with muddy sediments overlaid by live bivalve beds and/or shell consistently yielded the highest average catch, followed by mud without litter or with wood/leaf debris. Sand with or without litter yielded the lowest catches.

Bivalve beds harboring flounder included coot clam (Mulinia lateralis), blue mussel (Mytilus edulis), gem shell (Gemma gemma), oyster (Crassostrea virginica), hard clam (Mercenaria mercenaria), and arks (Noetia, spp.). Tested directly, the mean catch of young-of-year flounder was significantly higher at all sites with bivalves present than sites where bivalves were absent (1992-93 DEP data, p<0.035).

In summary, preferred nursery grounds for winter flounder are well defined by five bottom sediment/litter cover combinations. The addition of other physical factors did not enhance the usefulness of the model in describing the distribution of the fish. Unlike temperature and salinity, sediment type and litter cover do not change substantially year to year or season to season. Therefore designation and mapping of these habitats is straightforward and reliable.

Corroboration of the General Model

New sites sampled by DEP in 1994 and by Harbor Watch in 1990-94 corroborated the ability of this habitat model to explain variance in catch, and the importance of habitat 1. In order to make the results of the general ANOVA model applicable to all sites and situations, mean catch rates for each habitat type from the general model, and from each new site, were standardized by converting the actual numbers to a percentage of the sum of the means for all habitats present in each location (Tables 1 and 2). Results showed that at the new sites, flounder densities in habitat 1 and 3 again ranked first and second, while habitat 4 and 5 ranked lower. Habitat 2 was not well represented in the new sites and densities (mean catch) in that habitat type were quite variable. The distribution of fish found in the Saugatuck was statistically similar to the general model. Distributions were also statistically similar in Milford and Niantic in habitats 3, 4, and 5 only. The relatively high number of fish in habitat 1, and low numbers in habitat 2, did not match the expected proportions. One explanation might be that because 1994 was an
Table 2: Proportional abundance (%) of young-of-year winter flounder by habitat type in four sites compared to the general model. The percent of the total variance in catch explained by habitat differences (r²) is given for each site, with the sample size. Habitats not available (na) were excluded from analysis for that site.

<table>
<thead>
<tr>
<th>HABITAT</th>
<th>General Model</th>
<th>Saugatuck River</th>
<th>Norwalk River</th>
<th>Milford Harbor</th>
<th>Niantic River/Bay</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - Mud / bivalve-shell cover</td>
<td>39</td>
<td>39</td>
<td>64</td>
<td>63</td>
<td>77</td>
</tr>
<tr>
<td>2 - Mud / wood-leaf debris</td>
<td>19</td>
<td>na</td>
<td>na</td>
<td>9</td>
<td>na</td>
</tr>
<tr>
<td>3 - Mud / no litter cover</td>
<td>27</td>
<td>36</td>
<td>36</td>
<td>21</td>
<td>14</td>
</tr>
<tr>
<td>4 - Sand / any litter cover</td>
<td>9</td>
<td>8</td>
<td>na</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>5 - Sand / no litter cover</td>
<td>6</td>
<td>18</td>
<td>na</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

Sample size (tows) 1346 180 163 23 41
Variance explained (r²) 26% 39% 12% 53% 63%

These sites might have conformed better to the general pattern if catches from a few years were examined. Even with this limitation, the habitat model explained more than half of the variance in catch (r²>0.50) at sites sampled one year (Milford and Niantic), and 39% of the variance in Saugatuck over five years. The lack of diversity in habitat type probably limited the resolution of the model analysis for Norwalk, but the rank order seen in the general model was maintained.

Using the Habitat Model to Predict Preferred Sites

The general habitat model shows that, within a site, most young-of-year winter flounder will be found in a mud/shell habitat, and that more will be found in protected muddy areas than in high-energy sand areas. These results can now be used to predict which site would be expected to provide more productive winter flounder nursery grounds, and which site would provide less, if no other factors intervene. When mean catch for an entire site was paired with the percentage of preferred habitat in that site for all sites examined in multiple years, a significant relationship resulted (r²=0.67, p<0.02, Figure 2). This relationship can be used to rank sites in terms of their potential to provide productive nursery grounds for winter flounder.

Figure 2: Relationship between percentage of preferred habitat in a sampled area and the mean catch of young-of-year winter flounder. Dotted lines show 95% confidence intervals for the predicted linear relationship.
Literature Cited


Change in population structure and size composition of the American lobster (*Homarus americanus*) in Central Long Island Sound.

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Abstract

Population structure and size composition of a lobster stock in Central Long Island Sound were measured in 1978, 1979 and 1980, and measured again in 1993 and 1994 to evaluate changes in size and sex ratio of the stock. Carapace length of lobsters changed drastically in favor of the males in sixteen years (1978 - 1994). Sex ratio of the stock also changed from 1:1 female to male in 1978 through 1980, to 1:2 female to male in 1993 and 1994. This represents a doubling of the male population of the stock. The reason for the unequal effects of habitat conditions on carapace growth of both genders, and the cause for increased number of male lobsters in Central Long Island Sound is not known. However, dissolved oxygen in this section of Long Island Sound has decreased in the sixteen years from 8.29 mg/L in 1978 through 1980 to 6.58 mg/L in 1993 and 1994.

Introduction

Natural populations of organisms that reproduce sexually always have a ratio between the numeric value of male and female individuals of the organism. This ratio guarantees the perpetuation of the species by ensuring the existence and availability of enough individuals of the two genders during the mating season. In the case of the American lobster, information on population structure and size composition are abundant in the literature. Reports on sex ratio and size composition of natural stocks of the lobster (Briggs and Mushacke 1979, Ennis 1980, Skud and Perkins 1969, Krouse 1973, Cooper and Uzmann 1980, Scarratt 1968, Cooper 1970, Cooper et al 1975, Stewart 1972, Pecci et al. 1978) show that sex ratio and size composition are not uniform throughout the natural range of the species. It has been known that there are different stocks of the American lobster (for review, see Wilder 1963, Salla and Flowers 1968, 1969, Cooper and Uzman 1971, Stasko and Campbell 1980, Campbell and Mohn 1983, Harding et al. 1983, Campbell et al. 1984, Campbell and Stasko 1985, Haakonsen and Anoruo 1994), so less attention is paid to differences in sex ratio and size composition because they are regarded as variable functions of stock.

It is not known whether other factors, example, time and habitat conditions affect lobster stock such that sex ratio of a local population could become a dynamic attribute of time and environmental conditions. The present knowledge and understanding of sex ratio of the lobster will be questionable if sex ratio is significantly influenced by time and environmental conditions. Could time and environmental conditions affect sex ratio such that the natural balance between individuals of the two genders of a lobster stock is upset? A time related change in population structure and size composition of a lobster stock is the focus of this study. For continued existence and perpetuation of the lobster, we hypothesize that sex ratio is independent of time and environmental conditions, else the natural balance between the genders which is necessary for sustained reproduction and replacement of the species will be upset.
The term "stock" has different definitions, and its meaning varies from one author to another (MacLean and Evens 1981, Campbell and Mohn 1983, Pezzack 1987). The present paper defines "stock" as "...a group of individuals that sustain itself over time and that responds in a similar way to environmental changes within a discrete geographical area" (Campbell and Mohn 1983), and the definition as used here applies to the term "local population".

Materials and Methods

A total of 2262 lobsters were captured during the summer fishing seasons of 1978, 1979, 1980, 1993 and 1994 in Central Long Island Sound south of Branford. The area provides a year round lobster fishery along the channels of the Thimble Islands and the adjacent Wheaton-Brown reef. Summer fishing seasons begins in May and ends in August of each year. In 1978, 1979 and 1980, 75 double and single entry commercial lobster traps were used to trap lobsters. In 1993 and 1994 only 25 double entry traps were used in capturing. However the research team accompanied commercial fishermen in the summer of 1993 and 1994 fishing seasons to substitute for the limited catch due to inadequate number of research traps. The fishermen used single and double entry traps. All traps used throughout the study were baited with menhaden (Brevoortia), and traps were checked two times a week for lobsters.

Carapace length of lobsters were measured with a pair of calipers from the back of the eye socket along the dorsal line to the end of the carapace. Each lobster was sexed based on the structure of the first two pairs of swimmerets. Sublegal size lobsters were released after measurement while the legal size lobsters were given to local commercial fishermen. This arrangement guaranteed the safety of research traps and cooperation of the local fishermen. Scuba diving was used in the summer of 1993 and 1994 to augment trap-caught lobsters. The channels of the Thimble Islands and Wheaton-Brown reef were divided into transects to ensure thorough coverage by divers. Scuba diving for 84 man-hours along the transects yielded no lobsters.

Dissolved oxygen was measured about three meters from the surface throughout the study. The 1978, 1979, 1980 and 1993 dissolved oxygen data were collected manually from the Southern Connecticut University Research vessel, while the 1994 dissolved oxygen data was collected by the newly installed Continuous Environmental Monitoring Platform (CEMP). The CEMP was designed by Endeco/YSI, Inc. and it is comprised of a buoy to which antenna, radar reflector and other high technology instruments that monitor atmospheric wind speed and temperature, and water pH, salinity, temperature, total dissolved solutes, dissolved oxygen and conductivity were attached. The CEMP beams its data to an antenna mounted on the roof at Southern Connecticut State University and information received by the antenna is downloaded to a computer equipped with software to receive the information.

Statistical analysis of the data was done in two stages. In the first stage, data collected from each summer fishing season for each year of the study was tested against each other to separate year(s) with data that are significantly different. In the second stage, years with data that are not statistically significantly different are grouped together and tested against data from the other years to discern changes in stock structure and size composition due to time and change in environmental conditions. Statistical analysis of the data was done with StarView™, Abacus Concepts Inc.

Results

Change in carapace length of Central Long Island Sound lobsters from 1978 to 1994 due to gender is presented in Table 1. Analyses show that male and female lobster carapace lengths are not statistically significant different from 1978 to 1980, but the 1993 and 1994 male and female lobster carapace lengths are significantly different (Table 1). The same results are also obtained when male and female lobster carapace lengths are analyzed for legal- and sublegal-size lobsters in those years. Further analyses to compare the late 1970's data with those of the
Table 1. Gender-Related Change in Carapace Length (CL.) of Thimble Islands and Wheaton-Brown Reef Lobsters between 1978 and 1994.

<table>
<thead>
<tr>
<th>Year</th>
<th>Legal size&lt;sup&gt;a&lt;/sup&gt; (mm)</th>
<th>Sublegal size&lt;sup&gt;b&lt;/sup&gt; (mm)</th>
<th>Population (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Female Male P=</td>
<td>Female Male P=</td>
<td>Female Male P=</td>
</tr>
<tr>
<td>1978</td>
<td>86.37 86.70 0.74</td>
<td>75.21 74.66 0.42</td>
<td>77.23 77.07 0.85</td>
</tr>
<tr>
<td>1979</td>
<td>88.89 87.09 0.64</td>
<td>76.32 75.92 0.19</td>
<td>79.49 78.79 0.06</td>
</tr>
<tr>
<td>1980</td>
<td>87.64 87.11 0.62</td>
<td>74.24 73.89 0.69</td>
<td>76.38 76.04 0.74</td>
</tr>
<tr>
<td>1993</td>
<td>85.99 88.56 0.0017</td>
<td>74.69 77.36 0.0002</td>
<td>77.57 82.03 0.0001</td>
</tr>
<tr>
<td>1994</td>
<td>86.59 88.43 0.02</td>
<td>74.93 77.03 0.0039</td>
<td>78.20 82.00 0.0001</td>
</tr>
<tr>
<td>1978-1980</td>
<td>86.89 87.05 0.66</td>
<td>75.89 75.48 0.14</td>
<td>78.83 78.24 0.07</td>
</tr>
<tr>
<td>1993-1994</td>
<td>85.48 87.61 0.0019</td>
<td>73.88 76.57 0.0029</td>
<td>76.52 81.30 0.0001</td>
</tr>
</tbody>
</table>

<sup>a</sup> Legal size includes lobsters with CL greater than 81mm in 1978 through 1980, and greater than 82 mm in 1993 and 1994.

<sup>b</sup> Sublegal size includes lobsters with CL of 81mm and lower in 1978 through 1980, and 82 mm and lower in 1993 and 1994.

Table 2. Time-Related Change in Sex Ratio of Thimble Islands and Wheaton-Brown Reef Lobsters between 1978 and 1994

<table>
<thead>
<tr>
<th>Year</th>
<th>Legal size&lt;sup&gt;a&lt;/sup&gt; Female:Male</th>
<th>Sublegal size&lt;sup&gt;b&lt;/sup&gt; Female:Male</th>
<th>Population Female:Male</th>
</tr>
</thead>
<tbody>
<tr>
<td>1978</td>
<td>1:1.42</td>
<td>1:1.21</td>
<td>1:1.25</td>
</tr>
<tr>
<td>1979</td>
<td>1:1.06</td>
<td>1:1.30</td>
<td>1:1.23</td>
</tr>
<tr>
<td>1980</td>
<td>1:1.29</td>
<td>1:1.26</td>
<td>1:1.26</td>
</tr>
<tr>
<td>1993</td>
<td>1:3.60</td>
<td>1:1.76</td>
<td>1:2.24</td>
</tr>
<tr>
<td>1994</td>
<td>1:3.80</td>
<td>1:1.74</td>
<td>1:2.60</td>
</tr>
<tr>
<td>1978-1980</td>
<td>1:1.10</td>
<td>1:1.30</td>
<td>1:1.20</td>
</tr>
<tr>
<td>1993-1994</td>
<td>1:3.60</td>
<td>1:1.80</td>
<td>1:2.20</td>
</tr>
</tbody>
</table>

<sup>a</sup> Legal size includes lobsters with carapace length greater than 81mm in 1978 through 1980, and greater than 82 mm in 1993 and 1994.

<sup>b</sup> Sublegal size includes lobsters with carapace length of 81mm and lower in 1978 through 1980, and 82 mm and lower in 1993 and 1994.
early 1990’s, male and female lobster carapace lengths are grouped into two. One group consists of data collected in 1978, 1979 and 1980, and the second group consists of data collected in 1993 and 1994. Analyses of the two groups of carapace lengths show that male and female carapace lengths are not statistically significantly different at 5% level in the 1970’s, but are statistically significantly different in the 1990’s (Table 1).

Sex ratio of lobsters range from 1:1.2 female to male for the local population, 1:1.3 female to male for sublegal-size lobsters to 1:1.1 female to male for the legal-size lobsters from 1978 through 1980 (Table 2). However, lobster sex ratio doubled to 1:2.2 female to male for the local population, 1:1.8 female to male for the sublegal-size lobsters, and 1:3.6 female to male for the legal-size lobsters in 1993 and 1994 (Table 2). Analyses of sex ratio in the individual years of the study show the same trend of change in sex ratio of lobsters in Central Long Island Sound.

Analyses of dissolved oxygen show that a significant difference exists in dissolved oxygen concentrations in Central Long Island Sound between the late 1970’s and early 1990’s. The mean dissolved oxygen in the summer fishing seasons of 1978, 1979, and 1980 was 8.29 mg/l. In the summer fishing seasons of 1993 and 1994, the mean dissolved oxygen concentration in Central Long Island Sound was 6.58 mg/l. These dissolved oxygen concentrations are significantly different (p = 0.0001).

Discussion

The results presented here reflect change in population structure and size composition of lobsters in Central Long Island Sound in 16 years (1978 - 1994). The decision to repeat the late 1970’s study in 1993 was prompted by massive desertion by lobster fishermen in Central Long Island Sound. Lobster fishery in 1993 and 1994 was characterized by poor catch in this section of the sound. The fishermen claimed that lobster catch had dwindled seriously for about three years and there was strong suspicion that something unusual was happening to the local lobster stock.

The results show that there is shift in size of male and female lobsters between the late 1970’s and early 1990’s in Central Long Island Sound. Although it has been known that male lobsters are on the average larger than female lobster, the size difference between the genders has increased significantly between 1978 and 1994. Difference in carapace growth between the genders has shifted tremendously in favor of male lobsters in 16 years. Table 1 shows that no significant difference exists between male and female carapace lengths from 1978 to 1980. However, in 1993 and 1994, carapace lengths of male and female lobsters in Central Long Island Sound are statistically significantly different (Table 1).

There is also a shift in sex ratio of lobsters in Central Long Island Sound between 1978 and 1994 (Table 2). The sex ratio has shifted from 1:1.2 female to male from 1978 through 1980 to 1:2.2 female to male in 1993 and 1994. This result indicates a doubling of the male population of this lobster stock. The shift in sex ratio not only applies to the entire local population of the Central Long Island Sound lobster stock, but it also applies to the sublegal category. The sex ratio of this category of lobsters has been widely documented to be 1:1 female to male (see Cooper and Uzzmann 1980, Scarratt 1968, Cooper 1970, Stewart 1972, Cooper et al. 1975, Krouse 1973). The sex ratio of the sublegal lobster stock in Central Long Island Sound has shifted from about 1:1 female to male between 1978 through 1980 to about 1:2 female to male sixteen years later (Table 2). The shift in sex ratio of Central Long Island Sound lobsters is more magnified in the legal size category. Sex ratio of this group of lobsters changed from 1:1 in 1978 through 1980 to 1:4 in 1993 and 1994 (Table 2).

It is in fact disturbing to know that Briggs and Mushacke (1979) studied lobster stocks in Western Long Island Sound and noted that the local populations were dominated by females in both research catch and fishermen landing. Skud and Perkins (1969) reported similar results in offshore studies of northern lobsters. Stewart (1972) reported a range of sex ratios of lobsters tagged and recaptured in Rar Island plots in Connecticut. The
ratios ranged from 1:1.08 to 1:1.4 male to female; indicating lobsters stocks dominated by females.

The cause of the change in sex ratio and size composition of lobsters in Central Long Island Sound is not known. However, dissolved oxygen concentration in this section of Long Island Sound has changed from a mean of 8.29 mg/l in 1978 through 1980 to 6.58 mg/l in 1993 and 1994. Sex ratio of the sublegal category shows that the females in the category have experienced reduction in population relative to the males. It is interesting to note that the shift in sex ratio of lobsters is very dramatic when carapace length attains 82 mm and higher. This corresponds to the size female lobsters bear abundant eggs. Could it be that the dissolved oxygen concentration in Central Long Island Sound is no longer sufficient to support female lobsters, especially large females in berry? If this is true, perpetuation of the species in this section of Long Island Sound will be questionable because sustained replacement will be impractical if the stock is comprised of mostly males without sufficient females during the reproductive season. Analyses of dissolved oxygen show that dissolved oxygen levels in Central Long Island Sound are significantly less in 1993 and 1994 relative to the dissolved oxygen levels in 1978, 1979 and 1980. It may well be that other habitat conditions are responsible for both change in sex ratio, and shift in carapace growth of male and female lobsters. The 1978, 1979 and 1980 study limited the scope of the present work because no other habitat conditions were studied in those years. So there is no baseline data to compare a recent study of other environmental conditions beyond dissolved oxygen.

Preliminary results of this study led to the proposition to acquire the CEMP. An environmental monitoring system that is capable of recording habitat conditions over extended periods. Such a system could have made it possible to assess changes in the marine environment that could affect local lobster populations. It is also important to note that the results of this study are based on information obtained from trap-caught lobsters. Ennis (1980) reported that male lobsters outnumbered female lobsters in trap-caught samples while females outnumbered males in diver-caught sample in his study. In this study, scuba diving yielded no lobsters. However trap-caught samples of the late 1970's are compared with trap-caught samples of the 1990's. Moreover, Krouse (1973); Pecci et al. (1978), Stewart (1972) and Skud and Perkins (1969) studied sex ratio of lobsters using trap-caught samples. The results of the studies showed that sex ratio of lobsters remained 1:1 male to female. It is still not conclusive if method of capture has gender effect on lobsters such that investigations on population dynamics and sex ratio are impacted. In this study the same method is adopted sixteen years apart to evaluate changes in population structure and size distribution of lobsters in Central Long Island Sound.

IN MEMORY

This work is devoted to the memory of Dr. Harry O. Haakonsen (March 12, 1941 to February 2, 1995). Dr. Haakonsen was a Professor of Chemistry at Southern Connecticut State University. Although a Chemistry Professor, Dr. Haakonsen devoted his academic career to studies of the environment. He was interested in tracking studies of salmon and the American lobster. He held several positions including the Co-Director of the Center for the Environment at Southern Connecticut State University and Director of Outer Island: an island in the Thimble Islands used by Southern Connecticut State University for research and instruction.
References


Approaches for Oyster Reef Restoration in Long Island Sound: Understanding the Relative Importance of Local and Regional Controls of Population Dynamics

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Introduction and Background

Both the management and restoration of coastal habitats requires a thorough understanding of population- and community-level processes which influence them. Ecological habitats within these systems are often spatially fragmented and the organisms which inhabit them will likely be influenced by the size, morphology and spatial arrangement of individual habitat patches within a particular regional ecological landscape. For example, economically important resources such as oyster, clams and scallops often occur as distinct local populations which can either be managed locally or as a series of weakly inter-connected sub-populations. Factors affecting local population dynamics may not necessarily be similar to processes influencing regional dynamics. In addition, many important coastal habitats (e.g., seagrass beds, oyster reefs, mussel beds) create a spatially structured environment which can be critical to associated populations of other economically important organisms (e.g., crabs, fish). The spatial structure permits management efforts to focus on local sub-populations and their link to other life stages that occur in distinctly different areas. Furthermore, environmental problems, such as the impacts of disease organisms or the introduction of alien species are primarily problems of population and community ecology and are most likely managed at these levels. Understanding the success or failure of coastal management strategies will rely on understanding the conflicting importance of local dynamics of a single population or unit and the more regional processes such as recruitment and/or emigration that link the sub-populations together.

Population ecologists frequently invoke the term metapopulation to describe the dynamics of spatially fragmented populations of organisms which are linked together via dispersal of individuals between the sub-populations (Hanski and Gilpin, 1991 for a review). While the metapopulation concept is more than 25 years old (Levins, 1970), it has gained renewed interest in the ecological and conservation literature. With ever-increasing human-induced habitat fragmentation of plant and animal populations, increasing emphasis has been placed on describing specific requirements of species in local habitat patches necessary to maintain regional population persistence (e.g., Quinn and Hastings, 1987; Rolstad, 1991; Hanski and Thomas, 1994; Man et al., 1995). For instance, permanent or transient physical or biological differences among sites often results in local variation in mortality and reproductive rates of
organisms. As a result some sites may act as "source" sub-populations whose reproduction maintains less favorably situated "sink" sub-populations (Figure 1). Because assemblages of many species that are critical resources in coastal habitats should be viewed as metapopulations, it is necessary to understand the balance between local control of the dynamics of sub-populations and any broader-scale control resulting from the inter-connection of all the sub-population units.

While the metapopulation framework provides a more realistic description of natural population dynamics in spatially fragmented habitats than more traditional approaches, it can also provide important insights into the establishment and management of local habitats. For example, spatially fragmented populations are predicted to be particularly susceptible to sudden, catastrophic collapse as gradually increasing habitat destruction or harvesting pressure drops populations below the densities necessary to insure adequate recruitment from "source" sub-populations (Quinn et al., 1993; Whitlatch and Osman, in press). Knowledge of the quantity and quality of "source" habitats and their spatial configuration in a regional landscape will provide important insight into how best to undertake habitat and/or species restoration programs and possibly which habitat patches should be utilized and which should be left as refuge habitats.

**Oyster Management in a Metapopulation Framework**

The jump from metapopulation theory to the management of natural resources such as oyster populations is not great. Disease, habitat destruction and harvesting greatly affect the spatial and temporal variability of mortality and reproduction of oyster populations. A variety of efforts are being directed to restoring and rehabilitating oyster populations and one of the assumptions of developing self-sustaining populations is the supposition that existing "source" (seed) populations will supply oyster larvae for harvested ("sink") populations. Given the close match between the theoretical metapopulation constructs and different strategies for oyster management, it is important that this body of ecological and conservation theory be tested and explored in different management approaches.

Oyster habitats provide an excellent framework for the metapopulation approach as various sub-populations of oysters are distributed in discrete units which are inter-connected by a common larval pool for recruitment of new individuals to the sub-populations (Figure 2). It is also important to recognize that oyster habitats also contain other species which possess widely varying dispersal abilities which have one or more life-stages that are confined to a local habitat. For example, both oysters and many of the epifaunal species that attach to their shells are sessile and incapable of moving after attaching to the substrate. However, larval stages of these species vary widely in their dispersal abilities from those of oysters and barnacles that can remain planktonic and disperse for weeks to tunicates and bryozoans whose planktonic larval stages may only exist for minutes. In addition, more motile species such as demersal crabs and fish will disperse not only as larvae but also as migrating juveniles and adults. Thus, the entire community provides us with species representing a broad range of life histories and dispersal abilities. It also presents a challenge to assess the effects of variations in dispersal ability between local populations on both local and more regional population dynamics.

The degree to which an oyster rehabilitation or restoration area is isolated from other oyster habitats within a given ecological system will be critical to its local dynamics. For example, species with poor dispersal capabilities will colonize isolated reefs slowly or not at all. If these species are predators or parasites of key resource species such as oysters then sub-population isolation could potentially improve the productivity of oysters or other prey species. However, isolation could also have negative
Figure 1. A spectrum of metapopulation structures. The "mainland-island" model (A) indicates all migration of individuals occurs from a large "source" habitat to smaller "sink" habitats. While "source" and "sink" sub-populations can be of equal size with no outside migration (B), most natural metapopulations are represented by "source" and "sink" sub-populations of different size and shape and degrees of isolation (C).
Figure 2. A generalized metapopulation model for oysters. The model consists of "source" and "sink" sub-populations which are dependent upon a common larval pool for the recruitment of new individuals into the sub-populations. The model shows sub-populations with two size-classes (J = juveniles; A = adults) of oysters. The size-classes (node) are connected by arrows depicting transition probabilities of growth and/or survivorship (Fx) into the next node or the reproductive output (Fx) of each node. The width of the Fx arrows represents the relative contribution of each sub-population to the common oyster larval pool. Models of this form can be solved for the intrinsic rate of population increase which then can be used as a currency to evaluate potential population performance and the relative contribution of "source" and "sink" sub-population dynamics to the persistence and performance of the entire regional population (e.g., Whittach and Osman, in press).
effects on prey populations if predators or competitors colonize more rapidly than oysters or other prey species, or if larval dispersal between sub-populations is constrained by larval supply.

It is important to recognize that isolation is a parameter that can be controlled within any management plan, regardless of the design, structure or size of the restoration area. In addition, it is possible to conduct realistic field experiments to study which are the most effective restoration techniques for oyster habitat restoration and rehabilitation. For example, by manipulating isolation several important management-oriented questions can be addressed: How does proximity to existing oyster populations affect the successful establishment of new oyster habitat? What characteristics of established communities enhance their persistence? What is the potential for newly-created habitat and the increased dispersal of key species to increasing regional shellfish productivity? Does harvesting cause local extinctions within sub-populations? Are local extinctions absent when there is no harvesting?

While it may be possible to identify “productive” or “source” and “non-productive” or “sink” oyster sub-populations within a given region, it is always clear whether between sub-population differences in local productivity is a consequence of variability in the colonization process or is the result of differences in post-recruitment oyster growth and survivorship. Despite the potential of broad-scale dispersal at the regional scale, oyster recruitment is often temporally and spatially variable within- and between-regions (Loosanoff, 1966; Kennedy, 1986). The degree of connectivity between sites is not simply a function of proximity of sub-populations and is not always easily measured at the ecologically relevant spatial scale. Local variations in post-settlement processes can also contribute substantially to juvenile oyster survivorship and growth (Whitlatch and Osman, in press). Experimental studies using artificial reefs in eastern Long Island Sound further revealed that local persistence of populations can also be influenced by the life history characteristics of resident and colonizing species, population size-structure of residents and local interactions of both residents and colonists with predators and competitors (Osman and Whitlatch, in press).

The use of the metapopulation framework for assessing the oyster population performance also can incorporate how different abiotic and biotic processes impact the distribution and abundance patterns of different life history stages. This approach, therefore, promotes identification of potential life stage “bottlenecks” which may have a disproportionate influence on overall population productivity. For example, results of a simple oyster metapopulation model revealed harvest refugia have the potential of providing valuable protection against catastrophic collapse of a regional oyster fishery (Whitlatch and Osman, in press). Carefully conducted field studies are required, however, to determine the optimal size and spacing of harvest refugia in order to assess the nature of local and regional variability of larval dispersal and post-settlement mortality. It is widely recognized that larval dispersal of benthic invertebrates is highly variable in space and time and difficult to measure the appropriate spatial and temporal scales. The application of new methods for labelling and tracking oyster larvae (e.g., Levin 1990) may permit direct estimates of the degree of inter-connectiveness of sub-populations within a particular regional ecological landscape.

How spatial dynamics influencing natural populations and communities is an critical but poorly understood area in the field of marine ecology. Identifying what are the limits to extrapolation from small-scale studies, how processes interact across scales and how we develop new techniques for incorporating scale into ecology are also important questions for population biologists and resource managers. Given the fragmented nature of oyster reef habitats, coupled with the high degree in the variability of recruitment and post-settlement mortality patterns, we should proceed with caution when trying predict regional population dynamics of reef organisms from small-scale studies of a limited number of local sub-
populations. At present there are few tested approaches that enable us to recognize the limitations of scaling up from small-scale studies to the level of a specific region. The use of spatial patch dynamic models (e.g., Caswell and Etter 1993; Wu and Levin 1994) appears to be a powerful and promising approach for viewing ecological systems as mosaics of interacting patches which occur at distinct spatial and temporal scales.

Acknowledgments

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Literature and References


Panel Discussion 2

Hypoxia
Panel Discussion:
Research on Impacts of Hypoxia on Long Island Sound Living Marine Resources

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Introduction

The Long Island Sound Study (LISS) has evolved a phased, long-term plan to reduce nitrogen inputs to Long Island Sound. The linkages between nutrient inputs and subsequent hypoxia in the bottom waters of the Sound are fairly well understood and reliably simulated using quantitative analytical models. However, knowledge of the ecosystem-wide impacts of hypoxia in the Sound, and the marginal benefits/detrimental effects to living marine resources (LMRs) in the Sound that may ensue from changes in dissolved oxygen levels resulting from nutrient reduction practices, is poor. The high cost of reducing anthropogenic nutrient loadings and the need to monitor the benefits to LMR communities from nutrient reduction actions suggest that more research is required to adequately understand the response of LIS LMRs at the community and ecosystem levels to changing dissolved oxygen concentrations in the Sound. This special session of the 1996 Long Island Sound Research Conference was designed to highlight and address this need.

The session began with an overview by Mark Tedesco of EPA's Long Island Sound Office of the LISS nitrogen reduction plan. Don Miller of EPA's Narragansett Lab presented a summary of dissolved oxygen thresholds that have been developed in him and his colleagues to provide increasing levels of protection to the Sound's LMRs. Penny Howell of Connecticut's Department of Environmental Protection and Joel O'Connor of the Environmental Protection Agency commented on the nature and direction of future research on hypoxia and LMRs in the Sound. Gerry Capritulo of the State University of New York at Purchase described recent research conducted in his lab on the mechanisms of hypoxic impact on lower trophic levels in Long Island Sound.
Overview of Nitrogen Management Efforts for Long Island Sound

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Abstract: The Long Island Sound Study (LISS) has identified hypoxia, or low levels of dissolved oxygen, as a critical problem in the Sound, resulting in significant, adverse ecological effects in bottom water habitats. Oxygen concentrations below 3.5 mg/l, the level necessary to prevent most adverse impacts, have been recorded during the summer in western Long Island Sound each year from 1987-1996. The excessive discharge of nitrogen is tied to hypoxia by fueling the growth of planktonic algae.

The total nitrogen load to Long Island Sound is estimated to be 93,600 tons per year. Of this, approximately 29,900 tons per year are estimated to be from natural sources and 53,700 tons per year are associated with human activities.

In order to understand the relationship between nitrogen loadings and dissolved oxygen levels in the Sound, the LISS constructed water quality and hydrodynamic computer models that were extensively calibrated to observed field data collected over an eighteen month period. Based on preliminary model results, the LISS began implementing a phased approach to reducing nitrogen loadings to the Sound. Phase I, announced in December 1990, called for a freeze on point and nonpoint nitrogen loadings to the Sound in critical areas at 1990 levels. Phase II, approved in 1994, committed to low cost actions to begin to reduce the load of nitrogen below the 1990 freeze baseline.

To guide the next phase of management, the LISS has coupled the completed water quality and circulation models to provide a time variable, three-dimensional model called LIS 3.0. LIS 3.0 solves a series of mass balance equations for 25 state-variables (salinity, temperature, phytoplankton biomass, various forms of organic and inorganic nutrients, detrital organic carbon, and dissolved oxygen). It has approximately 6,500 grid cells to provide spatial detail.

Eleven land-based management zones, delineated primarily by using natural drainage basin boundaries, have been established to foster comprehensive watershed planning. For each management zone, point and nonpoint nitrogen loads were estimated and a menu of management options and costs to control these loads was developed. The LIS 3.0 model was used to identify the relative impact of nitrogen sources originating from different geographic areas on dissolved oxygen levels in Long Island Sound, combined with information on the feasibility and cost on nitrogen reduction, cost curves were developed and evaluated to identify a cost-effective level of reduction.

A series of management scenarios was then developed and tested using the LIS 3.0 model to evaluate the significance of changes in the duration, areal extent, and intensity of hypoxia resulting from management. The LIS 3.0 model forecasts that the duration and area of exposure to dissolved oxygen concentrations below 3.5 mg/l can be greatly reduced through aggressive management of point and nonpoint sources of nitrogen. Based on this work, proposed Phase III nitrogen reductions are being developed for release for public comment by the end of 1996.

Continuing questions facing resource managers are how low dissolved oxygen conditions affect living resources and how to assess the significance of changes in these conditions on the individual, population, and ecosystem levels.
PANEL NOTES: Research Needs for Hypoxia Issues and Living Marine Resources

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From a Fisheries Management stand point, we view hypoxia as a habitat impairment issue. That is to say, we know there is a fairly long list of finfish species normally found in the Sound in abundance that are consistently scarce or absent in areas with hypoxic waters. We have been operating under the working hypothesis that fish leave a hypoxic area rather than die. Particularly rapid onset of severe conditions has caused fish and lobster kills, but this has been observed only rarely. Dismissing the occasional fish kill as "acceptable impact", we still are left with the problem of determining whether the remaining habitat can support the biomass displaced from hypoxic areas without negative effects on growth and survival. Under low stock size conditions - as we are experiencing now with many species heavily exploited by sport and commercial fisheries - seasonal habitat loss may be only a minor limiting factor in overall Long Island Sound productivity. However, as exploited fish stocks rebuild in response to more aggressive management, available habitat can be expected to become a more important limiting factor, potentially hindering full stock restoration. We would like to have the Sound functioning at its highest level of productivity.

An important data gap in assessing the effects of hypoxia on the productivity of the Long Island Sound ecosystem is that all of the conclusions in the Long Island Sound Study Comprehensive Conservation and Management Plan are based on work in open water. Very little is known about the areal extent, seasonal duration, and annual persistence of hypoxia inshore. We also don't know as much as we'd like to about the role of these inshore embayments as nursery areas and feeding grounds. The functional decoupling of the Sound and its harbors may be the hidden impact of hypoxia. A barrier of low-oxygen water, either intruding from the Sound into the harbors, or the reverse, may create a situation where certain species, and/or certain life stages, are unable to reach suitable feeding and spawning areas even though the hypoxic zone itself is easily avoided and poses no direct threat. The open question then becomes: Is nearshore hypoxia preventing the Sound's harbors from functioning at their normal, and exceptionally high, biological potential?
The Technical Basis for Dissolved Oxygen Benchmarks to Protect Long Island Sound Living Marine Resources

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The Long Island Sound Study Living Marine Resources Committee has proposed three water quality categories to identify dissolved oxygen (D.O.) benchmarks for nitrogen reduction planning. The categories are: not protective, D.O.<2.0 mg/L at any time or <3.5 mg/L as a one day average; marginally protective, ≥3.5 to 5 mg/L as a one day average; protective, ≥ 5 mg/L as a one day average.

This paper examines the low D.O. effects information underlying these D.O. benchmarks. This information was developed largely at this laboratory and by a three year bottom trawl study in L.I. Sound conducted by D. Simpson, M. Johnson and K. Gottschall, Connecticut Department of Environmental Protection (CT DEP). These data are evaluated with the objective of identifying the D.O. conditions necessary to assure the survival, growth and propagation of resource and forage species. Protection of community as a whole is implicit with these protection objectives.

The threshold for 5% lethality (LC5%) for juvenile fishes is 1.9 mg/L, based on 24-hour laboratory tests with ten species. The slope of the lethal response curve for these fishes is sharp, with the LC50 often occurring only 0.5 mg/L below the LC50. Hence, should D.O. decline below 1.9 mg/L, there is the potential for considerable mortality among the sensitive species, as well as involvement of additional species. For example, at 1.6 mg/L, EPA data show that lethality of juvenile Crustacea begins to occur. A minimum benchmark of 2.0 mg/L would serve to protect juveniles from these effects.

A threshold of approximately 3.5 mg/L is suggested for other biological effects by both field and laboratory data. The CT DEP trawl study cites 3.7 mg/L as the incipient limiting D.O. concentration for total biomass of the demersal finfish community, and 3.5 mg/L as the incipient limiting D.O. for species richness. These values were based on the aggregated data for 23 species of demersal finfish. The incipient limiting D.O. was defined as a 5% reduction below the asymptote of a logistic plot of the catch data. Laboratory tests indicate D.O. conditions in the same range are lethal to larvae of some crabs. Mean 96-hour LC10s for the early larval stages of Atlantic rock crab (Cancer irroratus) Say mud crab (Dyspanopeus sayi) and longnose spider crab (Lihipia dubia) are 3.7, 3.4 and 3.1 mg/L, respectively.

The following biological effects above 3.7 mg/L were observed in the laboratory. Lethality was seen in crab larvae up to 4.8 mg/L, which is the mean LC 15 for two tests with late larval Say mud crab exposed through the molt to the megalopae stage. These tests were eight and ten days in duration. Larval growth in Say mud crab was reduced 25% at 4.2 mg/L, the mean of six tests. Also, there are two literature reports of effects in this range. Sakana and Joseph (1972) provide data indicating a 24-hour LC10 of 4.6 mg/L for larval striped blenny (Chondrostoma bonaius), and Bejada et al. (1987) observed abandonment of preferred bottom habitat ≤4.2 mg/L by red hake (Urophycis chaus).
The preceding information indicates the biological effects of D.O. in the 3.5 to 5.0 mg/L range primarily pertain to early life stages. Although our knowledge of these effects is limited at present, it is prudent to retain 5.0 mg/L as a protection benchmark for LI Sound. Protection of larvae is an important consideration in the Sound, since the larval period for a number of species coincides with summer hypoxia. Summer D.O. conditions in this range are common in the western Sound. In the Eastern Narrows, for example, subpynocline D.O. during 1993 and 1994 was below 5.0 mg/L for approximately 85% of the time between July and mid-September, and below 3.5 mg/L for half this period, based on weekly monitoring by the Interstate Sanitation Commission.
Mechanisms of Hypoxia Development and Future Research Needs
Long Island Sound Conference Panel Session Summary

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Current conventional wisdom argues that excess nitrogen entering Long Island Sound from diverse sources (especially sewage effluent) stimulates phytoplankton production, which goes under-utilized, settles to the bottom of the estuary, and leads to the development of hypoxia via bacterial decomposition pathways, with concomitant decreases in recruitment and survival of commercially important finfish and shellfish.

A question arising from this asks: shouldn't fertilization of the western Long Island Sound, and associated increases in algal biomass, stimulate secondary and higher production leading to enhancement of finfish (and shellfish) production, rather than to hypoxia?

**Hypothesis:** Differential successes among planktonic species experiencing eutrophic conditions is altering planktonic food web structure in the western Long Island Sound away from "traditional pathways" and towards microbial loop dominated pathways.

A three-year study, measuring a multitude of variables in nearshore waters of the Sound along a west to east gradient, by myself and others (funded by the Long Island Sound Research Fund of the Connecticut DEP; G. M. Capriulo, PI) addressed several questions designed to: 1) test the above hypothesis 2) develop contemporary baseline data on planktonic food web structure and associated nutrient dynamics of Long Island Sound (including a total nutrient balance sheet for NO₃, NO₂, NH₄, DON, PON, PO₄, and Silicate, N/P & N/Si ratios). 3) search for west-to-east gradients in microbial loop dynamics, species composition (of phytoplankton, protozooplankton, zooplankton and larval fish), and eutrophication from primary and higher production sources. 4) relate any observed differences to macro zooplankton and larval fish population dynamics.

**Summary of Findings and Conclusions of the Study**

1) Yearly and multi-year average concentrations of dissolved inorganic nutrient levels indicate similar (to only slightly higher in the west) nutrient concentrations across and west to east LIS gradient.

2) The relative proportioning among chemical species of nutrients often differs from west to east both contemporaneously as well as temporally, with NH₄ and DON at times more prevalent in the west (particularly in bottom waters).

3) The excess loading of nitrogen (and other nutrients) into the Sound are converted to elevated biomass in the west of both phytoplankton as well as zooplankton.

4) Size-fractionated chlorophyll data indicate little west to east differences in the 10-20 μm size fraction, while pointing to large differences in both the less than 10 and greater than 20 μm fractions, which are both higher in the west.
5) Occurring along with the enhanced phytoplankton biomass is slightly enhanced bacterial densities and growth rates. The densities show interesting seasonal bacterial cycles and appear to be related not to total chlorophyll levels but to densities of the nanoplanktonic algae.

6) Heterotrophic nanoplankton densities are also higher in the west and may be influencing bacterial dynamics.

7) Species composition of phytoplankton routinely differ among west to east stations, and appears to be related to N/P & N/Si ratios, as well as to ratios among nitrogen species.

8) Dissolved inorganic N/P ratios are routinely low (well below the Redfield Ratio) among all stations with the west exhibiting ratios (i.e. including DON) are similar among stations and typically above the Redfield ratio.

9) Associated with the bacterial and nano-algal enhancement is significant enhancement of ciliate species diversity in the west.

10) Copepod biomass is extremely enhanced in the west, indicating that while stimulating the microbial loop, eutrophication is also enhancing secondary production preferred by larval fish, comb jellies and other jellyfish.

11) Copepod biomass as well as fecal pellet production likely is a significant contributor to hypoxia in Long Island Sound.

12) Larval fish diversity was down, overall, as compared to Richard's & Riley's 1950's data. Yet, overall abundance was similar across the west to east gradient.

13) Hypoxic-level-low oxygen concentrations were rarely encountered in our near-shore stations. Given the above conditions, larval fish should not experience food limitations nor severe hypoxic stress in near shore waters. So, if juvenile and larval fish stocks are down, one must look else where, e.g. critical habitat loss of nursery areas and over fishing, for causes.

14) If larval fish fail to capitalize on the high copepod biomass in the west, ctenophore and other gelatinous zooplankton may be the beneficiaries, i.e. we may be enhancing economically uninteresting gelatinous zooplankton at the expense of fish.

NEW CONVENTIONAL WISDOM: Excess nitrogen stimulates microbial loop and phytoplankton biomass/production, which in turn stimulate microcrustacean biomass/production & fecal release, which likely both significantly fuel hypoxia, and stimulate gelatinous zooplankton production.

Future Research Needs:

1) Accurately determine the mechanisms by which hypoxia develops (e.g. study the role of copepod biomass & fecal pellets in the development of hypoxia).

2) Assess the fate of western Long Island Sound "excess" biomass/production (e.g. role of gelatinous zooplankton vs. larval fish).
3) Higher resolution examination of spatial & temporal patterns of larval fish species diversity and abundances.

4) Examination of spatial & temporal patterns of ctenophore and other gelatinous zooplankton abundances & their role as sinks for larval fish production as well as "excess" zooplankton production.

5) Examination of alternate reasons for possible low adult and juvenile fish stocks (e.g. overfishing, critical habitat destruction, fish sterility due to estrogen-analog compounds, predation from coastal birds).
Plenary Session: Hypoxia - Additional Research Needed

Joel O'Connor
Environmental Protection Agency, Region 2

It is difficult to contribute more about additional research needs after the presentations of Gerry Caprinlo and Penny Howell. They have ably summarized the most important needs. I can only underline some issues which seem to me important if we are to improve understanding of hypoxic impacts on resources (vice better understanding of where and when hypoxia occurs).

One obvious extension of existing knowledge is to quantify hypoxia and assess hypoxic effects within Sound embayments, and their implications for fish stocks in the Sound. The Adopt-a-Harbor Volunteer Water Quality Monitoring Program has already contributed to more thorough knowledge of seasonal dissolved oxygen concentrations within several harbors. I also understand that the Sound Study may use some existing models to quantify the conditions leading to hypoxia in some harbors. Although hypoxic/anoxic conditions have led to major fish kills within some harbors, we can only speculate about the implications for the open Sound.

Both field and laboratory experiments can obviously contribute to sorting out the relative importance of hypoxic and other impacts, and the specific modes of hypoxic impact. It is very encouraging to note that lab and field investigators work together closely in the LISS. This is a most significant feature of your experimental designs; each type of design benefits from and contributes to the other. The resulting insights meld both laboratory and field observations, making each of them more relevant than experiments by “us” and “them.” This degree of collaboration is fortunate because even the issues regarding individual stocks are complex enough to require all the expertise available.

Although it is important that LISS laboratory and field investigators continue to collaborate closely, I suggest that each group may stress different feature of experimental design. Controlled experiments may usefully emphasize rigor, whereas field work may stress innovation. Laboratory assays of the sort conducted by Don Miller and his colleagues already have tested and generally agreed protocols which enable comparisons across taxa and life stages. Valuable new findings result generally from rigorous applications of the same protocol on sensitive life stages. However, we know that most field experiments are not likely to be particularly valuable because any part of the system chosen for study is so variable and complex. Only innovative field designs of the sort conducted by Dave Simpson and Penny Howell have been particularly informative in the Sound. I do not recommend, of course, routine lab work and “far-out” field work. I am suggesting emphasis only. Good controlled experiments require lots of innovation in both design and interpretation, and useful field work needs the degree of rigor required to make credible contributions.

Also important in considering additional research needs are realistic expectations for new findings. Unrealistic expectations can both disappoint all participants, and confound long-term research planning. Even experiments of possible hypoxic effects on individuals stocks will be difficult to interpret, because other ecosystem forces (especially meteorology and exploitation) are so strong, yet loosely coupled and non-linear. One could even argue that hypoxic effects on individual stocks alone may not be broadly interpretable because stocks are influenced so strongly by the rest of the ecosystem. If so, this is another strong argument for collaboration between laboratory and field work.

So we have very limited understanding of hypoxic impacts in the Sound, these impacts maybe ecologically and economically consequential, and we should not expect to find out how consequential without lots more research. This is a superficial argument for more intensive research, recognizing that hypoxia in Long Island Sound is one of many consequential environmental issues competing for social resources.
Watersheds
Concentration and Deposition of Atmospheric Mercury Around Long Island Sound

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As part of a project to determine the amount of mercury (Hg) entering Long Island Sound (LIS), the important flux from the atmosphere is currently being measured at five locations in Connecticut and New York. The sampling sites consist of three co-located passive, bulk deposition collectors designed by the Swedish Institute for Environmental Research (IVL). Two week-long integrated samples are being collected at each site. Total, reactive, and monomethyl mercury species will be determined, as well as sulfate and particle-tracing radionuclides. Results from all sites will be shown and discussed. Available data from event sampling at Avery Point this Fall/Winter indicate relatively low concentrations (3.4 ng/L or 17pM, vol. weighted mean) of Hg in coastal Connecticut precipitation. Results from the bulk and event collections will be examined using ancillary data to compare with similar studies in Wisconsin and Florida and test the “Particle Conversion” hypothesis of Hg transformation in the atmosphere.

Additionally, studies of gas-phase Hg concentrations are underway. Gas-phase Hg accounts for the vast majority (>95%) of the atmospheric burden, and is the most frequently determined atmospheric species. However, its concentrations and diel behavior in coastal and urbanized regions such as LIS are not well known. Total gas-phase Hg is being examined on a multi-day integration basis at Avery Point, as well as in a near synoptic, continuous fashion during selected cruises running the length of LIS. Initial data from both of these studies will be discussed.
Metal Pollution in Wetlands around Long Island Sound

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Connecticut has been a center of mining, manufacturing and industrial activity since the early 1800's. Pollutants have been carried by the three major rivers in Connecticut to Long Island Sound and a record of metal pollution is preserved in sediments from wetlands surrounding the Sound and along its feeding rivers. We have analyzed sediment cores from Chapman Pond (Connecticut River), and the coastal marshes of Griswold Point, Ram Island (Stonington), Pataguansett (Niantic), Guilford and Clinton. Cores of about 1-1.5 meters were sliced in 2-3 cm samples which were dried and analysed for density, C$_{org}$, total Sulfur, Cu, Zn, Pb, Mo, Ag, As and major elements. Analyses for Hg are currently ongoing. Profiles of $^{210}$Pb were used to date the core tops and ages were extrapolated further downcore toward $^{14}$C dates. We calculated metal pollutant concentrations (corrected for natural background), sediment and metal accumulation rates, and cumulative pollutant inventories, as well as leachable cumulative Fe inventories and excess $^{210}$Pb inventories.

The data show the lowest metal pollution inventories on the east side and higher inventories further west along the Sound and in the freshwater wetlands. The metals Cu and Zn show no correlation with excess $^{210}$Pb inventories, ruling out atmospheric deposition as a significant source for these metals. The Pb pollution profiles show a complex accumulation history with an early 'Pb veil' possibly related to mining activities and hunting in colonial times, followed by a steep increase during the industrial revolution, and a still larger degree of pollution related to the burning of leaded gasoline, which strongly declines in strength from about 1970 on. The total cumulative Pb inventories show a poor correlation with $^{210}$Pb inventories, but we are currently plotting Pb subinventories (e.g., cumulative gasoline lead only) against partial $^{210}$Pb inventories to test for atmospheric transport pathways. The pollutant inventories show a strong positive correlation with leachable Fe inventories, indicating that particle-bound transport is the dominant process of pollutant dispersal. The individual pollution source regions can be fingerprinted by trace element ratios: e.g., the Connecticut River sediments are characterized by relatively high Zn/Cu, Zn/Pb and Zn/Fe inventory ratios compared to more eastern marsh sediments.
Metal Pollution in Coastal and Riverine Wetlands

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Abstract

Patterns of metal pollution in coastal and riverine sediments reflect the changes in pollution sources over time. Most metal transport is in particle-bound form, but atmospheric deposition of Pb forms an important contribution to marsh pollutant burdens. The degree of Hg pollution seems to scale with the size of the drainage basin, and annual Hg accumulation rates in marshes exceed the observed atmospheric Hg depositional flux by at least a factor of 30. The Connecticut River seems to supply a particular Zn-rich pollution component, possibly related to urban run-off. The metal pollutants in marsh systems probably were derived largely from direct pollutant sources along the rivers, and do not show evidence for the accumulation of integrated atmospheric metal deposition in the watershed.

Introduction

Industrialization has had a severe environmental impact, and metal pollution in riverine and coastal sediments is a ubiquitous result. Major metal sources in the environment have been or continue to be fossil-fuel power-generation stations, especially coal-fired plants (e.g., Cu, Zn, Pb, As, Se, Hg), cement plants (Pb, Zn), solid waste incinerators (Hg, Pb, Zn) and combustion of leaded gasoline (Pb). Such high-temperature processes produce large metal fluxes into the atmosphere, from where the metals are slowly removed by atmospheric deposition, either wet or dry. In addition, industrial sources may release waste fluids directly into fluvial systems (e.g., chemical industries, metal plating industry, paper mills), and storm overflow systems may lead to direct release of sewage and urban run-off into rivers. In addition, waste water treatment plants provide a steady flow of metals to rivers, probably including Hg. Seepage from landfills and abandoned or active mining areas may add to the metal releases.

Rivers carry this pollutant burden largely in a particle-bound form, either adsorbed on clay or organic matter. In river coves and wetlands, the suspended particles may settle out and so produce freshwater sequences of polluted sediments (Valette-Silver, 1992; Bricker, 1993; Cochran et al., 1993). Part of the suspended and bedload sediments enter the estuaries, where precipitation of hydrous Fe-oxides and organic matter may occur in the estuarine mixing zone. These fine-grained, poorly crystalline, newly formed particles are suitable substrates for metals and may end up with other suspended sediments in the estuarine marsh systems and mudflats; an unknown fraction is carried further out to sea. Coastal marshes and mudflats are the nurseries for many coastal faunal species, so the accumulation of these contaminated sediments is highly undesirable.

To understand the pollutant dynamics in a given region, we need to characterize the metal sources, provide evidence for the transport mechanisms, and try to determine the main sedimentary sink areas for toxic metals. The focusing of metals into coastal depositional environments can occur as a result of three sets of processes, which are not mutually exclusive:
1. *In situ* atmospheric deposition of pollutants in tidal wetlands (McCaffrey and Thomson, 1980; Bricker, 1993)

2. Atmospheric deposition of pollutants in the watershed, followed by erosion and transport of the polluted soil particles to the river, followed by deposition in riverine wetlands, coastal marshes and shallow marine muds. In this scenario, much of the atmospheric deposition from the drainage basin is focused into wetlands.

3. The atmospheric flux of pollutants accumulates in soils in the watershed area for an extended period. The main pollutant flux in the river is that from direct sources, industrial as well as urban. In this case, the wetlands accumulate metals from riverine sources in addition to the local *in situ* atmospheric deposition flux.

These processes are schematically shown in Figure 1, and our research aims at determining which of the three scenarios above is mainly responsible for metal pollution of riverine and coastal sediments. We use as evidence for particle-bound pollutant transport correlations between total pollutant burdens and sediment parameters. The processes outlined under 2. above would give rise to correlations between $^{210}\text{Pb}$ and pollutant inventories, because $^{210}\text{Pb}$ is an atmospheric tracer. The half-life of $^{210}\text{Pb}$ (about 22 years) is of the same order as the doubling time of metal pollution fluxes over the last century, which would create a roughly constant ratio between time-integrated pollutant and $^{210}\text{Pb}$ burdens if focusing of atmospheric deposition in the watershed into marsh systems is a significant process.

**Study Locations and Methods**

We studied salt marsh deposits from Barnstable marsh (MA), Barn Island marsh, Pataguansett marsh, Guilford marsh, Clinton marsh and Farm River marsh (all in Connecticut) and Dennis Creek marsh along Delaware Bay (NJ). Sediments were analyzed for many major and trace elements, including the pollutants Cu, Zn, Pb, Mo, As and Hg. All analyses were done by ICP-OES on *aqua regia* leachates, except for Hg which was done by cold vapor AAS on sediment leachates. We also determined several sediment parameters: density (wet and dry), Loss on Ignition (an organic carbon proxy) and $^{210}\text{Pb}$ - $^{226}\text{Ra}$ and $^{137}\text{Cs}$ concentrations (by gamma counting). Excess $^{210}\text{Pb}$ concentrations were calculated and the sediments were dated with the "constant rate of supply" and the "constant initial concentration" methods. Cumulative pollutant and excess $^{210}\text{Pb}$ inventories were calculated as well as pollutant accumulation rates, after correction for natural background according to methods described by Varekamp (1991).

The rationale for the study site selection was as follows:

a. The Barnstable marshes on Cape Cod, MA, have no major watershed or riverine system feeding into them. All pollutant supply is either *in situ* atmospheric deposition or from particles of marine origin.

b. The Connecticut marshes represent a diverse set of watershed drainage basin sizes and so can be used to test the various models.

c. A core from Chapman Pond, a cove along the Connecticut River, provides data on particle bound pollutants from that river.

d. The marshes/mudflats from the Connecticut River estuary provide a comparison for Chapman Pond and may define a Connecticut River pollutant end-member for Long Island Sound.
Results

Metal profiles from selected Connecticut marshes are shown in Figure 2. These profiles show clearly the onsets of pollution, at depths around 25 - 60 cm, dependent on the local marsh accretion rates. Dated sequences provide details on changes in metal fluxes with time and we focus here on a Pb pollution profile: profile P1 from Pataguansett marsh (Figure 2C) shows an onset of pollution in the late 1800’s, followed by a strong increase around 1930, and a decrease after 1970. Such a profile is best explained as showing the history of Pb emissions: the industrial revolution (coal burning, manufacturing), followed by leaded gas combustion, and the introduction of unleaded gas in the 1970’s. The trend in gasoline sales in Connecticut shows a similar pattern as the sedimentary Pb pollution, pointing towards leaded gasoline as a substantial source component for Pb. The pollution history in this core seems to be a direct reflection of the metal release pattern, suggesting that the lag time between pollutant release and accumulation is very short (< decade). This suggests either that in situ atmospheric deposition in a marsh was important or that Pb that was deposited in the drainage basin is effectively scavenged and carried as polluted soil particles immediately towards the river. The accumulation of Pb in many urban soils is evidence for the accumulation of Pb from atmospheric deposition in the watershed itself, and argues against the latter process of Pb scavenging from the watershed.

Cumulative Pb pollutant inventories show only a weak correlation with Fe inventories, a proxy for the abundance of fine-grained sediments in the marshes from Connecticut and Massachusetts, suggesting that in situ atmospheric deposition is an important pathway for Pb transfer into the marshes. The Barnstable (MA) marsh sediment core shows small inventories for Zn and Cu, but a sizeable inventory for Pb, suggesting that of the three metals, only Pb has an important atmospheric transport component. The high-temperature source for much of the Pb pollution make atmospheric transport an acceptable pathway. The marsh Cu inventories show a much stronger correlation with Fe inventories (Figure 2D), suggesting that particle-bound transfer is a dominant process in its transport history.

Plots of excess 210Pb inventories versus Zn or Cu inventories show very poor correlations. Most marsh 210Pb inventories can be best explained as resulting from in situ atmospheric deposition in the marsh, as they tend to be close to expected inventories for the observed local 210Pb deposition rates. This observation suggests that most particles that arrive in the wetlands have not been extensively exposed to the atmosphere for the last 100 years, and so can not have accumulated much pollutants from atmospheric deposition either. We tentatively conclude that most of the Zn and Cu in the wetlands is derived from river-based pollutant sources and that focusing of pollutants from atmospheric deposition in the watershed is only a minor component of the pollutant transfer history for these metals.

Cumulative pollutant inventory ratios may be used to fingerprint specific sources. The Zn/Cu inventory ratios are invariably high for all Connecticut River sediments at variable Zn/Fe ratios. The sediments from Long Island Sound marshes have lower Zn/Cu ratios and may carry a Connecticut River particulate component in addition to other, less Zn-rich pollutant components. Zn is an ubiquitous metal in many household products and the large urban water input component along the Connecticut River may provide this Zn-rich signature.

The Hg concentration profiles from cores in Barn Island marsh and Guilford marsh show good correlations with Fe inventories, suggesting particle bound entry into the marsh, even for this highly volatile element. The Hg accumulation rates are also a factor of about 30 higher than observed atmospheric deposition rates, suggesting that pollutant focusing is important. The whole marsh Hg burdens of
the two studied marshes are approximately proportional to the size of their watersheds, suggesting a Hg loading that scales with the drainage surface area. Further studies are needed to reveal the details of this relationship.

Conclusions

Metal pollution in most coastal salt marshes is widespread, but the Barnstable marshes (MA) show very low levels of Zn and Cu pollution and moderate Pb pollution. The data suggest that atmospheric transport of Pb is important, whereas Cu and Zn are largely transported in particle-bound form. The Connecticut River may be a relatively Zn-rich particle source for Long Island Sound and its marshes. Hg pollution shows strong particle-bound character, and the degree of Hg pollution scales with the drainage basin size. No strong correlations are found for 210Pb and metal inventories, making focusing of pollutants that were deposited by atmospheric deposition in the drainage basin an unlikely process. Pollutant patterns in marsh sequences reflect quite accurately changes in metal source strengths over time, indicating that the source signals are rapidly transmitted to the coastal zone; metal storage in intermediate riverine sedimentary reservoirs is limited. The drainage basins are probably accumulating the local atmospheric pollutant deposition flux, which may be slowly released over the next few centuries.

Acknowledgments

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References


Figure 1. Potential metal pollution pathways in a watershed and adjacent wetlands.
Figure 2.

A. Concentration-depth profiles for Cu and Pb in Patguansett marsh, CT.
B. Cu profiles in Dennis Creek marsh (NJ, core DCA) and Barnstable marsh (MA, core BAMC) show low-level pollution in Barnstable and much stronger pollution as well as high accretion rates in Dennis Creek.
C. Historic Pb pollution record and sales of gasoline in Connecticut show the probable origin of Pb pollution since about 1930-1940.
D. Cu-Fe inventory plot, showing the overall correlation for Connecticut marshes, suggesting that particle bound transport for Cu is important; the Barnstable core plots far off this array, indicating that particle-bound transport was less important in this marsh without a watershed.
Mass Balance of Heavy Metal Sources and Sinks in New Haven Harbor, Connecticut

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Introduction

Though heavy metals are among of the most toxic and persistent contaminants of estuaries, we lack a quantitative understanding of their sources, distribution, transport, and fate. For estuarine systems located in industrialized areas, such as urban harbors, this lack of knowledge is complicated by numerous inputs of metal pollution from point and non-point sources, and by removal and redistribution of contaminated sediments through dredging operations. In order to determine the relative importance of each of these factors for heavy metals in an industrialized estuary, a mass balance of Ag, Cd, Cu, and Pb was constructed for the Quinnipiac River/New Haven Harbor system. The information generated by this study can be used by ecosystem managers to improve water and sediment quality in the most cost-effective way.

Based on previous surveys of metals in sediments, New Haven Harbor is one of the most badly contaminated sites in Long Island Sound (e.g. Greig et al. 1977), an estuary located in one of the most densely populated areas of the country. Previous investigations of Long Island Sound estuaries cover unlike metals at widely separated locations, lack information on changes with discharge or time, are outdated or inaccurate due to contamination artifacts, and fall short of establishing a true mass balance. While previous research has tended to look at individual pieces of the puzzle, the current study examined the entire system in an integrated way by establishing a rigorous mass balance for heavy metals.

Study Site

New Haven Harbor is an embayment in the central part of the north shore of Long Island Sound and is the most active port in Connecticut. It is located at the mouth of three rivers: the Quinnipiac, Mill, and West. The City of New Haven has a long history of industrial activity, including metal fabrication and finishing, brass manufacturing, and arms production. Its waste water treatment system still employs combined sewers in over 30% of the city, which covers 1.600 ha. The largest river, the Quinnipiac, also has a highly developed watershed, and thus is potentially a significant source of metal pollution.

The harbor is divided into inner and outer sections by the Sandy Point breakwater on the west and Fort Hale Point on the east. The upland limit of the harbor was taken to be the point where the average low tide salinity was 20%. For the Quinnipiac River, this is close to the location of the Interstate 91 bridge. Fine-grained sediments and industrial development are almost exclusively restricted to the inner harbor. This is also the site of the three former sewage treatment plants (only one 60 MGD facility remains active), twenty-two CSOs, and the mouths of the three influent rivers. Each river passes through
a marsh system before entering the inner harbor. The Quinnipiack River's marsh system is the largest, with an area near 300 hectares.

Methods
Mass Balance Calculation

The mass balance calculation was carried out in a manner similar to that described in Benoit and Hemond (1987, 1990), taking into account important dissimilarities between estuarine and lacustrine systems. The goal was to identify and quantify all the major inputs and outputs of metals in the harbor. Using the difference between the sum of the these different fluxes, and the measured change in storage AS, any unmeasured production or removal processes would be identified.

\[
\Delta S = \text{Atm. Dep.} + \text{Rivers} + \text{Industry} + \text{STP} + \text{CSO} - \text{Burial} \pm \text{LIS} + \text{Unk}
\]  

(1)

Where: AS is change in standing stock, including surficial sediments and the water column. Atm. Dep is atmospheric deposition, Burial is burial in sediments below the zone of active exchange with the water column. Industry is permitted industrial discharges. LIS is exchange with Long Island Sound, CSO is combined sewer overflows, Unk is unknown sources or sinks, calculated by difference.

In this formulation, the upper mixed layer of sediments is defined as part of the harbor. This layer is the zone that undergoes rapid mixing and can continue to exchange metals with overlying water. Its depth can be determined from radionuclide analysis (Benninger et al. 1979, Peng et al. 1979, Robbins 1982, DeMaster and Cochran 1982, Carpenter et al. 1984, Stoddard et al. 1985).

Solving for the Unk term required integrating each source and sink term over a specific period, taking into account any temporal variations that occurred. For continuous discharges, such as rivers and STP effluent, rating curves were developed to account for the variations in metal concentrations over time. For intermittent discharges, like CSOs, a different method was established, characterizing the range of metal concentrations and frequency of discharge events. One virtue of the mass balance method is that closure can serve as an internal check when unknown sources and sinks are negligible. For this purpose, it is important to determine the uncertainty of each term of the mass balance so that the statistical significance of the difference term can be evaluated (Benoit and Hemond 1987).

Water samples

All water sampling was conducted following strict clean protocol as described in Ahlers et al. (1990), Benoit (1994), and Benoit et al. (1997). Particulate and dissolved fractions were separated in the field during collection with 0.45μm pore size in-line filters (Millipore Durapore). In the case of CSO effluent, metal concentrations were in the high parts-per-billion (ppb) range, allowing time-series sampling with an ISCO model 3700 portable autosampler. Subsequent steps, including filtration, were conducted in the lab using clean protocols.

For fresh waters, Pb, Cd, Cu, and Ag were measured after evaporative preconcentration (dissolved) or acid leaching (particulate) on a Perkin Elmer 3000 graphite furnace atomic absorption spectrometry (GFAAS). For sea water, sewage effluent, or fresh water with high salt content (due to road salts in the winter), metals were analyzed following metal isolation/preconcentration with a chloroform extraction and the complexing agent APDC/DDDC (Bruland et al. 1985). All water analyses were conducted in a class 100 clean room following clean procedures outlined in Benoit (1994).
Sediments

Sediment samples were collected either by divers with 12.5 cm I.D. PVC tubes or as 5 cm diameter gravity cores. Marsh cores were hand collected in 12.5 cm tubes. Metals in sediments were extracted by microwave digestion in Teflon bombs (Kingston and Jassie 1988) with concentrated HNO₃ and HF, followed by measurement using a Perkin Elmer 3300 simultaneous inductively coupled plasma atomic emission spectrometer (ICP-AES). Radionuclides were measured by non-destructive gamma spectrometry using a low-background planar Ge detector. Total and excess ²⁰⁶Pb were measured by the method of Cutshall et al. (1983) following a ≥ 21-day equilibration period in sealed cans to allow ingrowth of ²²²Rn daughters. ⁷Be was measured immediately following can sealing to confirm integrity of core tops and to assess short time-scale mixing.

For the mass balance, direct industrial discharge contributions and losses from dredging operations in the harbor were calculated from monitoring records filed with the Connecticut Department of Environmental Protection (CTDEP) and Army Corps of Engineers (ACOE).

Atmospheric deposition

Three local lakes were used as large-scale collectors to evaluate this term. Two sediment cores from each lake were analyzed for Ag, Cd, Cu, Pb, ²⁰⁶Pb, ⁷Be and ¹³⁷Cs. Trace metal inventories were corrected to account for metals added by sediment focusing and watershed contributions by dividing by the ratio of excess radionuclides compared to known direct atmospheric deposition (Kada and Heit 1992).

Rivers

Of the three rivers that drain into New Haven Harbor, the largest, the heavily industrialized Quinnipiac River, contributed over 90% of metals, and was studied in the greatest detail. A total of 38 bi-weekly metal measurements were correlated with discharge, and the resulting linear rating curves were all statistically highly significant (p < 0.001). These curves were then integrated using a daily time step, and a total yearly flux of river-borne metals was calculated. This value was corrected for substantial removal that occurs in a large salt marsh in the 0 - 20 psu reach of the estuary. A total of 45 cores taken throughout the marsh yielded a reliable map of trace metal distribution in the accumulating peat. These concentration values were multiplied by the sediment accumulation rate (based on dated cores and local relative sea level rise) to derive a removal rate. Heavy metal removal from the fresh water end-member by the marsh was 26% for Ag, 7% for Cd, 15% for Cu, and 35% for Pb.

Sewage treatment plants and CSO's

Periodic sampling revealed that unlike the highly variable loadings from the Quinnipiac River, total metal concentrations in STP effluent tended to be bi-modally distributed. Relatively low metal levels result from normal operating conditions and much higher values occur during secondary by-pass conditions (during storm events, high flows receive only primary treatment). Short residence times within the sewer system tend to minimize the time at any intermediate flow condition. Therefore, only the average metal values for these two conditions together with the daily flow were used to calculate the total metal input to the harbor.

Extensive sampling of CSOs revealed highly variable metal concentrations depending on such factors as time of day, length of antecedent dry period, and season. In addition, CSO discharge is not
gauged, but only whether or not flow occurs. For each CSO flow event during the year, metal concentrations for the most similar measured event were combined with calculated discharges to estimate total metal fluxes. Discharge volumes were based on storm sewer pipe diameters, CSO capacities, and pump station pumping rates.

**Industrial discharges**

Calculations were based on discharge permits, but this input is now a negligible part of the total mass balance for the harbor.

**Sediments**

A total of 22 cores were collected and analyzed for trace metals (Ag, Cd, Cu, Pb), transition metals (Al, Fe), radionuclides (67Fe, 210Pb, 226Ra, and 137Cs), bulk density, and organic matter as a function of depth. These measurements allowed for calculation of both losses to burial and ΔS, as well as for a normalization of the trace metals with Fe, Al, and organic matter to eliminate artifacts caused by dilution with coarse sediments. Sediments had a rapidly mixed zone in the upper 12 cm, and this was taken to be the region that was still interacting with the overlying water column. A simple box model was used to calculate the change in standing stock (ΔS) in the mixed layer based on the one year changes in metal inventory in the mixed zone, and the assumption that the mixed layer thickness remained constant over time.

The net burial flux to deep sediments was calculated from the product of: 1) accumulation rates derived from 210Pb and 137Cs dating techniques (Krishnaswamy et al. 1971, Ritchie and McHenry 1990), and 2) heavy metal concentrations in the accumulated sediment below the mixing zone. Both sediment accumulation rate and metal concentrations increased from the mouth to the head of the harbor in a predictable manner, so interpolation could be used for undated cores.

In addition to burial losses, metals were removed from the harbor bottom by dredging. Dredging operations in New Haven Harbor take place approximately every 15 years, with the most recent occurring in 1993. Approximately 15% of New Haven Harbor is allocated to shipping channels, turning basins, and berthing areas. Sedimentation rates for these areas were calculated from total accumulation between dredging periods by means of state and federal records. Based on the total area dredged and volume of sediments removed, an average sedimentation rate of 4 cm/yr for these areas was estimated. (Unusually high sediment accumulation rates in these zones probably is related to the over-deepening caused by dredging.) Multiplying this sedimentation rate by the heavy metal concentrations determined from both our gravity coring and metal concentration data yields losses due to dredging.

**Losses to Long Island Sound**

Sampling at the inner harbor mouth over the course of several tidal cycles (and as a function of water depth) allowed us to calculate the exchange flux based on tidal prism volume (Duxbury 1964, Anonymous 1971, McCusker and Bosworth 1979) and variations in metal concentration. Samples were collected at a station at the inner harbor’s mouth over full 12-hour tidal cycles for one spring and one neap tide during the summer and fall.

**Uncertainties**

Uncertainties were estimated for all source and sink terms based on variability of replicate samples, differences between independent methods of measurement (e.g., 210Pb vs. 137Cs dating), or variance from
predictive relations (e.g., concentration-discharge regressions). The uncertainty within each term is a function of both natural variability and the analytical uncertainty of the specific model or procedure used to calculate yearly fluxes. Uncertainties were combined via standard propagation of error methods to yield a net uncertainty for each term and also for their combination in the total mass balance. Minimization of uncertainties, especially for large terms, is necessary in order to test for mass balance closure and to evaluate of the significance of the Unk term.

Results and Discussion

The heavy metal mass balance for New Haven Harbor was constructed covering the period from March 1995 to March 1996. For all four heavy metals studied, the most important source and sink terms were the input of metals from polluted rivers and losses to sediment burial. The input from rivers varies with discharge, with snowmelt and significant rains storms (> 2.5 cm) contributing 50% of the total metal flux. Based on other research not reported here, we believe that most of the riverine flux derives from what today is nonpoint source pollution. In past decades, upstream industries contaminated river banks and floodplains which continue to act as a pollution source. The most important sink term was losses to burial, approximately balancing the riverine source. Sedimentation rates ranged from 0.3 cm/yr to 1.7 cm/yr following a general pattern of decline from north to south.

The remaining terms in the mass balance were all significantly lower than the riverine input and losses to burial. The majority of sediment cores had a small negative ∆S, with the exception of cores located near the STP and CSO outfalls, which tended to be slightly positive. On a harbor wide scale, the ∆S for Ag and Pb was approximately 10% of losses due to burial. Cd and Cu had higher decreases in the ∆S, approaching 20% of the burial flux. Atmospheric input to the harbor was calculated to be a very small term.

Tidal exchange exhibited different patterns for each metal. Substantial variability occurred from one tidal cycle to the next, and a small number of cycles were analyzed, so conclusions are only preliminary. Cu consistently was exported from the harbor at all depths on a year-round basis. Ag also was consistently exported from the harbor, however, bottom waters actually carry a net input, though rather minor, while surface waters exported Ag with concentrations greater than those of bottom waters by an order of magnitude. This difference is probably due to the large amount of Ag discharged in treated STP effluent (Sanudo-Wilhelmy and Flegal 1991, 1992). Cd and Pb showed more variability. Pb was exported in the summer and imported the rest of the year, while Cd showed the opposite pattern.

Management Implications

The Unk terms fall within the combined uncertainty of the mass balance and attest to the fact that the tidal exchange term, though uncertain, at least has the correct order of magnitude. Lacking further data, it is still impossible to say with certainty whether the harbor supplies metals to Long Island Sound or vice versa. What is clear is that the quantity of metals reaching the sound from the harbor is much smaller than the sum of inputs to the harbor. In other words, under present conditions New Haven Harbor does act to prevent substantial metal loading to Long Island Sound. People bypass this protective capability when they dredge the harbor and deposit the spoils in the Sound, as occurs roughly every 15 years.

Sewage treatment plants have often been implicated as key contributors of metals and other contaminants to aquatic environment (Hubbard and Hashim 1987, Seidemann 1991, Buckley and Winters 1992, Bricker 1993, Voutsinou-Taliadouri and Varnavis 1995, Bricker 1996). In this study, STP effluent
Sewage treatment plants have often been implicated as key contributors of metals and other contaminants to aquatic environment (Hubbard and Hashim 1987, Seidemann 1991, Buckley and Winters 1992, Bricker 1993, Voutsinou-Talaiadouri and Vamvlas 1995, Bricker 1996). In this study, STP effluent was dwarfed by riverine inputs. Although there are five additional STPs in its watershed, our measurements (Benoit et al, in preparation) reveal that nonpoint sources rather than STPs are currently responsible for most of the Quinnipiac River's metal burden. The relatively small contribution from STPs compared to past times may reflect the higher level of treatment (secondary vs. primary) mandated by existing regulations. Whatever the cause, we can state unequivocally, that further improvement of sewage treatment to remove greater quantities of metals would have a trivial effect on total metal loading in New Haven Harbor.

Acknowledgments

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References


Quantitative Relationships Between Watershed-Scale Stressors and Estuarine Condition for Long Island Sound in Comparison with Other Mid-Atlantic Estuaries

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Analyses of the 1990-1993 Environmental Monitoring and Assessment Program (EMAP) data for the mid-Atlantic region suggested that the primary stressor for small estuarine systems was sediment contamination. A pilot project has been conducted that developed quantitative relationships between watershed-scale (landscape) stressors and sediment contamination for estuaries within Chesapeake Bay (Comeleo et al., 1995). Two landscape stressors—land use pattern and point source pollution—were spatially analyzed for each individual watershed of 25 Chesapeake Bay estuaries using a geographic information system. Land use data were obtained from Thematic Mapper (TM) imagery classified by the EMAP Landscape Characterization Group Chesapeake Bay Watershed Pilot Project (U.S. EPA, 1994). Sediment contamination data for the same estuaries, available from EMAP (Strobel et al., 1995), were statistically reduced to one principal component for metals. Non-parametric statistical techniques were used to develop empirical relationships for the pilot study area between sediment contamination and developed land (positive), herbaceous land (negative) and point source loading (positive). Comparable analyses were performed on 77 estuaries across the mid-Atlantic region for which EMAP data were available. 13 of which are in Long Island Sound. Land use data for the entire mid-Atlantic region were derived from the U.S. Geological Survey Land Use Data Analysis database (Fugeas et al., 1983). Because of the dramatic differences in characteristics of the estuaries in the mid-Atlantic region, additional factors reflecting hydrologic regimes and sediment origins were incorporated in the statistical analyses involving the entire mid-Atlantic region. The results for the small estuarine systems in Long Island Sound are contrasted and compared with those across the mid-Atlantic region. We conclude it is possible to develop relationships between watershed-scale stressors and estuarine condition, such as sediment contamination, across large geographic regions.
Integrating RADARSAT Data to Support the Study of the Coastal Ecology of the Long Island Sound

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**Abstract**

RADARSAT is a satellite that offers researchers a new tool to analyze the earth's surface. It uses synthetic aperture radar to scan the earth in a number of different angles, resolutions, and image sizes. An active sensor, it can measure through clouds, day or night, and offers another perspective for information which has a wide range of applications for coastal researchers. Although synthetic aperture radar can seem daunting at first, the concepts behind it are fairly straightforward. In addition, integration with other data sources can generate a new level of knowledge advancement. Pointers to internet resources are included.

**Introduction**

Managers of the environment serve an important function and deserve to have the very best for their projects. Advancements in satellite mapping systems offer unique new benefits, but may not be implemented to their full potential due to the complexity of the technology. Synthetic aperture radar (SAR) has the potential to support a wide variety of coastal research projects studying the Long Island Sound.

SAR is a system that measures the intensity and time delay of the return signal of pulses of energy that are sent down and bounced off of the earth. These measurements provide information about the topography and composition of the earth's surface. The data collected has direct applications to agriculture, land use, forestry, geology, hydrology, flood mapping, ice monitoring and coastal zone analysis.

Specific applications of SAR to coastal zone analysis include oil spill detection and monitoring, coastline change analysis, and water circulation studies. In addition, because the intensity of the return energy is affected by the composition of the surface materials SAR can gather unique information regarding these features.

RADARSAT is one satellite that offers scientists flexible alternatives for capturing SAR data. Ultimately, the full power of SAR is generated when it is integrated with other data sources in a Geographic Information System (GIS) to create computer maps linked to databases of information.

**Synthetic Aperture Radar**

Aircraft have carried side-looking radar systems since the 1950's (Lillesand, 1994). Side looking allows the radar to perceive surface variations due to differences in the reflected return signal. SAR is a technique of side-looking radar that allows for a more efficient radar system. "These systems employ a short physical antenna, but through modified data recording and processing techniques they synthesize the effect of a very long antenna" (Lillesand, 1994).
RADAR: An Active Sensor. Unlike optical systems that rely on energy originating from the sun (which travels through and is affected by the atmosphere and its associated distortions), radar systems blast out a pulse of energy at a certain wavelength and record the signal that is reflected back to a measuring sensor. Rather than "seeing" the surface, the system "feels" the surface of the earth like a blind person reading braille. Since radar systems do not rely on energy from the sun, they can operate in cloudy conditions and at night.

The Most Popular Bands. Just as multispectral scanners divide the electromagnetic spectrum into slices, or bands, radar sensors measure their energy in bands. The most popular radar bands are the X band (2.4-3.75 cm.), the C band (3.75-7.5 cm.), and the L band (15-30 cm.). In addition, "radar signals can be transmitted and/or received in different modes of polarization. That is, the signal can be filtered in such a way that its electrical wave vibrations are restricted to a single plane perpendicular to the direction of wave propagation" (Lillesand, 1994).

Effect of Incidence Angle. Since the sensor is required to be side looking, the incidence angle plays a strong role in determining the qualities of the surface features that will be detected. A low angle will show more topographic relief, like the shadowing of the setting sun. A high incidence angle will allow the beam to reach otherwise shadowed areas, measuring more of the surface roughness. Looking at objects from more than one direction or height offers more information, especially when integrally processed (Corbley, 1995).

SAR and Earth Characteristics. In addition, earth surface characteristics play an important role in image analysis. Imagine a ball thrown downwards at an angle. Anything that would cause it to bounce back is a reflector. A wall makes an excellent corner reflector. Even a tree growing straight up can act like a wall. Of course, it depends on the size of your ball. A tiny "bb-gun" size ball will ricochet back off of any little rock or surface imperfection while a beach ball will bounce right over that imperfection and continue on to ricochet off of a large tree.

The same principle, called the Rayleigh criterion, applies to radar waves, except that the waves are diffusely reflected when the "root-mean-square height of the surface variations exceed one-eighth of the wavelength of sensing divided by the cosine of the local incidence angle" (Lillesand, 1994). Surfaces are specular reflectors when the "root-mean-square height of the surface variations is less than one-eighth of the wavelength of sensing divided by the cosine of the local incidence angle" (Lillesand, 1994). So the roughness of a surface and the shape and orientation of objects on it affect the reflections of the waves, as does the size of the radar waves and angle of incidence.

Reflectance and Dielectric Constant. Another consideration is the electrical characteristic of the terrain features. Features with a high complex dielectric constant reflect well. Wet features, such as moist soil and healthy vegetation, have a higher complex dielectric constant, as do metal objects. As a result, they show up brighter in a radar image.

SAR Advantages. In summary, "SAR image brightness is related to radar backscatter at the pixel level, and is a function of land and ocean surface roughness, vegetation canopy structure, and snow, soil, and vegetation moisture status. Radar sensors provide their own illumination and can therefore provide reliable temporal data independent of weather or sun illumination, through all seasons, and at all latitudes. Radar waves penetrate through clouds and, under certain conditions, through vegetation canopies and thin veneers of alluvial overburden, making it possible to explore regions of the earth's surface that are not accessible using other remote sensing techniques" (Evans, 1995).

Satellite Radar

Existing Satellite Radar. The Russian ALMAZ-1, Japanese JERS-1, European ERS-1 are three satellite radar systems that have been operational for the past few years and which are providing data for a number
of applications. "This unparalleled proliferation of high-quality, low-cost, quickresponse data can confidently be expected to usher in a period in which side-looking radar imagery will achieve a level of acceptance and use that will rival that of the multi-spectral sensors carried on the Landsat and SPOT satellites" (Pascucci, 1995).

[These existing] "... satellite radars follow a predetermined sun-synchronous orbit with a fixed-look direction for the radar sensor. There is no flexibility in aiming the radar beam relative to the orientation of [surface] structures. Resolution is fixed and significantly coarser than airborne radar. The depression angle is relatively large which results in foreshortening and layover effect. This appears on the imagery as overly bright, shortened, or lost slopes facing the satellite. The larger this depression angle, the stronger this effect (Dekker, 1994). RADARSAT, led by the Canadian Space Agency, makes progress toward overcoming these limitations. Launched in early November of 1995, RADARSAT is an SAR system designed to last approximately five years.

Flexibility "Radarsat will have several beam modes which will permit tradeoffs between depression angle (31-70 degrees), resolution (nominally 10-100 meters), and imaging swath width (45-500 kilometers) to meet a broad range of user requirements. This flexibility will allow the users to select a beam mode [fitting] the study area, view a certain area in several modes, and access any area in the world within three to six days" (Dekker, 1994).

Beam Steering Benefit "An interesting application of the adjustable incidence angle will be a process called 'radargrammetry', ... a technique used to extract elevation information from two images taken over the same area from different angles" (Corbley, 1995). In addition, "electronically steering the antenna range beam allows for a significant increase in the observation frequency", allowing for a site to be examined a number of times in a short period, which supports relief efforts (D’errico, 1995).

HH Polarization "Another feature of RADARSAT is its HH polarization; it has been designed to transmit and receive a horizontally polarized signal ... [which] is less sensitive to interference from slight wind disturbances on the ocean surface" (Corbley, 1995).

Image Analysis

"SAR data are currently being used for studies of ecology, hydrology, oceanography, ice sheets and glaciers, and geology. With the recent and planned launches of US and International SAR sensors, significant progress is also being made toward operational use of this new data type. Ecological applications include classification of land cover, measurement of above-ground woody plant biomass, and delineation of wetland inundation. Hydrologic applications include measurement of snow and soil moisture. Oceanographic applications include characterization of oil slicks and monitoring of sea ice thickness and motion. Interferometric SAR data have been used to measure surface topography and topographic change, and to monitor glacier ice velocity. Interferometric SAR processing also allows generation of high-quality digital elevation models which can be used to ortho-rectify data to high precision" (Evans, 1995).

GlobeSAR Teaching people to effectively employ Radarsat data is an important step in the promotion of the uses of SAR. Toward that end, Canada initiated a project called GlobeSAR that used aircraft flying with SAR equipment to collect data in a manner that simulated the data that would be collected by Radarsat. GlobeSAR was a five phase project begun in 1993, starting with workshops on defining the project, continuing with data acquisition and processing, leading to data analysis and evaluation, causing a desire for education, training and technology transfer, and culminating with reporting, seminars, and symposia (Lapp, 1994). Now that the RADARSAT satellite is up and running, actual data is available. The Canadian Space Agency maintains a web site at http://www.ccrs.nrcan.gc.ca/ and offers images and text that demonstrate applications.
Histogram Processing. Image processing is the key to satellite image analysis. The Digital Number (DN) value represents the intensity level of the reflected energy sensed by the receiver at a given instant of time. These DN values are processed and displayed on a monitor as pixels. The pixels (representing areas on the earth’s surface) with the lowest reflected energy are represented as darker on a grey scale, and the pixels with the highest levels of reflected energy are represented as whiter on a grey scale. A histogram represents the frequency of DN values in a range from 0 to 256. The range of display grey scale values can be employed to spread a certain portion of the DN histogram. For example, since water features tend to reflect back very little, spreading the display range across the lower end of the DN range allows for more detail of the water’s variation to be presented on the screen. In addition, DN values can be separated into equally sized “bins” based on their frequency of occurrence, called equalized contrast stretching.

Integration

RADARSAT data is one piece of geotechnological information that can be integrated with other pieces to form a vastly improved GIS (Corbley, 1995). Each technology offers particular benefits. Integrating data can be achieved using a number of different techniques and models (Ehlers, 1995). The choice of model or technique depends on the goals of the scientist. Perhaps a mixture of historic Landsat TM land use data, elevation data, and SAR data could be combined to offer a model of the ecological area. “An investigation conducted for the U.S. Geological Survey by Autometric Inc. demonstrated an unexpectedly large degree of synergy in the combined exploitation of airborne radar and the Landsat Thematic Multispectral Scanner. The results of the investigation, which involved geologic analysis of lineaments related to petroleum and gas exploration, demonstrated both the synergistic and additive contributions of radar when used in conjunction with a multispectral system” (Pascucci, 1995).

One of the main benefits for integration is the ability to fine tune the definition of the spectral classes in traditional remotely sensed optical images. Remember that optical sensors gather data in bands of light that can be mixed and matched to provide more information than the eye can see. Greater statistical separation and tighter boundaries are possible when processing data that are sensitive to radar detection.

Measurement of relevant features by actually going out and visiting them is another important component of data integration. Ground truthing by gathering data onsite permits the researcher to calibrate small portions of the image and apply that template to other parts of the image (with caution). Furthermore, field conditions at the time of data acquisition may have a substantial impact on the information contained in the data. For example, strong winds churn waves that drastically alter the reflection of the SAR signal.

Change Detection. An inherent concept of ecological analysis is the concept of change detection. “Change detection using satellite sensors relies on the difference of the Digital Number values between corresponding pixels in the two or more images acquired at different times over the same area” (Spiropoulos, 1993). One technique to examine changes involves assigning different colors to three geographically identical images that were taken over a period of time during which a significant change is suspected to have taken place. After processing, areas of mixed color indicate that a change has taken place (Wagner, 1994).

Coastal Programs

A number of coastal monitoring programs throughout the nation are under development which may aid in the advancement of coastal science. (Murphy, 1995; Copeland, 1994; Friel, 1992).

Lessons From Disaster. By analyzing the role of GIS information in disasters, important topics can be identified. For example, it might be important to check on sites that house toxic chemicals, or to limit access to water supply wells that might have a high probability of contamination (Speed, 1994). During the European floods of 1993, ERS-1 data was made available over the Internet to facilitate the analysis of the
situation (Wagner, 1994). In 1994, ERS-1 SAR data helped map the area around the broken-pipeline oil spill in Russian Republic of Komi. "Conditions of heavy cloud cover and short periods of daylight made it impossible to use purely optical images" (Allen, 1995). Part of an effective disaster control plan is the development of functional wildlife habitats that serve to protect the land and the structures on it, balancing human development versus the benefit of natural barriers to storm surges (Breedlove, 1992). James Dobbin Associates has developed an environmental assessment model that analyzes the physical environment, terrestrial living resources, marine living resources, and human and cultural resources of Hans Lollik Island, off the coast of St. Thomas. Their model proposes a multi-tiered hierarchy of conservation priorities that balances human desire against environmental value (Albers, 1991). This model could be designed to guide the rebuilding of ecologically significant areas. "Models for testing the impacts of planned activities and for developing a sustainable economic resource can be enhanced and revised using GIS technology to provide more informed decisions" (Judd, 1993).

Conclusion

As always, it is important to identify the outcomes or decisions that will result from the collection and analysis of the data. That is, the application determines the implementation of the flexibility of RADARSAT’s SAR data. A complete understanding of the technical, political, and environmental interactions is imperative for maximizing the benefit of any new tool.

INTERNET ADDRESSES FOR MORE INFORMATION

<table>
<thead>
<tr>
<th>Canadian Space Agency</th>
<th>NASA’s Jet Propulsion Laboratory</th>
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<th>David Stolarz</th>
<th>Earth Resources Laboratory</th>
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<td><a href="http://everest.hunter.cuny.edu/~dstolarz/">http://everest.hunter.cuny.edu/~dstolarz/</a></td>
<td><a href="http://www.noaa.gov/">http://www.noaa.gov/</a></td>
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References


Land Use and Land Cover Mapping of Connecticut and the New York Portions of Long Island Sound

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Introduction

In 1990, under a grant from the joint Long Island Sound Study (LISS) of the Connecticut Department of Environmental Protection and the United States Environmental Protection Agency, land cover maps of the state of Connecticut were prepared through computer-assisted analysis of satellite digital remote sensing data (Civo and Hurd, 1991; Civo et al., 1992). The accuracy of these data has proven to be adequate for the initial purposes for which they were intended, i.e., area-wide nonpoint pollution modeling using land use-dependent coefficients (Frink et al., 1993). However, categories of urban and suburban land cover, particularly low density development, were found to be some of the least accurate yet most essential categories for the development of nonpoint load estimates (Computing Solutions, Inc., 1993). Urban regions have been found to be a major source of nutrients to rivers, lakes, and estuaries (US EPA, 1995) It has therefore proven necessary to develop a procedure to create a new land cover map which better identifies different densities of urban areas and provides an up-to-date map for the state of Connecticut.

Classification Methods

Four methods of classification have been selected for evaluation in this project. These methods have been chosen to take advantage of improved spatial image data available in the form of SPOT panchromatic images and DOQs (Digital Orthophoto Quadrangles). It is imperative to evaluate the utility of using these types of data to determine if they improve the spatial and thematic properties of land cover classification maps. It is also necessary to determine the cost, in terms of monetary expense and time, for including these improved data types in land cover classification. Therefore, the four methods of land use and land cover mapping being evaluated are:

1. A multi-season spring/summer Landsat TM computer-assisted classification.

2. A fused Landsat TM and Spot panchromatic image computer-assisted classification.

3. On-screen digitizing of SPOT panchromatic images to highlight urban regions followed by a merging with a Landsat TM classification.

4. On-screen digitizing of Digital Orthophoto Quadrangle images to highlight urban regions followed by a merging with a Landsat TM classification.
4. On-screen digitizing of Digital Orthophoto Quadrangle images to highlight urban regions followed by a merging with a Landsat TM classification.

Image Data

A summary of the three data types being used in this project can be found in Table 1. The Landsat TM image data are serving as the basis for land cover mapping in all four methods. Although lacking a high degree of spatial resolution compared to other remote sensing products, the TM possesses higher multispectral resolution (six reflective bands from the blue through middle infrared wavelengths and a thermal band), thereby enabling improved distinction among many cover types.

<table>
<thead>
<tr>
<th>Resolution</th>
<th>LANDSAT TM</th>
<th>SPOT PAN</th>
<th>DOQ'S</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>30 meters (Refl)</td>
<td>10 meters</td>
<td>1 meter (.25 um)</td>
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<tr>
<td></td>
<td>120 meters (TIR)</td>
<td></td>
<td>2 meters (.50 um)</td>
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<tr>
<th>Spectral Bands (micrometers)</th>
<th>LANDSAT TM</th>
<th>SPOT PAN</th>
<th>DOQ'S</th>
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<tbody>
<tr>
<td>1:0.45-0.52</td>
<td></td>
<td>Pan - 0.51-0.73</td>
<td>Pan - 0.5-0.9</td>
</tr>
<tr>
<td>2:0.52-0.60</td>
<td></td>
<td></td>
<td>(NAPP CIR)</td>
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<tr>
<td>3:0.63-0.69</td>
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<td></td>
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<tr>
<td>4:0.76-0.90</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>5:1.55-1.75</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>6:10.4-12.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7:2.08-2.35</td>
<td></td>
<td></td>
<td></td>
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<tr>
<th>Repeat Coverage</th>
<th>LANDSAT TM</th>
<th>SPOT PAN</th>
<th>DOQ'S</th>
</tr>
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<tbody>
<tr>
<td>16 days</td>
<td></td>
<td>26 days (nadir)</td>
<td>Perhaps once every five years</td>
</tr>
<tr>
<td>11 off-nadir revisits per 26 days at 42° N</td>
<td></td>
<td></td>
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<table>
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<tr>
<th>Areal Coverage</th>
<th>LANDSAT TM</th>
<th>SPOT PAN</th>
<th>DOQ'S</th>
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<tbody>
<tr>
<td>180 by 170 km (or subscene)</td>
<td></td>
<td>60 by 60 km (nadir)</td>
<td>¼ USGS quad</td>
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<td></td>
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Table 1. Properties of remote sensing image data being examined.

The SPOT panchromatic image data are being merged, or fused, with the TM data to improve the spatial properties of the TM data and also being used for on-screen digitizing of primarily urban areas. Thematic Mapper data possess moderately high multispectral resolution enabling improved distinction among cover types, whereas SPOT panchromatic data possess moderately high spatial resolution, enabling discrimination at a finer level of detail. It has been determined that this finer level of detail allows for the identification of lower density residential areas, isolated buildings, and other small land cover features which may be indicative of a land use contributing the degradation of water quality. Together, the fused TM-SPOT data will maximize the accuracy and precision of the land use and land cover map. These investigators have refined data merging techniques based on principal component (Civco et. al., 1995) and wavelet transforms (Zhou and Civco, 1997) that have rendered high quality TM-SPOT fusion.

The digital orthophoto quadrangles (DOQ’s), like the SPOT image, are being used for on-screen digitizing of primarily urban areas. The one-meter spatial resolution of the DOQ’s allows for easier interpretation of land use and land cover features then with 10-meter SPOT panchromatic data. Figure 1 provides a visual contrast between the spatial properties of TM, SPOT panchromatic, and DOQ images for the same area of Torrington, Connecticut.
Figure 1. Image comparison of TM, SPOT panchromatic, and DOQ data for a portion of Torrington, Connecticut.

Study Areas

Prior to statewide implementation, evaluation of the four classification methods was conducted on two USGS 7\textdegree 30\textarcmin minute topographic quadrangles. These are the Essex quadrangle located in the neo-coastal region of Connecticut and the West Torrington quadrangle located in the northwest hills of Connecticut. The Essex quadrangle contains an abundance of estuarine marshes, inland wetlands, residential and commercial development of varying densities, and forest land. The West Torrington quadrangle contains sizable areas of residential and commercial development, forest land, wetlands, and agriculture. In addition, the West Torrington quadrangle contains areas of substantial relief ranging in elevation from approximately 600 feet to 1600 feet. Studying this type of terrain is important for evaluating the effect of topography on each of the data types and classification methods in terms of geometric properties and thematic accuracy.

Methodology

Multi-season TM Classification

Unsupervised classification was applied to multi-seasonal (May 8, 1995/August 28, 1995), 12-band images of both Essex and West Torrington to produce 100 classes each. These spectral clusters were identified and labeled into informational land cover categories. Supervised training signatures were then selected to augment the classes derived from the unsupervised classification. The signatures from both the unsupervised and supervised techniques were evaluated together and a new set of signatures was developed by merging and appending appropriate signatures from both techniques. These signatures were used in a maximum likelihood classification to derive the final multi-seasonal classification.
TM/SPOT Fused Classification

An inverse principal components technique was selected for fusion of the TM and SPOT images. In this method, the 30 meter TM data is resampled to 10 meter pixels and co-registered with the 10-meter SPOT image data. The synthesized 10-meter TM multispectral data are then transformed into principal components (PC). The brightness properties of the co-registered SPOT panchromatic data are matched to the first PC (PC1), which is an overall brightness image of the original data and is then substituted for PC1. Inverse PCA is then applied to project the data back into original Thematic Mapper spectral space which essentially results in a 10 meter Thematic Mapper image. Further detail on TM-SPOT data fusion can be found in Civo et al. (1995) and Zhou and Civo (1997). Unsupervised classification was applied to this image resulting in 200 classes. These were identified and labeled. Supervised signature selection was also performed and evaluated with those signatures from the unsupervised approach. Those signatures determined to provide the best classification were selected and a maximum likelihood classification was performed to produce a final classification image.

SPOT On-screen Digitizing

Road coverages and sewer areas were used to determine areas that were likely targets for on-screen digitizing since high densities of road networks and sewer areas are indicative of an urbanized environment. Once target areas were identified, the SPOT image was displayed on-screen and the areas digitized. The land cover features were digitized into the following categories: High Density Industrial, Medium Density Industrial, High Density Commercial, Medium Density Commercial, Low Density Commercial, High Density Residential, Medium Density Residential, Low Density Residential, Turf & Grass, Turf & Tree Complex, Forest, Water, and Bare/Exposed Ground. The distinction between the different density groups is somewhat arbitrary and based strictly on visual interpretation. A high density area is roughly composed of over 90 percent roof and pavement, a medium density area is between 50 to 90 percent roof and pavement, a low density area falls below 50 percent roof and pavement. Once the digitization was complete, the digitized areas were merged with the multi-seasonal TM classification to produce a seamless composite of land use and land cover derived from different sources.

DOQ On-screen Digitizing

The same procedure was used on the DOQ data as was used with the SPOT image. No new classes were identified so land cover features were digitized into the same categories as used in the SPOT procedure. These data were also joined with the multi-seasonal TM classification to produce a seamless composite of land use and land cover derived from different data sources.

Discussion

Classification of the Essex and West Torrington quadrangles have indicated that the TM/SPOT fusion classification provides the best results in terms of the ability to detect detail in urban areas and also isolated built-up areas scattered throughout the state. The TM classification, while producing visually appealing results was not fine enough to detect consistently the low density urban features that are of interest. However, this improved spatial detail of the TM/SPOT fused image results in the inability to classify urban areas in terms of densities (i.e., high density commercial and low density residential) and instead resulted in more detailed categories of roof, pavement, turf & grass, and turf & tree complex in
the urban setting. One method to overcome this problem is through the use of kernel-based spatial reclassification such as that described by Barnsley and Barr (1996). Also, by using state wide percentage impervious surface, being derived concurrently with the land cover information, density values could be assigned to the urban classes.

While only attempted in a small area, using SPOT data for on-screen digitizing was found to be difficult. This was due to two reasons. First, the SPOT image is not spatially detailed enough in some areas of the urban environment to allow for easy discrimination among the different types of land cover being digitized. It is difficult to distinguish a boundary between an industrial use to a commercial use to a residential use. Second, it was difficult to determine objectively and consistently the areal extent to which an urban area should be digitized. Even through the use of the roads and sewered areas coverages, isolated urbanized areas were missed, especially the rural residential and low density urban areas which are a major category of interest in this project. Further, these ancillary data predate the satellite images by as many as 12 years in Connecticut, thereby introducing substantial temporal disparity.

Lastly, the DOQ data, while providing an excellent source for digitizing, have proven to be too much data to handle. Each quarter quadrangle is approximately 45 megabytes in size resulting in one quadrangle consisting of 180 megabytes of data. Connecticut alone requires 116 quadrangles for complete coverage resulting in approximately 21 gigabytes of storage. This volume of data poses substantial logistical problems in attempting to use them in the way intended (i.e., on-screen digitizing and merging with satellite derived thematic information). In addition, not all the quadrangles are available for Connecticut in a usable form at this time. Therefore, the DOQ data will be used in a supporting role as opposed to a source of classification.

Based on these findings, a hierarchical approach is being recommended for generation of a land use and land cover classification. In this approach various land cover types will be classified independently of others, using different sources of image data depending on their ease of classification, and the need for improved spatial detail for some land cover features. Water, forest, and agricultural classes will be derived from multi-season TM imagery while urban regions will be classified using the TM/SPOT fusion image.

The advantages of pursuing this hierarchical method are several. First, it would decrease computation time since the significantly larger TM/SPOT dataset would not be needed for classifying water, forest, and agricultural features which do not require increased detail. Second, it would allow for better signature creation because of increasingly less spectral information to process the further down the hierarchy one gets. This will produce less confusion among classes. Lastly, it would allow a multi-season image to be used where necessary and leave the urban areas to single season classification. This is important since attempts at creating a fused multi-seasonal dataset have not produced satisfactory results. These poor results are due to the inability to combine images with different radiometric properties which exist between spring and summer images (leaf off and leaf on conditions).
References


Open Water
Sources and Cycling of Mercury and Methylmercury in Long Island Sound

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The environmental behavior and accumulation of Hg in aquatic organisms is driven by chemical and biologically-mediated reactions involving exceedingly small quantities of Hg in the atmosphere and natural waters. Methylmercury (MeHg), a neurotoxin, can be produced bacterially in aquatic systems and incorporated into the food chain [nearly all Hg in fish flesh (>95%) occurs as MeHg]. Information concerning the behavior and fate of Hg and MeHg in coastal regions such as Long Island Sound (LIS) is quite limited. The atmospheric and aquatic biogeochemical cycle associated with LIS and its environs will be affected not only by localized discharges, but from the airborne transport and deposition of Hg from regional and longer range sources. We have initiated a study of the loadings, movement, behavior, and fate of Hg and MeHg in LIS. Our long-term plan is to incorporate the scientific results into a biogeochemical cycling and mixing model which can be used for predictive purposes (e.g., MeHg in fish), resource management strategies, and risk assessments to public health.

Here we present the initial findings of our study. The objectives are to assess the reactivity and fate of Hg and MeHg entering LIS from three principal external sources (rivers, sewage/wastewater and the atmosphere), and to determine the internal production of MeHg in the surficial sediment of LIS and adjacent wetlands. A preliminary mass balance used to evaluate the input and export of Hg in LIS yields an annual supply of Hg to LIS from rivers, wastewater treatment facilities, and atmospheric deposition of ca. 450 kg. Mercury removal to the sediments is estimated to be ca. 490 kg/yr, implying that most of the Hg entering LIS is retained in the sediment. However, the efflux of Hg⁺ to the atmosphere from surface water as determined in August (0.35 kg/day) is significant. This research is continuing, and additional data on sources, source strengths, sinks and Hg (and MeHg) biogeochemistry in LIS will be presented and discussed.
A Lagrangian Study of Nitrogen Dynamics in Eastern Long Island Sound

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Nitrogen has been identified as the primary factor leading to eutrophication in Long Island Sound. The Connecticut River accounts for 16% of the total nitrogen load into the Sound and is the major source of nitrogen in eastern Long Island Sound. As part of a Connecticut DEP-sponsored project, we are investigating the transport and transformations of nitrogen from the Connecticut River. We carried out cruises during the summer of 1994 and the spring of 1995, at times typical of the minimum and maximum river flow. These times may also represent radically different food-web structures that are likely to affect the cycling and transport of nitrogen. On both cruises, we tracked a parcel of water with a drogue and examined the time-dependent transformations of different nitrogen pools (PON, DIN, DON and total N) during several days. We also quantified the flux of downward PON, employing free-drifting sediment traps. We hypothesized that the total changes in nitrogen with time were driven by the sinking flux of PON. We also determined the net horizontal flux of nitrogen. We will discuss the results of this study in light of our hypothesis and from the point of view of water quality management of Long Island Sound.
Biosensors for Monitoring Microbes and Toxic Pollutants in Long Island Sound.

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Many problems related to evaluation of pollutants (microbes, organic and inorganic substances) in Long Island Sound (LIS) could be solved if biosensors were available to monitor LIS for these pollutants rapidly and inexpensively. Recent work at the Waterborne Disease Center has led to the development of such biosensors. These biosensors use micron paramagnetic microspheres, coated with monoclonal antibodies, with each antibody selected for the capture of a specific pollutant. The antibody-coated microspheres are placed in a housing and the housing immersed in the water for on-line capture. When water flows through the housing, pollutants are tapped by the antibody-coated microspheres. After recovery, the bound pollutants can be assayed by PCR, or immunochemical assays such as ELISA. Using an on-line capture system allows hundreds of liters of water to be monitored for different types of pollutants including microbial (viruses, bacteria, protozoa), and toxic substances, such as organic and inorganic substances.

This paper describes laboratory experiments and field studies with this on-line biosensor technology. The chemistry of antibody attachment to the microbeads, the design and construction of the housings and their successful use to monitor polio viruses from waste water and *Giardia* and *Cryptosporidium* from drinking water will be presented.

Biosensor technology can be used to capture a wide spectrum of pollutants and is useful in situations where large volumes of water must be monitored continuously and in an on-line manner. This would include monitoring in LIS as well as aquaculture facilities.
Observations of Convergence and Downwelling at the Front of the Connecticut River Plume with SCUD and TOAD.

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Advancement of our understanding of river plumes has been hindered by the lack of synoptic observations with sufficient spatial resolution to reveal the structure of the velocity and density fields. We present the results of observations with novel instrumentation that resolves the frontal boundary of the Connecticut River. The observations were obtained with a rigid, ship-mounted array of three electromagnetic current meters and five conductivity-temperature sensors. In addition, a 600 KHz broad band acoustic Doppler current meter, and a conductivity-temperature package were towed at the surface. The two instrument packages combined revealed the velocity field from 0.6 m below the surface to within 1.5 m of the bottom with 0.5 m vertical resolution and the density field in the upper 3 m with a resolution of 0.6 m. Typical ship speeds and sampling rates resulted in a horizontal resolution of between 2 and 5 m for the vertical array, and 10 and 25 m for the towed instruments.

Observations were made during the latter half of the ebb in Long Island Sound, when the river plume was well-established and the front was moving to the west at approximately 0.1 m/s. Two transects normal to the front revealed a horizontal convergence in the across-front velocity components of 0.06 s⁻¹ at 0.6 m below the surface. This was associated with a salt-induced horizontal density gradient of 3 kg/m³. These patterns are consistent with existing theories and laboratory observations. An along-front transect with these towed instruments in the zone of maximum surface convergence showed that downwelling of approximately 0.25 m/s occurred at the front. Though never before observed in the field, vertical velocities of this magnitude are consistent with a simple theoretical argument based on continuity and low frequency along-front variations.
Residual Circulation in Long Island Sound: Inverse Model Estimates From Data

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Tidal and lower frequency "residual" currents in Long Island Sound are estimated from data. An inverse model is used to interpolate between current measurements, and to extrapolate into unsampled regions. The inverse model uses dynamics to compensate for poor sampling. The technique is applied in central and eastern Long Island Sound. These regions are distinguished by different tidal current strengths and different amounts of bathymetric relief. Both factors have important effects on the inverse solution. Results include horizontal maps of currents that vary in time, and error maps for judging reliability.

The ability to distinguish between tidal and residual currents is critical because residual flows determine the long-range transport of nutrients, pollutants, heat and other quantities that are crucial to the environment. Currents have been measured with great precision from moving ships, with an acoustic Doppler current profiler (ADCP), and at fixed locations with current-meter moorings. Both techniques suffer from fundamental sampling problems that obscure the distinction between tides and lower frequency currents. Ship-mounted ADCP's provide good spatial resolution of the current field, but generally at the expense of little or no resolution of its time variation, and moored current measurements have good time resolution but poor spatial coverage. In the inverse model, dynamics play a critical and explicit role in overcoming the sampling problems.
Observations of the Hydrography and Circulation in Eastern Long Island Sound

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We report the results of observations on the currents, salinity and temperature fields obtained in an extensive field program in Eastern Long Island Sound in the fall of 1994 and spring of 1995. The data set consists of 45 day records from 6 current meters on four separate moorings, 20 days of ship surveys with conductivity, temperature and depth profilers and an acoustic Doppler current profiler, and 10 days of quasi-Lagrangian drifter trajectories. These surveys were designed to resolve the tidal and seasonal variability in the north-south as well as the east-west structure of the hydrographic fields.

Our preliminary analysis shows that higher salinity water is found in the deeper portions of the basin and along the northern shore of The Sound. Though there is a signature of the Connecticut River outflow in the vicinity of the river mouth, the most significant and coherent mass of freshened water appears on the southern shore. In the summer, this southern shore water is also warmer with both the mooring and drifter data showing that the subtidal motion is to the east, out of The Sound.
Posters
Planktonic, Physical, and Meteorological Processes in the Development of Hypoxia in the Western Narrows of Long Island Sound

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The role of the plankton community in the development of hypoxia received little research attention during the Long Island Sound Study leaving many questions unresolved. In 23 cruises spanning the summers of 1992 and 1993, biomass, respiration, production, and grazing were measured for the phytoplankton, bacteria, and flagellates in a stratified water column near Execution Rocks lighthouse.

Mid-summer, nitrogen-limited phytoplankton production was found to respond to nutrient influx from rainfall of the preceding seven days ($r^2=0.78$). This suggests that the failure of sewage treatment and collection systems to handle impacts of stormwater flow in the W-LIS watershed is an important issue for hypoxia management. Bacterial production was uncoupled from phytoplankton production, yet dependent on total POC ($r^2=0.73$). Regression analysis of these data indicated that respiration in the subpycnal water column could, on average, be attributed 41% to phytoplankton, 22% to bacteria, and 8% to flagellates.

A water column model incorporating physical and biological processes indicated that dissolved oxygen concentrations in subpycnal waters are strongly influenced by vertical mixing caused by surface winds and the respiration of both phytoplankton and bacteria feeding on detrital material. Through most of the season subpycnal oxygen demand was dominated by planktonic rather than benthic respiration.
Heavy Metals and Radionuclides Reveal Sediment Sources and Accumulation Rates in Jordan Cove, Connecticut

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Six cores were collected from the length of Jordan Cove, Connecticut, and analyzed for radionuclides (210Pb, 226Ra, 137Cs, and 60Co) and metals (Ag, Cd, Cu, Pb, Fe, and Al). Sediment accumulation rates decrease in a landward direction from 0.84 cm/y near the mouth, to 0.40 cm/y near the head, and are faster than relative sea level rise at this site (~ 0.3 cm/y). 60Co and Ag are derived from sources outside the cove, presumably the Millstone nuclear power plant and regionally contaminated sediments, respectively. The decay-corrected 60Co increases down the cores to a depth corresponding to an average age of 22y. Before this date, current 60Co levels are too low to be detected. This declining input over time suggests that the 60Co may be the result of a release that occurred more than two decades ago.

Cu, Pb, and Zn in the cores all correlated well with each other and with Fe, but poorly with either Al or organic matter. Their source cannot be assigned either to Long Island Sound or Jordan Brook.

The combined data suggest that Long Island Sound is an important source of sediment to the cove, although indirect evidence supports the possibility that some sediment is also supplied from the watershed by Jordan Brook. Sediment quality has declined in the cove over the past 60 years, but only slightly.
Modeling Three-Dimensional Structure of Tidally-Induced Residual Currents in Semi-enclosed Channels

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A three-dimensional barotropic numerical model is applied to study the vertical and horizontal structures of tidally-induced residual currents. To highlight the nonlinear effects of friction and the bottom slope, both the Coriolis and the convective terms in the momentum equations are neglected. By using a 'sine-sigma' vertical coordinate transformation and a cubic-spline representation of the vertical current profiles, the model can resolve the vertical structures of the residual currents near the surface. Two sets of experiments have been made to show the effect of the channel length: one of which examines a channel with a flat bottom, and the other a V-shaped bottom. The results show that, for both cases, the residual currents are into the channel at the surface above the mean sea level. As a result of the mass conservation, most water under the mean sea level is directed out of the channel. For the case of the V-shaped bottom, the vertically integrated residual current is out of the channel in deep water regions and into the channel in shallow water regions. Resonance happens in both cases when the channel length is slightly less than 1/4 or 3/4 of the wavelength as a consequence of friction. The residual currents in the V-shaped channel are larger than those in the flat-bottomed channel because there is a stronger nonlinear effect due to the bottom slope in the former case. When resonance occurs, magnitudes of the residual currents below the surface in both the V-shaped and the flat channel can reach 25 cm/s and the mean residual current in the V-shaped channel has an order of 10 cm/s. These values are consistent with the theoretical estimates of Ianniello (1977) and Li and O'Donnell.
Real Time Environmental Monitoring System Records Unexpected Six-Hour Cycles of Hypoxia in Long Island Sound

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Monitoring System Available to the LIS research community
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Abstract

This paper describes two remote environmental monitoring systems now available for public use, and striking fluctuations in dissolved oxygen levels recorded during September and October, 1995. The monitoring systems were deployed at four locations near New Haven and Branford to provide continuous, real time evaluation of surface and bottom levels of dissolved oxygen, pH, conductivity and temperature, and wind speed, wind direction, air temperature and air pressure. Dissolved oxygen levels ("DO") in the study areas fluctuated almost continuously in daily, tidal and six-hour cycles during much of 1995, with oscillation amplitude ranging from 0.3 to more than 4 ppm. Observations that DO levels can dip suddenly from 5 to 0.5 ppm and then return quickly to 4.6 ppm suggest that brief but repeated hypoxic episodes - less than one or two hours in duration - may have significant, sub-lethal or lethal impacts on sensitive marine life. Evidence of such brief fluctuations suggests that DO monitoring in many areas of the Sound should be continuous rather than weekly or bi-weekly. Collected data have been made available via the INTERNET at http://scsu.cstateu.edu/~martin/seadata.html. Inquiries are invited concerning data access, monitoring system tours, and use of these systems for educational, research and commercial projects.

Introduction

For more than a decade, bottom-water dissolved oxygen levels have periodically dropped to concentrations too low to sustain healthy marine life over much of the western Long Island Sound (see Conversi and Swanson, 1994; Welsh, 1994 and this volume for reviews). Concern for the health of lobster populations near the Thimble Islands of Branford, Connecticut, an area not generally known to suffer from severe hypoxia, led to the deployment of continuous monitoring systems that might record transient hypoxic events not detected by weekly or bi-weekly analyses. Observations of transient hypoxia reported here are of interest both because of their unexpected severity and because of the prominent six-hour cycle of high and low oxygen concentrations. The two remote monitoring systems used in this study were purchased with Connecticut state funds for research explicitly designed to serve researchers, educators and commercial interests by generating data for the world wide web. Southern Connecticut State University has therefore made both systems available for use by qualified members of the public and private sectors, subject only to funding and scheduling constraints. Anyone who wishes to deploy these monitoring systems at a location of particular interest is invited to contact the Southern Connecticut State University Center for the Environment (203-392-6265).

Editor's note: this paper is also accessible on the World Wide Web, at:
http://www.cststateu.edu/~martin/hohpp

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Monitoring System Description

Each environmental monitoring system contains (i) a 9.5-foot high by five-foot wide discus buoy-platform (4 ft below, 5 ft above water not counting the 6 ft radio transmission antenna); (ii) above-water sensing equipment for wind speed, wind direction, solar battery voltage and air temperature or pressure; (iii) two pulsed Endeco-YSI 600 subsurface sensors for shallow and deep measurement of dissolved oxygen, pH, temperature and conductivity; (iv) solar panels and batteries for continuous power; (v) a VHF-FM radio transmitter with a range of 20 to 30 miles that broadcasts data to shore at programmable time intervals (e.g., every 15, 30 or 60 minutes); (vi) a computer that reports minimum, maximum and average wind speed for each time interval, computes values of salinity, specific conductance and total dissolved solids from conductivity and temperature data, and stores accumulated data from each sensor for delayed retrieval in the event of radio transmission failure, and (vii) anchors and ancillary floatation devices to secure the system and prevent below-surface entanglement of sensor and anchor lines. The on-shore bay station consists of a radio transceiver, fixed 20' antenna (presently mounted on the roof of Jennings Hall at Southern Connecticut State University), and a personal computer with YSI software for data management. One of the monitoring systems has a barometric pressure sensor; the other has an air temperature sensor. Further information about this and similar systems is available from the manufacturer, Endeco-YSI (Bedford, Massachusetts, (800) 765-4974, WWW.EMS.YSI.COM), from the web site of the Chesapeake Bay Observing System (WWW.CBOS.ORG/WWW), and from reports and publications by scientists at the University of Rhode Island and Applied Science Associates, Inc. (Opshinsky et al., 1996; Spaulding et al., 1997).

Results

Monitoring occurred at two locations in New Haven Harbor and two locations near Branford. At each site, upper sensors were suspended one meter beneath the surface, while lower sensors were approximately one meter above the bottom, suspended by chain, wire and an underwater float providing thirty pounds of lift. From November, 1994 through June, 1995, monitoring system I was located in New Haven harbor at 41°17'08"N, 72°54'53"W (water depth = 10 ft). During July and early August, this system was moored to the dock on the eastern side of Outer Island, the outermost of the Thimble Islands, with only the above-water air sensors and lower subsurface sensors operating (depth = 6 feet). On August 16th, system I was moved due west to 41°14'24"N, 72°47'42"W. This location is just east of Branford Harbor, about halfway between Negro Heads Reef and Gangway Rock (water depth = 21 ft). System II was placed at the outer edge of New Haven Harbor on June 29th, near Savin Rock by the west end of the middle breakwater at 41°13'42"N, 72°56'00"W (depth = 21 ft). It was removed on August 9th after battery failure resulting from solar panel connector de-lamination.
Figure 2: Map of the Gangway Rock-Negro Heads Reef area, southeast of Branford Harbor, in which six-hour cycles of hypoxia were observed. The monitoring station was located about halfway between Gangway Rock and the reef, where water depth was approximately 20 feet. Notice the proximity of deeper, potentially hypoxic areas just to the south and southwest of the monitoring system.

This period of observation included only one hypoxic event during which bottom DO remained below 4 ppm for longer than 24 hours. This event occurred from September 14th to 16th at the Gangway Rock/Negro Heads location. Independent DO measurements were not taken at this time, so sensor drift remains a possible but unlikely explanation. DO sensor malfunction appears unlikely because (1) DO values returned to normal after the relatively brief hypoxic period, and (2) bottom pH values dipped and rose in approximately six-hour cycles in phase with DO readings. We therefore received two independent measures of water quality that displayed similar six-hour cycles. From September 23rd to 28th, bottom DO, pH and a third parameter, temperature, varied in prominent six-hour cycles, suggesting that the six-hour cycles observed from the 14th to 16th were actual rather than chance events or products of sensor malfunction. The observed DO fluctuation became so severe at one point that DO dropped as low as 0.5 ppm, only to rise above 4.6 one hour later (Fig. 3). Six-hour DO and pH cycles persisted almost continuously through most of October (Fig. 4).
Figure 3: Hourly readings from 12:00 am 9 21 95 to 11:00 pm 9 30 95. Notice the daily cycles of wind speed, air pressure and battery voltage, the tidal cycle of salinity, and the semidiurnal cycles of dissolved oxygen, pH and, in the center of the figure, temperature. Conductivity, specific conductance and total dissolved solids are not shown because they parallel salinity. High and low tides are indicated by dashes in the DO graph. Marks for high tide are somewhat higher than those for low tide.
Figure 4: Hourly readings from 12:00 am 10/19/95 to 11:00 pm 10/19/95. This figure contains data collected immediately after that displayed in Figure 3. Notice the aberrant 99th value (10/3/95, 9 pm) for bottom DO, pH and salinity, and the sharp rise in salinity values in the center of the figure associated with an average wind speed of 30 mph. The steady upward drift in surface DO is presumably due to sensor drift rather than an increase in DO above 12 ppm. High and low tides are indicated by dashes in the DO graph.
Figure 5: Tidal cycles and then daily cycles of DO observed in New Haven Harbor from 4:00 pm, 15 January to 11:00 pm 31 January, 1995.

Two other kinds of dissolved oxygen cycles were observed during 1995: 24-hour (daily) cycles, and 12-hour (tidal) cycles (Fig. 5). Daily DO cycles occurred in New Haven Harbor and at Outer Island at least some of the time during each month monitored. Tidal cycles occurred almost as often, in both locations. During these cycles, DO never varied by more than 0.5 ppm.

Discussion

Advantages and disadvantages of remote monitoring systems:
In our experience, remote environmental monitoring systems can be reliable, cold-, salt- and storm-resistant systems for data collection throughout the entire year. The continuous record of regular, transient episodes of hypoxia near Branford during September and October, 1995, is a good example of the kind of information routinely gathered by these systems. This data set provides a very detailed view of hypoxia that complements information gathered every four hours (Pellegrino et al., 1994), weekly (Anderson and Taylor, 1994; Sattler & Perz, 1994), bi-weekly (Conversi & Swanson, 1994; O'Neal & Olsen, 1994), monthly (Pellegrino et al., 1994) and annually (Conversi & Swanson, 1994). Continuous measurement of DO, pH and turbidity at different depths may in the future provide a basis for understanding the observed DO cycles.

Radiotelemetry systems have important advantages over other monitoring systems. If data are regularly monitored on-shore, then transient events of special interest can be detected as they start, and on-site measurements can be obtained by investigators who rush to the site of interest before desired evidence has
vanished. This kind of monitoring system also allows unusual events to be intensively monitored without a hasty field trip, since measurement intervals can be reduced from the on-shore computer to increase the amount— and therefore the accuracy and reliability—of data obtained. Unexpected sensor malfunction can also be quickly detected, so repair and re-calibration can be completed before events of interest have been missed.

Data sets generated by these systems contain rich combinations of information not readily available otherwise. Unusually large data sets are generated, enabling researchers— and educators and students— to see patterns and relationships that would certainly be invisible with fewer readings. As presently configured, each system is able to produce 57,600 values per month when programmed for 15-minute transmission cycles (4 cycles per hour x 20 parameters per transmission cycle x 24 hours/day x 30 days/month = 57,600. In principle, even more data can be obtained, since each station supports up to ten independent sensors, including sensors for turbidity, oxygen reduction potential and solar radiance not presently included in our stations.) Such large amounts of information can be a critical advantage when searching for otherwise-hidden cycles and long-term relationships between highly variable parameters that may be of marginal statistical significance. We believe this large-data-set advantage makes this type of system especially appropriate for long-term monitoring of hypoxia and other kinds of intermittent pollution.

Remote systems do have some disadvantages, however. Some sensors require weekly cleaning during summer months, when plankton growth is relatively rapid, or bi-weekly cleaning when growth is slower. Dissolved oxygen sensors are well known to drift as a result of such biological activity, so regular membrane cleaning or replacement and re-calibration are necessary. Sensors one meter beneath the surface can be retrieved and cleaned with little effort, however bottom sensors require a powerful hoist to lift them from the water prior to cleaning. Modifications to allow bottom sensors to be retrieved without such a hoist are apparently incompatible with the present anchoring system, which is designed to resist even the severest storms. When highly precise values are not required, this disadvantage may be avoided if calibration readings are taken with a second set of sensors, lowered to the same depth as bottom sensors, and these readings are used to correct transmitted readings.

Origin of six-hour cycles unclear

A variety of possible explanations have been considered for the six-hour cycles of hypoxia.

(1) The cycles could be an electronic artifact. It seems quite improbable, however, that three different sensors (DO, pH and at one point, temperature sensors) would all fluctuate synchronously every six hours, even if the deviations were caused by a common factor such as bottom sediments stirred by tidal currents. Evidence that these sensors are indeed independent is provided by the relatively low correlation between DO and pH values (the correlation coefficient is approximately 0.5) and by the infrequent, aberrant readings involving DO and pH but not salinity or temperature sensors, and DO, pH and salinity sensors but not the temperature sensor (see Figures 3 and 4, at approximately the 60th reading in each).

(2) Six-hour cycles may occur because bottom sensors touch the underlying sediment when tidal currents have pulled the surface buoy to either side of the main anchor. The cable linking the surface buoy, bottom sensors and sensor anchor may be tilted as much as 45 degrees from vertical if the surface buoy is pushed by wind and currents with sufficient force. Bottom sensors, normally three feet above bottom when the lowest six feet of chain is held upright by an underwater float, could have been lowered by almost one foot during periods of tilt, possibly low enough to reach loose hypoxic sediment or a very thin layer of hypoxic bottom-water. This explanation seems improbable for two reasons. It is unlikely that the surface
buoy would tilt the chain only for brief periods, regularly every six hours, day after day, week after week. Longer periods of tilt, and periods of variable length, would be expected. In addition, the cable linking the buoy, sensors and sensor anchor is longer than links to the main buoy anchors, so the sensor cable was designed to retain slack all times.

(3) The cycles may result from marine organisms growing on sensor surfaces. This growth may have been sufficient to alter DO and pH only when tidal currents were absent every six hours, at high and low tide. As above, there is no reason to think that such growth could lead to regular, parallel deviations over such long periods of time on different sensor surfaces. The very rapid return of both DO and pH to normal values after each hypoxic period, and the relative steadiness of maximum DO and pH readings between hypoxic events, both suggest that our DO and pH sensors were not fouled by marine growth.

(4) A gradient of hypoxia extending up from bottom sediments, perhaps six inches or several feet, may have shifted upward at high and at low tide, when currents and bottom-layer mixing were reduced. Oxygen-consuming sediment stirred up by tidal currents may remove oxygen and cause hypoxia only until tidal currents once again mix oxygenated water from above with hypoxic layers below. This explanation is consistent with Bohlen’s (1987, 1992) descriptions of sediment and “fluff” re-suspension during each tidal cycle, with maximum concentrations 1 m above bottom occurring at lowest current velocity. DO changes are generally relatively slow, usually occurring over hours, days or weeks, so this fluff re-suspension mechanism may be insufficient to explain the magnitude and rapidity of observed DO declines — unless an unusually concentrated mix of highly-active, oxygen-consuming substances and microorganisms was present.

(5) Two different bodies of hypoxic water moving into the sensor area, one at high tide, the other at low tide, may have caused the hypoxic cycles. It appears unlikely, however, that separate hypoxic water masses surrounded the bottom sensors so regularly, over so many weeks, for almost exactly the same length of time each cycle, with neither body of water ever remaining near the sensors for a noticeably longer period of time, and neither ever missing the sensors entirely. The regular rise and fall of bottom temperature in late September suggests a six-hour cycle of water movement but does not establish a causal link between this movement and the observed hypoxia. Water movement associated with measurable salinity fluctuations during late September and October occurred only when cyclic hypoxia was absent, as if more saline water prevented rather than caused the hypoxia (Fig. 6).

Need for further, continuous, real time monitoring;

Very brief periods of inadequate oxygen can permanently injure or kill sensitive organisms, even if daily-average levels remain high. Consequently, minimum rather than average oxygen levels must be monitored — and minimums can only be observed by continuous measurement over long time periods. Observations that oxygen levels can fall as much as four ppm within one hour, to concentrations far below LC₅₀ levels for sensitive species (cf. Miller et al., 1992), raise the possibility that large areas of eutrophic estuaries like the LIS may be subject to occasional, very brief episodes of hypoxia that dramatically affect sensitive populations. Since investigations of distress, illness and mortality associated with transient fluctuations can best be conducted if research teams are alerted to hypoxic events when they are occurring, DO measurements are needed in real time. We invite the LIS research community to employ both of Dr. Haakensen’s remote environmental monitoring systems specifically for this kind of investigation, as well as for the many other kinds of research that require large, rich data sets acquired over long time periods.
Figure 6: Sharp declines in DO (shown here as large deviations between each reading and a running average) occurred only when salinity values were stable, as if intrusion of more saline bottom-water prevented DO cycles, or caused them to move elsewhere. Graphed values represent the difference between each salinity and DO reading and a running average of six consecutive data points, calculated with the formula:

\[ \text{Deviation of reading } R1 = (R1 - \text{Average (R1+R2+...+R6)})^2. \]
Personal note:

Prof. Haakonsen passed on shortly after his radiotelemetry system became operational. His co-authors believe it appropriate to note what a pleasure it was to work with a person of such foresight and grace. We wish Harry well, and suggest that the monitoring system he worked so hard to establish be referred to as Dr. Haakonsen's wherever it may be located in the future.

Acknowledgments

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References


Feeding Habits of Juvenile Winter Flounder (*Pleuronectes americanus*) within a Coastal Marina and Adjacent Intertidal Habitats

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The winter flounder is an important commercial and recreational species along the temperate Atlantic coast. There has been considerable interest in fishery research quantifying trophic interactions both between and within finfish populations. Feeding habits and trophic overlap were examined between four size classes of juvenile winter flounder collected from within a marina basin and from adjacent intertidal flats. The study area is a large 400-slip marina (Cedar Island marina) located in Clinton Harbor (Clinton, CT).

Polychaetes were the major food source for flounder < 99mm both within the marina and on the flats. Crustaceans were dominant in the larger size classes. The dominant prey species within the marina and the flats were, however, distinctly different. The dominant prey species within the marina (*Streblospio benedicti*) is a stage I (opportunistic), while over the flats a stage III (equilibrium) species (*Leitoscoloplos robustus*) predominated.
Coastal Marina Basins as Potential Fishery Habitat with Special Emphasis on Nursery Function

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Marina basins are man-made dredged habitats that are conspicuous features of coastal ecosystems. Marinas have recreational and economic importance, but their ecological role in coastal ecosystems is largely unknown. The major purpose of this study was to evaluate the functional role of a coastal marina basin as fishery habitat with major emphasis on nursery function. The study area is a 400-slip marina (Cedar Island Marina) located in Clinton Harbor (Clinton, CT).

Finfish community structure within the marina basin (1989-1993) was monitored on a weekly basis using a series of 1 cubic meter fish traps and a 1 meter beam trawl. A total of 37 finfish species representing 25 families were collected from within the marina basin. The numerical dominants were found to be winter flounder, tomcod, white perch, grubby and blackfish.
Culture of the Bay Scallop, *Argopecten irradians* Within a Small-boat Marina on Long Island Sound (Connecticut)

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An innovative suspension-culture rack system was designed to evaluate the potential of intermediate aquacultural grow-out of shellfish seed within a marina in Clinton, CT. Conventional dock space in the marina was modified by cutting out sections of the decking. The cut-out sections were replaceable allowing normal usage of the dock. Wire-mesh cages (1m X 0.5m X 0.5m), containing four shelves were constructed and suspended below the modified docks. Scallop seed were contained on the shelves of the cages within flexible plastic mesh bags with temporary closures of slit PVC pipe at the ends. About 6,000 animals with an initial shell height of 15.5 mm were reared at different densities and in different mesh sizes from June through November of 1995. The use of the space under the docks caused little interference with normal marina activity. Based on the findings of this project there seems to be a good scallop seed at marinas as a step in seed transplant efforts to restore scallop fisheries to natural habitats.
Macrophage Aggregation in Winter Flounder (*Pleuronectes americanus*) from Long Island Sound

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Abstract

Macrophage aggregates in fish are collections of white blood cells that have sequestered various breakdown products such as melanin. An increase in number of these aggregates is correlated with age and/or environmental stress (for a review see Wodke, 1992). The presence of macrophage aggregates in fish is accepted by the EPA as a biomarker that could possibly be indicative of a stressful situation for fish (Wodke, personal communication, 1994).

Winter flounder (*Pleuronectes americanus*) were collected from sites from eastern (off Old Saybrook, Connecticut) and western Long Island Sound (Huntington Bay). These fish were sacrificed, and various tissues (spleen, heart, muscle, liver, and kidney) were excised and examined for the presence of macrophage aggregates. Tissues examined from only one of the twenty fish obtained from the eastern Sound had macrophage aggregates in any appreciable quantities, whereas tissues from three out of six fish collected from the western Sound had an abundance of macrophage aggregates.

Since Huntington Bay is closer to New York City, a large population center, its waters are generally described as being more polluted than the waters from a more easterly longitude. Here we have an example where the an increase in the quantity of macrophage aggregates correlates well with increasingly poor water quality.

In this poster display, these are photos of normal flounder tissue, flounder tissue with macrophage aggregates, and needlefish (*Scomber saxatilis*) tissues with macrophage aggregates. The needlefish tissues were obtained from a fish that died of old age (it was 8 years old) and so was thus probably considerable older than the 150 - 200 cm flounder we examined. The photos are provided to show the variety in size of the macrophage aggregates — either species or age induced.

Further work needs to be done to see if processing fish can be streamlined to see if the observation of macrophage aggregates is an efficient biomarker of environmental stress. Differences in patterns due to age or species can also be explored.


Acknowledgments

Paul Cheung from the New York Aquarium provided the needlefish tissue samples and some expertise on macrophage aggregates. Dave and Pete Simpson of the Connecticut Department of Environmental Protection were instrumental in fish collections from the eastern Long Island Sound. Jane Gallagher and her Oceanography course crew (from the City College of New York) provided the samples from Huntington Bay. Allison Jones, a Columbia University student at the time, processed most of the eastern Long Island Sound tissues. She was supported by the Howard Hughes Foundation. Students in the Columbia University Fall, 1994 and Spring, 1995 Cell and Developmental Biology project lab processed the samples from Huntington Bay.
Connecticut Department of Environmental Protection Long Island Sound Water Quality Monitoring Program

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Since 1991, the Connecticut Department of Environmental Protection (CTDEP) has been monitoring the water quality of Long Island Sound. The primary goal of this monitoring program is to develop a long-term database from which the effectiveness of management actions to reduce nitrogen inputs to the Sound may be evaluated. Year-round monthly sampling at eighteen stations, from the Western Narrows to Block Island Sound, provides nutrient and phytoplankton concentrations, and water column profiles of temperature, salinity, irradiance and dissolved oxygen. Additional biweekly summer sampling at 40-50 stations provides data on the recurrent low dissolved oxygen condition known as hypoxia. Five-and-one-half years of data including six summer seasons, show areal, volumetric and temporal variability in the development and persistence of this low dissolved oxygen condition. Analysis of factors such as weather patterns and precipitation can explain some of the variability observed. The CTDEP encourages the research community to make use of the monitoring program and the resultant database as an aid to complementary research efforts in Long Island Sound.
Sidescan-Sonar Studies of Sedimentary Environments in Long Island Sound

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Continuous-coverage and reconnaissance high-resolution sidescan-sonar surveys have been conducted in Long Island Sound (Fig. 1). The images produced from these surveys reveal the variability of the sea floor and improve our understanding of the processes that control the distribution of bottom sediments, trace metals, and benthic habitats. Eight continuous-coverage sidescan-sonar surveys have been completed in areas adjacent to the Norwalk Islands, Milford, Faulkner Island, Hammonasset Beach State Park, Roanoke Point, Niantic Bay, New London, and Fishers Island Sound. The reconnaissance survey (lines spaced 2.4 km apart) covers most of the Long Island Sound basin that is >10 m deep and provides a regional perspective of the bottom sedimentary environments. Acoustic-backscatter patterns in the sonographs from both kinds of surveys permit differentiation of sedimentological (i.e., changes in sediment texture) and geomorphic (i.e., shoals, moraines, bedrock outcrops) attributes which allow us to produce detailed sediment and bottom-feature maps of the Sound. Areas of high backscatter on the sidescan images usually contain coarser grained sediments (i.e., glacial drift or areas characterized by erosion); whereas areas of low backscatter tend to contain finer grained Holocene marine deposits which could contain higher trace-metal contents than the coarser deposits. Anthropogenic features visible on the images include shipwrecks, pipelines, cables, and trawl and dredge marks. Together, the continuous-coverage and reconnaissance surveys show that the benthic environments in Long Island Sound vary spatially over short distances. Because of their irregular, patchy nature, these environments are clearly too complex to be accurately mapped by measurements made solely at discrete sample locations.
Figure 1. Map of Long Island Sound showing the locations of continuous-coverage 100kHz sidescan-sonar surveys which were completed as part of a USGS/Connecticut DEP/UNH cooperative. Map also shows the locations of the spaced sidescan lines collected as part of the reconnaissance component of this project.
The Cycling of Elemental Hg (Hg\textsuperscript{0}) in Long Island Sound, CT

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The biogeochemical cycling of Hg in the coastal environment is of great importance due to its tendency to bioaccumulate in the highest trophic levels (e.g., fish), and the inherent toxicity of methyl-Hg. Elemental Hg is a major component of this cycle, as its long atmospheric residence time (~1 year) allows for transport over global scales. Further, Hg\textsuperscript{0} is produced in surficial marine waters through both biotic and abiotic mechanisms, which leads to supersaturation and subsequent evasion to the atmosphere. Our August, 1995 survey of Long Island Sound (LIS) suggests that Hg\textsuperscript{0} production acts to "reflect" a significant fraction of the annual Hg input (up to 25%). We examined Hg\textsuperscript{0} profiles at six stations along the central axis of LIS, in conjunction with laboratory studies of the mechanisms which produce it in coastal sea water. All experiments were performed using sea water pumped from Fisher's Island Sound, CT, and consisted of spiking sea water treatments with picomolar levels of Hg\textsuperscript{1+}, followed by sparging and collection of Hg\textsuperscript{0}.

August, 1995 Hg\textsuperscript{0} concentrations were highest in the surface waters at all stations (294-893) fM) with the exception of one off of the Connecticut River, where physical mixing appears to have homogenized the water column. Autoclave, filtration, and metabolic inhibitor experiments on FIS sea water indicate that Hg\textsuperscript{0} is produced from labile Hg primarily as the result of the metabolic activity of picoplankton (cyanobacteria, small phytoplankton, bacteria), which is related to photosynthesis, degradation of organic matter, and the availability of labile Hg. Continuing studies will include additional axial surveys of LIS in spring and summer, 1996 (including the effects of depth, wind-induced mixing, temperature, and light), with concurrent laboratory examinations of FIS sea water.
224 Ra Distribution in Surface and Deep Water of Long Island Sound: Sources and Horizontal Transport Rates

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Abstract withdrawn

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Evidence for Transformation and Transport of Nitrogen from the Connecticut River Westward into Long Island Sound

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The Connecticut River is the largest riverine source of nitrogen to Long Island Sound, but it enters Eastern Basin so close to the Race that its contribution to eutrophication of the Sound's inner basins has been considered inconsequential. We measured the transformation and transfer of nitrogen entering from the river in March, when river flow was high and physical stratification and biological metabolism were both low, and in August, when river flow was low but physical stratification and biological activity were both greater. Horizontal and vertical distributions of nitrogen species at fixed stations along the edge of the river plume were measured, along with salinity, temperature, and chlorophyll-a fluorescence and downwelling irradiance. These same measurements were made at telemetered drifter buoys which followed water masses outside the plume over several days. Net directional flow of water was analyzed from continuous ADCP measurements, and sediment traps were attached to the buoys to measure vertical flux of organic carbon and nitrogen. We also analyzed the characteristics of the phytoplankton and zooplankton communities and those of the trapped particles.

Contrary to our expectations, riverine water took longer to exit the Sound in March during high flow than in August during low flow. The temporal trade-off between seasonal rates of riverine input, physical mixing and biological processing was different between March, when the phytoplankton were dominated by large cells and August, when it was dominated by small cells. Nevertheless, during both periods, rates of transformation and vertical transport allowed substantial amounts of nitrogen to be sequestered in the lower water column, whence it could be horizontally exchanged with inner basins of the Sound.
Field and Culture Studies for the Development of a Commercially Viable Nori Aquaculture Industry in New England

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The red alga Porphyra, or nori as it is commonly called, is a major source of food for humans throughout the world and is the most valuable maricultured seaweed in the world today. In 1992, approximately 15 billion sheets were produced (N. Takaoka, per. comm.), with an annual value of over $2.0 billion U.S. dollars (Jensen, 1993). Porphyra is used in the Japanese delicacy “sushi”, it is a major source of taurine (Noda et al., 1975) that controls blood cholesterol levels (Tsujii et al., 1983), and it is a valuable health food (Mumford and Miura, 1988). Nori contains high levels of protein (25-50%), vitamins (> vitamin C than in oranges), trace minerals and dietary fiber (Noda, 1993), as well as being delicious. It also serves as a preferred source of the red pigment r-phycoerythrin, which is utilized as a fluorescent “tag” in microscopic evaluations.

As the U.S. is primarily dependent upon Japan, and to a lesser extent China, and Korea, for imports of nori. The development of a competitively produced American product will be a major asset (Bird, 1990). Such an industry will provide a fresher and healthier product, as well as establish a domestic source of r-phycoerythrin. It will also promote an alternative utilization of other aquaculture lease sites (e.g. shellfish and salmonid). Previous attempts to culture nori on the West Coast of the United States and Canada have been unsuccessful. The failure was not due to the market size, economic viability of the participants, nor the biological aspects of cultivation, but solely on the inability of nori farmers to obtain aquaculture lease permits in the coastal waters of Washington State. Political pressure brought to bear by riparian land owners and commercial fisherman was too much for the fledgling industry to overcome (Merrill, 1989). The political forces that resulted in the collapse of the Washington State effort have not present in coastal New England. The State Legislatures in Connecticut and other New England States have been overwhelmingly supportive of lease site acquisition, stature changes and extension support.

In initiating a nori cultivation program in northeastern Maine (i.e. Cobscook Bay, Washington County), Coastal Plantations International, Inc. (CPI) received the support of the salmon aquaculture industry, the local population and officials of the State of Maine, Northeast Regional Aquaculture Center of the U.S. Department of Agriculture, and the U.S. Department of Commerce. The geographical isolation of this region
has historically limited economic diversification. Its population is an underutilized, marine experienced labor resource. The development of a labor intensive algal mariculture industry is expected to significantly reduce the unemployment rate and the reliance on a single dominant, but vulnerable, source of employment—salmon farming. Whether or not seaweed aquaculture will ultimately succeed in the Northeast will depend in large part upon several "key" factors, including: (1) successful transfer and modification of Japanese and Chinese nori cultivation technology to Maine coastal environments; (2) development of genetically improved species ("cultivars") of marketable nori that will extend the growing and harvest season in New England; (3) expansion of the area presently used for cultivation (i.e. beyond Cobscook Bay in Washington County). Because no local nori species has yet been studied, nor domesticated for cultivation, CPI has primarily utilized a commercially valuable asiatric taxon, Porphyra yezoensis. It was developed during the 1960's by strain improvement programs on P. tenera and P. yezoensis (Patwary and van der Meer, 1992). Although P. yezoensis has many desirable features, it was selected for growth conditions in northern Japan and may not be optimal for Maine's coastal environments. Therefore, it is logical to establish a cultivar improvement program for local Porphyra species, just as has been done in Japan. Through such a program, genetically improved nori cultivars would be developed, which should be better adapted to local conditions than P. yezoensis. In this context it should be noted that the growing season for Japanese nori in New England is very short and limited to the summer and fall.

In a recent synopsis of red algae from the Canadian Maritime Provinces, Bird and McLachlan (1992) record six species of Porphyra (i.e., P. amplissima, P. linearis, P. leucosticta, P. purpurea & P. umbilicata) and note that some taxa may be "form-species". Thus, there may be an underestimation of species richness for this geography and a detailed taxonomic revision may be required. No doubt a similar situation exists in New England where five of these same taxa are recorded, except for P. purpurea (cf. Hehre and Mathieson, 1993; Mathieson and Hehre, 1986; Schneider et al., 1979; Taylor, 1957). With these factors in place, our lab at UConn-Stamford and 3 other New England universities (Northeastern University, the University of New Hampshire and the University of Maine) and Coastal Plantations International, Inc., have been awarded a federal grant from the National Sea Grant College Program, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, to expand the development of a farm cultivating native nori species for the growth of a sustainable nori aquaculture industry. Our research program is coordinating a field and culture assessment of "native" Northwest Atlantic Porphyra from Long Island Sound to the Canadian Maritime Provinces. We are attempting to clarify their taxonomic status, and provide cultures of unique and valuable native nori strains within the existing commercial nori farm at Eastport Maine.

Delineation of Porphyra taxa: distributional ecology and phenology of Porphyra taxa in New England

As noted previously, the species of Porphyra from the northwest Atlantic are in need of a detailed taxonomic revision/verification, as several "form-species" compromising similar entities may exist (Bird and McLachlan, 1992; Lindstrom and Cole, 1992, 1993). Monthly-seasonal collections are being made at selected sites near Eastport, Maine, as well as in New Hampshire and Connecticut, in order to compare inter- and intra-specific phenological patterns, including differences between northern and southern New England (Mathieson, 1989; Mathieson and Hehre, 1986; NUSCO, 1992). That is, some species like P. leucosticta and P. umbilicata are recorded year-round in Connecticut, with their highest frequency of occurrence during January-June. The former species is uncommon in northern New England, while the latter appears to be abundant year-round within this local. By contrast, P. linearis has a very limited occurrence during late winter in southern New England, while it is more abundant seasonally and spatially in northern New England. Limited knowledge is available about the phenology of P. amplissima and P. purpurea (cf. Bird and McLachlan, 1992). In attempting to foster a better taxonomic understanding of these plants we are employing a broad range of field and laboratory (culture) investigations. Initially we are evaluating their species composition and phenotypic variability in a wide range of open coastal and estuarine habitats, utilizing voucher
specimens and photographic records. Ultimately we will correlate morphometric patterns (i.e., length, width, color, etc.) with several abiotic factors (i.e., temperature, salinity, nutrients and water motion) and attempt to delineate between phenotypic and genotypic variability. In identifying the different taxa of Porphyra we are utilizing a variety of relevant and/or recent treatises (e.g., Conway, 1964; Kapraun et al., 1991; Kornmann and Sahling, 1977; Lindstrom and Cole, 1993; Rueness, 1977; Schneider and Searles, 1991; Taylor, 1957), including the excellent photographs in Bird and McLachlan’s (1992) recent text. We are also reserving samples from each major collection for genetic analysis, which is being done in collaboration with A. Kline and C. Neefus (University of New Hampshire). They are using isozyme and DNA techniques. Recent DNA studies by Still and Waaland (1993) emphasize the potentials for differentiating “cryptic” diversity within Porphyra taxa.

Development unialgal cultures of the different Porphyra taxa and “strains” found in New England

Spore cultures have been initiated (i.e. via carpospore) from collections of “native” taxa described above. In so doing, small portions of blades are scrubbed with sterile cotton swabs in sterile seawater. Tissue is then dried at 10°C for 24 hours and then reimmersed in an enriched seawater culture medium (von Stosch’s or Provasoli’s Enriched Seawater). After spore discharge (anywhere from 1 to 24 hours), the foliose sections are extracted and saved for future genetic analyses. Individual carpospores (or monospores) are cultured in the sterile enriched seawater media. The resulting vegetative conchocelis stages (or regenerative monospore producing plantlets) are then maintained and cultured using the enriched seawater medium (see above) at 5-20°C, 10-50μmol photon m⁻² s⁻¹, under a wide variety photoperiods (16:8; 12:12; Light:Dark). Conchospores are induced by simultaneously decreasing the photoperiods and temperature.

Collections of different Porphyra species have been made at diverse coastal and estuarine sites within Maine, New Hampshire and Connecticut. P. umbilicalis is by far the most abundant species spatially and temporally within the Gulf of Maine and Long Island Sound (LIS). It occurs throughout the year within diverse coastal and estuarine habitats, i.e. in the mid to low intertidal zones in the Gulf of Maine and into the upper intertidal in Long Island Sound. P. amplissima is most abundant within the northern Gulf of Maine, particularly occurring during the spring-summer within coastal and disjunct estuarine locales. It is most abundant within the low intertidal and subtidal zones and appears to be absent south of New Hampshire. P. linearis is presently forming localized ephemeral populations within the upper intertidal zones of open coastal habitats. It occurs within the Gulf of Maine in the winter and disappears by early spring. In eastern Long Island Sound it occurs in January and disappears in late March. It is rarely found in western Long Island Sound. P. leucosticta young fronds are initiated in early winter on the fronds of Dumontia contorta within open coastal tide pool habitats within the Gulf of Maine. As the winter progresses, it may be found epiphytically on other algae in the mid to low intertidal zones and into the upper sublittoral zones within the Gulf of Maine and Long Island Sound. By late spring (early June) the leafy thalli disappear.

An extensive conchocelis and vegetative culture collection of Porphyra (both native and nonnative species) have been established. Conditions for good vegetative conchocelis growth of P. amplissima is from 5-100 μmol photon m⁻² s⁻¹ and 5-15°C. It has an upper lethal temperature of 15°C. Conditions for conchosporangium induction and conchospore maturation by P. amplissima is from 5-25 μmol photon m⁻² s⁻¹ at 5-15°C from 2-4 weeks. Sexual maturation of the leafy gametophyte takes about 4 weeks at 50-100 μmol photon m⁻² s⁻¹ and 5-15°C. Conditions for good vegetative conchocelis growth of P. linearis is from 5-100 μmol photon m⁻² s⁻¹ and 5-10°C. It has an upper lethal temperature of 15°C. Conditions for good vegetative conchocelis growth of P. leucosticta is from 5-100 μmol photon m⁻² s⁻¹ and 5-15°C. It has an upper lethal temperature of 15°C. Monospore production by an asexually reproducing Porphyra umbilicalis is from 10-100 μmol photon m⁻² s⁻¹ and 5-20°C. Vegetative growth of P. umbilicalis occurs over similar range of photon fluence rates and temperatures.
Ultimately the most promising plants (i.e. ones that have the most advantageous shapes, especially blade length; appropriate maturation periods for particular sites; sufficient monospore production; and unique pigment composition) are being made available for "grow-out" at Coastal Plantation’s facility in Eastport, Maine later in the Spring of 1997. Before moving any genetic stocks into experimental production, vegetative conchoecia material are being introduced as "clean seedstock" produced from unialgal cultures into shell cultures. Our project is providing a variety of fundamental "baseline" information regarding taxonomic status, ecological requirements and potential for enhanced mariculture with "native" species (P. amplissima, P. linearis, P. leucostroma, & P. umbilicalis).

References


Benthoscape Structure and Infaunal Community Responses in Central and Western Long Island Sound

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Side Scan mosaics of two extensive seafloor areas in the central (east of Stratford Shoal) and western (southeast of the Norwalk Islands) basins of Long Island Sound were developed and are being used to study the spatial and temporal dynamics of benthic habitats and communities. Both benthoscapes (in analogy to terrestrial landscapes) are comprised of large-scale elements (patches) differing primarily based on sediment type and typography. Image analysis of the side scan digital records and analysis of video records reveal varying degrees of seafloor heterogeneity in the benthoscape elements and along transition zones among the elements. These detailed analyses reveal (1) a higher degree of benthic habitat diversity in these regions of the Sound than suggested from previous studies, and (2) that the spatial scales and components (e.g., small-scale biogenic vs. mesoscale physical topography) of significant heterogeneity differ among patch types.

Benthic infaunal communities are being sampled four times a year (April, June, August, and October) in a nested, hierarchical design. The data collected are being analyzed to determine the degree of community and species population associated with multiple scales of spatial and temporal variation in benthic community structure occurs at the meso-scale (on the order of km2) and can be related to habitat features evident at this scale on the side scan images.