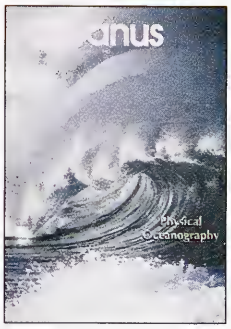
Oceanus

Volume 36, Number 2, Summer 1993

Coastal Science & Policy II

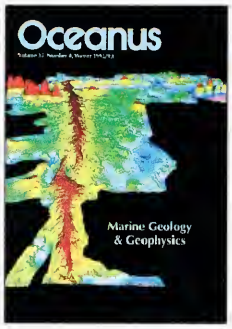
Oceanus
VOLUME 35

Marine Chemistry



Physical Oceanography

Biological Oceanography



Marine Geology & Geophysics

A Primer of Contemporary Oceanography

plus additional reading lists & slides to order!

Together these four issues offer a broad look at important issues and advances in today's marine sciences. Order your four-issue set today for only $29 (includes shipping and handling).

Please send me ___ sets of *Oceanus* Volume 35 at $29*
Payment method: ❑ Check enclosed ❑ MC ❑ Visa

❑ Send me the FREE Additional Reading List.
❑ Send me information on Primer Set illustrations available as slides.

Order toll-free by calling 1-800-825-0061

* for deliveries to Canada, the price is $33; outside the US, Mexico, and Canada, $37.

Send your order to:
Oceanus Magazine
Att: M. Stevens
P.O. Box 6419
Syracuse, NY 13217

Name _____
Address _____
_____
Telephone _____
Card Number _____
Expiration Date _____
Cardholder's name _____

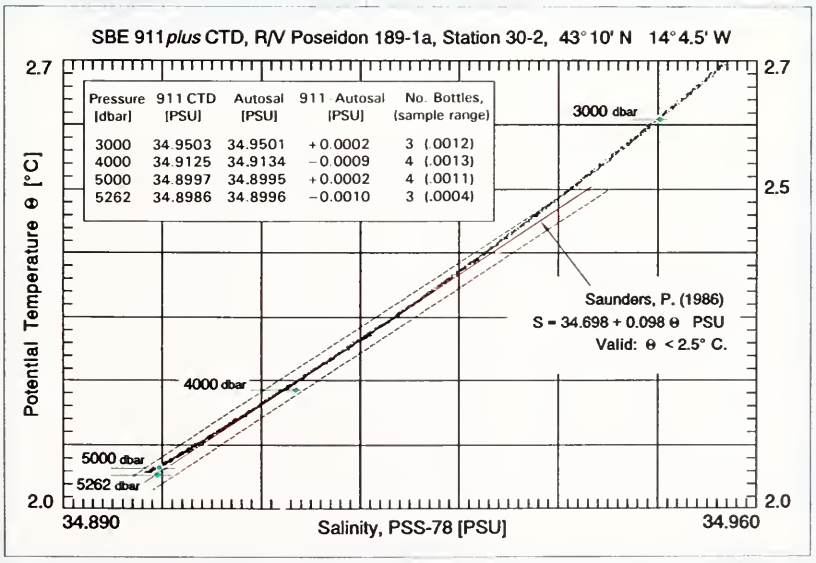
Please allow 4 to 6 weeks for delivery.

Sea-Bird Wins in CTD Trials

In May 91 Canada's Bedford Institute of Oceanography performed comprehensive lab and at-sea comparisons of EG&G, Guildline, and Sea-Bird CTD systems. Bedford's conclusion that the Sea-Bird "has the intrinsic resolution and accuracy needed for WOCE-standard work" resulted in purchase of Sea-Bird 911*plus* CTD systems for their deep-ocean hydrographic program.

In similar trials conducted in January 1992 by Germany's Institut für Meereskunde/Kiel, our *911 plus CTD* again outperformed all other participating systems - including the EG&G Mark 5, NBIS Mark 3, and FSI Triton. The T-S plot below is representative of the superb results consistently obtained with the Sea-Bird CTD System during the IFM/Kiel intercomparison.

IFM/Kiel test results include overlaid down-and-up profile plots of *911 plus* data closely matching the historic Θ-S relationship in the N.E. Atlantic (Saunders, 1986, JPO, v.16(1)), and falling within the 0.002 PSU rms tolerance (dashed lines) of the Saunders parameterization. The 48-scan averages plotted below were obtained from raw 24 Hz full-rate data; there has been no editing, fitting, or post-correction of any kind. The data agree to within 0.001 PSU with averaged bottle values from 3000 to 5262 dbar (table and dots), and to better than 0.003 PSU with *every* bottle from 0 to 5262 dbar.



SBE
SEA-BIRD ELECTRONICS, INC.
1808 - 136th Place Northeast
Telex: 292915 SBEI UR

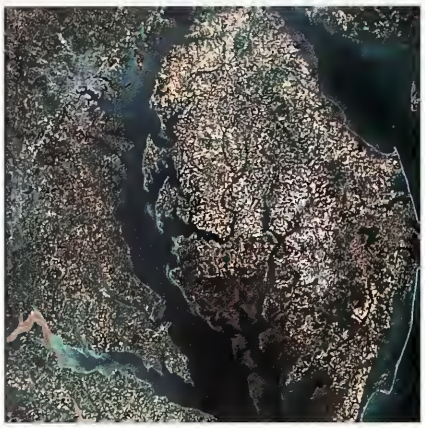
Telephone (206) 643-9866
Bellevue, Washington, 98005 USA
Fax (206) 643-9954

COASTAL SCIENCE & POLICY II

Juliette Murguia

Page 25

EOSAT



Page 35

Rick Maloof

Page 29

Departments

Copyright © 1993 by the Woods Hole Oceanographic Institution.

Oceanus (ISSN 0029-8182) is published in March, June, September, and December by the Woods Hole Oceanographic Institution, 9 Maury Lane, Woods Hole, Massachusetts 02543. Second-class postage paid at Falmouth, Massachusetts and additional mailing offices.
POSTMASTER: Send address change to Oceanus Subscriber Service Center, P.O. Box 6419, Syracuse, NY 13217-6419.

Headings and Readings

Bruce Tripp

Page 58

MBARI

Page 74

Boxes & Sidebars

Books

On the cover: The evening sun sets behind the palms of Costa Rica. Photo © Rick Maloof.

Vicky Cullen
Editor

Lisa Clark
Assistant Editor

Justine Gardner-Smith
Editorial & Marketing Assistant

T.W. Casalegno
Publishing Consultant

The views expressed in* Oceanus *are those of the authors and do not necessarily reflect those of* Oceanus *Magazine or its publisher, the Woods Hole Oceanographic Institution.

Editorial responses and advertising inquiries are welcome. Please write:

Oceanus Magazine
Woods Hole Oceanographic Institution
Woods Hole, Massachusetts 02543,
or call: 508-457-2000,
extension 2386.

For subscription service within the US, Canada, and Mexico, please write: *Oceanus* Subscriber Service Center, P.O. Box 6419, Syracuse, NY 13217-6419, or call (toll free) **1-800-825-0061**. Individual membership rate, $25 per year; Students, $20; Libraries and Institutions, $35. For Canadian subscriptions, add $8 to basic rates for GST. Single-copy price, $9 each ($8 plus $1 shipping and handling); 25% discount on orders for five or more. Please make checks payable to the Woods Hole Oceanographic Institution.

◆ ◆ ◆

Subscribers outside the US, Canada, and Mexico, please write: *Oceanus*, Cambridge University Press, Journals Marketing Department, The Edinburgh Building, Shaftesbury Road, Cambridge CB2 2RU, England. Individual subscription rate, £25 per year; Students, £16; Libraries and Institutions, £47. Single-copy price, £9. Please make checks payable in pounds sterling to Cambridge University Press.

◆ ◆ ◆

When sending change of address, please include mailing label. Claims for missing numbers from the US will be honored within three months of publication; overseas, five months.

Oceanus and its logo are ® Registered Trademarks of the Woods Hole Oceanographic Institution. All Rights Reserved.

Oceanus

International Perspectives on Our Ocean Environment

Volume 36, Number 2, Summer 1993 ISSN 0029-8182

WOODS HOLE OCEANOGRAPHIC INSTITUTION
1930

Published Quarterly by the
Woods Hole Oceanographic Institution

Guy W. Nichols, *Chairman of the Board of Trustees*
James M. Clark, *President of the Corporation*
Charles A. Dana, III, *President of the Associates*

Craig E. Dorman, *Director of the Institution*
Sallie K. Riggs, *Director of Communications*

Editorial Advisory Board

D. James Baker
President, Joint Oceanographic Institutions Incorporated

Sallie W. Chisholm
Professor, Department of Civil and Environmental Engineering, Massachusetts Institute of Technology

John W. Farrington
Associate Director and Dean of Graduate Studies, Woods Hole Oceanographic Institution

Gunnar Kullenberg
Secretary, Intergovernmental Oceanographic Commission

Margaret Leinen
Vice Provost for Marine Programs and Dean, Graduate School of Oceanography, University of Rhode Island

James Luyten
Senior Scientist and Chairman, Department of Physical Oceanography, Woods Hole Oceanographic Institution

W. Stanley Wilson
Assistant Administrator, National Ocean Service, National Oceanic and Atmospheric Administration

Permission to photocopy for internal or personal use or the internal or personal use of specific clients is granted by *Oceanus* Magazine to libraries and other users registered with the Copyright Clearance Center (CCC), provided that the base fee of $2 per copy of the article is paid directly to CCC, 21 Congress Street, Salem, MA 01970. Special requests should be addressed to *Oceanus* Magazine.
ISSN 0029-8182/83 $2.00 + .05. GST R 128 372 067. PRINTED IN USA.

Coastal Erosion's Influencing Factors Include Development, Dams, Wells, and Climate Change

David G. Aubrey

The demographic flight to the coast, begun in early civilization, continues unabated worldwide according to latest studies. The percentage of population living on the coast is expected to remain relatively constant over the next few decades, but the total numbers will increase as the population increases. Recent coastal battering by hurricanes and extratropical storms poses questions about coastal habitability and the real economics of coastal development. Hurricanes Hugo (1989) and Andrew (1992) in the southern US and Bob (1991) in the northeast, as well as various coastal storms, recently caused widespread damage to coastal property. Repair costs are borne by private individuals as well as the public in various direct and indirect ways. As these costs escalate, it is fitting to ask what the future portends for storm and coastal-flood damage.

We know that development pressures will continue to increase along the coast, but what will happen concurrently to natural-hazard threats to this infrastructure? Though much emphasis has been placed on sea-level rise, the broader issue is climate change in general. Here, we consider climate change in both its natural and anthropogenic perspectives. Without becoming mired in the debate about the greenhouse effect and human influence on climatic shifts, we can examine some of the broad classes of natural hazards that might accompany climate change. There are several categories of possible global-change effects on coastal erosion.

Relative Sea-Level Rise

In the early 1980s, an Environmental Protection Agency (EPA) report postulated increases in global sea level up to 4 meters during the next 100 years. Though balanced somewhat by other, lower estimates of sea-level rise, this higher extreme grabbed public attention. During the next decade, scientists attempted to concur on a more reasonable estimate of global sea-level rise due to climate change. Recent credible estimates suggest that approximately 10 to 20 percent of EPA's earlier maximum estimate is most reasonable. This estimate is for *global sea-level rise* in the ocean basins. Geologists have argued for more than a decade that *relative sea-level rise*, the combination of land movement and ocean rise, is a more critical coastal management consideration than sea-level rise alone. In some places, land subsidence due to tectonism (reshaping of Earth's surface through rock movements and displacements) and other factors increase relative sea-level rise; in others, the coast is actually rising compared to sea level. Climate change will primarily affect the global sea-level rise signature, and hence is of concern for the future. However, in many places local effects will continue to dominate global sea-level rise for decades to come, and effective coastal management requires recognition of this factor.

For example, a global map of relative sea-level rise, estimated from tide gauge records, shows anything but a uniform rate of rise. Rather, these numbers suggest that coastal managers must consider such local effects as tectonism, and not rely solely on present and anticipated global average values. In the future, any climate-induced increase in rate (if it occurs) will have to be factored into local considerations.

Human Influence on Local Subsidence

Human activities such as groundwater withdrawal and hydrocarbon extraction can cause land to subside. These very local phenomena can have severe effects. For example, oil extraction at Terminal Island in Wilmington, California, resulted in nearly 8.8 meters of subsidence in three decades! As a consequence, roads and bridges had to be rebuilt, levees were constructed, and drilling was modified. A global subsidence map clearly shows many cases of local coastal subsidence due to groundwater withdrawal. Perhaps the most celebrated case is Venice, Italy. During the 1950s, surface water gave way to higher-quality groundwater as the primary source for household and industrial water supplies. With today's greater awareness of the effects of concentrated groundwater withdrawal, wells can be engineered to minimize such impacts. In Bangkok, Thailand, for example, where subsidence rates reached 10 centimeters per year in some areas in the early 1980s, well-field re-engineering prevented canals that had been filled to form roads from reverting to canals during river floods.

Coastal Storms

Presently coastal storms cause major damage to coastal facilities and infrastructure. Tropical cyclones are the most feared: One 1970 typhoon in Bangladesh caused more than 250,000 deaths, and a similar storm there in 1991 left more than 100,000 dead. Though most storms have less-adverse impacts, there is concern about storm-activity trends if the global climate changes. There are three storm aspects to consider: changes in frequency, intensity, or path. Any one of these can cause an increase or decrease in coastal erosion. Unfortunately, we are unable to predict the storm trends well. Work done in the mid-1980s by Kerry Emmanual (Massachusetts Institute of Technology) shows that tropical-storm intensity can be expected to increase under certain assumptions of climate change. However, storm frequencies and pathways are not as predictable. How should shorelines be managed in the face of such uncertainty? As recent storms have shown, the storm climate is strongly variable from year to year, and coastal managers must plan for such variability. Ten years of benign weather don't argue for another ten years of such weather. This longer-term variability and susceptibility must be incorporated adequately into policy considerations. Human nature being what it is, we often tend to discount distant history in favor of our more recent experience.

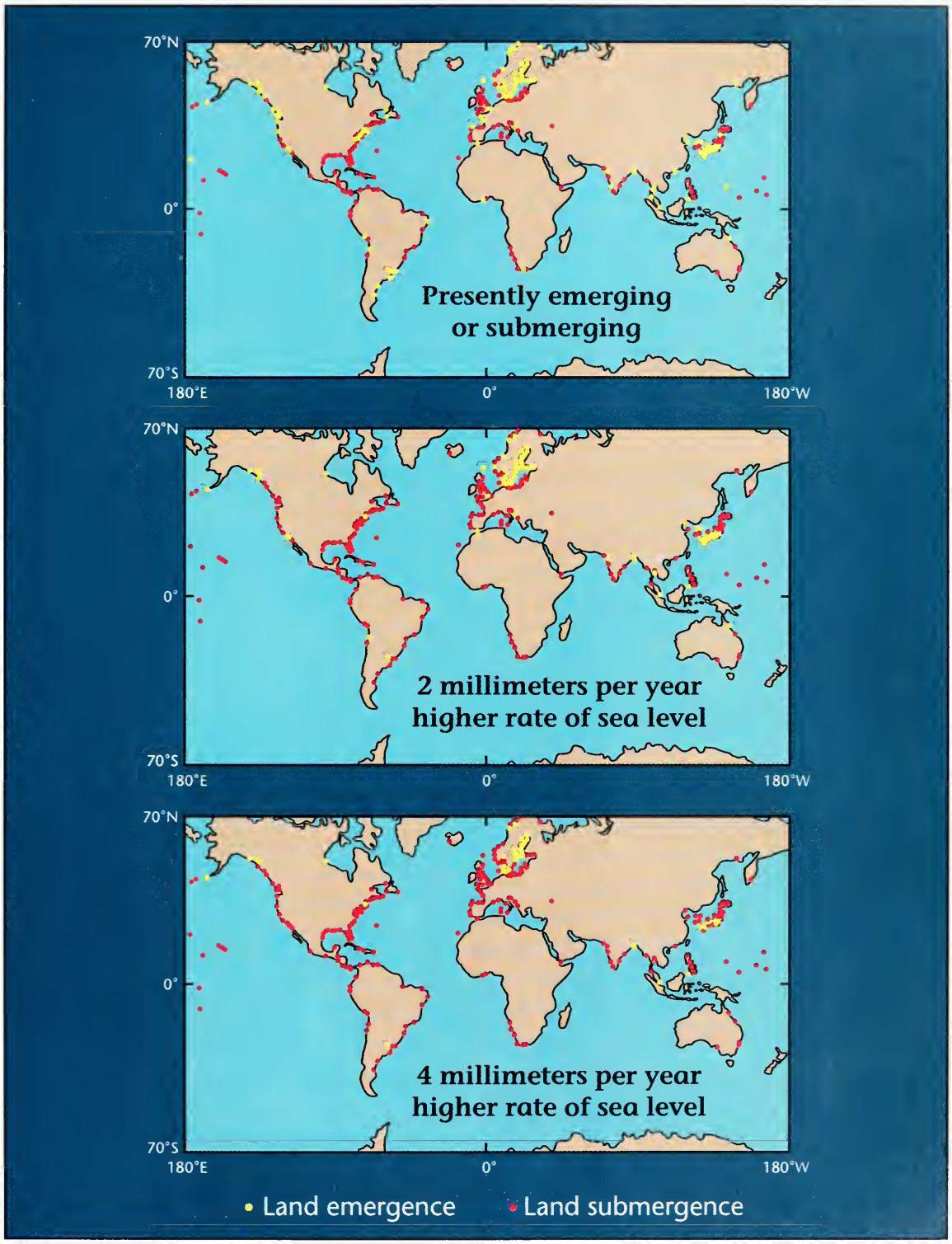
How should shorelines be managed in the face of such uncertainty?

Altered Sediment Delivery to the Coast

Coastal development viability depends not only on the energy of the destructive natural forces, but also on the ability of coasts to heal themselves after storms by providing an adequate sediment supply. Increased river diversion and damming have reduced the flow of sediment to many coasts. Reduced sediment delivery leaves a deficit of sand on beaches, lessening their self-healing capabilities. There are many examples of human activities reducing sediment supply and consequent increase in coastal erosion. Some sediment-supply change may be linked to climatic variations: a shift toward a more-or-less arid climate can increase or decrease sediment supply, depending on the region. Long-term variations in precipitation and river flow, as well as human activities affecting these parameters, will therefore continue to concern coastal managers.

Destruction of Coral Reefs and Other Biogenic Sources

Biogenic sediment is an important component of the general sediment supply. In many tropical areas, the primary beach material consists of degraded shells, reefs, or other biogenic materials. As climate changes, the ability of corals to keep up with sea-level rise may also change, altering the amount of sediment they produce. Furthermore, naturally nutrient-poor tropical island waters are being altered by continuing development, which tends to increase nutrient levels and change the structure of coastal tropical ecosystems, leading to loss of corals in some areas. This chain of events eventually will result in increased erosion, both through alteration of sediment supply and loss of direct wave sheltering by the massive offshore reefs. A geographically related issue is storm protection



Jack Cook/WHOI Graphics

If in the future the rate of absolute sea-level rise increases 2 millimeters per year (center map) and 4 millimeters per year (bottom map), some land regions will submerge (red areas) and others will emerge (yellow areas). The present situation is recorded in the top map.

provided by marshes and mangroves. Human activities—such as marsh destruction and using mangroves as a local fuel source—are eliminating these resources in many areas, thereby reducing the biogenic shield against erosion. The importance of these resources for shoreline protection as well as for ecosystem balance is not well understood the world over (see Zedler and Powell, page 22).

Though climate change may have some adverse effects on corals and other biogenic sediment sources, it can also have a positive impact. Warmer water temperatures may expand the corals' geographic range beyond the tropics. However, coral bleaching (a recent disease killing many corals) and related problems also have been linked to increased temperatures, so the balance of biogenic input is unclear in a warming-ocean scenario. Finally, scientists speculate that beach rock, the hardening of beach sands into rock that lines the coasts of some tropical regions, may become more abundant as water temperature rises, thereby increasing protection and reducing erosion. These areas of research must be addressed before we can accurately estimate the effects of climatic changes on tropical beaches and their sediment supplies.

Environmental pressures on the world's coasts will continue to increase, with or without global change. Increased habitation, greater development, more pollution—these are the byproducts of denser coastal population. Changes in natural disasters affecting the coasts will accompany rising population: Storm climate, sediment supply, and natural coastal protection all may change along with climate. How do we plan for this? Is there something we can do now to prevent or anticipate such change?

Fortunately, simple options can help alleviate some of the longer-term surprises before they become too damaging. Developing uniform guidelines and practices for shoreline management is a useful step in this direction. What types of guidelines? Simple exercises, such as identifying dominant sediment sources, clarifying exposure to natural hazards such as storms, and quantifying the shoreline's susceptibility to various human pressures (such as nutrient supply and coastal armoring), can

Steve Aubrey

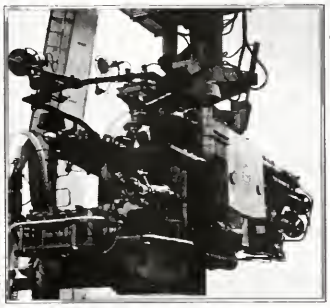
Fringing reefs in the Caribbean provide a protective shield against coastal erosion.

all help us understand the vulnerabilities. Once the vulnerabilities are understood, measures can be taken to monitor the system for future changes, implementing mitigation appropriate for that concern. For instance, reduced thermal discharge or nutrient input near coral reefs, improved river management practices and sediment bypassing techniques, or introduction of alternate sediment sources, may all play a role in mitigation if there is early warning. By recognizing the specific susceptibilities of different coastal areas, we can develop land- and water-use practices as well as mitigating factors that can retard coastal erosion and loss of coastal resources. Such guidelines could be developed under international aegis, such as the United Nations, and distributed widely for implementation into national plans and programs. These guidelines must recognize the value of the shoreline, its sediment sources, and the biogenic components to the continued health and viability of our shorelines.

Dave Aubrey, a Senior Scientist at Woods Hole Oceanographic Institution, has enjoyed the opportunity to visit many world beaches and coasts for his research. Some unique experiences include being tear-gassed in Korea, chased by water buffalo in China, nearly being arrested in South Africa, and dining on interesting fare in many places, all for the sake of science.

HARBOR BRANCH
HAS A SPECIALIZED FLEET
TO MEET YOUR NEEDS

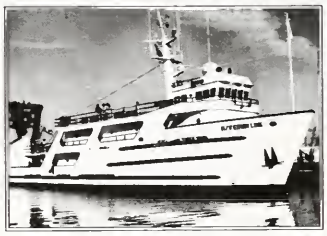
JOHNSON-SEA-LINK I and II submersibles are battery-powered underwater laboratories that can dive to 3,000 feet, supporting a pilot and one observer in the forward acrylic sphere and a technician and one observer in the aft chamber. The two submersibles are equipped with still and video cameras, manipulators, "critter gitters," and other sophisticated equipment that enables researchers to observe, photograph and collect specimens.



Over the last 20 years, J-S-L I and II have conducted over 5,000 dives. Typical applications include benthic and/or midwater observations, photo/video documentation and collection of organisms; dump site inspections and monitoring; punch and box coring; search and recovery; bottom surveys; archaeological site documentation and recovery; and environmental impact studies.

JOHNSON-SEA-LINK I

R/V SEWARD JOHNSON, 176'



R/V EDWIN LINK, 168'

These vessels are equipped with wet/dry labs, environmental rooms and accommodations for up to 20 and support manned/unmanned submersible operations and surface oceanography.

Other applications include large towed systems support, deployment and retrieval of moored devices, hydrographic applications, and diving support.

R/V SEA DIVER, 100'

Important to any fleet is the drydocking and servicing facilities. Harbor Branch has a 1,000 ton marine railway which can be submerged to accommodate vessels of 12 ft. draft, 180 ft. length, and 40 ft. width.

Installations of specialized oceanographic equipment, inspections, maintenance, repairs, surveys, modifications, and other services can be provided by qualified specialists.

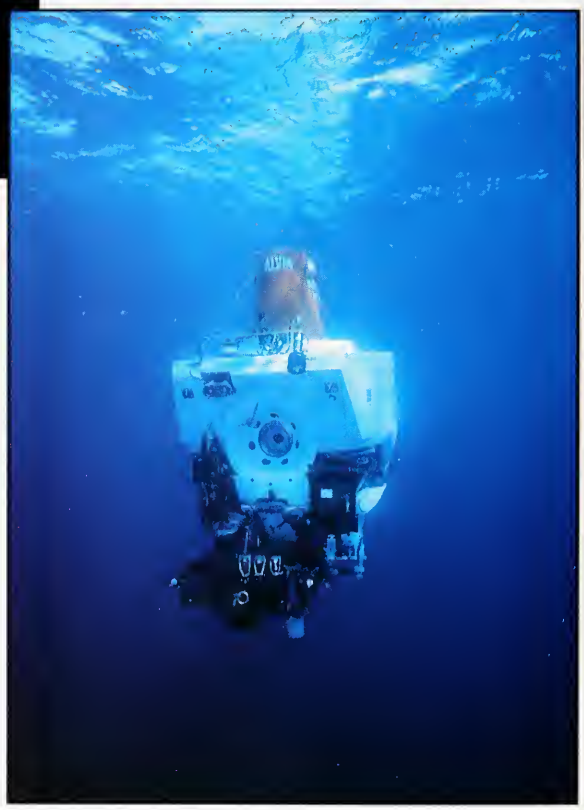
1000-ton Marine Railway

Contact Tim Askew, Marine Operations Director, (407) 465-2400, ext. 262.
Contact Chuck Brenn, Railway Services, (407) 465-2400, ext. 274.
Fax number (407) 465-2116

HARBOR BRANCH OCEANOGRAPHIC INSTITUTION, INC.
5600 U.S. 1 North, Ft. Pierce, FL 34946.

Explore Educational Programs at Woods Hole Oceanographic Institution

Applied Ocean Sciences & Engineering, Biology, Chemistry, Geology & Geophysics, Physical Oceanography... Postdoctoral Awards, Summer Student Fellowships, Research Fellowships, Summer Study and more...



With a commitment to the future, the Woods Hole Oceanographic Institution, one of the world's leading oceanographic centers, offers unique experiences in graduate and post-graduate studies. WHOI sponsors numerous fellowship and traineeship programs, and offers graduate degrees through a Joint Program with the Massachusetts Institute of Technology, providing a first-rate education through both hands-on experience and classroom instruction by many of the world's leading oceanographers. WHOI also offers select educational outreach programs for the K-12 grades.
Find out today what WHOI can do for you.

For more information contact the Education Office of the Woods Hole Oceanographic Institution.

WOODS HOLE OCEANOGRAPHIC INSTITUTION 1930

Woods Hole Oceanographic Institution

Education Office
86 Water Street
Woods Hole, Massachusetts 02543-9903
Telephone (508) 457-2000, ext. 2200
Fax (508) 457-2188

An Introduction—

Coastal Science and Policy II

© Rick Malouf

This is the second of two sequential *Oceanus* issues focusing on the coastal zone's scientific aspects and its intertwined and difficult policy and management concerns. Our "Coastal Science & Policy I" issue (Spring 1993) offered insights on a variety of coastal subjects ranging from the Boston Harbor Project to coastal flood insurance to tides and their effects.

This second coastal issue brings you contemporary insights from Charles Nittrouer on how rivers influence the ocean, from Joy Zedler and Abby Powell on wetlands research, and from Scott Nixon on how nutrient runoff from land affects coastal waters.

Judith McDowell describes the pathways coastal water contaminants take to reach and reside in marine animal tissues, as well as what effects they may have on the animals. The International Mussel Watch, decribed by John Farrington and Bruce Tripp, takes advantage of the common blue mussel's proclivity to store contaminants and employs them as sentinels for coastal pollution. Twenty years ago, there was a small oil spill in Wild Harbor, Massachusetts. John Teal reviews it's history and draws a hopeful conclusion about oil-contaminated areas. Oil-spill models and their uses are discussed by Malcolm Spaulding, and Ronald Atlas explores spill remediation by microbes.

The current vulnerable status of world and US fisheries, resources that were once thought to be inexhaustible, is reviewed by Michael Sissenwine and Andrew Rosenberg. They also offer a "report card" on fishery management and call for the US to do better. David Aubrey, who wrote a thoughtful introduction and coauthored one of the Boston Harbor articles for "Coastal Science & Policy I," in this issue identifies several factors that influence coastal erosion and discusses ways to help protect the health and viability of our shorelines.

Today's US Navy mission, newly redefined with the close of the Cold War, brings a greater need for knowledge of coastal waters; Kenneth Brink and John Orcutt, members of the National Research Council's Ocean Studies Board, discuss how this will impact the oceanography community.

In this month's Creature Feature, Cheryl Dybas tells the story of larvaceans, who form a link between the tiny plankton and larger animals in the marine food chain. Cheryl "visited" the habitat of one of these creatures through the "eyes" of a remotely operated vehicle at the Monterey Bay Aquarium Research Institute (MBARI) last summer. MBARI is one of two most interesting institutions that have opened in the last decade in Monterey, California. The other is the Monterey Bay Aquarium. Two most interesting people who are among the principal driving forces for these institutions—David Packard and Julie Packard—are profiled in this issue by Nora Deans and Judith Connor, who describe how a special family has applied its vision to the marine world.

Clear human vision is needed on all aspects of our coastal ocean. William Boicourt summarizes what we know about the delicate environment of the estuary, which includes such heavily urbanized areas as Chesapeake Bay and San Francisco Bay, and notes that scientists and coastal managers, politicians, and public interest groups are beginning to work together to preserve estuaries. Such cooperation is advisable not only nationally, but internationally as well, for, as Dave Aubrey reminded us in the last *Oceanus*, coastal issues are global, and the interconnectedness of coastal areas is real.

Vicky Cullen

Controlling the Ingredients that Flow to the Sea

Oceanic Processes Near River Mouths

Charles A. Nittrouer

...then oceans "are what rivers feed them."

If people "are what they eat," then oceans "are what rivers feed them." Our bodies receive additional inputs, such as the air we breathe, but the primary supply is through the food and liquids we put into our mouths. Similarly, oceans receive oxygen and other gases through exchange at the air-sea interface, but the primary input of most materials is through river mouths. Wind-blown particles also enter the ocean from the air. Other notable sources of input to the ocean include mid-ocean ridges and glaciers. But on a worldwide basis, rivers supply a great mass of dissolved and particulate materials—over a billion tons each year of dissolved chemical components, and over 10 billion tons of sediment and organic particles.

Processes within our bodies operate on the ingredients we receive; some are eliminated and others are transformed. Similar processes of selection and transformation occur in the ocean, and the site for some of the most important processes is the ocean near river mouths. These processes control the quality and quantity of ingredients delivered to the world ocean. They also control the character of the oceanic environment near the river mouth—whether the water is turbid, whether primary productivity occurs, whether radioisotopes remain dissolved or are removed to the seabed, all depend on the river.

The character of the ocean near river mouths is affected by both terrestrial phenomena, such as floods of the river, and by marine phenomena, such as tides and waves. The superposition of terrestrial and marine influences makes for great complexity in processes near mouths of rivers. Some of this complexity actually occurs within the river mouth as the estuarine processes described in the article beginning on page 29. Additional complexity occurs farther seaward on continental shelves, and the processes in this region that influence the fate of riverborne ingredients are the focus of this article. The diversity of shelf processes requires us to consider a full range of oceanographic disciplines.

The Changjiang River plume water shows a stark contrast to the blue water of the East China Sea. The differences in these waters lead to important processes—some of which are quite complex.

River Plumes Carry Varied Loads to the Sea

Dissolved chemical components and suspended sediment enter the ocean as part of a low-salinity surface plume. Coriolis force (Earth's rotational force) tends to carry a plume toward the right in the Northern Hemisphere, but many other factors can control the plume's direction. The angle between the estuary and coast, the water depth, and the salinity of the plume are particularly important as the plume first leaves the confines of the river mouth. Farther seaward, shelf currents and wind patterns become more dominant. For most locations, these factors vary through different times of the year, such that a river plume can completely reverse its direction. The Columbia River plume in the Pacific Northwest is a good example. During the summer, winds and currents cause the plume to flow southward, whereas winter conditions result in a northward trajectory.

Plume direction influences the plume materials' final destination. The contents of a plume directed offshore may escape the continental shelf, while the contents of a plume that hugs the coast may be trapped nearshore. A plume affects the parts of the ocean it reaches. The very turbid nearshore plumes of the Amazon and Changjiang Rivers prevent primary productivity by severely limiting light penetration. In more distant parts of the plume, sediments have been removed by settling, and nutrients associated with the plume can stimulate primary productivity.

The impact of a river plume is dramatically demonstrated by the Amazon plume and the color of the seawater in its path. Typical equatorial water near the coast of Brazil is brilliant blue. The brown muds of the Amazon plume dramatically change it to the color of chocolate milk. And as the suspended-sediment concentrations drop below 10 milligrams per liter farther along the plume's path, the color changes to a pea-soup green due to the presence of phytoplankton.

Materials are Transformed Near River Mouths

The transition region from terrestrial to marine environments is a dynamic location where river-supplied materials undergo many important transformations. The salinity transition from fresh to ocean water

exposes the riverborne load to different geochemical conditions and to a new biological community.

In saline conditions, many dissolved metals are attracted to the negatively charged surfaces of suspended particles. Grazing marine phytoplankton may also remove dissolved nutrients from the water. Both of these examples demonstrate transformations from dissolved to particulate materials, and this generally reflects the bulk of changes. However, some transformations occur in the opposite direction; for example, the natural radioisotope radium is released from suspended particles as they travel from fresh to ocean water.

Transformations near river mouths cause particulate materials to become larger in size. In saline conditions, the charges on particle surfaces create attractions that bring particles together to form aggregates, a process known as flocculation (or, sometimes, coagulation). In addition, zooplankton feed upon the phytoplankton found near river mouths and package the remains in the form of fecal pellets. Both inorganic flocs and biological fecal pellets sink much faster than their constituent particles, allowing for efficient removal of materials from the surface plume.

The selectivity of transformation processes near river mouths has a strong impact upon the character of the coastal and, indeed, the world ocean.

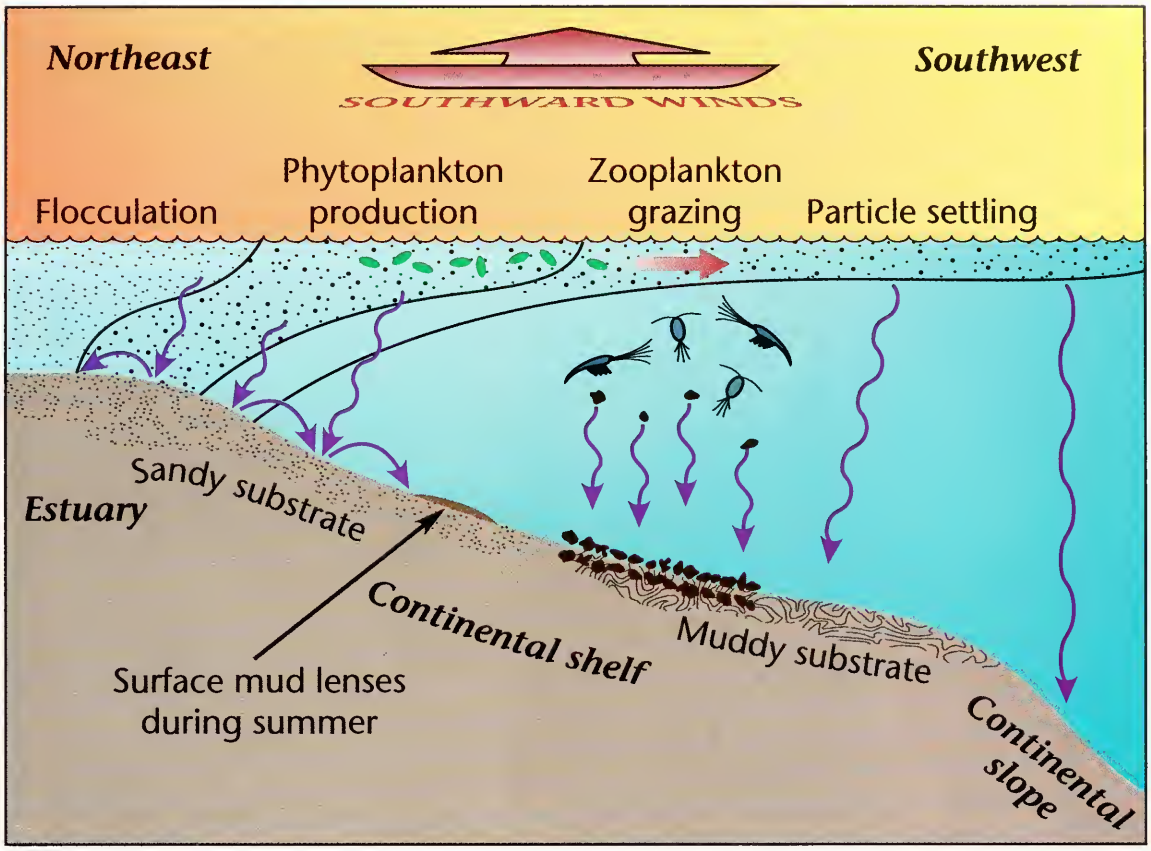
The time that exiting water spends near the river mouth determines the effectiveness of processes that remove dissolved and particulate materials to the seabed or that export them from the shelf. Many of the same influences on the direction of a river plume also cause variations in plume speed. Local winds and coastal currents can cause the water to quickly transit the adjacent shelf or to pond near the river mouth.

Plume water's residence time on the shelf has a direct effect on the fate of materials discharged by a river. The settling of suspended particles is among the simplest mechanisms to envision. A strong turbulent flow tends to keep fine particles in suspension for greater distances. Weak flows and ponding of plume water allow individual particles and aggregates (flocs and fecal pellets) to sink near the river mouth. Other relevant processes are the attraction of chemical components to the surfaces of particles and the uptake of nutrients by phytoplankton. These removal processes' efficiency near river mouths is largely dependent on the time available. The greater the residence time of river water near its mouth, the more effectively its dissolved and particulate loads will be trapped there.

Riverborne Material Meets Diverse Fates

The transformation processes that affect the constituents of river plumes do not affect all materials equally. The most reactive materials are removed near the river mouth, and sink into underlying shelf water that commonly has a landward component of flow. Other materials are removed farther seaward, where underlying currents can sweep them in any direction. And some materials escape the continental shelf to become part of the world ocean as plume water melds with ocean water.

The composition of sediment particles discharged by a river typically includes a range of mineral types that depend on drainage-basin characteristics, such as bedrock and weathering conditions. Montmorillonite (also known as smectite) is a common mineral that forms very small grains (a couple of microns or less in size). For this reason, montmorillonite can differentiate itself from other minerals, because its nonflocculated grains are carried hundreds and thousands of kilometers from a river mouth.



Winds and currents carry the Columbia River plume southwestward during spring and summer. Processes active on the shelf near the river mouth package some of the particulate and dissolved effluent into larger-particle aggregates that sink to the seabed. Material not removed on the shelf escapes with the plume to the continental slope.

The same can happen to organic material discharged by a river. Vegetated debris buried in soils forms detritus that is much finer than leaves and branches directly washed into streams. Off the coasts of Washington and Oregon, terrestrial organic materials derived from eroded soils can be found beyond the continental shelf, whereas the coarser detritus does not escape much beyond the river mouth and nearshore areas.

Dissolved components may be subject to a complicated series of selective transformation processes near river mouths. For example, nutrients are utilized by phytoplankton, which in turn are grazed upon by zooplankton. Their fecal pellets sink and decompose, once again releasing some of the nutrients. The processes of nutrient uptake and bacterial decomposition are both selective and cause different materials to have different fates.

The selectivity of transformation processes near river mouths has a strong impact upon the character of the local coastal ocean and, indeed, upon the world ocean.

Seabed Processes Act Upon Riverborne Material

River-mouth areas are important repositories for material entering the ocean, due to the combination of high supply rates and intense transformation processes. However, ultimate retention depends on more than processes that remove materials at the water surface and carry them to the seabed. Physical erosion, biological resuspension, and chemical decomposition act upon the seabed to place dissolved and particulate materials back into the water column.

Currents and waves generally erode less than 10 centimeters into the seabed, and most benthic animals are restricted to the upper 10 centimeters. Chemical decomposition operates to greater depths in the seabed, altering sediment and releasing dissolved materials to pore spaces (tiny spaces between grains of sediment). However, escape from pore spaces is largely dependent on physical erosion and biological burrowing. Therefore, in most cases, materials buried more than about 10 centimeters can be considered retained near a river mouth.

An important consideration for burial is the rate of sediment supply to the seabed. More rapid rates reduce the effectiveness by which materials are returned to the water column. Part of the reason is the simple process of rapidly burying material below more than 10 centimeters of sediment. However, rapid sediment input can also inhibit biological and physical processes. Burrowing animals seldom inhabit shelf areas where the sediment accumulation rate is greater than 2 centimeters per year. In addition, rapid sediment supply can create a mud slurry (known as fluid mud) at the seabed surface that protects it from erosion by waves and currents.

The burial process is also selective. Benthic animals eat certain sediments and defecate those sediments into the water column. Waves and currents tend to erode particles based on characteristics such as grain size. Therefore, certain materials are buried and kept near the river mouth, and other materials are returned to the water column.

Rapid sediment input can also inhibit biological and physical processes.

Timing is Everything

The presence and magnitude of processes active at a particular river mouth affect the character of that location, but the relative timing of the processes is also important. Probably most critical is the timing of peak discharge from the river compared to the timing of oceanic processes.

For most mid- and high-latitude rivers, peak discharge of water, dissolved components, and suspended sediment occurs in the spring. This may be delayed into summer if snow melt is an important source of water. Seasonal variability resulting from meteorological and physical-oceanographic phenomena is characteristic of most coastal settings. For example, winters are commonly the period of the most energetic winds, waves, and currents. Time dependence also is demonstrated by other relevant processes, such as nutrient upwelling, phytoplankton blooms, and feeding by zooplankton and benthos.

Among the timing considerations is the direction of the plume during the period of peak discharge. In addition, turbid water discharged during the period of the spring bloom will stifle phytoplankton production. Suspended sediment released during quiescent summer months may be deposited near the river mouth. The fate of riverborne materials (water, solutes, and particulates) depends on the sequential timing of many phenomena.

The Example of the Amazon River

Let's consider the case of the Amazon River and its impact on the world ocean. The Amazon discharges about 10 percent of the particulate and dissolved materials supplied by rivers worldwide. Processes on the continental shelf near the Amazon mouth control the fate of this material.

Peak discharge for the Amazon occurs during May and June in response to the rainy season in its drainage basin. This is a relatively quiescent

period on the shelf because trade winds are weak. Thick layers of mud are deposited temporarily along the adjacent shoreline. Eventually about 15 percent is transported northwestward beyond the region of the river mouth, with progressively increasing concentrations of montmorillonite. Even this small fraction of Amazon discharge dominates sediment supply over 1,000 kilometers along the coast of South America. The remaining 85 percent of sediment is trapped near the mouth and has formed a deltaic feature.

Silica deposits turn the Amazon River a muddy brown during the rainy season.

Silica is an important nutrient for primary productivity. For the Amazon shelf, high turbidity nearshore displaces most production to the mid- and outer-shelf areas. Diatoms on the Amazon shelf remove about 25 percent of the dissolved silica supplied by the Amazon, and use it to form their skeletons. After death, some of the skeletons are buried, but most dissolve. About 80 percent of the biogenic silica synthesized by diatoms on the Amazon shelf is released back to the water column. Therefore, only about 5 percent of the silica in the river's discharge remains near the river mouth. The remaining 95 percent enters the global pool of silica, and most is deposited in the Southern Ocean surrounding the Antarctic continent.

The Amazon system demonstrates the local, regional, and global relevance of river discharge and of the processes on the continental shelf near the river mouth. It also demonstrates the interdependence of various processes.

What Do We Need to Know Next?

Many diverse processes impact the fate of riverborne materials. Processes operating near the mouths of rivers cover disciplines from meteorology to physical, chemical, biological, and geological oceanography. Many advances have been made toward understanding the individual processes, but we are just beginning to understand the coupling between them. This will be an important responsibility of future coastal research on areas near river mouths.

Most oceanographic research near river mouths to date has focused on large rivers located at mid latitudes. A broader diversity of study areas is needed, including high and low latitudes. Tropical settings are particularly important, because much dissolved and particulate load is created by the weathering and rainfall that is characteristic of these locations. Although the world's few largest rivers are the major contributors to global budgets, the sum effect of thousands of moderate and small rivers is also important and much more poorly understood.

What rivers feed the ocean is changing. Farming, forestry, and mining have caused some rivers to double and triple their mass discharge. For other rivers, dams and agricultural diversions have completely eliminated discharge. And in most cases, human habitation along river banks is adding a wide assortment of pollutants.

Future research will provide a better understanding of traditional and new processes operating near river mouths and their fundamental contributions to the world ocean. It is also important to learn how human manipulation of river discharge influences local, regional, and global ocean conditions.

As a boy in Pennsylvania, Chuck Nittrouer frolicked in local rivers and in the ocean at the Jersey shore. After a bunch of years in college and graduate school and doing research along coasts around the world, he discovered that rivers and oceans meet. Although he now knows where rivers go, he is still trying to figure out where their passengers go. This has led him to investigate continental shelves and the areas landward and seaward of shelves. He is also investigating the perplexing question of "where glaciers and their passengers go." His discoveries are now being made as a Professor of Geological Oceanography in the Marine Sciences Research Center at the State University of New York in Stony Brook.

Reading Lists Are Available!

Would you like to know more about oceanic processes near river mouths, managing coastal wetlands, or any of the other topics addressed in Coastal Science & Policy II?

***Oceanus* authors provide lists of suggested additional reading on the subjects of their articles.**
So if you'd like to know more about any of the articles in this issue, please call:
Justine Gardner-Smith at 508-457-2000, ext. 2386
to request a reading list.

Managing Coastal Wetlands

Complexities, Compromises, and Concerns

Joy B. Zedler and Abby N. Powell

It looks so simple the first time you walk into a coastal salt marsh. Here is a plant community that changes visibly as its gentle topography slopes from the upland to the tidal channel. In the high marsh, small shrubs and mat-forming grass are dominant; in the middle marsh, pickleweed is everywhere; next to the channel, tall cordgrass is conspicuous. Obviously, the ecosystem is controlled by factors that change with elevation—greater inundation at the lower end, more exposure to evaporation at the upper end. First impressions about the influence of inundation and exposure are right; the assumption of simplicity is dead wrong.

Marshes at this bay, Bahia de San Quintín in Baja California, Mexico, are excellent "reference ecosystems" for damaged wetlands farther north, since linkages with both the upland and coastal habitats are still intact.

Joy Zedler

In over 20 years of observing and studying southern California's marine-dominated wetlands, we still marvel at their complexity. The more we look, the more we see. What makes these systems complex is what makes them interesting. It's also what makes them difficult to manage and almost impossible to duplicate when we try to build them "from scratch." Why people try to build coastal wetlands is discussed later. Here, we'd like to describe the many facets of our region's wetlands and instill an appreciation for some of the complicated interactions among the species that live there.

While elevation is a useful attribute to measure in a salt marsh, it doesn't explain much about what goes on from day to day or year to year. Let's take just one elevation zone, the lower cordgrass marsh, and explore it further. In southern California, only the lowest elevations of the salt marsh support cordgrass (*Spartina foliosa*). This is in contrast to the broad expanses of cordgrass-dominated marshes along the Atlantic and Gulf of Mexico coasts. The center of distribution for this genus of grass is subtropical; it grows best in warm seasons and at salinities below those of seawater (about 35 parts per thousand). Yet in southern California, the cordgrass usually has to contend with salinities between 35 and 50 parts per thousand, and it seems to grow year-round, (at least in most years), even when water temperatures are only 12 C in the daytime. Through the year, the cordgrass canopy changes from gray-brown in mid winter, when most of the tall stems from the previous year are dead but still upright, to bright green in June, when the old dead stems have washed away, and the current year's stems are growing at peak capacity.

What makes these systems complex is what makes them interesting.

Much of our knowledge about what controls the dynamics of salt marshes comes from long-term observations of Tijuana Estuary. This is the largest undissected wetland in the region—it has no freeway or railroad running through it. It is an oddity in that respect, and because this estuary is still intact, it serves as a liaison with the past—a hint of what the region's salt marshes may have been.

Long-term observations are important, because southern California is a region of many extremes. Even though our winters are mild and our waters don't freeze, we have high variability in rainfall and even higher variability in stream flow. In other words, we have catastrophic floods in some years and no freshwater inflow in others. In the past 13 years, there have been three major floods at Tijuana Estuary. Tidal flushing, the other main hydrologic variable, is also unpredictable. In these same 13 years, Tijuana Estuary had one major closure; the estuary was nontidal for 8 months in 1984. Closures are more likely where local or upstream topography is altered and sediments are mobilized. If sediment accumulates in the estuary, little tidal water can move in and out to maintain a deep ocean inlet; the estuary mouth silts in and tidal flushing declines or disappears.

Extreme environmental conditions have taught us much more about what controls the distribution and abundance of cordgrass than data on changes with intertidal elevation has revealed. Extended freshwater flooding lowers soil salinity to below that of the ocean (in 1980, for example, the average salinity was 15 parts per thousand in April, long after the floods of January and February). Seed germination and seedling establishment are more likely at this time. These are rare but important events, although not essential for year-to-year persistence, since the

Abby Powell

High-tide refuges for light-footed clapper rails become scarce when wetlands are surrounded by incompatible land uses. With a lack of refuges, these endangered rails may experience greater exposure to predators.

cordgrass is a clonal (vegetatively reproducing) species. When seedlings do establish, cordgrass distributions can expand, and new patches can appear on bare mudflats or among the canopies of pickleweed that have ventured onto the mudflats. Cordgrass patches established in previous floods increase their rate of vegetative expansion to perhaps twice their usual rate, and each stem grows taller and more robust. The floods not only lower the stress of salinity, but they also transport nitrogen to the marsh. Either nitrogen or low salinity can stimulate cordgrass growth; when they occur together, as with flooding, it's a bonanza for the marsh. Tall, robust canopies form. How that affects the marsh animals will be discussed a bit later. But first, we need to consider what happens when another controlling factor occurs: closure of the tidal mouth.

The year that Tijuana Estuary closed to tidal flushing was one of sparse rainfall, with little runoff or stream flow to blast through the tidal mouth and insure a deep, self-maintaining opening. Instead, sand from along the shore gradually filled the inlet, because the estuary had accumulated too much sediment from both the watershed and the coastal dunes to sustain tidal flushing. It takes a fairly large volume of water flowing in and out each day to keep an estuary mouth from closing. Decades of dune overwashing and floodborne sedimentation had reduced that volume. In early April 1984, the mouth closed. It took eight months of planning, permitting, and dredging to open the mouth and reestablish tidal flows. In the interim, the hot, dry weather desiccated marsh soils, increased soil salinities to over 100 parts per thousand in the salt marsh, and increased water salinities in the channels to 60 parts per thousand. High salinities and other shifts in water chemistry killed most of the macroinvertebrates and many of the fishes. Huge areas of cordgrass died out; it shrank in both distribution and canopy stature.

During the period of closure, one of the "trademarks" of Tijuana Estuary, the light-footed clapper rail (*Rallus longirostris levipes*) disappeared. More than 40 pairs of this year-round cordgrass marsh resident were

The Light-Footed Clapper Rail

© Juliette Murguia

THE LIGHT-FOOTED CLAPPER RAIL resides along a 200-mile strip from Santa Barbara, California, to San Quintín, Baja California, Mexico. This subspecies of clapper rail is nonmigratory, and prefers wetlands supporting tall, dense stands of Pacific cordgrass. In early spring, the rails build nests of dead vegetation and marsh debris. The nest can float during high tides and floods, but is anchored to the surrounding cordgrass. Tall leaves over the nest are loosely woven to hide the 7 to 11 eggs from the eyes of predators. After hatching, additional brood nests are built for the chicks. By late summer or fall, the young move away from their parents' territory and must learn to survive on their own.

Although we do not know historically how many light-footed clapper rails were supported by southern California's salt marshes, we do know that populations have suffered a severe decline. In 1922, A.B. Howell noted "...they used to be common on our marshes...they are certainly less well protected, and much less numerous than the northern bird about San Francisco Bay. In addition, their range is being restricted by reclamation of the marshes, and the future of the subspecies is not that bright."

In 1973, the subspecies was listed as endangered by both the federal government and the state of California. Most recently it was estimated that approximately 275 pairs of light-footed clapper rails remain in only 13 coastal salt marshes. Three of these marshes, Upper Newport Bay, Tijuana Estuary, and Seal Beach National Wildlife Refuge, support over 85 percent of the remaining population.

Reasons for the severe decline of light-footed clapper rails are overwhelmingly related to habitat loss and degradation. Large areas of coastal marshes have been destroyed, and those that remain are severely disturbed. Cumulative impacts to rail populations include heavy predation, exposure to contaminants, and loss of genetic diversity. Recovery plans for light-footed clapper rails include restoring habitat and improving habitat quality, managing predators, and perhaps propagating birds in captivity for reintroduction. In the end, the restoration of coastal salt marshes should be planned to ensure the survival of many species of plants and animals, including the endangered light-footed clapper rail.

nesting at the site before the closure. It took four years for the cordgrass to regain its predisturbance distribution, and an additional two years for the rail population to recover.

From observations of extreme events we learned what catalyzes major episodes of cordgrass recruitment and mortality. Lowered soil salinity allows expansions in distribution and abundance; hypersaline droughts have the opposite effect. Some of the complexities of the marsh were also revealed. For example, we saw how the clapper rail depends on tidal flushing. When the marsh was nontidal, there was only a sparse cordgrass canopy to protect the rail from predators, and only a few invertebrates to provide its food (crabs, snails, amphipods). No wonder the rails left or died. It took another type of episode to reveal how the rails and other salt marsh fauna depend not just on cordgrass but on *tall* cordgrass, thus revealing more intricacies of this complex ecosystem. Attempts to reconstruct cordgrass marshes expressly for use by the light-footed clapper rail provided that learning experience.

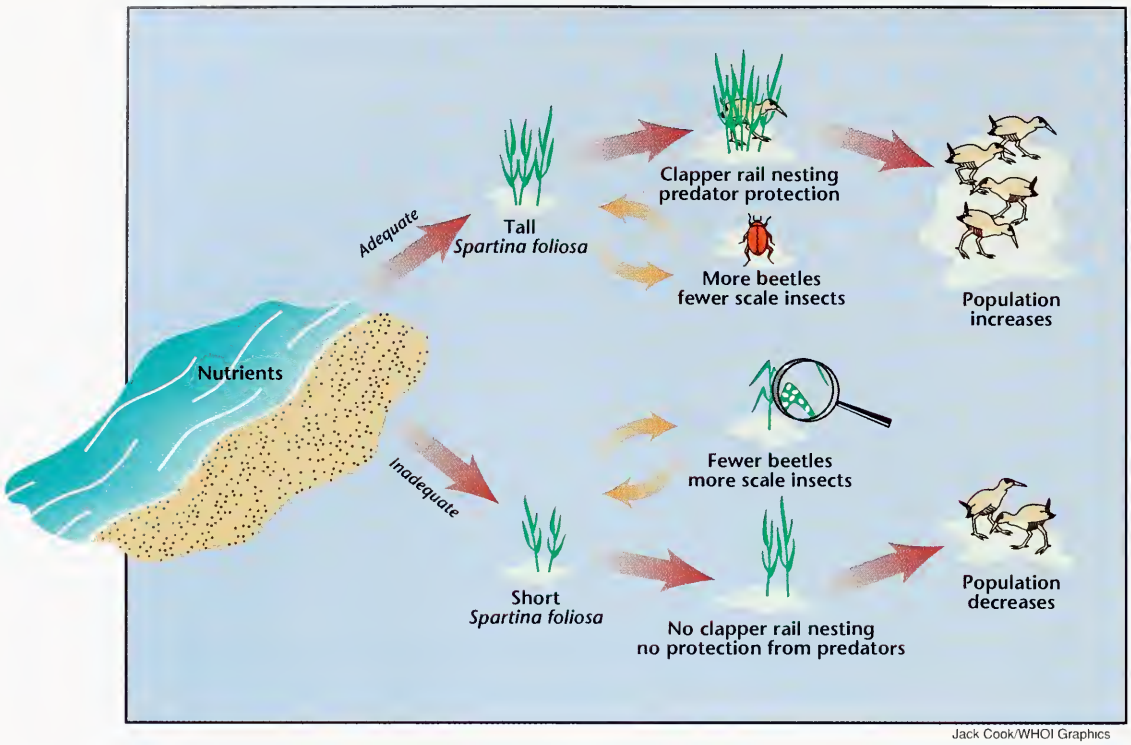
Joy Zedler

At San Diego Bay, there are three "manufactured" marshes, none of which supports clapper rails. Studies that began in 1987 show that most of the cordgrass is short, a problem that was later traced to poor nitrogen status of the soil (derived from sandy dredge spoils). Comparisons of marshes with and without clapper rails indicate that the critical attribute of a good cordgrass habitat is the occurrence of at least 90 stems per square meter that exceed 60 centimeters in height. Adding nitrogen to the soil increased plant heights somewhat, but there was a "fly in the ointment"—in this case, a scale insect on the cordgrass. Plants grew well for three years, but then an outbreak of scale insects (*Haliaspis spartina*) decimated the canopy. Never had we seen outbreaks of this native herbivore in the natural salt marshes. What was the link between short plants and scale insects? Donovan McIntire (a local naturalist) thought the scale's predator, the native beetle (*Coleomegila fuscilabris*) might be missing. Kathy Williams (San Diego State University) tested the idea and found that the beetles fed voraciously on the scales in the lab, but, when introduced in the field, they lacked sufficient high-tide refuges, because the short cordgrass was inundated at high tide. Thus another complication was exposed—tall plants were necessary not only for rail nesting, but also for beetles that keep herbivorous insect populations in check.

Lisa Levin

White spots on the leaves of cordgrass (above) are hungry scale insects that thrive in the absence of predatory beetles. These scales are native to the salt marsh, but their populations rarely "explode" in natural marshes. An abundance of native predatory beetles (left) may be the key to controlling scale insect outbreaks.

The marsh is not simple, and its control mechanisms are not obvious. Observations of species distributions over an intertidal elevation gradient



Jack Cook/WHOI Graphics

Once thought to be a simple task of growing plants at the correct intertidal elevation, the restoration of cordgrass ecosystems that can attract and sustain the endangered light-footed clapper rail is now recognized as a very complex undertaking. This conceptual model shows only a few of the known "players" in this complicated ecosystem.

do not reveal the complex interactions among soil nutrients, cordgrass, clapper rails, crabs, scale insects, and beetles. What we know about these intricacies has been gleaned from years of study, observation of system responses to extreme events, and attempts to construct wetlands from dredge spoils. It is far too early to assume that we fully understand how the cordgrass marsh functions. When we can rebuild one that attracts and sustains clapper rails, we might claim some success. In the meantime, there is much to be learned about the middle and upper marsh communities, the transition to upland habitats, the coastal dunes, the intertidal flats, and the channels.

Management Issues

Southern California's coastal wetlands share many of the same management issues with coastal wetlands everywhere. They occur at the mouths of rivers, where urban and agricultural land uses compete for their strategic landscape position. They are sinks for all manner of activities and all materials that are discharged within their watersheds. In addition, they are subject to the whims of a variable sea level.

Global climate changes constantly, and sea levels have fallen and risen as ice ages have advanced and retreated over the millennia. Such changes have been gradual, and wetlands have migrated up- and downslope, exposing or inundating habitats. Human-induced increases in global temperatures brought about by the release of "greenhouse gases" are likely to cause unprecedented future sea-level changes. As global temperatures increase, the ocean temperature will have a delayed response, resulting in water expansion and the melting of polar ice caps and glaciers. Although predictions vary, it is generally accepted that sea

levels will rise an average of 0.3 meters over the next 60 years. In some places—where the coast is sinking because of land subsidence—the effective sea-level rise may be even higher. This rapid increase in sea level will cause many coastal wetlands to drown unless marsh vegetation has the opportunity to "migrate" upslope. Unfortunately, most coastal wetlands in southern California are boxed in by development and incompatible land uses, or by naturally steep topography. In the few cases where wetlands may still be uninterrupted by development or roads, upslope soil types may not have the appropriate characteristics for wetland vegetation to propagate or thrive. In addition, many of the animals dependent on southern California salt marshes may not have dispersal mechanisms that would allow them to move to another marsh if their resident marsh disappears. The light-footed clapper rail, listed as federally endangered, and Belding's Savannah sparrow (*Passerculus sandwichensis beldingi*), on the California endangered list, may be examples of poor dispersers.

In addition to sea-level rise, global climate-change models predict changes in air temperature, precipitation, and evaporation rates in this region that would also affect coastal wetlands. If winter rainfall increases as predicted in southern California, freshwater inflows may increase and thus accelerate sedimentation and accretion rates in the marsh. In this case the impacts of sea-level change may be offset only if marsh-surface buildup keeps pace with rising water levels. Changes in inundation and salinity balances will certainly affect the zonation of salt-marsh vegetation. It is difficult, however, to predict changes to wetlands caused by global warming and sea-level rise when we barely understand how just one of our coastal habitats functions.

© Juliette Murguia

Belding's Savannah sparrow (Passerculus sandwichensis beldingi), *on the California endangered list, may be an example of a "poor disperser."*

California has lost 91 percent of its wetland area, and the remaining coastal wetlands have experienced significant fragmentation over the past 50 years. As development of our coastlines continues, the few remaining salt marshes become smaller in area, less connected to each other and surrounding natural habitats, and lose their functional capabilities and resilience. These changes are what we refer to as cumulative impacts—as alterations continue, natural ecosystems are less able to function. For example, many animals are area-sensitive and cannot effectively maintain viable populations in small habitat patches. As local populations slowly decline, the animals may disperse to appropriate nearby habitats. However, if dispersal is limited by the biology of these species, by hostile surrounding environments, or by the lack of suitable habitats, local extinctions will occur. Another problem that animals face when habitats are fragmented is

increased mortality. The necessary high-tide refuges (resting and hiding places during the highest water levels) for clapper rails are limited in urban areas where there are no buffers surrounding their habitat. Clapper rails have been observed on roads and in people's yards during periods of flooding. Rails may be killed by domestic predators (cats and dogs), hit by cars, or poisoned by contaminants. The impact of this exposure to lethal environments is becoming apparent as rail populations continue to decline. What approaches can we take to predict the vulnerability of wetland habitats, and what policies follow from those predictions?

What approaches can we take to predict the vulnerability of wetland habitats, and what policies follow from those predictions?

Better Ways to Solve Problems

Sound wetland management is a good idea no matter what region is of concern. It is especially important where only a small portion of the native resource remains. In California, we have the highest rate of wetland loss in the nation—only 9 percent of our historic wetlands remain. Nationwide, the average is 53 percent. We can never know all that we have lost. We do know that many species have declined, that some have become endangered with extinction, that fisheries have declined, and that open space is at a premium. And we know that losses will continue, even if there is a strong policy or mandate for "no net loss." "Net loss" to most decision-makers and developers means trade-offs: Old wetlands can be dredged or filled for the sake of "progress" by building new wetlands somewhere out of the way as compensation. But we've already indicated that the art and technology of wetland replacement cannot claim success. What, then, should be the management approach?

We can identify several scenarios which are not mutually exclusive:

- full protection of all remaining wetlands and restoration of a significant portion of what has been lost;
- establishment of mitigation banks, with damage to historic wetlands allowed only after the new wetlands have demonstrated their functional equivalency with natural wetlands;
- ranking of wetlands, with full protection for the most critical types and compensatory mitigation for all others that would be damaged; and
- use of mitigation ratios on the order of 10:1 (tenfold replacement for each acre lost) with adaptive management approaches to insure that the process of restoration/construction will gradually improve.

None of these approaches is even closely approximated by current practices. The typical scenario includes at least some of the following elements. A developer or agency identifies a "need" to destroy all or part of a wetland. A cursory examination of the wetland determines that little habitat value is likely to be lost in the area of impact. Alternative sites outside the wetland are listed but dismissed as not practicable (usually because it would cost more to build elsewhere). A mitigation plan is devised to reduce impacts, such as making another part of the wetland wetter or replanting disturbed areas of the wetland. (The mitigation procedure is a little more complicated if endangered species or pristine systems are involved, but damage is still possible.) With resource agency input, a mitigation ratio of anywhere from 1:1 to 4:1 is assigned, and an attractive schematic for the wetland restoration is devised. Public reviews provide opportunities for highly paid consultants to extol the

virtues of the mitigation plan. Environmental volunteers protest, but their voice is a negative one, and decision makers vote for "progress." Then the project proceeds; several mistakes are made; unforeseen problems develop, making the impacts greater than anticipated. Often, the mitigation project is delayed, if it is implemented at all. If constructed, the wetland fails to achieve its promised objectives. The end result is that habitat is irreversibly lost, and the mitigation project fails to provide habitat that is functionally equivalent to historic wetlands.

There must be a better way. We suggest the following:

- a regional plan for wetland preservation and restoration (set permanent limits on damages);
- long-term plans that consider future alterations due to climate change and cumulative impacts;
- clear goals for maintenance of biodiversity;
- mandatory inclusion of technical advisory panels for major decisions regarding wetland destruction;
- up-front mitigation, with 10 or more years to demonstrate "success" prior to project approval;
- mitigation ratios on the order of tenfold replacement for every acre destroyed, unless it can be demonstrated that lesser ratios are effective in supporting sensitive species; and
- wetland restoration for its own sake, as proposed by the National Academy of Sciences National Research Council, which recommends restoration of 10 million acres of wetland by 2010.

Strong measures are needed to protect remaining coastal wetland habitats.

Mitigation is Not a Panacea

Salt marshes are complex ecosystems. In southern California, we know the most about the lower cordgrass marsh that supports the light-footed clapper rail, an endangered resident bird. Yet attempts to reconstruct habitat for this bird demonstrate that we don't fully understand the marsh. We know that nitrogen and reduced soil salinity help make plants grow tall, that scale insects don't attack the plants where the cordgrass is tall enough to support predatory beetles, and that tall vegetation makes good nesting habitat. However, we don't know how to supply just the right amount of nitrogen or to control salinity so that other problems don't develop.

Since human population and development pressures are intense in southern California, strong measures are needed to protect remaining coastal wetland habitats. Mitigation is not a panacea—plans and good intentions are not sufficient to compensate for damage to habitat remnants in a region where 90 percent of the wetland area has already been destroyed. Decision makers must recognize that biodiversity is already at risk; they must "just say no" to further damage until scientists have worked out the techniques for creating fully functional wetlands, and until these "demonstration wetlands" have been successful in maintaining biodiversity through floods, droughts, inlet closures, and other natural environmental extremes.

Joy Zedler grew up on a midwestern farm, where she began playing in the mud at an early age. Farm life taught her the necessity of conserving and restoring resources and an attitude that broken things must be fixed, not discarded. Perhaps this is what

attracted her to the disturbed wetlands of central Wisconsin, while a graduate student at the University of Wisconsin at Madison, and drew her to the highly modified coastal wetlands of southern California, while a professor at San Diego State University. Zedler now directs SDSU's Pacific Estuarine Research Laboratory, which specializes in research to improve coastal wetland restoration efforts.

Abby Powell is a Research Ecologist with the US Fish & Wildlife Service National Wetlands Research Center. She completed her undergraduate work at Cornell University in New York, headed to California for her master's degree at San Diego State University, and finally traveled to the midwest where she received her Ph.D. at the University of Minnesota. Her experience with the Atlantic, Pacific, and Great Lakes "oceans" has given her a unique perspective on coastal wetland birds. The conservation problems are the same, although the salt content and species differ.

Our Coastal Seas

EMECS '93

ENVIRONMENTAL MANAGEMENT OF ENCLOSED COASTAL SEAS

EMECS 93 is hosted by the State of Maryland and the University of Maryland, with support from the National Oceanic and Atmospheric Administration (USA), the Governors' and Mayors' Conference for the Protection of the Seto Inland Sea (Japan), and other national and international organizations.

Come join us on the shores of the Chesapeake Bay, on November 10-14 in Baltimore, Maryland, for an engaging international conference where participants will debate issues surrounding the effective management of coastal seas.

EMECS 93, which follows the first EMECS conference held in Kobe, Japan in 1990, will investigate the relationship between science, governance and citizen activism. A key theme will be a "sense of place"—how law makers, managers and users can learn to value coastal seas not only as economically valuable natural resources, but as special places, worthy of our protection and care.

For information about EMECS 93, contact:

Secretariat, EMECS 93
Helene Tenner, Conference Director
Tawes State Office Building, 580 Taylor Avenue
Annapolis, Maryland 21401
Phone (410) 974-5047; Fax (410) 974-3158

Estuaries

Where the River Meets the Sea

William C. Boicourt

As the world's population has grown and moved toward the sea, the oceanic effects of this progression have been felt first and most acutely in the estuary. Perhaps this should come as no surprise, for the estuary is where the river, with all its waterborne materials draining off the altered landscape, meets the sea. But there is more than proximity at work here. The estuary is nearly a world unto itself, buffered from a strong marine influence by a controlled communication with the ocean, and protected by enclosing coastal boundaries. Within this domain, the estuary's unique water motion retains and recycles nutrients essential to living organisms, inducing the richest productivity per square kilometer on the earth's surface. Labeled the "protein factory" by writer H.L. Mencken, an estuary such as Chesapeake Bay is made bountiful through the workings of physical, chemical, and biological engines in complex and sometimes mysterious balance. We are learning that these balances can be very delicate, and that humans can tilt and dramatically shift the outcome,

© Rick Maloof

Hundreds of rivers, creeks, bays, and sounds merge into Chesapeake Bay, the largest estuary in the US. Wicomico River, located on the Eastern Shore, is one of the larger of these waterways.

usually to their own detriment. We are also learning that the estuary forms only a fragile line of defense for the coastal ocean.

The gradual rise in sea level that created estuaries from ancient river valleys, glaciated grooves in the landscape, or faults in the earth's crust also produced natural harbors. These were fortuitously situated where maritime commerce could connect to the hinterlands via river highways. Cities grew, creating "urban estuaries" threatened not only by unnatural amounts of nutrients, sediments, and toxic materials drained from the watershed, but also by the concentration of human activity on the edge of major fish and waterfowl habitats. These estuarine habitats support both native and transient populations. Because their shallow marshes and seagrass beds serve as spawning grounds and nurseries for mobile fish as well as havens for migrating birds, their influence extends far beyond the confines of the local estuary.

Jack Cook/WHOI Graphics

The steep, geologically young US west coast exhibits few estuaries compared to the east coast (see opposite). Puget Sound is an example of a fjord-type estuary, and San Francisco Bay was formed primarily by shifting of the earth's crust.

A quick tour of the coastal US reveals how many of the larger estuaries have become urban. Starting in the northeast, the large estuaries of the Gulf of Maine, such as Penobscot Bay, are relatively rural. Boston Harbor represents both an urban water body and an environmental cause célèbre. It is, however, just barely an estuary. Narragansett Bay, not far to the south, is a genuine estuary flowing in a series of glacial grooves, loosely separated by islands, with the city of Providence located at its head. The rivers that drive Long Island Sound's estuarine circulation discharge along its broad northern flank. At its western end, Long Island Sound is connected to the most urban of estuaries, the Hudson River, via the East River. The Hudson River and most of the larger estuaries to the south are river valleys drowned by the rise in sea level that followed the last ice age.

From Delaware Bay south, the river valleys were cut from low-lying, coastal-plain sediments. Delaware Bay seems placidly nonurban in its lower reaches, where it opens like the bell of a trumpet toward the sea. Extensive salt marshes border the broadening estuary. Immediately upstream, the Delaware River connects the Bay to Wilmington, Philadelphia, and Trenton. In Chesapeake Bay, the largest estuary in the coastal US, there are locales where the view in all directions is nearly as unspoiled as in the days when Captain John Smith first set eyes on these waters. But the bay and its tributaries reach to Baltimore, Washington, Norfolk, and nearly to Richmond. The bay is so large that it is not just one estuary, but a 300-kilometer-long backbone connecting a series of tributaries such as the Potomac, Rappahannock, York, and James rivers, each robust estuaries in their own right. South of Chesapeake Bay, the broad North Carolina sounds and the estuaries and tidal marshes of the South Atlantic Bight are comparatively nonurban. The estuaries of Wilmington (North Carolina), Charleston (South Carolina), Savannah (Georgia), and Jacksonville (Florida) are modest exceptions. On the Gulf Coast, long stretches of shallow, barrier-island lagoons are punctuated by truly

urban estuaries, such as Tampa Bay, Mobile Bay, the lower Mississippi River, and Galveston Bay (connected to Houston via the Ship Channel).

On the West Coast, the steep, geologically young, California coastline has precluded the development of estuaries. The major exception is a notable one, both for its preeminent status as an urban estuary, and for its manner of creation. San Francisco Bay, crossed by the San Andreas fault (which parallels nearby Tomales Bay estuary), was formed primarily by movements of the earth's crust. To the north, the estuary of the mighty Columbia River, vigorously stirred by strong tides, appears nearly wild, despite commercial navigation upstream to Portland. Human control of natural river flow, however, has dramatically altered annual cycles. Our tour of the coastal US ends in a water body that is both urban and a fine example of a fjord-type estuary, Puget Sound. The glaciers that carved the deep channels now connecting Seattle and Tacoma to the sea left a mound of rubble at their feet. Not far seaward from Seattle, this mound acts as a sill, and salt water entering from the ocean must flow over it.

Jack Cook/WHOI Graphics

The many estuaries of the eastern US coast come in a variety of sizes and types. Some locales on the largest estuary, Chesapeake Bay, are still unspoiled.

It is now clear that not just urban estuaries, but also wild and apparently pristine estuaries, face accelerating human stress. In the few locations where this threat is being met with action to restore and preserve the resource, costs to society are proving very dear. For instance, the US Environmental Protection Agency estimates that over $600 million is spent annually toward cleaning up Chesapeake Bay. Developing and maintaining the political will to dedicate these kinds of monies for environmental remediation has not been easy. In the process, the role of science and scientists has at times been central, while at other times, it has seemed peripheral or even irrelevant. Regardless of this history, scientists are now increasingly challenged to identify key environmental problems, help formulate solutions, and provide ongoing guidance to restoration efforts. Billion-dollar decisions often hang in the balance. In the face of this challenge, scientists seldom feel comfortable with the present state of knowledge, nor are they encouraged by the complexity of the system revealed by recent research. Fortunately, in their attack on the multifaceted interrelationships, they are empowered by new tools,

EOSAT/Earth Observation Satellite Co

This natural-color satellite image of Chesapeake Bay is from November 1985, when fall floods carried large amounts of sediment seaward in the tributaries. The land's impact on the estuary is especially dramatic. The dark-brown regions (at right) are wetlands. The Potomac River (second river from the bottom) becomes extremely muddy as it passes by Washington, DC.

not only to observe the estuary, but also to separate, analyze, and recombine the individual processes that make up the working whole.

What is an Estuary?

Before discussing estuaries further, perhaps we should define the term "estuary." Dictionaries are of little help here. They talk of tides, and rivers, and the sea, but the definitions range widely and never converge on unifying characteristics. Scientists have embraced the definition offered by D.W. Pritchard (Professor of Oceanography at Johns Hopkins University and Director of Hopkins' former Chesapeake Bay Institute, and later a professor at State University of New York at Stony Brook): An estuary is a semi-enclosed coastal body of water which has a free connection with the open sea and within which seawater is measurably diluted with fresh water derived from land drainage.

Now this may sound a bit intricate and overly precise, but it is carefully crafted to reflect the fundamental conditions that lead to a unique pattern of estuarine flow. Partial enclosure is necessary to provide a constrained pathway along which fresh water and salt water mix. In a coastal embayment lacking these side boundaries, buoyant river water spills out and spreads broadly over the denser seawater, at the mercy of the winds and forces arising from the earth's rotation. If seawater is not diluted by fresh water, then there is no mixing, and without mixing there are no spatial differences in density to drive the characteristic estuarine circulation.

When these conditions are satisfied, river water entering the estuary moves seaward, floating over heavier salt water entering from the adjacent ocean. As it moves, the fresh water mixes with seawater in the lower layer, and becomes progressively saltier toward the mouth of the estuary. Conversely, seawater moving toward the head of the estuary loses some of its salinity in the process. This interplay of lighter fresh water and heavier salt water seems intuitively easy to comprehend. But there is more. As the fresher water moves seaward in the upper layer, the initial river flow is joined by more and more water moving up from the lower layer. By the time it reaches the mouth of the estuary, the flow discharged by the upper layer to the sea may be six to ten times the flow of the river discharge at the head. In the lower layer, the flow of seawater entering the estuary at its mouth is nearly as strong as the outgoing flow above. How can this be? What drives this dynamic circulation? It almost sounds as if we are getting something for nothing. It turns out that the energy for this amplification comes from the winds and tides. These forces create turbulence, which vigorously mixes fresh water and seawater, thereby creating spatial gradients in water density that drive the two-layer estuarine motion.

As might be suspected from the discussion of influences on estuarine circulation, the global variety of land forms and rivers produces a broad spectrum of estuarine types, with remarkably different realizations of the defining circulation. At one end of the spectrum is the salt-wedge estuary, where wind and tidal mixing are relatively weak, and where the water entering from the sea forms a "wedge" of undiluted salt water under the outflowing fresh water. Salt transfer is primarily one way, from the lower layer to the upper layer. The lower Mississippi River is an example of a salt-wedge estuary. At the other end of the spectrum is the well-mixed estuary, where tidal and wind mixing are sufficiently active to nearly eliminate top-to-bottom differences in salinity. In the middle range of estuarine types is the partially mixed estuary, where wind and tidal mixing transfers salt water and fresh water in both directions, but still allows significant stratification, or vertical changes in salinity. The Chesapeake Bay and most of its tributaries are partially mixed estuaries.

The consequences of this somewhat mysterious estuarine circulation to the plants and animals that inhabit the estuary are manifold. First of all, most of them owe their very existence to this water motion because the flow helps retain nutrients and sustain the remarkable productivity typical of estuaries. Many estuarine species that have weak-swimming life stages rely on horizontal flow to move great distances, from spawning grounds to nurseries within the estuary, or from far reaches of the continental shelf into the estuary. The blue crab *Callinectes sapidus*, for instance, releases its eggs in late spring near the mouth of Chesapeake Bay. All summer, crab larvae drift over the continental shelf, growing from stage to stage. In early fall, some are returned to the estuary, carried into and moved up the estuary by the lower-layer estuarine circulation. The eastern oyster is often found far upstream from its spawning grounds. Oyster larvae, like most planktonic organisms, can't swim very far, but they make the most of their abilities by swimming or sinking, thereby taking advantage of the upstream flow in the lower layer of the estuary.

A variety of circulation patterns occurs in estuaries. In extreme form, the "salt wedge" estuary, water entering from the sea forms a "wedge" of salt water beneath the outflowing fresh water. Wind and tidal mixing are weak, and salt transfer occurs mainly from the lower layer to the upper layer. Where the salt wedge reaches the sediment, there is a "turbidity maximum." Here tidal currents keep sediments suspended, making the water virtually opaque.

Jack Cook/WHOI Graphics

In the upper reaches of many estuaries there is a region called the turbidity maximum, where sediment suspended in the water reduces

clarity to the point where a diver literally cannot see a hand at arm's length. This feature is a result of the estuarine circulation, where fine-grained sediment delivered by the river is retained and resuspended many times by the ebb and flow of tidal currents. Because many toxic substances are attracted to the surfaces of these sediment particles, some fear that such trapping processes created by the two-layer flow might produce local regions with unacceptably high levels of contamination.

Assessing Human Impact on the Estuary

In order to restore and preserve our estuaries, we must be able to detect and evaluate changes wrought by human activity. In the face of accelerating environmental stress, our ability to assess trends in the health of estuarine waters has been woefully inadequate, and almost always retrospective. We are learning that human impacts on the estuary, which should be among the most detectable in all the ocean, do not appear as sudden, obvious jumps in measured signals. They are typically subtle, creeping changes in sometimes unexpected indicators, slowly manifest over many decades.

In the presence of "noise" from the more vigorous short-term variations produced by storms and the seasonal progression, many of these impacts go undetected. For instance, scientists have known that the deeper waters of Chesapeake Bay are regularly depleted in oxygen each summer. A decade ago, some suspected that the intensity and areal extent of this anoxic region was increasing, and that this increase was caused by overstimulation of the food chain by introduction of more and

Chesapeake Bay Foundation

Students aboard Stanley Norman, *a "skipjack," or traditonal Chesapeake Bay sailing workboat, test water quality for the Chesapeake Bay Foundation.*

more nutrients—especially nitrogen and phosphorous—from municipal sewage and water draining off farmlands. But though the historical record of anoxia seemed long (30 years), it proved so noisy and full of gaps that scientists could neither agree on its interpretation, nor unambiguously detect a trend. As a result, more than a decade of further measurement and analysis has been necessary to form a consensus that man has indeed deleteriously altered the balance in this estuary.

Perhaps an equally disturbing trend in Chesapeake Bay has been the wholesale decline of seagrasses, which provide nurturing sanctuaries for juvenile fish and crabs, and food for waterfowl. Because the start of this decline was coincidental with the introduction of agricultural herbicides in the early 1970s, the cause seemed obvious to scientist and layman alike. However, research showed that it was probably not herbicides, but a surfeit of nutrients that provoked destructive algal growth on the surface of seagrasses, robbing them of light necessary for survival.

In San Francisco Bay, the primary problem is less what the river is bringing to the bay than what it is not. Wholesale diversion of the flow from the Sacramento and San Joaquin rivers for municipal and agricultural uses has, over the past century, progressively decreased the amount of fresh water delivered to the bay. This diversion has changed the estuarine circulation within the bay, allowing deeper penetration of salt, and markedly reducing the habitat available for its living resources. In the Columbia River estuary, human control of river flow is also leading to uncertain changes. The grand dams and storage reservoirs that hinder the upstream migration of salmon also greatly alter the seasonal progression of river flow to the estuary.

EOSAT/Earth Observation Satellite Co.

In this brilliant false-color satellite image of San Francisco Bay, bright green denotes healthy vegetation, hot pink shows bare soil areas, and the deep purples indicate areas of urban development.

Unfortunately, these human-induced changes are proving difficult to document, and even more difficult to ascribe to any particular cause. But it is not always the multiplicity of smoking guns that proves most frustrating. Detective work cannot proceed very far without clues, and the trail of clues to environmental change gets cold very quickly. Few monitoring records extend sufficiently far back in time to cover the period of change. Even if changes were clearly understood, linking these changes to effects on fish and waterfowl is often beyond the state of the science. The task of separating the effects of environmental change on fish from great natural year-to-year population variations is further complicated by resource harvest (or overharvest) unpredictability. What is even more worrisome is that it is not a one-way street from an altered environment to effects on fish populations. For instance, some have estimated that there were enough oysters in Chesapeake Bay at the turn of the last century to filter the entire bay water volume through their siphons in less than a day, clarifying the water in the process. With overharvesting and disease bringing the oyster industry to near collapse, this same feat takes almost a year. The resulting turbidity in the water reduces the amount of sunlight penetrating to the depths of the bay, and greatly limits the amount of light available for plants and animals.

Is Science Up to the Challenge?

In the past two decades, scientists have used such classical concepts as the two-layer flow pattern to significantly advance our understanding of the motion of estuarine waters and the interactions among its living organisms. As observational techniques improved, they began to reveal a rich variability and complexity that sometimes appeared at odds with conventional paradigms. A divide-and-conquer approach has been employed during this exploration in an attempt to isolate mechanisms and define their individual contributions to the circulation and to the ecosystem. Important examples are the surprising, sudden changes in flow forced by winds and surges of entering rivers. Subtle residual circulations were discovered, generated by the ebb and flow of tidal currents over an uneven bottom. In larger estuaries, long wavelike oscillations of the water surface, called seiches, akin to water sloshing in a dishpan, were revealed as an important mode of motion (see *Oceanus*, Spring 1993). Many biological and chemical processes, once thought to be steady or slowly varying, were found to change rapidly and over small spatial scales. Although the divide-and-conquer approach has served us well in shedding light into some of the dark corners of estuarine processes, the revealed complexity has been daunting. As more and more intricate detail is discovered in the myriad components of the system, the task of combining these individual descriptions into a working, interconnected whole seems increasingly difficult. In the face of these complexities, it is all too easy to view estuaries as chaotic, hopelessly unpredictable, and ultimately unmanageable systems. Perhaps worst of all, this view only strengthens the opinion of some who feel that estuarine scientists cannot see the forest for the trees, but see each estuary as unique unto itself, specific to the local situation and sharing few processes in common with other estuaries.

Restoration and preservation of coastal-ocean water bodies is clearly not solely a scientific issue.

Fortunately, this extreme view, though not altogether unfair, is changing. Scientists, armed with the knowledge gained from focusing on the trees, are beginning to look beyond their own estuaries, to form underlying principles, and to place order in this perceived chaos. This process has been greatly aided by some new weapons, such as acoustic current measurement techniques, remote sensing from satellites, and laboratory simulations of the larval transport of bottom-dwelling organisms. Perhaps the most important development has been the maturing of computer modeling techniques, for these models' ability to combine the multiplicity of individual mechanisms into an accurate description of the entire system is crucial for the support of efforts to restore and preserve our estuaries.

Restoration and preservation of coastal-ocean water bodies is clearly not solely a scientific issue. By the same token, neither is the translation of scientific results into public action solely the province of managers or politicians. Although the communication among these groups has not traditionally been easy, there are some encouraging developments in such urban estuaries as Chesapeake Bay and San Francisco Bay, where the urgency for action is very clear.

The demonstrated success of a few scientific efforts in identifying problems and potential solutions has fostered a sense that scientists care about the application of their results to fulfill societal needs. Scientists, in

turn, are beginning to appreciate the workings of managers, politicians, and public advocacy groups to educate and convince the public that action, sometimes expensive action, is required. Finally, both scientists and managers are developing an unaccustomed, but necessary, longer-term perspective on environmental changes in the estuary, which usually span many decades. Evidence for this movement is the cooperation shown in carrying out long-term monitoring of estuarine processes. In Chesapeake Bay, for instance, two complementary monitoring programs are under way, including shipboard surveys and an observing system of sensor buoys and tide-level recorders reporting in real time via radio telemetry. Although the motivation and goals of these efforts are clear, the high costs of maintaining quality measurements and the need to continue them far into the indefinite future require strong support from the community. Scientists, managers, and environmental advocacy groups have worked together to inform the public of the state of the bay, and the necessary action to restore and preserve the resources. In turn, this awareness has been translated through the political realm into support for the monitoring programs. Such partnerships are essential if there is any hope of controlling the environmental consequences of the increased urbanization of our estuaries.

The high costs of maintaining quality measurements and the need to continue them into the indefinite future require strong community support.

William C. Boicourt is a physical oceanographer at the Horn Point Environmental Laboratory of the University of Maryland's Center for Environmental and Estuarine Studies. He was raised in western Massachusetts, spending summer vacations on Cape Cod, near a large oceanographic institution (from which he later received the B.H. Ketchum Award). For graduate work, he abandoned the rocky coasts and clear waters of New England for the murky waters and salt marshes of Chesapeake Bay. His primary research interests are estuarine and continental shelf circulation, and the interactions between these two water bodies.

Nutrients and Coastal Waters

Too Much of a Good Thing?

Scott W. Nixon

We have to think about the issue of nutrient inputs differently than we think about almost all other pollutants or contaminants.

Some years ago, I received an invitation from the US Fish and Wildlife Service to address a scientific meeting in New Orleans about the importance of maintaining freshwater flows into estuaries and coastal lagoons. My specific task was to point out that rivers and streams bring nutrients (nitrogen and phosphorus) into estuaries, and thus make them productive. The Fish and Wildlife Service was trying to convince the US Army Corps of Engineers, among others, not to build so many dams and freshwater diversion projects. I accepted their invitation.

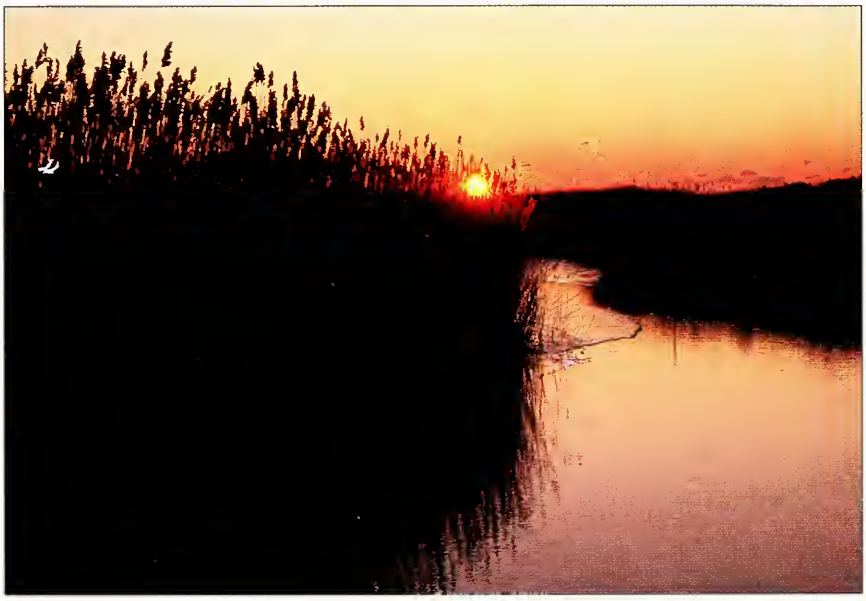
Three days later, another invitation arrived. This one came from the organizers of a workshop sponsored by the National Science Foundation. They were interested in working with farmers and the agricultural chemicals industry to reduce nonpoint-source pollution in estuaries. The term "nonpoint source" is used loosely to mean pollution that doesn't enter from a sewage treatment plant or an industrial dishcharge pipe. Rainfall running off a field is an excellent example of a diffuse (or nonpoint) source of pollution. My task was to point out the serious problems that nutrients from fertilizers can cause if they get into estuaries and coastal waters. I accepted their invitation, too.

I still remember the week of the two invitations for several reasons. First, it was a surprising burst of popularity—I seldom receive two invitations of *any* kind in one week. Second, by agreeing to speak on both sides of the same issue, I felt embarrassingly like the typical academic scientist in the cartoons. We've all heard the joke about the corporate executive who only hired one-armed scientists so they couldn't say, "on the one hand...but on the other hand...." Third, the obvious conflict in the invitations made me realize that we have to think about the issue of nutrient inputs differently than we think about almost all other pollutants or contaminants. For example, it is hard to imagine anyone giving a talk on the importance of maintaining or increasing the discharge of petroleum hydrocarbons to estuaries. We may argue about how much copper is required to cause a measurable reduction in

estuarine productivity or biodiversity, but there is virtually no question that we should discharge as little copper as economically and technologically possible. The questions surrounding nutrients are more difficult.

On the One Hand

For about 100 years we have recognized that the supply of inorganic nitrogen and phosphorus is an important factor regulating the productivity of the sea. Across a broad scale, it is now possible to see a rough quantitative relationship between the rate of nutrient supply and the annual primary production and average standing crop of phytoplankton. If a logarithmic scale is used to capture the large ranges observed, the data will fall along a straight line, but on a regular or arithmetic scale, the plot is hyperbolic. Productivity and chlorophyll first rise rapidly with



© Prentice K. Stout

The author's research indicates that nitrogen and phosphorus inputs to Narragansett Bay, Rhode Island, increased dramatically in the 30 years from 1880 to 1910, and only modestly since then.

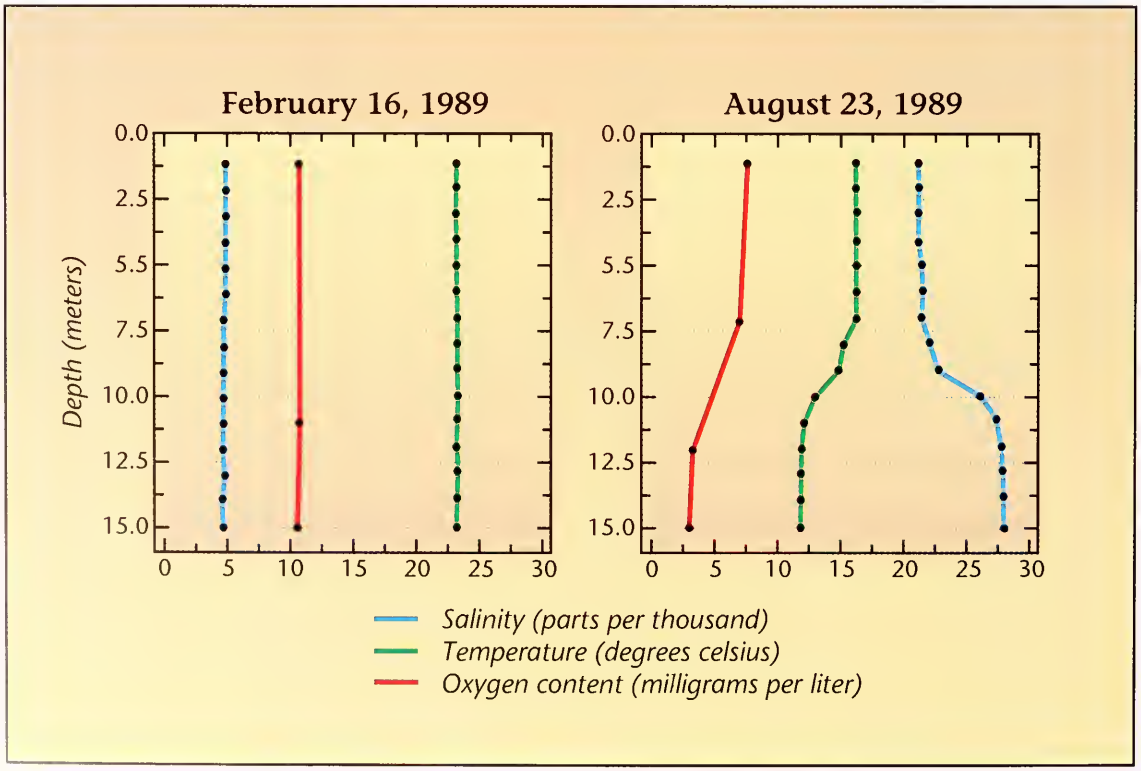
increasing nitrogen input, then level off or rise much more slowly at higher rates of input. This is the familiar limiting-factor curve that illustrates the law of diminishing returns. We are accustomed to seeing similar plots for algal cultures grown with different rates of nutrient supply, or for yields of crops with different amounts of fertilizer applied. Of course, other factors in addition to nutrient supply influence productivity and chlorophyll, and it is difficult to estimate nutrient fluxes, primary production, or mean chlorophyll concentrations for large areas. For all of these reasons, it is not surprising that there is more scatter in this relationship than we see in controlled laboratory cultures or field plots. The substance of the relationship, however, confirms that higher nutrient inputs, at least up to a point, are associated with increasing productivity. Since it is also possible across a very broad scale to relate primary production to the yield of fish and shellfish from marine systems, we can link nutrient inputs in a quantitative way with increased secondary production.

On the Other Hand

If nutrients added to the sea do the same general things they do on land—increase the production and standing crop of plants and the yield of animals—why is there so much concern about nutrient inputs to estuaries, lagoons, and other coastal ecosystems? In its 1990 *Report to Congress on the National Water Quality Inventory*, the Environmental Protection Agency (EPA) ranked "nutrients" as the major cause of impaired estuaries in the US. The National Oceanic and Atmospheric Administration (NOAA) and the EPA jointly produced a national strategic assessment of the susceptibility of US estuaries to nutrient discharges, and they are now involved in a national assessment of the state of nutrient impact in our coastal waters. *AMBIO*, the journal of the Swedish Academy of Sciences, recently devoted a special issue to nutrient impacts in the Baltic Sea area. A 1990 report from the United Nations Environmental Programme on *The State of the Marine Environment* predicted that increased nutrient discharges from the growing human population will create a worldwide problem in the next 20 to 30 years if corrective measures are not taken, and the Danish Environmental Protection Agency is sponsoring an international scientific meeting on coastal marine nutrient enrichment in the fall of 1993.

Most of the concern over nutrient inputs arises because of a fundamental difference between the environments of terrestrial and marine plants. The land plants we fertilize so eagerly and at such great expense live and die in air containing about 210 grams of oxygen in each cubic meter. The atmosphere above the soil contains a vast, relatively well-mixed reservoir of oxygen to which the plants contribute when they are

When the water column is well-mixed (left), salinity, temperature, and oxygen content remain relatively constant from the surface to the depths. However, if the system becomes stratified, all change (right). This data is from the County of Funen, Denmark, and is further explained in their report Eutrophication of Coastal Waters, *issued by the Department of Technology and Environment.*



Jack Cook/WHOI Graphics

Funen County Council/Biologist Nanna Rask

*Starfish (*Asterias rubens*) in Helnæs Bay, Denmark, seek elevated surfaces in their upward search for oxygenated water.*

photosynthesizing during the day. At night, after photosynthesis has ceased, the plants continue to respire and take up oxygen from the atmosphere. So long as the plants are growing, they produce more oxygen during the day than they consume at night. After the plants die, the animals, fungi, and bacteria that metabolize and decompose the organic plant matter also draw oxygen from the large supply in the atmosphere. But because the air around the animals and decomposing plant material is always being mixed by the wind and other currents, the local oxygen supply remains high.

In contrast to the air, coastal seawater is completely saturated with oxygen when it contains only some 5 to 10 grams per cubic meter. When the water is warm, it holds the least oxygen. This is unfortunate, because plants, animals, and bacteria have higher oxygen consumption rates at warmer temperatures. Even more important, however, is the fact that water is less easily mixed than air. As a result, it is easier to deplete the smaller reservoir of oxygen in local areas. This problem is particularly acute when seawater becomes stratified. In this situation, there is little or no mixing between the surface water and the bottom. As oxygen is depleted in the bottom water, there is no way for it to be mixed up to the surface where it can take up more oxygen from the atmosphere through diffusion.

Stratification occurs in two ways. First, surface water traps most of the heat from the sun and becomes increasingly warmer and lighter than the deeper water. Second, fresh water is lighter than salt water and tends to float at the surface where it enters the sea. Salinity differences promote much stronger stratification than temperature differences. Of course, the sea is not still, and even though it is less turbulent than the air, there are waves and currents acting to mix the surface waters with those below. The degree of stratification in any area varies, depending on the balance between factors that increase the buoyancy of the surface and the energy that is available to mix waters of different densities.

While coastal areas are obviously particularly susceptible to stratification because they receive freshwater runoff from land, they are also the areas in which large amounts of tidal energy are often available for

mixing. As a result, it is possible to find estuaries and other coastal systems with a great range of stratification. Most of Narragansett Bay is relatively well-mixed all year; the deeper areas of Chesapeake Bay are strongly stratified all summer; the Pamlico River estuary is intermittently stratified through much of the year. Many lagoons are connected to the sea only through narrow channels or passes between barrier spits and islands. The narrow passes allow only a small amount of tidal energy into these systems, so they must be mixed largely by the wind. If the lagoon is very shallow and well-oriented with respect to the prevailing winds, the waters may be well-mixed virtually all the time. If instead it has a large freshwater input, deep areas, or only a short fetch, the lagoon may be mixed only by less frequent higher energy winds.

When oxygen levels fall sharply, fish, benthic animals, and other organisms that require oxygen become stressed.

The practical impact of these differences between air and water is that water exhibits a delicate balance between the oxygen consumed in the metabolism of organic matter and the rate at which physical mixing processes can renew the oxygen-depleted bottom water. If the mixing is too slow, oxygen levels in the deeper water will decline. When the oxygen falls below about three grams per cubic meter, the water is called "hypoxic," and fish, benthic animals, and other organisms that require oxygen to respire become increasingly stressed. When all of the oxygen is consumed, only specialized organisms that consume organic matter using sulfate, nitrate, and a few other oxidized compounds instead of free oxygen can survive. When sulfate, rather than oxygen, is being used in respiration, hydrogen sulfide is produced instead of carbon dioxide. Hydrogen sulfide causes the "rotten egg" smell often associated with badly polluted marine areas. Even among two-armed scientists, there is general agreement that this is not a desirable condition. Since increasing the nutrient input will increase the production of organic matter by marine plants, there is great concern that the consumption of this additional material will deplete the oxygen from the bottom waters of a larger and larger area of the coastal environment.

A Note on Hugging Green Plants

Some of my botanist friends have bumper stickers on their cars asking, "Have you hugged a green plant today?" We are supposed to engage in this unusual practice in order to show our appreciation for all the oxygen that plants put into the atmosphere, thus making it possible for us to breathe. This idea is carried forward in arguments for saving rain forests and protecting phytoplankton from such dangers as increased ultraviolet radiation, etc. Unfortunately, the popular notion that more plants mean more oxygen has made it hard for some people to understand why growing more plants with more nutrients may mean less oxygen in coastal waters.

The problem arises because the production of organic matter by plants during photosynthesis (which produces oxygen) and the consumption of organic matter by plants, animals, and microorganisms during respiration (which consumes oxygen) are separated in space and/or time. A simple example is that of a stratified bay, where net plant growth through photosynthesis takes place in the sunlit surface water. During the day, the phytoplankton produce more oxygen than they consume; oxygen concentrations in the surface water become supersaturated, and oxygen

diffuses into the atmosphere. At the same time, dead organic matter, including phytoplankton, zooplankton fecal pellets, etc., sinks through the bottom waters and onto the sediments, where it is respired. There is little or no light, and no photosynthetic production of oxygen. Oxygen concentrations in the bottom water decline. During the night, phytoplankton and other organisms in the surface water continue to respire, and oxygen concentrations there begin to drop. As soon as the water is less than 100 percent saturated, however, oxygen begins to diffuse into the surface

Funen County Council/Head of Section Søren Larsen

A massive sea lettuce bloom occurred in the surface waters of eastern Seden Strand (Denmark) in August 1982. Large plant blooms such as this have strong effects on oxygen levels in the water, from the surface to the bottom.

water from the atmosphere. In the bottom water, respiration continues and, because the water is stratified, the diffusion of oxygen from the surface water into the bottom is much slower than the consumption of oxygen in respiration. Oxygen concentrations continue to decline. It is not hard to see that this situation will soon lead to bottom waters and sediments that are first hypoxic (oxygen deficient), then anoxic (devoid of oxygen). As more plant material is produced in the surface, more oxygen may be added to the atmosphere, but more organic matter will also fall to the bottom, and bottom-water oxygen supplies will be exhausted more rapidly.

Even in unstratified waters it is possible to have a large bloom of plants resulting in a large net production of organic matter and oxygen, followed by a period of net consumption when oxygen concentrations fall significantly. During the bloom, oxygen becomes supersaturated and diffuses into the atmosphere. Organic matter may accumulate over many days of net growth and net oxygen loss to the atmosphere. At some point, conditions become unfavorable for the plants and many die during a short period of time. The large pulse of dead organic matter is quickly respired by animals and bacteria, and oxygen cannot diffuse into the water from the atmosphere fast enough to balance respiration. Unless there is lateral mixing with oxygen-rich water from outside the bloom area, conditions may become hypoxic or even anoxic.

The same separation of production and consumption occurs on land, but the well-mixed reservoir of oxygen in the atmosphere is so large that we do not notice the cycle. However, there used to be a quaint and quite

unnecessary Victorian ritual of removing the house plants from sickrooms at night, lest they compete with the invalid for air. On a longer time scale, most of the oxygen produced by land plants during their growing season is later consumed. Net oxygen production only occurs where and when there is a long-term net accumulation of organic matter as in peat bogs, forest floor litter, or accumulation of detritus in river or stream beds.

Nutrients and Eutrophication

So far I have only focused on the potential for increased nutrient inputs to result in oxygen depletion. This consequence of nutrient enrichment is the best understood, and the consequences of hypoxia and anoxia are straightforward—reduced diversity, fish kills, mass mortality of benthic animals, bad odors, bacterial slimes, etc. There are, however, a variety of other changes that may take place in coastal ecosystems if they are exposed to increasing nutrient enrichment. I have to say *may* take place because the evidence documenting these changes is less compelling or complete than that for oxygen depletion.

"Eutrophication" is a fuzzy term borrowed from our colleagues who work on lakes. They, in turn, borrowed it from medicine, where it meant "healthy."

In a recent series of workshops sponsored by EPA and NOAA, experts from around the country identified what they felt were characteristic features of coastal environments that had been over-enriched with nutrients. Their list included such things as:

- reduced diversity,
- a shift from large to small phytoplankton,
- a shift in the species composition of the phytoplankton from diatoms to flagellates,
- increased incidence of toxic phytoplankton blooms,
- increased incidence of undesirable phytoplankton blooms,
- increased seaweed biomass,
- loss of seagrasses,
- a shift from filter-feeding to deposit-feeding benthos,
- a shift from larger, long-lived benthos to smaller, rapidly growing but shorter-lived species,
- increased disease in fish, crabs, and/or lobsters, and
- increased production of some greenhouse gases.

From this exercise it became obvious that the potential exists for a very complex series of changes to occur in coastal ecosystems exposed to nutrient enrichment. Some of these changes, such as the loss of seagrasses, are much better documented than others, such as the link between nutrients and fish disease.

All of the conditions listed above, plus increases in plant biomass and production, and the reduced oxygen concentrations described earlier, are often cited as symptoms of coastal marine *eutrophication*. This is a somewhat fuzzy term borrowed from our colleagues who work on lakes. They, in turn, borrowed it even earlier from medicine, where eutrophy meant healthy or adequate nutrition or development.

The traditional view in limnology was that lakes became more eutrophic over time as they accumulated nutrient inputs from the watershed. As a lake aged, it accumulated organic matter and sediment, and eventually became a wetland, then dry land. The concept of eutrophication as a part of landscape evolution was later modified to include "cultural eutrophication," the rapid aging of lakes due to human

Funen County Council/Biologist Nanna Rask

Eelgrass beds about 1 meter deep in Helnæs Bay, Denmark, were relatively clear in June 1987 (left). In contrast, those about 1.5 meters deep in the Archipelago of South Funen were covered with filamentious algae in 1990, a symptom of coastal marine eutrophication.

Funen County Council/Biologist Nanna Rask

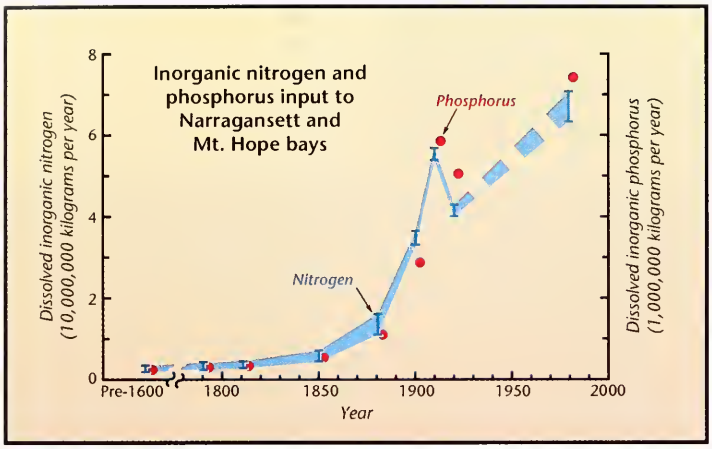
nutrient discharges. By comparing the productivity and chlorophyll levels of lakes receiving different rates of nutrient input, it was possible for limnologists to develop rather specific operational definitions for lakes that were considered oligotrophic (slightly productive), mesotrophic (moderately productive), eutrophic (highly productive), and hypertrophic or dystrophic (so productive that normal lake trophic structure and biogeochemical cycles were severely disturbed).

Until about the last 25 years, there was little concern about eutrophication in coastal marine systems. It was generally believed that rapid flushing rates of estuaries (compared to most lakes), as well as the greater mixing energy (from the tides) would prevent them from responding to nutrient enrichment in the same way that lakes did. That view has clearly changed as more estuarine research has been carried out and as nutrient inputs to many estuaries and lagoons around the world have continued to increase dramatically. As yet, however, we do not have general agreement about reliable quantitative definitions for different degrees of eutrophication in coastal marine ecosystems.

Increasing Inputs

Prior to European settlement, the watershed of Narragansett Bay (the estuary I know best) was about 95 percent forested, and the human population was very small. We know from modern studies that intact, mature forests hold tightly to the nitrogen and phosphorus they contain.

Before the industrial revolution, the concentrations of nutrients in rain must also have been very low. Under these conditions, I have estimated that the combined nutrient inputs from land and atmosphere to Narragansett Bay were about equal to those entering the surface waters of the Sargasso Sea, a well-known area of very low productivity in the open ocean. The impressive fisheries of New England's estuaries that were described by William Wood and other early visitors must have been sustained by the nutrients in coastal ocean waters that were continually brought inshore by the tides and estuarine circulation. My best estimate is that this source was five to ten times larger than inputs from land and atmosphere, at least up to about 1800. Today, the situation is quite different, and about five times more inorganic nitrogen enters Narragansett Bay from the land and atmosphere than from the coastal ocean. How and when did this come about?



Jack Cook/WHOI Graphics

Terrestrial and atmospheric sources are responsible for releasing inorganic nitrogen and phosphorus into Rhode Island's Narragansett and Mt. Hope bays. This graph depicts an estimate of those inputs. The blue band gives a minimum range for the uncertainty of the estimates. The lack of data between about 1930 and 1980 makes it especially difficult to reconstruct inputs during that period.

Human activities have increased nutrient flows to the coast in many ways, including forest clearing, the destruction of riverine swamps and wetlands, the application of large amounts of synthetic fertilizers, the use of large amounts of nitrogen and phosphorus in various industrial processes, the addition of phosphorus to detergents, the production of large populations of livestock, the high–temperature combustion of fossil fuels that has added large amounts of nitrogen to acid rain, and the expansion of human population in coastal areas. The relative importance of these activities obviously varies from place to place, but in older urban, industrial areas like Narragansett Bay, one particular event had a dramatic impact on the fertilization of the estuary.

On Thanksgiving Day 1871, running water was introduced in the city of Providence, Rhode Island, to the accompaniment of a 13-gun salute and the ringing of church bells. Once running water became available, indoor plumbing and flush toilets soon followed. This technology almost immediately required the construction of sewer systems to collect wastewaters and carry them out of the city for discharge into various rivers and the bay.

Public water and sewer systems proliferated rapidly throughout the urban areas of the northeast between about 1870 and 1910. Before this, the disposal of human waste, the major source of nitrogen and phosphorus in the watershed, had involved a relatively dry technology—cesspools and privy vaults. With the introduction of the water-carriage system of waste disposal, however, the intensive fertilization of urban estuaries began. Early sewage-treatment plants reduced the nutrient flow somewhat between about 1900 and the 1920s or 1930s, but many cities failed to maintain the plants or to expand them as population grew. As a result, they became increasingly ineffective. The economic stresses of the Depression and World War II continued the decline.

I have tried to estimate the historical input of nutrients to Narragansett Bay using a complex mix of data on human population, street paving, horse populations, water and sewer systems, calculated atmospheric nutrient deposition, changing land use, analyses of textile-industry nutrient emissions, old chemical analyses of rivers, etc. The surprising result suggests that inputs of nitrogen and phosphorus increased dramatically over just a 30-year period between about 1880 and 1910. The increase since that time has been modest. Unfortunately, there are no data to tell us what the bay was like before nutrient inputs increased so sharply.

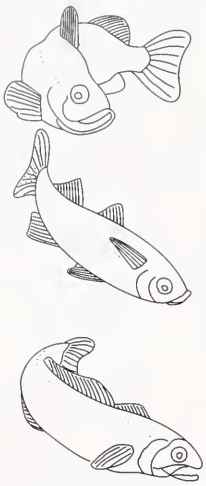
The history of other estuaries may be very different, of course, and many of those along the southeastern and Gulf coasts of the US have experienced rapid population growth only in recent decades. Because shallow coastal lagoons everywhere were less desirable as ports, they were often spared from the urban and industrial development found in larger river-mouth estuaries. Nutrient inputs to those systems have been driven largely by agriculture and, in recent years, by suburban and vacation housing. In rural areas, houses are served by individual on-site sewage disposal systems consisting of septic tanks and leach fields. Unlike the old privies, these systems process large amounts of water as well as human waste, and they contaminate the groundwater with nitrate that eventually reaches coastal ecosystems.

It is almost certain that the world's coastal waters will continue to receive ever-increasing amounts of nitrogen and phosphorus from the growing human population. Because both of these elements are essential in human nutrition, we cannot help releasing them to the environment. The large amount of protein we consume makes us particularly important as emitters of nitrogen. While it has proven practical to remove many metals and organic pollutants from wastewater, only a very few sewage-treatment plants have been able to sustain an effective nitrogen-removal program. Phosphorus removal is more economical, but nitrogen is the nutrient having the greatest impact on the productivity of most of the world's coastal marine waters. The situation is different in lakes, where phosphorus control is an effective strategy to prevent eutrophication.

Many estuaries and bays are already among the most intensively fertilized environments on earth, and we are still far from fully understanding the long-term consequences of further enrichment.

Because nitrogen and phosphorus are essential in human nutrition, we cannot help releasing them to the environment.

Scott W. Nixon is a Professor of Oceanography at the University of Rhode Island and Director of the Rhode Island Sea Grant College Program. Both titles make him uncomfortable, since he is in no position to profess anything about oceanography and his colleagues would laugh if he claimed to direct the diverse Sea Grant research and outreach program. He received his Ph.D. in Botany (another uncomfortable title) from the University of North Carolina at Chapel Hill in 1970 and has spent the past 23 years studying the nutrient dynamics and productivity of estuaries, bays, and shallow lagoons in Rhode Island and other interesting places.



US Fisheries

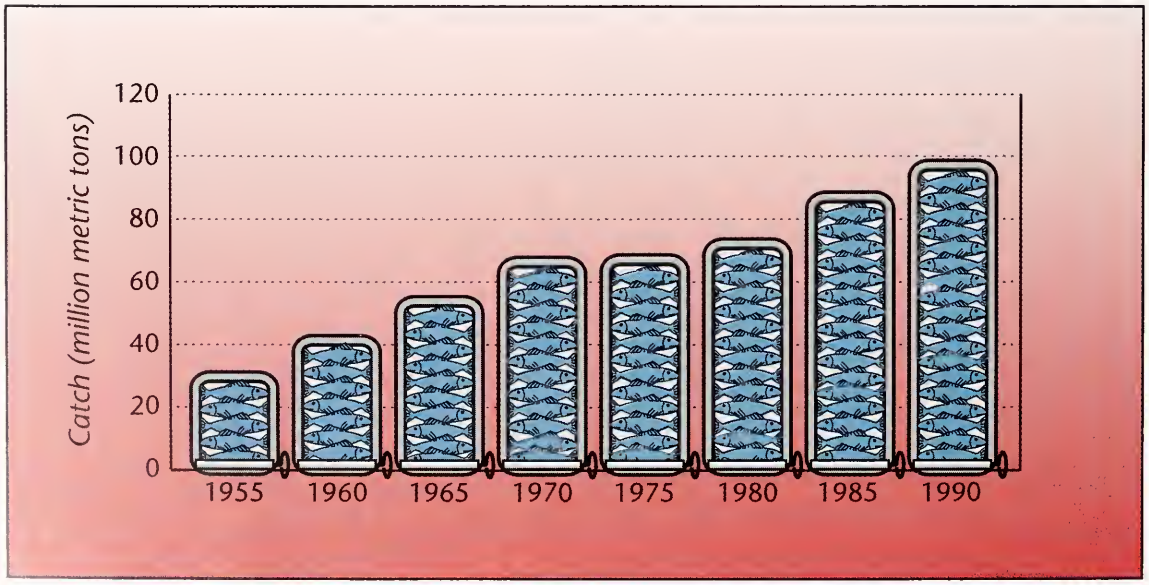
Status, Long-Term Potential Yields, and Stock Management Ideas

Michael P. Sissenwine and Andrew A. Rosenberg

Coastal waters support the world's richest fisheries, with 95 percent of the worldwide catch taken within 200 miles of shore. These fisheries account for more animal protein for human consumption than poultry, lamb, or beef. Fishing is also a valuable form of recreation. The worldwide number of marine recreational anglers is unknown, but there are about 17 million in the US alone.

Today fisheries are beset by problems that threaten the many benefits they provide. Marine fishery resources were once believed to be virtually inexhaustible. It is now clear that these resources are vulnerable to an overabundance of fishing vessels and fishermen, who are catching too many fish.

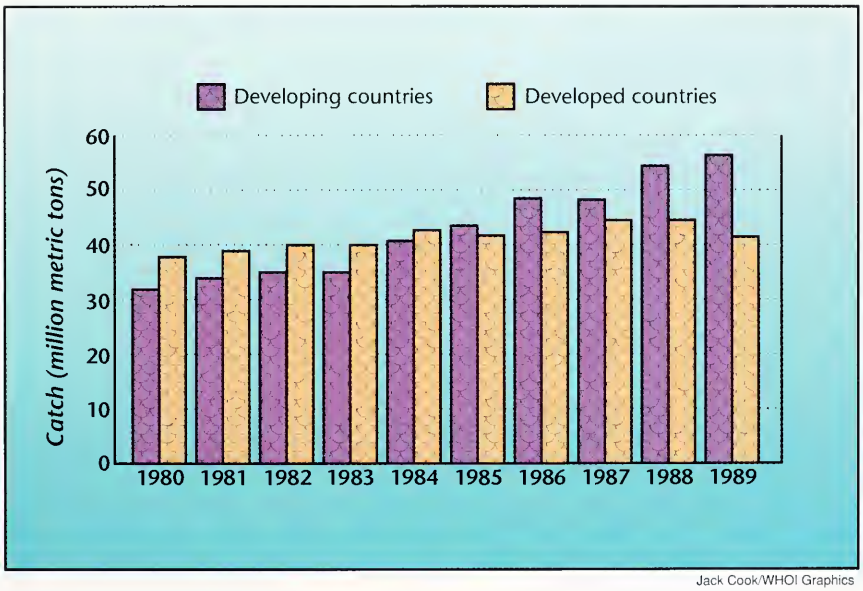
The worldwide fishery catch, including finfish and shellfish, has increased rather steadily for more than three decades. But most experts



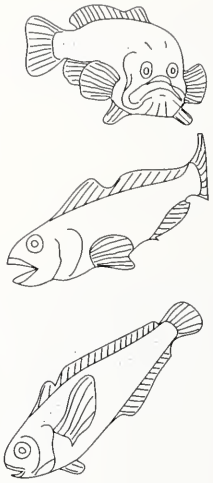
Jack Cook/WHOI Graphics

believe the recent leveling off of catch indicates that fisheries are now fully or overutilized, and producing near the global maximum sustainable yield. Along with the increase in catch, there has been a shift in the catch proportions from developed (wealthier) to developing (poorer) countries: Developing countries now account for more than half the worldwide catch.

Although fisheries worldwide are collectively harvesting the approximate maximum sustainable yield, many individual fisheries are declining or depleted, particularly in the North Atlantic. The United Nations Food and Agriculture Organization describes about one-third of the fisheries it tracks as heavily exploited, overexploited, or depleted. It also estimates that fishing costs exceed revenues by $16 billion annually, or 20 percent—that is, fisheries are losing money. The deficit, which is probably offset by government subsidies, occurs because the harvesting capacity (or number of fishing vessels) exceeds the available fishery resource. This situation is known as overcapitalization, and is an expected consequence of unregulated participation in fisheries (anyone who wants to fish, can). Today most fisheries are overcapitalized. Even when the total catch amount is controlled, the incentive exists for more and bigger vessels to race for the limited amount of fish, until fishing is no longer a wise investment.



Jack Cook/WHOI Graphics



The worldwide fishery catch from 1955 to 1990 (far left) is broken down into amounts taken by developing and developed countries (left).

US Fisheries: An Historical Perspective

Fishing is one of the oldest, if not the oldest, of US industries. The first European visitors to North America were attracted by abundant coastal fishery resources. Fish were important to the Pilgrims in 1620 when they landed on Cape Cod, Massachusetts. In addition to his other accomplishments, Secretary of State Thomas Jefferson reported to the first session of Congress in 1791 "...on the subject of the Fisheries of the United States." And a thriving marine science community was born in 1885 when Spencer Baird established the world's oldest fisheries research laboratory in Woods Hole, Massachusetts.

Throughout most of history, marine fisheries have been essentially unmanaged, with the exception of a few regulations on fishing seasons,

areas, or size limits. It was not until the 1960s, when large factory trawlers from Europe and Asia began fishing off US coasts, that the fishing industry and the public recognized that more regulation, or "fisheries management," was necessary. In 1977, the US extended its jurisdiction over fishery resources from 12 to 200 miles off shore. The law that extended fisheries management, known as the "Magnuson Act" (for Senator Warren Magnuson of Washington state), established eight regional Fishery Management Councils to formulate Fishery Management Plans to be implemented by the Department of Commerce's National Marine Fisheries Service (NMFS). The act's purpose was to end overfishing, which was primarily blamed on foreign vessels, and to encourage US fisheries to expand and replace foreign fisheries. Congress is now considering reauthorization of the act, which expires this year. It is timely to consider the US fisheries status.

NOAA National Marine Fisheries Service/Woods Hole

Surveillance of foreign fishing vessels, such as this Russian trawler, was common around Georges Bank in 1970.

Status of US Fisheries

The most comprehensive source of information on US fisheries is the NMFS publication, *Our Living Oceans*, which considers 236 groups or "stocks"of fish, including about 450 different species. The US shares several of these fishery resources with other fishing countries because fish migrate into and out of US waters. The US also has some vessels that fish on the high seas and/or in other countries' jurisdictions, such as tuna fisheries in the western Pacific.

The total recent average yield, from 1989 to 1991, for fisheries of US interest is about 6.6 million metric tons (mmt) of fish or shellfish. This is about 7 percent of the global catch. The US proportion is about 5.0 mmt, placing the US sixth among fishing nations. In 1991, US commercial landings provided fishermen with $3.9 billion in revenues, which translated to tens of billions of dollars in business for the US economy. In addition, there are about 17 million Americans that participate in recreational marine fishing, producing economic and intangible benefits that contribute to the quality of life in this country.

Whenever possible, *Our Living Oceans* gives an estimate of each stock's Long-Term Potential Yield (LTPY). This is the maximum average yield that could be taken in the long term if a proper balance were struck between fishing level and resource productivity (catching only what is produced, but no more). When this balance is achieved, a stock is considered "fully utilized." If more fishing effort is needed to maintain the LTPY, the stock is considered "underutilized," and if there is more fishing effort than necessary, it is considered "overutilized." In addition, *Our Living Oceans* classifies stocks as "below," "near," or "above" the abundance level that on average produces the long-term potential yield. Stocks may be below or above the LTPY level because of either past or current over- or underutilization, respectively, or as a result of natural variability.

The long-term potential yield from all the fisheries of interest to the US is estimated as 9.5 million metric tons. This is about 40 percent higher than the recent average yield. Groundfish, or fish that live near or on the

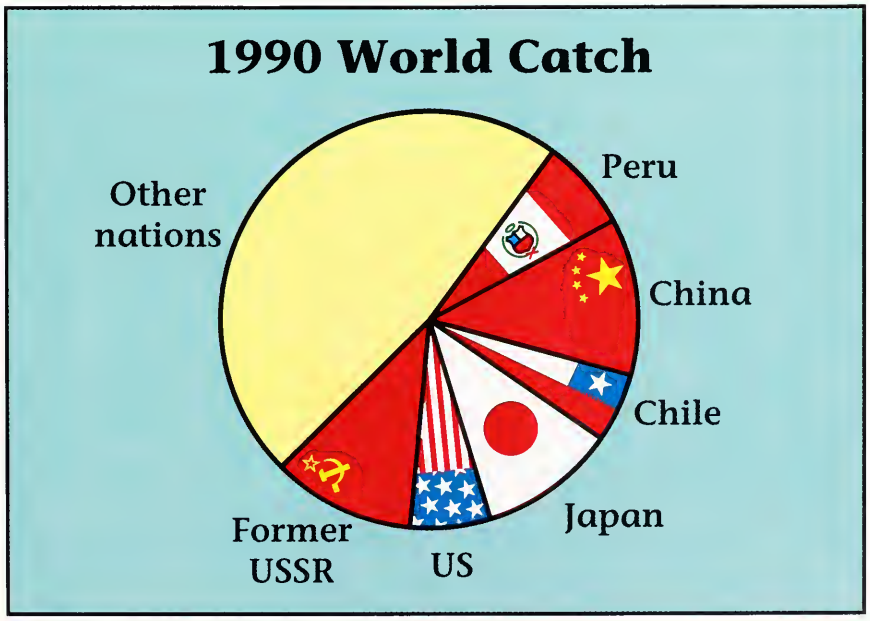
bottom, account for 48 percent of the LTPY, and highly migratory and coastal pelagic (living well off the bottom) species account for 43 percent. The remaining 9 percent is almost equally divided between anadromous (those that spend most of their lives at sea but spawn in rivers) and nearshore fish and shellfish. However, some of the potential yield is shared with neighboring countries and high-seas fishing nations.

The LTPY cannot simply be divided between US and foreign countries. As abundances change, spatial distributions may also change, which affects the relative availability of resources to US fishermen. Proportions may also change as a result of international fishery management agreements. However, if the LTPY is prorated between the US and foreign countries based on the yield's recent proportions, the "prorated US LTPY" would be 7.7 million metric tons, or 81 percent of the total LTPY. Most of the difference is accounted for by Pacific and Atlantic highly migratory species. The prorated US LTPY is about 50 percent higher than the US recent average yield.

By region, the largest long-term potential yield is off Alaska (40 percent), and the smallest is off the West Coast (11 percent). But, the order of potential value by region does not correspond to the order of potential yield. If the current commercial price is applied to the LTPY of each stock (which also includes some recreational catch), the estimated LTPY value is highest for the northeastern US. But there is also a difference when comparisons are made between regions for the value of the prorated US LTPY. In this case, the Alaska region also leads in long-term potential value.

To achieve the long-term potential yield, it is necessary to increase utilization of 12 percent of the stocks, maintain current utilization of 26 percent, and reduce utilization of as many as 28 percent. There is insufficient information to make a judgment for about 34 percent of the stocks. Abundances for 30 percent of the stocks must be allowed to increase to near the LTPY level, and abundances for about 10 percent should be expected to decline toward the LTPY level as they become fully utilized.

Jack Cook/WHOI Graphics



Relative shares of world fisheries catch by the six leading nations and all others in 1990.

For 29 percent of the stocks, abundances are near the LTPY level and should be maintained. But for 31 percent of the stocks, the abundances relative to LTPY are unknown.

By region, the northeastern and southeastern US have the largest percentages of overutilized stocks (45 percent and 33 percent, respectively). The traditional New England groundfish and flounder fishery illustrates the problem of overutilization instigated by foreign vessels, but more recently perpetuated by the US. None of the fish groups off Alaska are considered overutilized, but 20 percent are below the level necessary to produce the LTPY because of either historic overutilization or natural variability. The Alaska groundfish fishery is a good example of the transition of fisheries off the US from foreign to joint venture between US and foreign companies to domestic dominance.

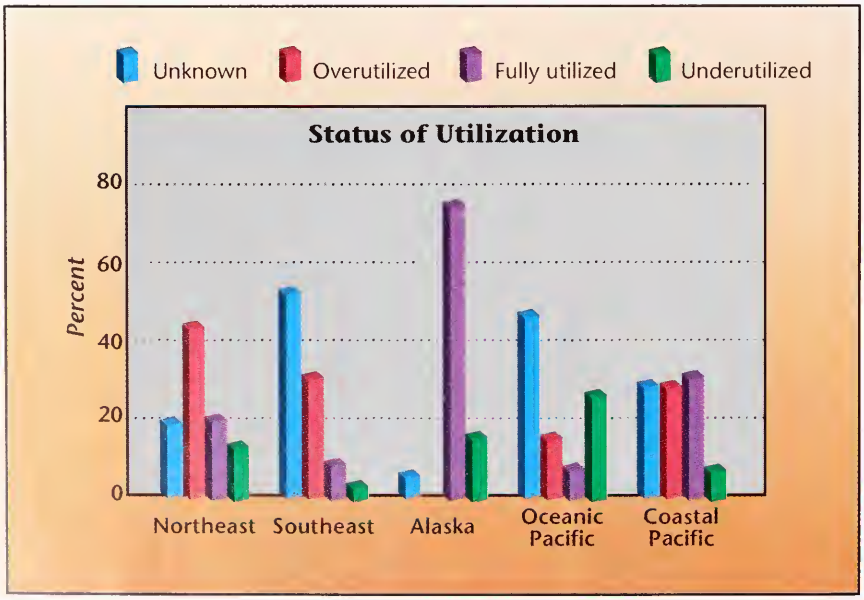
Some Concerns

One of our purposes is to offer a "report card" on fisheries management. But rather than assign a letter grade, we leave readers to draw their own conclusions. One thing is clear: The US can do better.

Of the stocks for which we have sufficient information to judge their status, 43 percent are overutilized. These include some of the nation's most important fishery resources such as: New England groundfish and flounders, Atlantic sea scallops, Atlantic bluefin tuna, Atlantic swordfish, large coastal sharks, Atlantic menhaden, spiny lobster in the southeast, Pacific Ocean perch, North Pacific albacore, and many nearshore oyster, hard clam, and abalone stocks. Even some of the populations that are no longer overutilized are below the abundance level necessary to produce their LTPY, such as rockfish off Alaska and Pacific sardines.

The northeastern and southeastern regions of the US show the largest percentages of overutilized stocks.

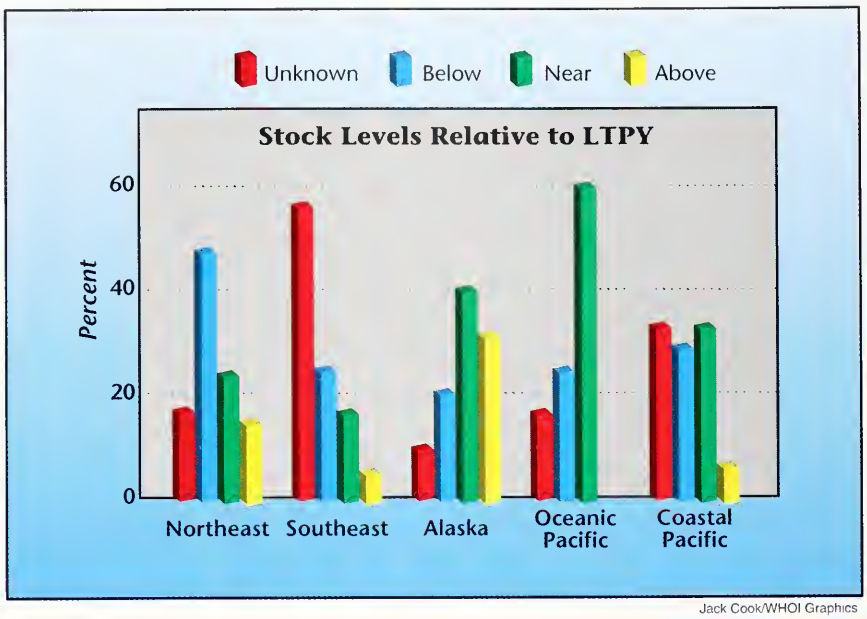
One of the primary reasons the US extended jurisdiction to 200 miles in 1977 was to end overutilization of fishery resources. Recently, National Marine Fisheries Service scientists compared the 1977 fishery resource status (to the extent it could be determined) to the current status. The comparison indicates that overall there has been relatively little change, with improvement in some regions (such as Alaska) and deterioration in others (the southeast).



Jack Cook/WHOI Graphics

Overutilization not only leads to stock depletion; it is also a cause of economic inefficiency, as the cost of catching fish is too high and prices to consumers increase

accordingly. The problems of overutilization and resource depletion are usually accompanied by overcapitalization, which exacerbates economic problems and intensifies pressure to continue overutilization. For example, a recent report on New England groundfish indicates that the resource could produce $350 million more in gross income annually and 14,000 additional jobs. A recent NMFS analysis indicates that the potential increase in net value of US fisheries is about $2.9 billion annually and hundreds of thousands of jobs. These are very crude first approximations, but they indicate the gravity of the situation.



Jack Cook/WHOI Graphics

Abundance level relative to the long-term potential yield (LTPY) level, by region.

One factor that hampers fishery management is insufficient scientific information. For example, the status of 34 percent of the fish stocks is unknown, and for populations where the status is known, the information is imprecise. This means that fisheries managers are either too restrictive and waste benefits in the short term, or they are not restrictive enough and jeopardize long-term benefits. In practice, imprecise information has been used to argue that fish are abundant, so fishing does not need to be restricted. Such arguments have led to many resource collapses.

The Future: Improving the Odds

Recall that the principle law that authorizes management of US marine fisheries, the Magnuson Act, is before Congress for reauthorization this year. It is tempting to blame the Magnuson Act for the problems facing US fisheries, but the issues are far more complex. First, it is important to recognize that the problems confronting US fisheries are common throughout the world. This is not an excuse, but it does imply that a legal framework for fisheries management that is unique to the US is not the primary problem. Of course the Magnuson Act can—and should—be improved, but fundamental issues need to be addressed regardless of how the act changes.

There are numerous examples of uncontrolled growth in fishing fleets until the catching capacity far exceeds the sustainable yield. A fleet will continue to grow until there is no longer an economic incentive for other vessels to join it. At this point, proposals to reduce catch (to conserve the fishery resource) are met with strong opposition, because most vessel owners cannot survive even a short-term catch reduction. Because scientific information on fish stocks is always uncertain, there is

a tendency to make risk-prone decisions with hope that the situation is really better than the science indicates. This cycle of overcapitalization, economically and biologically unhealthy fisheries, and risk-prone decisions, in the face of uncertain scientific information, continues until fish stocks collapse, leaving acute economic and social consequences.

The best way to break this cycle is to control access before overcapitalization occurs. But it is never too late. Controlled access schemes can be designed to prevent overcapitalization from worsening, and to foster incentives for the needed reductions. It is also necessary for fisheries managers to make tough decisions that err toward conservation (risk adverse) rather than mortgaging the future (risk prone). However, unless the scientific bases of these decisions are reasonably precise (in the eyes of decision makers and the affected fishing industry), tough, effective decisions are an unlikely outcome. We believe that many of the problems faced by US fisheries today can be alleviated by employing a strategy that encompasses elements of controlled access, risk-adverse decisions, and an expanded scientific information base for fisheries management.

Fisheries managers must make tough decisions that err toward conservation rather than mortgaging the future.

Acknowledgments: *Our Living Oceans* is the annual report of the US National Marine Fisheries Service on the status of living marine resources, including fish and shellfish, marine mammals, and sea turtles. It was prepared by more than 60 scientists and other staff. Numerous other individuals contributed indirectly. These are the people that deserve credit for most of the information in this article. Copies are available free of charge from the National Marine Fisheries Service, Office of Research and Environmental Information, Room 6314, 1335 East-West Highway, Silver Spring, Maryland 20910.

Michael P. Sissenwine has been the Senior Scientist of the National Marine Fisheries Service (NMFS, headquartered in Silver Spring, Maryland) since 1991. He is responsible for providing scientific oversight for diverse research programs conducted by more than 1,000 NMFS scientists and support staff in 29 laboratories throughout the country. He specializes in population dynamics, renewable-resource management, and fisheries ecology. His involvement in fisheries research has a pragmatic basis rather than a natural attraction. His decision to attend the University of Rhode Island was too late to qualify for financial aid in his first year, but he was recruited into a research assistantship by a faculty member who was ahead of his time in recognizing the value of mathematics in biological and ecological research. Since then, Sissenwine has become fascinated by the relationship between research and policy in fisheries management. In fact, he views fisheries as a mesocosm of many complex scientifically based policy issues.

Andrew A. Rosenberg worked for six years in London as the Deputy Director of the Renewable Resources Assessment Group at Imperial College. His research there included the development and implementation of an assessment and management system for the Falkland Island squid fishery, studies on Antarctic krill, the development of length-based methods of fish stock assessment, analysis of multispecies fisheries in the North, Barents, and Mediterranean seas, and the impact of acid rain on fish stocks in Norwegian lakes. He moved to NMFS in 1990 as the Fishery Management Council liaison for the Northeast Fisheries Science Center, where he took a primary role in transmitting scientific advice to managers. In 1992, he became assistant to the NMFS Senior Scientist on stock assessment issues, conducting reviews, and serving as scientific editor for Our Living Oceans. *His research interests are in stock assessment methodology and fishery management.*

New (Coastal) Directions for Naval Oceanographic Research

THE UNITED STATES NAVY, primarily through the Office of Naval Research (ONR) and its corporate laboratory (Navy Research Laboratory) and sponsored universities, has long been a primary supporter of ocean science and technology. Its interests have led to American world leadership in a number of aspects of oceanography. Thus, the Navy's involvement has been, and continues to be, important to the health and direction of the ocean sciences.

The past two or three years have brought great changes to the US Navy's mission because of the dissolution of the Soviet Union and the challenges presented by conflicts in newly independent states and in developing countries. The new mission was recently enunciated in a white paper entitled "From the Sea: a New Direction for the Naval Service," signed by the Secretary of the Navy, the Chief of Naval Operations, and the Commandant of the Marine Corps. It departs from previous plans by proposing a heavier emphasis on amphibious operations and makes few statements about the traditional Navy mission of ocean-wide sea-lane control. This document has led to a new coastal or littoral emphasis, which affects ocean science research because it assigns new naval importance to understanding the ocean from the surf zone out to the adjacent ocean, and to such strategic regional areas as the Mediterranean.

The impact of the Navy's new emphasis on the ocean science community was discussed at a January 1993 National Research Council Ocean Studies Board meeting with officials representing both research and operational sectors of the Navy. Some of the important new themes discussed include the following:

- ONR is now actively involved in funding marine environmental quality research to provide advanced technologies for improving conditions in harbors and estuaries that may have been affected by naval operational activities, at naval bases or in other areas.
- The high performance of modern weapons and surveillance systems is increasingly dependent on environmental considerations, such as atmospheric visibility. This places a greater stress on weather and ocean prediction and on improved instrumentation to characterize the highly variable littoral region. It is also increasingly important to understand, during the design phase, how systems will be affected by oceanic and atmospheric conditions.
- A wide range of oceanic conditions, such as wave height or bottom conditions, affect the ability of the armed services to conduct amphibious operations. These need to be better understood and predicted on an operational time scale.
- The use of remote sensing to acquire surveillance information and environmental data is crucial to achieving these capabilities. The Navy must be capable of knowing the operational environment in forward areas and be able to forecast this environment for weapon-system performance and operational activities at sea and over the beach.
- Close cooperation between Navy and academic ocean scientists will become increasingly important as funding to Navy laboratories tightens.

Relations between the Navy and the academic community have always been good, and all parties want to maintain the constructive relationship. New definitions of Navy needs imply a different emphasis to the relationship, but should not disturb the healthy underlying partnership.

Ken Brink (Woods Hole Oceanographic Institution) and John Orcutt (Scripps Institution of Oceanography) are both members of the Ocean Studies Board.

Kenneth H. Brink and John A. Orcutt

How Marine Animals Respond to Toxic Chemicals in Coastal Ecosystems

Judith E. McDowell

Contaminants may accumulate in organisms through exposure to contaminated water, food, or sediments.

Two decades ago, articles on coastal pollution were rare in the popular press, except for reports of environmental disasters such as the *Torrey Canyon* oil spill off the coast of Great Britain in 1967. Today, coastal pollution issues are debated daily in the press, with topics ranging from legislation for coastal habitat protection to remediation of local pollution problems. Is coastal pollution more widespread today than 20 years ago, or are we as a society just now beginning to address longstanding problems? Unfortunately, in many instances it is the latter. Many contaminated sites along the US coastline have suffered toxic chemical inputs for decades. How have organisms within these ecosystems been affected by these chemicals?

Natural biogeochemical processes govern the distribution, fate, and effects of contaminants in coastal marine environments, and influence their availability for ingestion or absorption by marine animals. Contaminant accumulation in organisms may occur through exposure to contaminated water, food, or sediments. In the long term, contaminants of biological concern such as metals and organic compounds are associated primarily with particulate matter. Transport of these particulate-bound contaminants within coastal areas usually coincides with sediment transport processes; thus there are numerous examples around the world where coastal sediment deposits reflect waste-disposal histories. For example, current levels of polychlorinated biphenyls (PCBs) in New Bedford Harbor, Massachusetts (US), polycyclic aromatic hydrocarbons (PAHs) in Boston Harbor, Massachusetts (US), and trace metals in Tal Estuary (UK) reflect decades of waste generation and disposal.

For contaminants to affect marine biota and the human consumer and disturb ecological systems, they must first become available to organisms within benthic ecosystems. Types and sources of marine contaminants include metals from industrial discharges, halogenated

hydrocarbons (usually containing chlorine or bromine) from industrial and agricultural discharges, and petroleum hydrocarbons derived from accidental oil spills, municipal discharges, and urban runoff. As toxic chemicals transfer through marine food chains, they may cause specific ecological changes at each trophic level, or they may "bioaccumulate" in commercial resources and thus be transferred to humans. Measurements of impact are largely related to contaminant distribution, and the most serious ecological and human health concerns are limited to localized events.

Bruce Tripp

New Bedford Harbor in Massachusetts is one of the world's urban coastal water bodies where sediment deposits reflect waste-disposal history, in this case especially polychlorinated biphenyls (PCBs) generated in the manufacture of electronic capacitors from the 1950s through the early 1970s.

Ecologically speaking, contamination in the marine environment can cause changes in species distribution and abundance, habitat, energy-flow patterns, and biogeochemical cycles. Marine populations are threatened by species loss (as a result of reproductive or developmental failure), habitat destruction, new or unusual interspecies interactions that affect community structure and function, and decreased ability to recover. The impact of habitat alteration on fishery resources is becoming a prominent ecological concern.

General trends in contaminant distribution in coastal ecosystems have been defined, but critical information on the biological effects of contaminants, specifically on population processes, is lacking. Recent studies of the incidence of tumors and other histopathological disorders in bottom-dwelling fish and shellfish from contaminated coastal areas suggest a possible link between contaminant levels and increased incidence of histopathological conditions. (Histopathology is the study of tissue changes caused by disease.) Besides histopathological damage, sublethal toxic effects of contaminants in marine organisms can impair physiological processes (altering the energy available for growth and reproduction) and other reproductive and developmental processes, including causing direct genetic damage.

Sentinel organisms such as marine bivalve molluscs may be especially sensitive as indicators of ecological condition, as they reflect the bioavailability of a wide range of contaminants as well as the biological consequences of contaminant exposure. Bivalve molluscs have been used extensively during

the past two decades to monitor chemical contamination, and, more recently, to monitor biological effects (see International Mussel Watch, page 62). Exploring the relationships between chemical contaminant levels and biological responses in bivalve molluscs has elucidated the toxic action of specific compounds and groups of compounds. However, our knowledge of cause-and-effect relationships between contaminants and biological consequences is still incomplete for many species.

Organic contaminants such as PAHs and PCBs are called lipophilic or "fat-loving," as they bind to and accumulate in fat tissue, and are highly resistant to degradation in the marine environment. These compounds or their metabolites can accumulate to high levels in animal tissues and interfere with normal metabolic processes that affect growth, development, and reproduction. The bioavailability, bioconcentration, and toxic effects of lipophilic contaminants are related to their pharmacological and toxicological properties. Bivalve molluscs have limited capacity to detoxify organic contaminants, resulting in their uptake and accumulation at high concentrations.

Biological effects associated with bioconcentration of lipophilic contaminants have been attributed to the uptake of specific compounds or their metabolites, rather than the total body burden of hydrocarbons or chlorinated hydrocarbons. Organisms' biological responses to toxic chemicals can be manifested at four levels of biological organization:

- the cell, including biochemical reactions,
- the organism, integrating physiological, biochemical, and behavioral responses,
- the population, including alterations in population dynamics, and
- the community, resulting in community structure and dynamics changes.

For predictive purposes, we must understand responses at each level of organization before any compensatory mechanisms at the population or community levels occur. From the cellular level to the community level, the degree of system complexity, the number of compensatory mechanisms available, and the lag time for measuring responses increase dramatically, thereby increasing the predictive difficulties at each level. For example, chronic exposure to chemical contaminants can result in alterations to a population's reproductive and developmental potential, possibly resulting in changes in population structure and dynamics. It is difficult to ascertain, however, the relationship between organisms' chronic responses to contaminants and large-scale alterations in marine ecosystem function and the sustainable yield of harvestable species. Understanding reproductive and developmental processes provides the critical link between individual organisms' responses to contaminants and population consequences.

For bivalve molluscs, exposure to lipophilic organic contaminants has resulted in impaired physiological mechanisms, histopathological disorders, and reduced reproductive potential. Empirical data suggest there are linkages between 1) histopathological,

Studies of contaminant concentration by the common blue mussel, Mytilus edulis, *are helping scientists understand the contaminants' effects on the animals' reproductive, developmental, and metabolic processes.*

Bruce Tripp

Marine Organism Responses to Chemical Contaminants

	Responses	Effects at the Next Level
Cell	Toxication Metabolic impairment Cellular damage	Toxic metabolites available Disruption in energetics and cellular processes
	Detoxication	Adaptation
Organism	Physiological changes Behavioral changes Susceptibility to disease Reduced reproductive effort Decreased larval viability	Reduced population performance
	Readjustment in rate fuctions Altered immunities	Population regulation and adaptation
Population	Changes in age/size structure, recruitment, mortality, and biomass	Negative impacts on species productivity as well as coexisting species and communities
	Adjustment of reproductive output and other demographic characteristics	Adaptation of population
Community	Changes in species abundance, species distribution, and biomass Altered trophic interactions	Replacement by more-adaptive competitors Reduced secondary production
	Ecosystem adaptation	No change in community structure and function

Bioconcentration may be influenced by many physicochemical properties interacting with one another.

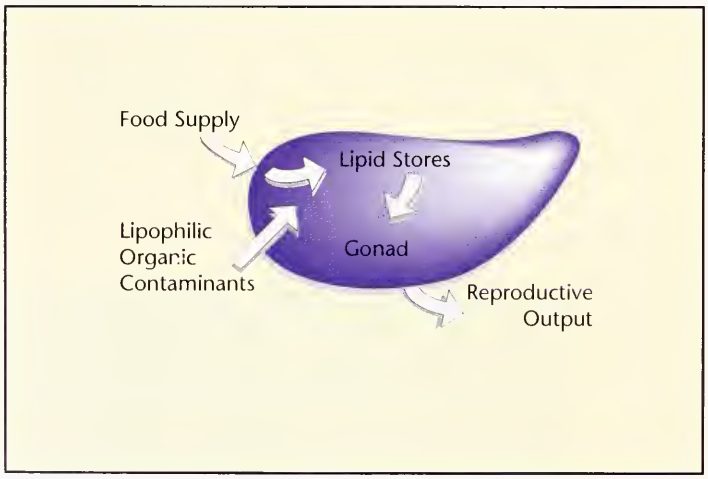
bioenergetic, developmental, and reproductive abnormalities; 2) the physiological and molecular processes involved in contaminant uptake, retention, and loss; and 3) the toxicity or transformation of lipophilic contaminants. Uptake and bioconcentration of organic contaminants by marine bivalves depends on a specific compound's bioavailability, the duration of exposure, and the population's physiological condition. Species differ in their uptake rates due to differences in filtration rate, lipid content, and habitat. Bioavailability and organic contaminant release from bivalve molluscs vary as a function of the contaminant's solubility, concentration, and partitioning between tissues and water. (This is estimated by a method that measures the octanol/water partition coefficients of individual compounds.) Differences in contaminant concentrations among bivalves from different habitats may be the result of physicochemical differences in the availability of sediment-bound contaminants.

Bioconcentration may be influenced by many physicochemical properties interacting with one another, and may be affected by seasonal

differences as well. These factors may include differential uptake and release rates, diet, differential contaminant distribution within the organism, seasonal variability in the organism's lipid content, and changes in metabolism. A seasonal variation in biological responses to contaminant uptake and bioconcentration may depend on specific metabolic processes, such as the storage and mobilization of lipid reserves during reproduction.

How do marine bivalve molluscs adapt to perturbations in their environment? Many marine animals depend on lipid storage for energy reserves during periods of low food supply, and also use those reserves during reproduction. Optimizing lipid storage and mobilizing lipid reserves are therefore critical to marine animals' reproductive and developmental success. Understanding lipid metabolism in marine animals provides insight to some of the biochemical and physiological processes regulating adaptive responses and reproductive success. Factors that alter an organism's ability to accumulate and use lipid reserves may subsequently alter its reproductive potential.

Specific cellular and physiological responses of bivalve molluscs to lipophilic organic contaminants include alterations in cell structure and function; observed alterations include degenerated digestive gland tissue, atrophied digestive tubules, and degenerated reproductive tissues. High levels of lipophilic contaminants have been measured in the common blue mussel (*Mytilus edulis*) exhibiting pathologically altered digestive cells, abnormal lipid distribution, and altered digestive cell architecture. In the *Mytilus edulis* reproductive system, lipophilic organic contaminants caused reduction in the numbers of lipid storage cells (in the mantle) and ripe gametes, as well as increased gamete degeneration.



E. Paul Oberlander/WHOI Graphics

We are investigating basic aspects of lipid metabolism in marine bivalve molluscs, the relationship between lipid accumulation and allocation to reproduction and development, the toxic actions of lipophilic organic contaminants (such as petroleum hydrocarbons, PCBs, and PAHs), and how these contaminants interfere with lipid metabolism. Through laboratory and field investigations we have examined the effects of lipophilic contaminants on the seasonal cycle of lipid accumulation and allocation to gamete production in *Mytilus edulis*. Mussel populations from uncontaminated Cape Cod habitats accumulate lipid reserves during the late fall and early winter, until maximum lipid concentrations are detected during early spring. Lipid accumulation coincides with the onset of gamete development. Once gamete release begins (mid April through early summer), lipid reserves decrease to a minimum value from late summer

Many marine animals depend on lipid storage for energy reserves during periods of low food supply, and also use those reserves during reproduction.

through early fall, and the seasonal cycle begins again.

At sites where mussel populations are exposed to lipophilic organic contaminants such as petroleum hydrocarbons and PCBs, lipid accumulation is reduced, gamete formation is impaired, and reproductive output is diminished. For example, during the spawning period, gametes were resorbed by mussels, rather then released. Resorbing gametes to storage cells may serve as a reallocation of energy reserves, a resistance strategy for surviving the effects of contaminant exposure. Alterations in lipid composition are consistent with other observations of histopathological damage and reduced reproductive effort in bivalve molluscs in response to lipophilic contaminants.

Examining the mechanisms of lipid transport in bivalve molluscs may provide a clue to how contaminants affect reproduction. Understanding these processes may also lead to the development of biomarkers for bivalve molluscs, based on histopathological and biochemical alterations in the reproductive cycle. Our current studies focus on clarifying the mechanisms of lipid movement from storage sites within the animal to its developing gonad, and how such mechanisms are impaired by exposure to lipophilic organic contaminants.

Using sentinel organisms such as bivalve molluscs to monitor chemical contaminants and toxic effects may shed light on the ecological condition of coastal ecosystems and on improvements in water and sediment quality that result from pollution-control measures. These organisms cannot reveal solutions to all problems, but they have become important components of international and regional monitoring programs.

At sites where mussel populations are exposed to lipophilic organic contaminants, reproductive output is diminished.

Judith E. McDowell is a Senior Scientist in the Biology Department at the Woods Hole Oceanographic Institution. She became intrigued by the adaptive capabilities of marine animals when she was six years old and discovered her first tide pools on the coast of New Hampshire. Undeterred from those early career aspirations, she has been investigating the physiological ecology of marine animals and the effects of toxic chemicals on physiological processes in marine animals for the past 25 years.

INTERNATIONAL MUSSEL WATCH

DELIBERATE AND inadvertent discharges of chemical contaminants of environmental concern to the world's coastal ocean will continue for the foreseeable future, as human population increases and human habitation intensifies in the coastal zone worldwide. The goal of the International Mussel Watch Project is to provide an assessment of the status and trends of chemical contaminants in the world's coastal waters. These data are critical for protecting both the health of people who consume seafood and the health of coastal ecosystems.

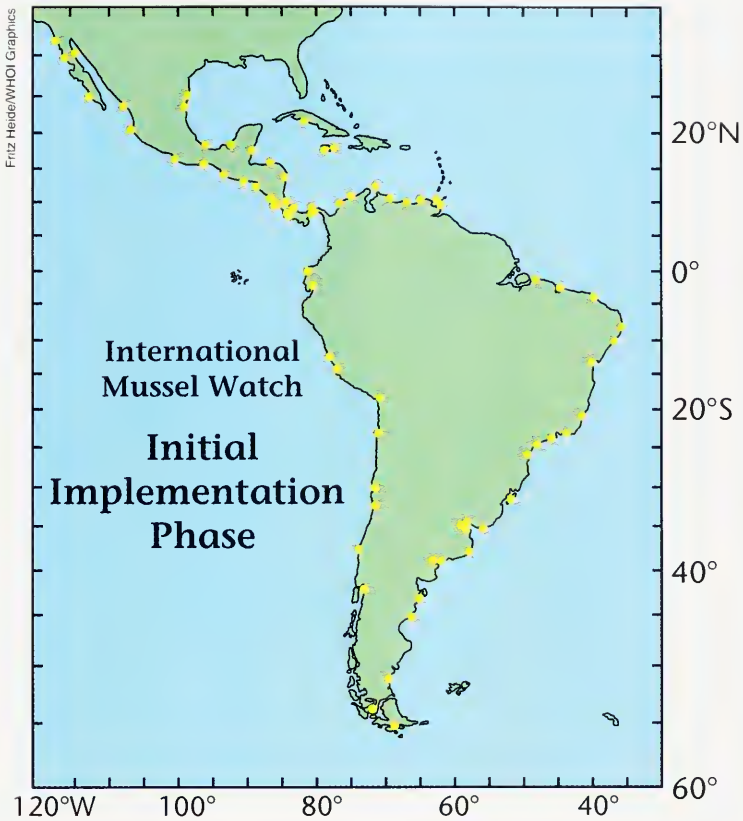
The International Mussel Watch Project is a story of patience and persistence. Its genesis is easily traced to a 1975 *Marine Pollution Bulletin* editorial by Edward Goldberg (Scripps Institution of Oceanography) that called for a global marine monitoring program to serve as a "springboard for action." Goldberg outlined a global-scale monitoring program based on the concept of a sentinel organism capable of detecting trends in concentrations of several important marine contaminants. These included chlorinated pesticides (examples are DDT and lindane), fossil-fuel hydrocarbons, and radionuclides from the nuclear fuel cycle and nuclear weapons testing fallout. Since the 1970s, scientists of several countries have been using common bivalve organisms, such as the blue mussels and oysters, to monitor chemical contaminants in coastal waters.

Bivalve mollusks are good monitors for several reasons that include their ability to bioconcentrate the chemical contaminants of interest and their sedentary nature, which makes them representative of a specific place. Bioconcentration involves the animals absorbing and storing chemicals contained in food or in the water that surrounds them and crosses membranes such as gill surfaces. The result is that coastal water contaminant concentrations of parts per trillion (10^{12}) to parts per billion (10^{9}) (that is, 1 part chemical in a trillion to a billion parts of water), can be magnified hundreds or thousands of times in bivalve tissue. These seemingly minuscule amounts of chemical contaminants in the environment can have detrimental effects on biological and environmental processes, and at higher levels they may pose a threat to public health.

Proof of the underlying concept of this work began with the research of Philip Butler (US Environmental Protection Agency) and colleagues, starting in 1965. They used bivalves to assess the geographic extent and severity of chlorinated pesticide contamination, especially the DDT family of pesticides, in coastal ecosystems of selected US coastal areas. A three-year prototype monitoring program using the "Mussel Watch" approach was initiated in 1975 by Goldberg and colleagues from several institutions. This effort involved chemical analyses of annual collections of bivalve tissue samples from over 100 locations around the US mainland coast. Its success spawned an operational monitoring program initiated in 1984 by the US National Oceanic and Atmospheric Administration (NOAA) as an integral component of the National Status and Trends Program.

National efforts in several other countries, including the UK and France, and multinational efforts such as those of the International Council for the Exploration of the Seas (ICES) in northern Europe, were undertaken during the mid to late 1970s and early 1980s. Scientists involved in these programs were anxious to expand the monitoring effort to include the coastal waters of developing countries, many of which are located in tropical areas of the Southern Hemisphere, and account for substantial portions of the world's coastal area. The need for national or regional programs in these areas was

John W. Farrington and Bruce W. Tripp



Nearly 80 sampling sites are included in the Initial Implementation Phase of the International Mussel Watch Project.

communicated to the UNESCO Intergovernmental Oceanographic Commission (IOC) and the Regional Seas Program of United Nations Environment Programme (UNEP).

As a result of all these efforts, the International Mussel Watch Project was officially launched as a UN-approved program in 1986. Conclusions of several small scientific workshops indicated that the simultaneous implementation of a worldwide field program in all areas of the tropics and Southern Hemisphere was not economically feasible. Therefore, a phased approach was adopted and the Initial Implementation Phase, coordinated by an International Mussel Watch Project Secretariat based in the Coastal Research Center of Woods Hole Oceanographic Institution (WHOI), focused on South America, Central America, and the Caribbean. The project is funded by IOC, UNEP, and US NOAA, supplemented by funds from WHOI Sea Grant, and in-kind contributions from WHOI, the Geochemical and Environmental Research Group at Texas A&M University, and the International Atomic

Energy Agency (IAEA) Marine Environment Laboratory in Monaco, as well as numerous scientists and laboratories in host countries.

A little over 15 years after Goldberg's editorial in *Marine Pollution Bulletin*, members of the International Mussel Watch Committee and representatives of UN programs in the South American–Caribbean region met in Costa Rica to organize the final aspects of the Initial Implementation Phase. During 1991 and 1992, with the assistance of many host country scientists, International Mussel Watch Field Scientific Officer José Sericano (Texas A&M University and the IAEA Marine Environment Laboratory, Monaco) personally collected more than 350 samples from almost 80 sites along the South American, Central American, and Caribbean coastlines.

Several local participating scientists retained portions of the collections for their own work, and samples from all sites were shipped to two central analytical laboratories located at Texas A&M University and at the IAEA laboratory in Monaco. Analyses from the Initial Implementation Phase focused on chlorinated pesticides and PCBs. Analyses of other chemicals of environmental concern may be undertaken in the future using the archived samples.

The initial round of analyses is complete, and an initial data interpretation meeting was recently convened in Brazil at the Institute of Oceanography, University of São Paulo. The draft final report is in preparation and will be distributed for review this summer (1993) to all participating host country scientists. If the enthusiasm of the participating scientists is a guide, then the program has successfully established a network of cooperating scientists who will continue to monitor chemical contamination in the region's coastal waters. This Initial Implementation Phase of International Mussel watch has: 1) generated high-quality data on chlorinated pesticide and PCB concentrations in the Central/South America–Caribbean coastal region, 2) served as a "field test" of a large-scale international marine monitoring program for chemical contaminants, 3) created a western-hemisphere international network of coastal environmental scientists, 4) provided a forum for training and discussing analytical results, and 5) created the institutional structure for a global-scale coastal monitoring program. Continued support for the participating scientists and more effective integration of the data from the monitoring program into policy and management for wise use of the region's coastal resources are the next challenges. We expect that these challenges will be supported by the international community, because International Mussel Watch has been recognized as a legitimate tool for coastal monitoring by the 1992 UN Conference on Environment and Development, held in Rio de Janeiro. Agenda 21 adopted by that conference charges, "States should...make systematic observations on the state of the marine environment....[and] should consider: (c) supporting and expanding international programmes for systematic observations such as the Mussel Watch Programme...."

Meanwhile, plans are under way for International Mussel Watch Phase II in the Asian Pacific Rim area. The preliminary scoping workshop was organized by Ed Goldberg at the UN University in Tokyo in December 1992. Patience and persistence pay off! ✪

John W. Farrington is Associate Director for Education, Dean of Graduate Studies, and a Senior Scientist at Woods Hole Oceanographic Institution (WHOI). Bruce W. Tripp is a Research Associate, and Assistant Director of the Coastal Research Center, also at WHOI.

A Local Oil Spill Revisited

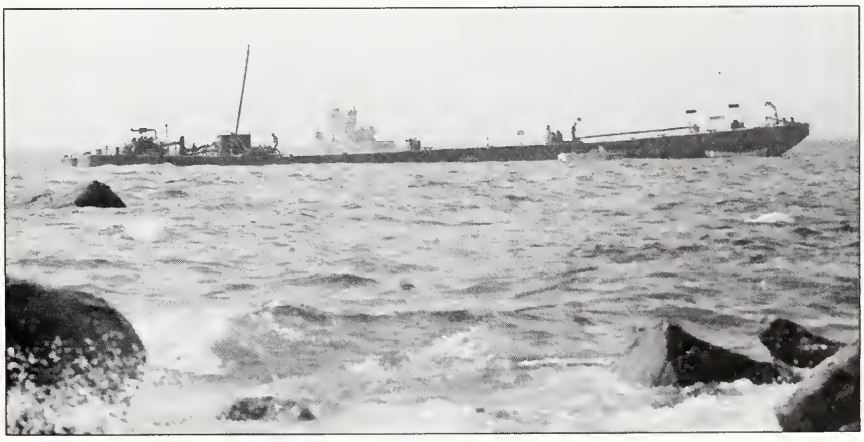
John M. Teal

In October 1969 George Hampson and Howard Sanders (Woods Hole Oceanographic Institution, WHOI) described a "Local Oil Spill" in *Oceanus*. The spill had occurred a month before when the barge *Florida*, loaded with no. 2 fuel oil, ran into some rocks in Buzzards Bay off West Falmouth, Massachusetts. In a more general article in that same issue of *Oceanus*, Max Blumer wrote, "The immediate, short term effects of oil pollution are obvious and well understood in kind if not in extent....In contrast, we are rather ignorant about long term and low level effects....I fear that these may well be far more serious...."

In the summer of 1989, one month shy of 20 years later, we visited the Wild Harbor marsh area that had suffered the greatest impact from the spill to see if we could find any traces of the event in the marsh ecosystem. During those 20 years, the site has been visited by graduate students in marine ecology, by reporters seeking information about current oil spills but also interested in seeing the effects of the Wild Harbor spill, and by visiting scientists curious about one of the world's best-studied oil spills.

For more than a decade after the spill, an oil sheen appeared on the surface of the water when mud from the most heavily oiled parts of the marsh was disturbed. During the second decade, the marsh's appearance returned to normal. Beginning three to five years after the spill, most of the oiled area was reinvaded by marsh grasses and occupied by marsh

The Falmouth Enterprise



An oil spill that followed the 1969 grounding of the barge Florida *off West Falmouth, Massachusetts, was monitored for two decades.*

animals. An observer unfamiliar with Wild Harbor would have been unable to detect the oiled areas after 10 years.

The Spill: Oil in Wild Harbor

The oil barge went onto the rocks off West Falmouth, Massachusetts, on a still, foggy September 1969 morning, spilling about 180,000 gallons of no. 2 fuel oil. This is the thin home-heating oil we all use, and is very similar to diesel oil. (About 60 to 65 spills of this size would be equivalent to one *Exxon Valdez* spill.) After the oil spilled onto the water, the wind rose and drove oil onto the Wild Harbor shore. The surf mixed oil, water, and sediments at the shoreline, making the oil-sediment mixture heavy enough to sink. This mixture contaminated several square kilometers of bottom to water depths of over 6 meters. Subsequent storms continued to extend oiled-sediment bottom contamination over the next several months. Eventually, the affected area was several times larger than it was during the first few weeks after the oil came ashore. Oil entering the quiet waters of the marsh was not mixed into the water but was carried up with the tide and deposited on the grass and surface of the sediment. As the tide ebbed, the oil ran down animal burrows and seeped into marsh sediments. The most heavily oiled places were the quiet cul-de-sacs that naturally accumulate sediments and anything else driven by the wind into the area, the Wild Harbor boat basin, and a small tidal creek in the Wild Harbor salt marsh. Some not-very-effective efforts were made to disperse the oil and to boom off the harbors and marshes—25 years ago the equipment was primitive, and there were no emergency-response teams ready to try to contain the oil.

John Teal

Sparse or absent marsh grass marks oiled areas of Wild Harbor one year after the spill.

Studies Began Immediately

Studies of the effects of the oil spill began immediately, because there were shellfishermen, nature lovers, town officials, and scientists living so close to the area that they could smell the oil as it approached the shore. George Hampson and Howard Sanders did some of the most important immediate work, sampling benthic organisms right after the spill. They found that 95 percent of the benthic amphipods (small, bottom-dwelling crustacea important as fish food and in controlling bottom ecology) were killed in the heavily affected areas. They determined this by counting corpses, something that had to be done immediately, before the remains decomposed. With the resident amphipods gone, neighboring individuals moved into the area and were also killed by the oil. Fish, lobsters, crabs, annelid worms, and snails were all killed and washed up on beaches. Within days of the spill, the Falmouth shellfish warden, George Sousa, photographed shellfish beds with a striking pock-marked appearance where soft-shelled clams killed by the oil had decomposed in place. Sousa also observed that scallops in West Falmouth Harbor (where the oil slick did not enter) contacted sufficient oil in the water that they were anesthetized and became easy prey for fish.

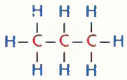
Shellfishing was closed over a distance of several kilometers that year, and for at least six years after the spill in Wild Harbor.

Sanders and his collaborators studied the spill's impacts for three years after it occurred. Following the death of the benthic organisms, opportunistic species of annelids (Capitellids) became the most abundant fauna. These small, red worms are animal "weeds" that can quickly

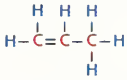
Petroleum Chemistry

Petroleum and most of its "oil" products are composed of tens of thousands of related compounds. For purposes of discussing their fates and effects, most can be conveniently divided into four categories: alkanes, cycloalkanes, olefins (or alkenes) and cycloalkenes, and aromatics.

The simplest group are the **alkanes**, characterized by straight or branched chains of carbon atoms joined by single bonds. Chemists illustrate hydrocarbons by drawing the bonds between carbon atoms. Each carbon has four bonds, and if nothing else is shown, then all of the bonds not linked to another carbon atom have a hydrogen atom attached at that point. So, propane, an alkane with three carbon atoms, shown as  is really



An **olefin** has at least one unsaturated bond, meaning that athe carbons are linked by a double or triple bond and there are fewer hydrogens in the molecule. Propene, an alkene corresponding to propane, is  or



Cycloalkanes are alkanes that are joined to themselves to form five- and six-membered ring compounds. Cyclohexane has two hydrogens on every carbon:  The corresponding olefin is cyclohexene: 

Aromatic hydrocarbons are ring structures in which every other carbon-to-carbon bond is double. The simplest aromatic hydrocarbon is benzene with a six-carbon ring. Because of the special chemistry of aromatic rings, you cannot know just where the double bonds are, so they are usually drawn by putting a circle within the hexagon:  or 

Polynuclear aromatic hydrocarbons or PAH are composed of a number of benzene rings, such as naphthalene with two benzene rings: 

All of these classes of hydrocarbons can have side chains attached in place of some of the hydrogens, giving rise to compounds such as pristane, a common natural hydrocarbon found in nature:  or 2,5 dimethyl naphthalene, a PAH in oil: 

Alkanes are found in nature as waxes, secreted onto the surfaces of many organisms as a waterproofing. These waxes typically have an odd number of carbon atoms, usually from 21 to 31, and are common in marsh sediments. They are nontoxic, and readily degraded by microorganisms where oxygen is available. Cycloalkanes (especially large ones) are generally nontoxic, and degrade very slowly. White mineral oil that you buy at the store is composed mostly of large cycloalkanes. Olefins are not found in petroleum, although they are produced by the cracking process and occur in gasoline and light oils. Some are also made by organisms. They vary in toxicity.

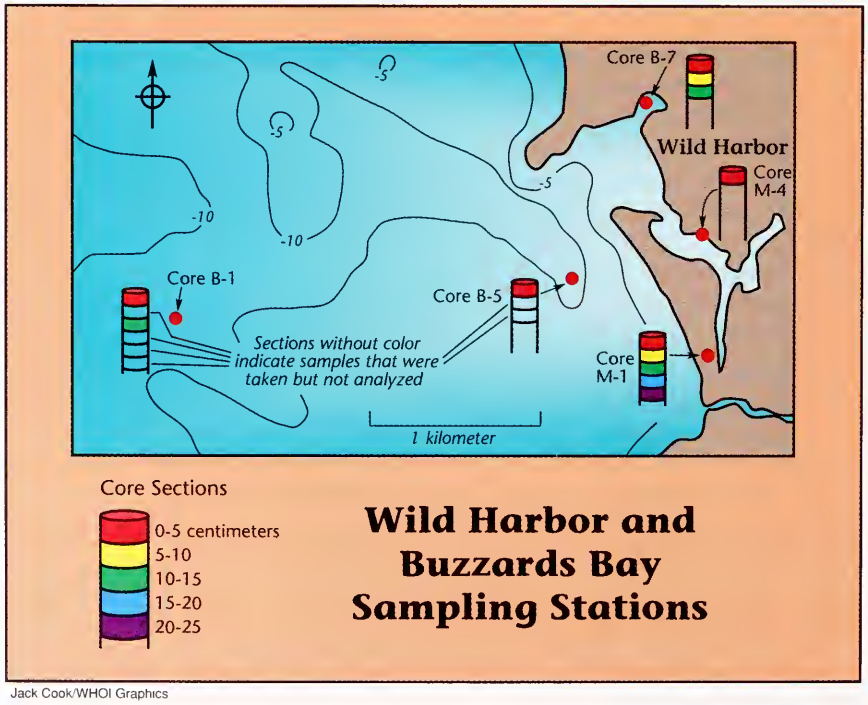
Aromatic hydrocarbons are the most soluble and toxic components of oil (especially in the two- to three-ring sizes) and the ones that are carcinogenic and tetratogenic (especially in the four- to five-ring sizes). Aromatics are characteristic of petroleum, but are also produced by combustion in automobiles, industrial power plants, and all sorts of fires. Those produced in combustion tend to have few, if any, side chains, while those in petroleum may have many, giving one way of distinguishing the source of hydrocarbon contaminants.

Finally, there are other components of crude oil. For example, asphaltenes are very large molecules with little biological activity that are the principal component of road asphalt. There are molecules like those above that have an oxygen, nitrogen, or sulfur atom in them (therefore not strictly hydrocarbons), some of which are very toxic. The entire story is complex, and far from being completely understood.

exploit the opportunity offered by a disturbance that kills previously resident animals, such as a sewage outfall or periodic anoxia. They became extremely abundant for a few years, then declined as the local fauna gradually became more diverse and nearer to normal for the region. Further studies in 1973 and 1974 showed continuing recovery. At the fifth anniversary, the boat basin remained heavily contaminated, its fauna reduced in abundance and still dominated by opportunistic species.

It was initially easy to recognize the oil within the tissues of the marine organisms sampled, including some fish and herring gulls. But many animals are able to induce enzyme systems within their bodies, usually in their livers, that degrade the aromatic petroleum compounds. This was investigated in the mummichogs (marsh minnows) and fiddler crabs at Wild Harbor by Kathryn Burns and by John Stegeman (both at WHOI in the late 1970s; Burns is now at Bermuda Biological Station). Burns found that the fish rapidly developed an enzyme system: Fish sampled in 1974 had a much lower oil content than those sampled in 1970. The fiddler crabs, on the other hand, also induced an enzyme system, but to such a small extent that there was no reduction in oil body burden between 1970 and 1974. The level in the crabs probably represented the maximum concentration they could accumulate and still survive. Stegeman found that the Wild Harbor mummichogs continued to show high levels of these enzyme systems eight years after the spill.

The salt marsh grass, *Spartina*, was killed where it was coated with oil in 1969, along a band a few meters wide next to the tidal creeks. The oil penetrated as far as 70 centimeters into the intertidal muds, twice the depth to which oil was detected in the subtidal boat-basin sediments. The following year the oiled marsh was almost bare. Since the marsh was in a sheltered cove, the marsh mud was not washed away and recolonization by grasses and other marsh plants gradually took place.



Jack Cook/WHOI Graphics

A Wild Harbor bathymetric chart shows the sampling stations and sections of subtidal and marsh cores analyzed for hydrocarbons

Initial growth in the second summer was sparse but deep green in color, probably because of the high level of nutrients in the mud from the dead organisms and the lack of competition from neighboring plants. By the third summer, much of the marsh's grassy areas seemed to have recovered, although the most heavily oiled places (those containing more than 1 milligram of oil per gram of mud) were still almost bare. Eight years after the spill, a few bare areas still held 1 milligram of oil per gram of mud.

Fiddler crabs were affected in several ways besides the initial kill. Male crabs are highly territorial, so areas with lethal concentrations of oil acted as traps, killing the residents, which opened territories to neighboring individuals who moved in only to be killed in turn. The same thing happened to the subtidal benthic amphipods. In areas where there were lower-than-lethal doses of oil, the crabs were anesthetized, moved slowly, were unable to escape their predators, and were eaten. Finally, throughout the winter the crabs remain buried in the mud where, in this case, they were continually subjected to oil at the higher concentrations characteristic of the deeper sediment layers.

The West Falmouth oil degraded by losing the lighter compounds through evaporation, dissolution, decomposition, and, especially in the cases of the paraffins and olefins, by microbial decomposition. There are no resins or asphaltenes in light fuel oil. The heavier aromatic compounds are the longest lasting, especially in the deeper layers of the sediments where there is no oxygen to support microbial degradation. Analyses of the intertidal sediments in 1973 showed clearly the mixture of cycloalkane compounds in concentrations as high as 2 milligrams per gram. Analyses of the aromatic compounds in 1976 showed concentrations of 1.5 milligrams per gram still present in some surface areas, with most of the compounds having two rings and many side chains, or three rings with side chains, that is, they contained over 10 carbon atoms and were not very volatile or soluble in water. Traces of oil at some depths showed very little degradation beyond that which had occurred before the oil reached the marsh, while it was still in the slick.

All of these studies from the first few years after the spill showed that while there was considerable recovery, in heavily oiled fine sediments with deep penetration, the oil remained for years. Animals that fed on and burrowed into those sediments continued to be affected by the oil. The oil continued to degrade throughout the study period, but was still clearly recognizable—and toxic—in the anoxic sediments after seven years.

John Teal

John Farrington (left) and Bruce Tripp borrowed a nearby signpost to help retrieve a recalcitrant core during Wild Harbor sampling in 1989.

The Spill Area 20 Years Later

We sampled the area after 20 years to see to whether the oil was still present, and if so, whether or not it had changed in composition (and therefore potential effect), and whether intertidal marsh sediments retained oil to a different extent than subtidal sediments. While there have been other oil spills in Buzzards Bay since 1969, fortunately none have entered the Wild Harbor area to confound the picture. We sampled marsh sediments in the most heavily oiled portion of the marsh (M-1—at lower right in the figure opposite), in a spot a few meters away (M-4) that was less heavily oiled than M-1, the most heavily oiled subtidal spot at the bottom of Wild Harbor (B-7), a lightly oiled subtidal site (B-5), and the original reference sites—Sippewissett Marsh and a subtidal site (B-1).

Acknowledgments: The research described in this article resulted from work done by many people at WHOI. Howard Sanders, Max Blumer, Fred Grassle, George Hampson, Kathryn Burns, John Farrington, Bruce Tripp, John Stegeman, Bruce Woodin, and Curtis Phinney all contributed in various ways, with the last six being involved in the 20-year follow up.

Born and raised on the rolling plains of Nebraska, John M. Teal naturally went into oceanography as a profession. He has always maintained that the closest thing to the Nebraska landscape in general appearance is the rolling hills (swells) of the Sargasso Sea (except for the difference in wetness). He got into oil spills and their consequences by accidents too complex to describe here, and has since been able to continue to be considered an expert mostly by doing little in the field except for advising others. In keeping with his tradition in this field, almost all of the actual laboratory work on the Wild Harbor oil spill was done by those listed in the Acknowledgments.

Sediments were sampled by coring that was routine except at M-1. There, as water filled the hole once we had removed the core, we saw droplets rise to the surface, spread out, and show the rainbow sheen characteristic of an oil layer. Putting a hand into the hole and removing a bit of sediment produced the characteristic smell of fuel oil. Our laboratory analyses showed this was a remnant of the no. 2 fuel oil spilled 20 years before.

At the most heavily oiled marsh site, the oil was still present to a depth of 15 centimeters with a concentration of 1 part per million (dry weight basis) at the 15-centimeter depth from which we saw the oil droplets. At the deeper level, though the analyses showed more oil than in the control sample at that depth, we could not be sure it was oil from 1969. Our analyses showed that the oil has remained for at least 20 years in the most heavily oiled and protected intertidal sediments. A trace remains in the most heavily oiled subtidal sediments, but certainly most has gone. Subtidal mixing of sediments by weather and by animal activities, even in this protected site, must have been sufficient to release almost all of the oil into the water or oxidized sediments so it could be washed away or degraded. If the former, then it was diluted enough so that we could not detect it at the other subtidal sediment-sampling sites.

The question remained about whether the oil remaining in the marsh sediment could still be having an effect on the marsh ecosystem. Clearly there is still enough oil there that if it were released into the water en masse it would poison the resident animals. It seems not unlikely that there has been a release at some slow rate from the reservoir down in the mud, either by diffusion or by dissolution into water moving slowly through the sediments with the tides. There were crabs actively moving about on the surface of the undisturbed mud where we took the cores, and there were mussels in the mud adjacent to the hole. None were obviously being affected by oil. We sampled these animals, and fish and clams from the tidal creek about 1 meter away, to see if we could find hydrocarbons in their tissues in excess of that in animals collected from the reference marsh. We found a trace of oil in the Wild Harbor Marsh fiddler crabs, which burrow into the muds and feed on the mud surface. The mussels and fish from Wild Harbor were no more contaminated than specimens from the control marsh. The fish, however, did show an elevated level of the enzyme system that responds to oil contamination, which could be the result of contact with the remaining 1969 oil, but could also be a response to some other pollutant.

In summary, there is still some of the oil spilled in 1969 in the marsh sediments, though most of it (probably more than 99 percent) is gone, and virtually all is gone from the subtidal sediments. The marsh heavily damaged 20 years ago is now visually no different from other marshes in the area. There is still enough oil in a few local areas to kill animals that burrow into those sediments, but whether or not this happens would be very difficult to detect. Probably the only significant, although small, remaining danger would be if the still-contaminated marsh muds were to be disturbed sufficiently to release the trapped oil. Nature does clean itself up after an oil spill, though it can take a couple of decades.

We can't pretend to have all the answers, but this recent work indicates that some of our more extreme fears at the time of the spill were not well founded. The immediate catastrophe of an oil spill is worse than the long-term effects.

Bacteria & Bioremediation of Marine Oil Spills

VIRTUALLY ALL MARINE ECOSYSTEMS harbor indigenous hydrocarbon-degrading bacteria. These hydrocarbon degraders comprise less than one percent of the bacterial community in unpolluted environments, but generally increase to one to ten percent following petroleum contamination. Various hydrocarbons are degraded by these microorganisms at different rates, so there is an evolution in the residual hydrocarbon mixture, and some hydrocarbons and asphaltic petroleum hydrocarbons remain undegraded. Fortunately, these persistent petroleum pollutants are, for the most part, insoluble or are bound to solids; hence they are not biologically available and therefore not toxic to marine organisms. Carbon dioxide, water, and cellular biomass produced by the microorganisms from the degradable hydrocarbons may be consumed by detrital feeders and comprise the end products of the natural biological degradation process.

Bioremediation attempts to accelerate the natural hydrocarbon degradation rates by overcoming factors that limit bacterial hydrocarbon degrading activities. Many commercial inocula have been developed to "seed" oil spills, in an attempt to augment the capabilities of the indigenous microorganisms. Seed inocula have yet to be proven beneficial in field applications, although laboratory testing and evaluation by the National Environmental Technology Assessment Corporation (NETAC), supported by the US Environmental Protection Agency, have identified both potentially beneficial and ineffective products.

While seeding may someday be useful, current bioremediation treatments of oil spills rely upon adding fertilizers to support the growth of indigenous hydrocarbon-degrading microorganisms. The *Exxon Valdez* oil spill formed the basis for a major bioremediation study. In the largest application of this emerging technology to date, bioremediation augmented other cleanup procedures. Application of the oleophilic fertilizer Inipol EAP 22 produced dramatic results in test plots: The surfaces of oil-blackened rocks on the shoreline turned white and were essentially oil-free within 10 days of treatment.

The striking visual results strongly supported the idea that oil degradation in Prince William Sound was limited by the amounts of available nutrients, and that fertilizer application was a useful bioremediation strategy. Both Inipol and a slow-release fertilizer were approved for shoreline treatment, and their use comprised a major part of the cleanup effort. Bioremediation became the major method for shoreline cleanup following initial physical washing, which had left oil, particularly subsurface oil, still contaminating the shorelines.

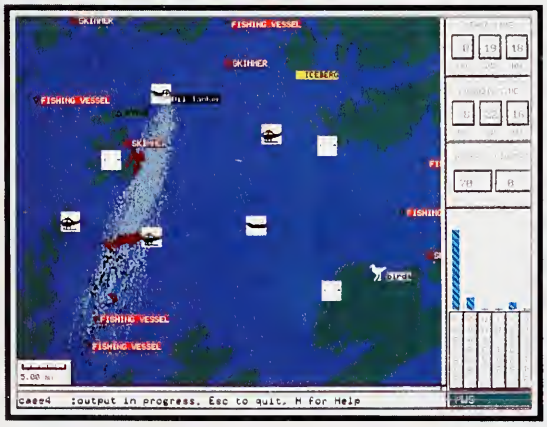
Monitoring tests demonstrated no adverse ecological effects from bioremediation, confirming toxicity testing that had established the safety of the amounts of fertilizer applied. Field monitoring also showed that fertilizer application sustained higher numbers of oil-degrading microorganisms in oiled shorelines. Rates of biodegradation were enhanced, as evidenced by the chemical changes detected in recovered oil from treated and untreated reference sites.

Proving the efficacy of bioremediation in these monitoring efforts was difficult due to the patchiness of the oil distribution. The branched hydrocarbons pristane and phytane, which are often used as internal standards, were rapidly degraded by the indigenous bacteria of Prince William Sound; these bacteria probably were adapted to the biodegradation of terpenes, which are structurally similar to pristane and phytane and occur naturally in Prince William Sound from the surrounding pine forests. It was necessary to use hopane, a compound resistant to biodegradation, as an internal standard along with multivariate statistical analyses in order to prove that biodegradation was effective. It appears that the fertilizer application enhanced the natural rate of hydrocarbon degradation by about five times.

—Ronald M. Atlas,
Professor of Biology at the University of Louisville, and consultant to Exxon and the US Environmental Protection Agency on bioremediation of the Alaska oil spill

OIL SPILL MODELING...

RECENT EVENTS HAVE LED to a new public interest in oil spill modeling. Large spills, including *Exxon Valdez*, the Persian Gulf spill, the Shetland Islands spill by the oil tanker *Braer*, and the passage of the comprehensive Oil Pollution Act of 1990 have brought oil spill issues into mainstream thought. The Oil Pollution Act specifies that all oil-industry facilities must have oil-spill contingency plans, including fixed facilities such as refineries and transport vessels such as ships and barges. Spill models are used primarily in oil spill contingency planning, spill response, and as a basis for impact or natural-resource damage assessment following a spill. In spill contingency applications, the model is used to identify which resources are at risk if a spill should occur, and to evaluate the effectiveness of proposed response plans. The latter usually include cleanup equipment selection, positioning, and deployment strategies. For spill-response activities, the model



This model predicted the trajectory for an oil spill in upper Prince William Sound. Cleanup resources are denoted by various icons.

forecasts the transport and fate of spilled oil to provide information useful in directing and optimizing cleanup equipment use. Oil spill models, integrated with impact models or natural resource damage assessment models, are increasingly used in post-spill investigations to evaluate impacts or damages. Impact assessments vary from models of oil hitting a static resource (such as a habitat or a bird nesting area) to complex ecological and economic modeling for evaluating present and future losses of fish, birds, and wildlife, and associated economic losses.

Spill models are normally constructed by linking mathematical formulations to represent oil transport and fate processes. Fate processes of primary interest include spreading, evaporation, entrainment (oil dispersion into the water column), emulsification (incorporation of water into the surface oil), and oil-shoreline and oil-ice interactions. The transport calculation (or trajectory) determines the oil movement in space and time. The fate portion of the model estimates the oil transport between various environmental compartments; for example, evaporation is oil transport from the sea surface into the atmosphere. Most models use a mass balance approach to track the amount of oil in each compartment (sea surface, atmosphere, water column, stranded on shoreline, decayed in ice, and on the seabed). The more sophisticated models allow us to describe the oil mass balance based on subsections of the distillation or boiling-point curve, which allows accurate tracking of the oil's toxic, volatile, aromatic fraction.

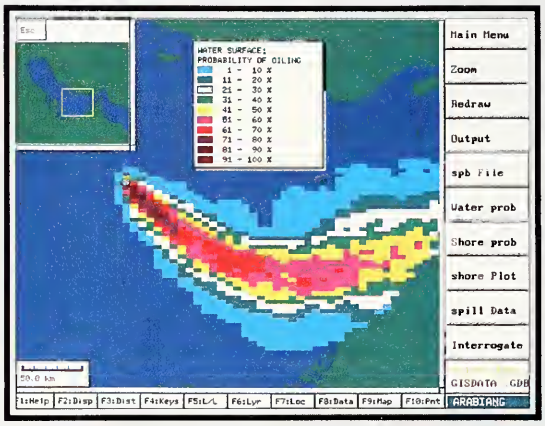
Models are typically run in one of three modes: forecast/hindcast, statistical, or receptor. In the forecast/hindcast mode, the model predicts the trajectory and fate for a specified spill scenario (release location, oil discharge rate, duration, oil type, and start date). Environmental data, such as currents and winds, are included in the model data base, are user specified, or are provided by real-time observations. This information can be derived from climatology, historical observations, or data that assimilates hydrodynamic and meteorological models. Stochastic mode simulations statistically vary the current and wind data. These models provide the probability contours for oil affecting open-water areas, shorelines, or biological, socioeconomic, or other resources at risk. Receptor mode simulations are like stochastic mode simulations,

Malcolm L. Spaulding

except they run backward in time. These calculations identify spill areas from which a particular resource is vulnerable. Predictions are normally given in the form of probability contours and minimum travel times that specify how likely it is that spills at different sites will affect specific resources. The forecast/hindcast mode is typically used for spill response, spill exercises, and hindcast of specific events. Stochastic and receptor mode simulations are primarily used in spill contingency planning and risk analysis.

The most advanced spill models operate on portable computers and use a "shell-based" structure. The shell consists of the modeling software and user interface, which remains common for all applications. The user can readily switch from one operational area to another by simply selecting the appropriate location database, which includes information on the shoreline location and type, wind data, and currents. An embedded geographic information system (GIS) is usually available to organize and manipulate data. Software tools are also available to allow the user to access externally prepared GIS data, overflight information, real-time wind and current measurements or model results, biological resources at risk, cleanup equipment type, location, and status, and other relevant data. The models employ extremely user-friendly interfaces, operate quickly and effectively in a standalone mode in the field, and use clear, concise color graphics for data entry and displaying model output. Hard copy or digital output is readily available. Through the use of sophisticated data-management techniques and software design, worldwide modeling capabilities are available on personal computer platforms. Model setup, simulation, and prediction distribution can typically be completed within 30 minutes of spill notification.

Models are routinely used in responding to all major spills. They provide critical information to help the on-site coordinator direct the response equipment and personnel. Verification efforts have shown that model predictions give a good representation of spill movement and weathering, provided that accurate information is available on the oil release and the environmental conditions (winds, waves, and currents). Spill models will become increasingly sophisticated with the development of improved fate algorithms, incorporation of information from data assimilating hydrodynamic and meteorological models, and direct electronic linkages to real-time observing systems. Basic spill models are being extended to include atmospheric, impact-assessment, and natural-resource damage-assessment components, as well as more comprehensive geographically referenced environmental data. The long-term goal is to evolve spill models into decision-support systems that employ artificial intelligence techniques to optimize spill response and minimize spill environmental impact.



This input screen allows a modeller to specify wind data as input to a spill model.

Malcolm Spaulding is Professor and Chair of Ocean Engineering at the University of Rhode Island. His primary research interests are predicting the transport and fate of pollutants in estuarine and coastal environments and computational fluid dynamics. He has been actively involved in oil spill modeling for the last 20 years, and is struggling to make model forecasts as accurate as hindcasts.

David Packard and Julie Packard

Monterey Bay Profiles in Depth

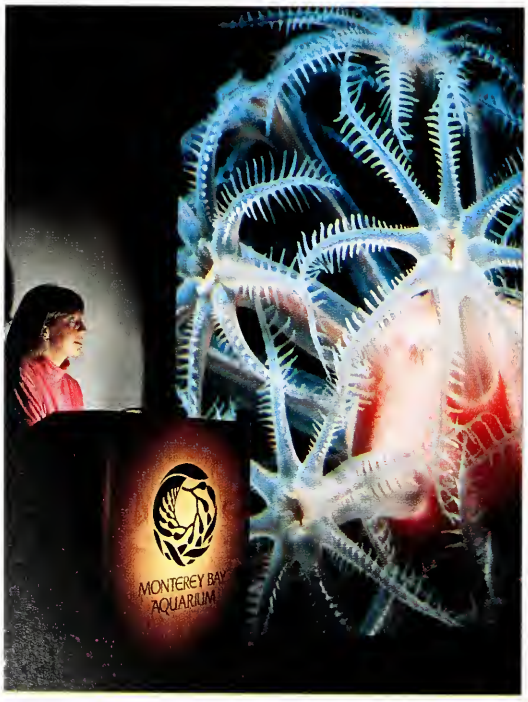
Judith L. Connor and Nora L. Deans

In a large auditorium at the Monterey Bay Aquarium, 200 people watch a huge video image of a twinkling comb jelly. "What is that thing?" a girl in the audience calls out. "It's a newly described species of comb jelly or ctenophore," answers an interpreter standing at a podium in the front of the auditorium. "We call it the rabbit-ear ctenophore because of those two long projections. It was discovered and described by scientists at the aquarium's sister institution, the Monterey Bay Aquarium Research Institute."

As the comb jelly drifts from view, the interpreter explains to the audience that the video images are coming from a camera on a remotely operated vehicle, or ROV, working deep in Monterey Bay. "The video is being transmitted through optical fibers in the cable that connects the vehicle to a research vessel on the surface of the bay. The scientists on board the ship are seeing the images for the first time, and we are seeing what they see, less than three seconds later, through a microwave link to the auditorium. Here, I'll show you what the ROV looks like."

The interpreter touches a computer monitor built into the podium. Instantly, the huge video screen displays an underwater scene of the remotely operated vehicle. The audience stirs with excitement; adults and children fire off questions: Where are they working today? How often does the aquarium show this program? Who's paying for all this?

This "Live from Monterey Canyon" program is a unique collaboration between two institutions: the Monterey Bay Aquarium and the Monterey Bay Aquarium Research Institute. Scientists at the research institute use the ship and remotely operated vehicle three or four times a week to study the depths of Monterey Canyon. And every day that they are out there working, visitors to the aquarium can watch live video images of the research and learn about the science process.



Monterey Bay Aquarium

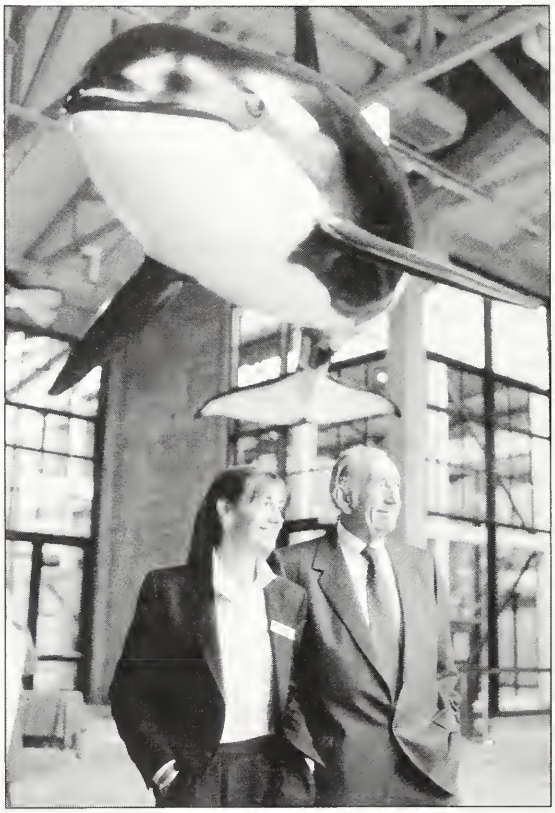
Live...from Monterey Canyon....

Who's responsible for this unique combination of research, technology, science education, and conservation on the coast of central California? An unusual father-daughter alliance makes it possible: The father and daughter are David Packard, with his background in engineering and high standards of excellence, and his daughter Julie Packard, a marine biologist with a passion for conservation. Their visionary work is supported by the Packard Foundation.

An Early Decision for Engineering

Born in Pueblo, Colorado, in 1912, David Packard knew at a young age what he wanted to be—"I decided I was going to be an engineer when I was still in grade school. I grew up with a feeling for mechanical things." In addition to his interest in physical sciences and technology, Packard was always fascinated by the natural world. "I spent a lot of time fishing in the Colorado mountains. I started fishing when I was still in grade school, not more than 12 years old," Packard recalls.

His feeling for mechanical things took him to Stanford University where he earned his bachelor of arts degree and a master's degree in electrical engineering. In 1939, he formed a partnership with his friend and Stanford classmate, William R. Hewlett. From its origin in a small garage in Palo Alto, California, the Hewlett-Packard Company became an international manufacturer of measurement and computation products and systems used in industry, engineering, science, and education. With money made in the computer industry, David Packard and his wife Lucile established a foundation to support environmental and educational projects.



Monterey Bay Aquarium

Julie Packard and her father, David Packard

Both David and Lucile made serious commitments of public service: Lucile promoted the arts, as well as medical care at the Stanford Children's Hospital; David served as an advisor on science, technology, and defense to several US presidents and Congress.

As parents, they imparted their love of the outdoors to their children, as well as strong family ethics of conservation and public service. And the Packard children, especially two daughters professionally trained in marine biology, piqued their parents' interest in the marine environment and in the idea of an educational aquarium devoted to Monterey Bay. In the 1970s, David and Lucile Packard funded the building of the Monterey Bay Aquarium.

Planning the Aquarium

After visiting all of the major aquariums in this country and abroad, David Packard concluded, "Most aquariums were on a fixed budget and had to cut corners and do things you wouldn't want to do if you weren't

constrained that way. We decided if we were going to do it, we'd better do it right." The Packards spent $55 million and took seven years to do it right, opening frontiers in aquarium technology. "This has paid off because we've been open nine years and it's as good as new."

David Packard worked closely with exhibit developers and architects during the building of the aquarium. His engineering talents helped conquer exhibit problems that developed: he invented wave machines for the aviary and the kelp forest exhibits, devised and built an exhibit to track the tides, and created other exhibit components in his foundry and shop.

Using the best materials, innovative design, and new technologies, the Packards created a world-class aquarium.

Using the best materials, innovative design, and new technologies, the Packards created a world-class aquarium devoted to life in Monterey Bay. The architecture reflects its setting on historic Cannery Row—and echoes the old Hovden Cannery it replaced on the waterfront.

As revolutionary as the materials and design is the aquarium's regional approach: All of the exhibits feature sea life and communities from Monterey Bay, the heart of the nation's largest marine sanctuary. More than 100 exhibits fill 23 major galleries displaying over 6,500 plants and animals. Among the landmarks is the 28-foot-deep kelp forest exhibit, a giant experiment that worked. No one has ever before succeeded in growing kelp on such a large scale. Like a window into the bay, the exhibit captivates visitors who stand at the base of the swaying kelp forest, looking up at the schools of fish darting through sunlight playing on fronds at the surface, and seeing, for the first time, this entire ecosystem from holdfast to surface. A giant success, the kelp in the exhibit grows at the same rate as the kelp out in the bay.

"The bay is a key part of our identity, what sets us apart, " explains Julie Packard, aquarium director. "It's our regional approach that's unique, the exploration of a whole habitat. And in our new exhibit wing currently under construction, we'll be able to tell the whole story of the bay by including the open ocean and deep sea."

Just as the aquarium embraces the bay, it also embraces public education and conservation issues. Julie Packard recalls, "The other strong interest of my father's that made him very enthusiastic about the aquarium, and, in turn, the marine environment, is education. He has always been dedicated to the importance of science education. What really drew him toward the aquarium project was this chance to share with the public, to really enlighten people about the natural world."

Education programs at the aquarium include free on-site programs for over 70,000 school children who visit each year, outreach programs at schools, libraries, beaches, and migrant camps, members' programs, and a lively teachers' institute called "Wet Science." All this is made possible by a dedicated corps of more than 700 volunteers and volunteer guides.

Passing the Conservation Ethic to the Next Generation

Julie, the youngest of the four Packard children, shares her father's passion for education, and attributes her interest in science education to the Packard family environment. "I developed a really strong conservation ethic from childhood because of my family's appreciation of the natural world, and from becoming involved in the family foundation with my father, working on land acquisition and open-space preservation issues. Actually, my interests were more terrestrially oriented until

college, when some courses in intertidal biology really sparked my interest and opened up a whole new realm."

After earning her bachelor's and master's degrees in biology from the University of California at Santa Cruz, Julie conducted research on the cultivation of commercially valuable seaweeds. In 1979, she became the aquarium's project director, working closely with other family members and a team of exhibit developers and designers.

Julie assumed the directorship when the aquarium opened in 1984, and her leadership has been most keenly felt in the aquarium's strong education programs and conservation ethic. Her vision is to get beyond awareness to change habits.

"The aquarium's mission is to raise the consciousness and heighten awareness of the ocean's role in all the earth's systems, including the terrestrial systems so often focused on by conservation organizations," Julie explains.

"My father and I share a vision of getting the public more involved and able to make informed decisions, of sharing science with the public, and of getting conservation organizations to work more closely with the scientific community. We're making new regulations every day in this country, and we must understand how these natural systems work. It must be our highest priority."

In a recent survey by *Parade* magazine (March 14, 1993), the Monterey Bay Aquarium was named the best aquarium in the country by its peers, and it takes its role as a leader in public education very seriously. "I'm really enthusiastic and proud of our education programs," remarks Julie, "especially our teacher programs and our unique relationship with our sister institution, the Monterey Bay Aquarium Research Institute."

Monterey Bay Aquarium

The kelp forest is but one of the aquarium's innovative exhibits that depict Monterey Bay habitats.

The Monterey Bay Aquarium Research Institute

The research institute began at a symposium held in May 1986 at the aquarium. David Packard organized the one-day think tank of prominent deep-sea researchers and asked them to imagine a new research institute on Monterey Bay. What could they expect to discover?

Expect the unexpected was the response. Stanford University's Tjeerd van Andel pointed out that some remarkable discoveries—like the animal communities near deep-sea thermal vents—have been complete surprises. Build an "acoustic observatory" offshore, Scripps oceanographer Walter Munk told the group. The ideas were varied, but the visiting scientists agreed that the Monterey Canyon offered wonderful research opportunities to explore the deep sea close at hand.

It was the technological barriers to working in the deep sea that caught David Packard's imagination, and the symposium reinforced his

desire to have a significant impact on ocean science. "It seemed to me that with the other activities around the bay, the Naval Post Graduate School, Moss Landing Marine Laboratories, University of California at Santa Cruz and Hopkins Marine Station (of Stanford University), we had an opportunity to build up a real center of ocean science here."

To fulfill his vision of bringing together engineering and scientific research, Packard established the Monterey Bay Aquarium Research Institute (MBARI) in 1987 as an independent, nonprofit center for marine research. Bruce Robison, a biological oceanographer at the University of California, Santa Barbara, when he took part in that 1986 symposium, joined the new research institute in 1987. Robison recalls the excitement of those days—a feeling that continues today, "Mr. Packard told us not to be afraid to fail. If you don't fail occasionally, you're not taking the risks needed to make major forward progress."

Monterey Bay Aquarium

ROV Ventana *is tethered to MBARI's R/V* Point Lobos. *Ventana is equipped with cameras and instruments.*

Now, MBARI's unique oceanographic center provides an environment where 23 engineers and a scientific staff of 27 can take risks with the goal of developing state-of-the-art equipment and innovative methods for deep-sea research. The scientists and engineers work in teams on projects that apply technology to research problems, developing advanced water-sampling systems, chemical sensors, and a network of acoustical devices, and using the remotely operated vehicle to study the depths of the bay.

The idea of using a remotely operated vehicle to study Monterey Bay developed from a seed planted during Packard's appointment as US Deputy Secretary of Defense from 1969 to 1971. At the Pentagon, he was responsible for military projects using photography, including those taken from manned submarines. "I kind of put two and two together and decided they could do just as good a job, maybe a better job, with unmanned vehicles."

MBARI's remotely operated vehicle *Ventana* gets plenty of use: 168 days at sea in 1992. And engineers at MBARI are developing and building a new remotely operated vehicle. That ROV and a new ship planned for 1994 (see inside back cover) will allow scientists to explore waters to 4,000 meters deep, four times deeper than ROV *Ventana's* range.

ROVs support research ranging from studies of undersea landslides caused by the 1989 Loma Prieta earthquake to the behavior of delicate gelatinous animals like ctenophores and the distribution of cold-seep communities in the bay. In December 1992, geologists used *Ventana* to drill the submarine canyon walls. That successful drilling was a first for any ROV, and produced the first cores of granodiorite and metamorphosed sediment from the Monterey Canyon.

Peter Brewer, who left the Woods Hole Oceanographic Institution in 1991 after 24 years on the scientific staff to become MBARI's Executive Director, finds working with David Packard inspiring. "David Packard

has the ability to visualize a unique mix of scientific research and technology, and his vision is extraordinary. He's like a lighthouse, tall, with scanning vision, in the way he brings his beacon of attention and intelligence to focus on an issue or problem. As a result of associating with him, my own personal vision is now sharper and brighter."

The Packards' long-term goal is to make contributions to science and technology and raise public awareness. "We need more educated people to solve the incredibly complex problems facing us," declares Julie Packard. "My vision and my father's vision is a major research institution working hand-in-hand with a major public education institution. No aquarium in the world is close to doing what we're doing—thanks to our collaborations."

Judith L. Connor is Senior Research Associate at the Monterey Bay Aquarium Research Institute. She received her Ph.D. from the University of California at Berkeley, where she studied the ecology of tropical reef algae. Now, she works on marine habitats far below the sunlit waters, studying deep-sea biology and geology in the Monterey submarine canyon.

Nora L. Deans is Publications Manager at the Monterey Bay Aquarium where she directs a natural history publishing program and the production of educational materials. With a degree in journalism and biology from the University of Michigan, she has pursued her fascination for the sea as a natural history writer and editor for almost 20 years, most of those at public aquariums. She also edits Current: The Journal of Marine Education *for the National Marine Educators Association.*

TECHNOLOGY
MTS
93
"Requirements in the Nineties"

MTS '93

"TECHNOLOGY REQUIREMENTS IN THE NINETIES"

September 22-24, 1993
Long Beach Convention Center ★ Long Beach, California

Technical Sessions Will Highlight:
- Advanced Marine Technology
- Marine Resources
- Ocean & Coastal Engineering
- Marine Policy & Education
- And More!

International Business Forum will feature selected countries and trade organizations from:
- Japan
- England
- South Africa
- Canada
- Mexico
- Norway

New for '93 — Technology Transfer Seminars and Exhibits

The Exposition will be host to over 125 organizations who will display the latest marine technology available today.

Manufacturers of ocean engineering products and firms offering related services are invited to exhibit their products and systems.

Don't miss the rewarding opportunity!

Call Today for a Complimentary Exposition Pass!!!

10% Discount for Registration Received Prior to September 1, 1993!

Call today to find out more about Attending and/or Exhibiting:

MTS '93
c/o J. Spargo & Associates, Inc.
4400 Fair Lakes Court
Fairfax, VA 22033
Tel: (703) 631-6200 Fax: (703) 818-9177

Oceanographic Research Vessels: Then, Now, and in the Future

Richard F. Pittenger and Robertson P. Dinsmore

The coastal zone is a region of transition between the land and sea. The US Atlantic, Pacific, and Arctic coastlines total 88,633 miles, and an additional 10,980 miles of coastline borders the Great Lakes. About 80 percent of the US population lives within an hour's drive of the shore. These numbers attest to the importance of coastal marine science: In order to grapple with the great diversity of conflicting activities within this region, a well-ordered research program is essential.

As upon the open sea, the oceanographer's chief tool for studying this region is the research vessel. Before World War II, most research vessels were limited to coastal service by their small sizes. Typically these vessels were converted fishing boats or pleasure yachts, pressed into serving the developing needs of science investigators. The early 1960s witnessed the "Golden Era" of American oceanography. Encouraged by the National Academy of Science, oceanographic science focused on blue-water (or deep-sea) research, and a number of larger ocean-going research vessels were built. During this period, little attention was paid to specific coastal science needs, and small research vessels were primarily ships inherited from the World War II era and earlier.

With growing environmental awareness in the late 1960s and early 1970s, considerable research interest turned toward the coastal zone, where there were concerns about water quality, population increase, fisheries health, oil production, and the effects of recreation. The coasts came to be regarded as highly vulnerable, if not fragile, areas.

The President's Commission on Marine Sciences (the Stratton Commission) Report of 1970 gave special attention to the coastal zone and the facilities to serve it. As a result, the National Oceanic and Atmospheric Administration and the University-National Oceanographic Laboratory System (UNOLS) were organized, and the term "coastal zone management" came into use.

UNOLS is an association of 56 ocean science research institutions that operate and use the 26 vessels in the US academic research fleet. The association's goal is to assist in the coordination and scheduling of ships and equipment to make efficient use of finite resources. UNOLS is also charged with advising federal funding agencies on future facility requirements for oceanographic research.

At the first UNOLS meeting in 1972, critical facility needs were defined. Capable coastal research vessels were high on the list, and a subcommittee was appointed to examine the needs for coastal zone research facilities. The subcommittee's chief recommendations included modern, capable, coastal research vessels assigned and operated on a "regional" basis. From this emerged the *Cape*-class vessels (R/Vs *Cape Hatteras, Point Sur,* and *Cape Henlopen* assigned respectively to the Duke University/University of North Carolina Oceanographic Consortium, Moss Landing Marine Laboratories in California, and the University of Delaware). To make these

facilities more available, consortia were formed to coordinate and participate in the vessels' operation.

In the early 1980s, the US oceanographic community faced a crisis as most large ocean research ships (longer than 51 meters) were either at or were approaching the end of their useful service lives, and some intermediate size (45 to 61 meters) ships would soon need mid-life refits. All of the UNOLS university ships were inadequate for the next set of global oceanographic tasks such as the World Ocean Circulation Experiment, Joint Global Ocean Flux Study, Ridge Inter-Disciplinary Global Experiments, and other large-scale research projects being planned. Through the UNOLS fleet-improvement committee and other vehicles, the community galvanized to action. They assembled a fleet-improvement plan that gained the support of the National Science Foundation, the Oceanographer of the Navy, the Office of Naval Research, and Congress. The plan, completed in 1990, called for the following:

- R/V *Conrad* was replaced by R/V *Ewing* (operated by the Lamont-Doherty Earth Observatory of Columbia University).
- R/Vs *Knorr* and *Melville* (operated respectively by the Woods Hole Oceanographic Institution, WHOI, and the Scripps Institution of Oceanography at the University of California, San Diego) were lengthened, re-engined, and modernized. The upgrades have been highly successful.
- The purchase of three new *Agor* 23-class vessels by the Navy as replacements for research vessels *Thompson*, *Washington*, and *Atlantis II* (operated by the University of Washington, Scripps, and WHOI). *Agor-23* is finished and operational, *Agor-24* is being built, and *Agor-25* will be built starting in 1994.
- R/Vs *Oceanus*, *Wecoma*, and *Endeavor* (operated by WHOI, Oregon State University, and the University of Rhode Island) have begun mid-life upgrades.
- Plans to design and build an arctic research vessel are under way.

The large so-called "blue-water fleet" is now in excellent shape for the next 25 years.

While these vessels can do considerable near-shore research, there is currently a need for specialized vessels and other infrastructure to support coastal zone research. Demands now being placed on the few existing coastal research vessels far outweigh the ships' capabilities.

Recognizing the need for a thorough review of the nation's infrastructure to support coastal research and monitoring, the National Science Foundation sponsored a three-day workshop in February 1993, hosted by the Virginia Institute of Marine Science. The conference brought together 76 scientists and marine operators from major coastal laboratories, as well as representatives from government agencies. Although the coastal regimes and scientific disciplines represented at the meeting were widely diverse, all agreed that modern, capable, coastal research facilities are urgently needed.

Coastal research and monitoring need to be improved beyond previous measures for several reasons:

- Population pressure: 46 percent of the

NOAA National Marine Fisheries Service/Woods Hole

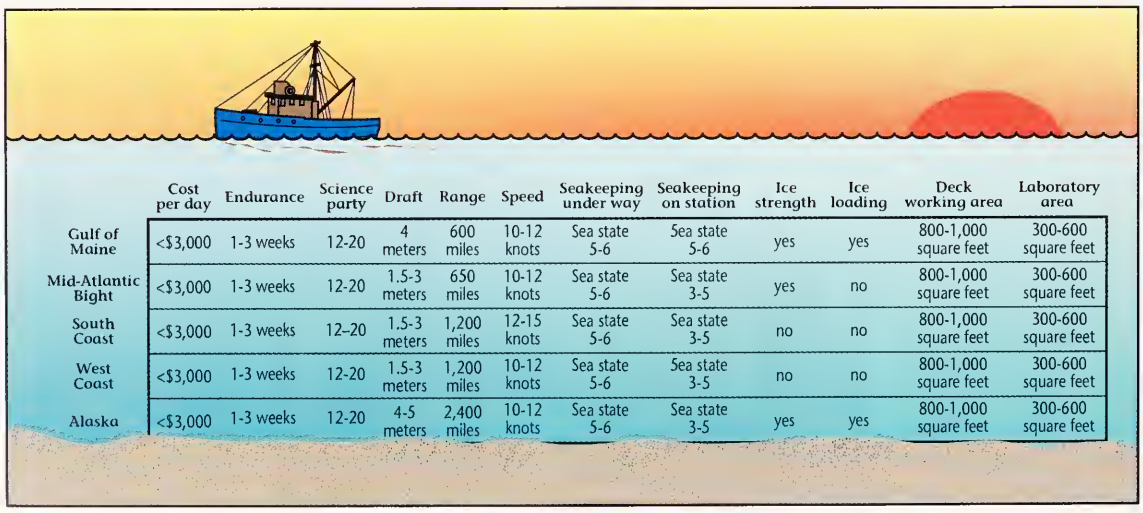
By their very nature and limited capability, most early research vessels were coastal vessels. Here, in 1871 zoologist Spencer Baird (far left) and associates set out from Woods Hole.

US population now lives within the coastal zone, and 80 percent lives within 50 miles of a coast (including the Great Lakes).

- Commercial and pleasure uses of the coastal zone are increasing.
- Fisheries are endangered.
- Continued use of nonrenewable resources will bring a greater need to exploit offshore minerals and oil.
- Pollution assessment, monitoring, and remediation are receiving more attention and funding.
- The US Navy is changing its focus to concentrate on regional, littoral, coastal regions rather than on the traditional blue-water mission of the Cold War.

The conference concluded that while modern ships will continue to be the primary tool of the coastal oceanographer, other research and monitoring facilities are essential if we are to better understand our coasts and estuaries. These include aircraft equipped with remote-sensing instrumentation, satellites with both optical and radiometric sensors, moored arrays, fixed platforms and piers, remotely operated vehicles (ROVs), communication links with all the above, and improved data-processing and information-management systems. As expected, the conference's principal focus was on research vessels. There was no consensus on the single type or even size of "ideal ship" for coastal research. Regional needs vary, and a vessel for estuarine research can be vastly different from one suitable for winter operations on the continental shelf. There was, however, general agreement for some criteria applicable to all modern coastal vessels, such as improved seakeeping and station keeping (ability to operate comforably at higher sea states), shallower drafts, ability to quarter larger scientific parties than currently possible, improved over-the-side equipment handling and sampling techniques, and, of course, low operating cost.

The group looking at larger coastal vessel needs was more specific in its recommendations for a high-capability ship: a vessel 50 to 60 meters long with a draft of 3 meters or less, that could accommodate at least 20 scientific personnel, with the best available seakeeping, science laboratory, and shipboard instrumentation. The group focusing on small vessels considered a broader range of sizes and capabilities based on

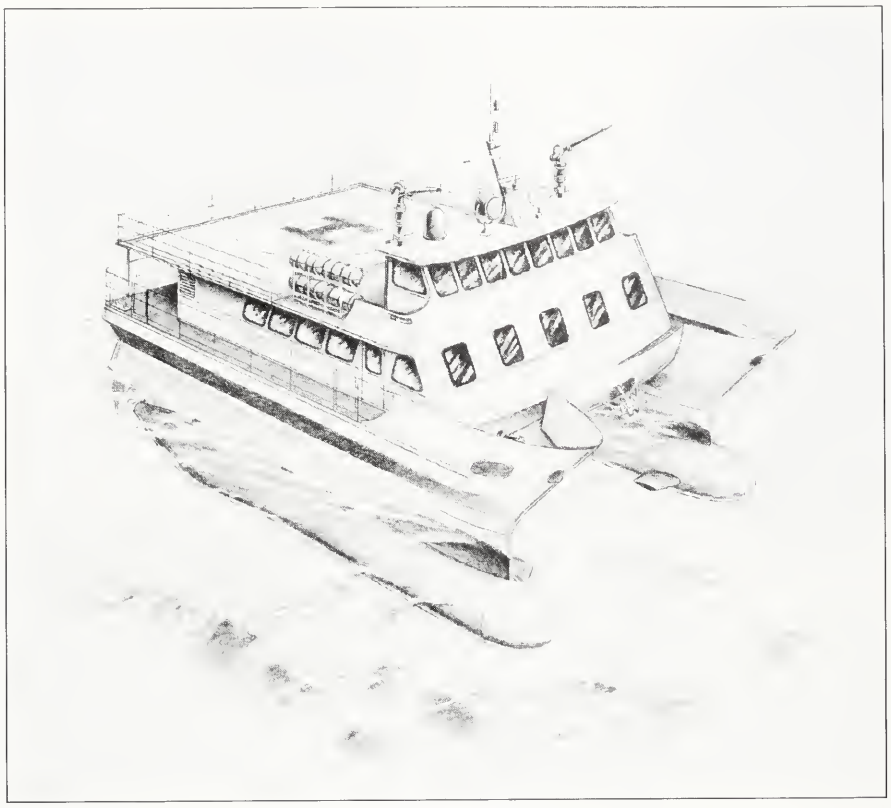


	Cost per day	Endurance	Science party	Draft	Range	Speed	Seakeeping under way	Seakeeping on station	Ice strength	Ice loading	Deck working area	Laboratory area
Gulf of Maine	<$3,000	1-3 weeks	12-20	4 meters	600 miles	10-12 knots	Sea state 5-6	Sea state 5-6	yes	yes	800-1,000 square feet	300-600 square feet
Mid-Atlantic Bight	<$3,000	1-3 weeks	12-20	1.5-3 meters	650 miles	10-12 knots	Sea state 5-6	Sea state 3-5	yes	no	800-1,000 square feet	300-600 square feet
South Coast	<$3,000	1-3 weeks	12–20	1.5-3 meters	1,200 miles	12-15 knots	Sea state 5-6	Sea state 3-5	no	no	800-1,000 square feet	300-600 square feet
West Coast	<$3,000	1-3 weeks	12-20	1.5-3 meters	1,200 miles	10-12 knots	Sea state 5-6	Sea state 3-5	no	no	800-1,000 square feet	300-600 square feet
Alaska	<$3,000	1-3 weeks	12-20	4-5 meters	2,400 miles	10-12 knots	Sea state 5-6	Sea state 3-5	yes	yes	800-1,000 square feet	300-600 square feet

Jack Cook/WHOI Graphics

These characteristics were identified as appropriate for coastal research vessels at a recent conference for coastal research and monitoring. Sea state units range from 0 to 9; these are relative numbers: 0 is flat calm, 9 indicates mountainous waves. Seakeeping is the ability to do normal work in the sea states indicated. Lab and deck areas are in square feet. Ice loading is the ability to sustain freezing spray buildup on superstructure in winter storms or cold weather.

Alan C. McClure Associates



A new type of vessel that offers increased seakeeping in a relatively small size is the Small Waterplane Twin Hull (SWATH) ship. The 30-meter workboat design shown here can be easily adapted for coastal research use.

differing regional requirements. Two size ranges emerged: "day boats" in the 15- to 25-meter range, mostly for short cruises in protected waters, and "expedition vessels" in the 25- to 40-meter range, customized for their regions of operation.

Conference participants examined new and developing technology and considered how it might be applied to research needs in the coastal zone. Modern moored arrays, satellite sensing, and acoustic imagery were of special interest. Advances in each of these fields coupled with high-speed interactive communications and data processing will allow synoptic measurements (many measurements at the same time over a large area) of coastal processes that were previously unavailable. New ship technologies, such as shallow-draft catamarans, jack-up rigs, and Small Waterplane Twin Hull (SWATH) ships, also offer exciting possibilities for coastal research and monitoring. SWATH ships, especially, provide a highly stable platform for a relatively small hull, allowing cost-effective work to be performed in locations and at times not before possible. (See the inside back cover for a feature on Monterey Bay Research Institute's SWATH vessel now under construction.)

The conference ended on an optimistic note. A compelling case has been made for new and improved coastal research facilities, especially ships.

Richard F. Pittenger is Associate Director of Marine Operations at the Woods Hole Oceanographic Institution (WHOI). Robertson P. Dinsmore, former Chairman of the Marine Operations Department, is now a Marine Operations Consultant at WHOI.

Beautiful, Ethereal Larvaceans Play a Central Role in Ocean Ecology

Cheryl Lyn Dybas

Shimmering pink light glowed in the waters of Saanich Inlet on Vancouver Island, British Columbia, in July 1968, thanks to the "bloom" of a little-known but common marine animal *Oikopleura dioica*, a species of larvacean. By midsummer, *Oikopleura* numbers in Saanich Inlet had reached the millions, turning the sea a luminescent rose. The larvaceans were feeding on large numbers of phytoplankton, microscopic plants floating near the surface of the inlet.

Resembling jellyfish, larvaceans are finger-shaped creatures that spin fragile webs of mucus around themselves. Their gossamer "houses" are usually the size of a walnut or smaller, but can, in rare cases, reach two meters in width. Like fine nets, the webs act as filters to trap smaller members of the plankton.

Larvaceans are found in the surface waters of the world's oceans, where phytoplankton are plentiful. The class Larvacea is the most specialized in the subphylum Urochordata, or Tunicata, and contains some 70 species. Larvaceans are so called because the adults have retained the larval characteristics of other tunicates, a tadpole-shaped body and a tail. Three main families of larvaceans are known: the Oikopleuridae, which spin bubble-shaped houses; the Fritillaridae, with their butterfly-shaped houses; and the rare Kowalevskiidae, with houses that resemble umbrellas.

Larvaceans drift in the sea in numbers almost too great to imagine. Where abundant, they often reach a density of several thousand per cubic meter of seawater. Along the Atlantic Coast in the waters of Delaware Bay, *Oikopleura dioica* can occur in numbers of 3,000 to 5,000 per cubic meter. In a single 10-minute net sampling of the bay's waters, more than 270,000 of another larvacean species, *Fritillaria borealis*, have been caught. Scuba diving among larvaceans is like swimming in a snowstorm, says larvacean expert Alice Alldredge of the University of California at Santa Barbara. Poetically inclined divers have compared floating among these ethereal creatures to "being brushed by thousands of fairy wings."

Creatures with umbrellas of opal or rose-pink, touched with a tint of blue; fiery pelagiae, which light our path through the waters with their phosphorescence.

—Jules Verne
20,000 Leagues Under the Sea

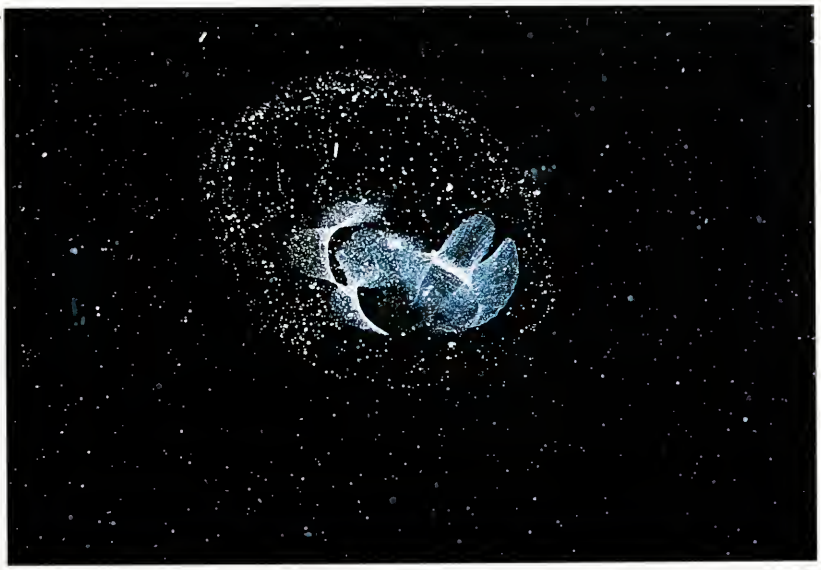
With their intricate passages and miniature nets, larvacean webs are one of the most complex external structures built by any organism. The animal continuously beats its tail to draw water into its hollow house, which is interlaced with a variety of filters for excluding particles too large to ingest. Once water has been sieved for plankton, it flows up both edges of the arched

"wings," out another set of openings, and back into the sea. Most larvaceans discard their houses and secrete new ones every four hours or so, the amount of time it takes for the incoming-flow filter to become clogged with debris. Some species, however, manufacture new houses every few minutes.

Larvacean feeding nets have fascinated marine scientists for more than a century, and led to the discovery of the nanoplankton—extremely small drifting plants of the seas. These lilliputian plants were discovered in the 19th century by German biologist Hans Lohmann when he observed them in the filters of larvacean houses. "Man has not yet succeeded in devising suitable means for the capture of the tiny members of the plankton," wrote the British biologist Sir Alister Hardy in his 1965 classic The *Open Sea: Its Natural History*. "That larvaceans should have solved the problem so efficiently makes one marvel all the more at these unusual animals." Larvacean filters trap coccolithophores and dinoflagellates, small organisms that make up the nanoplankton; few animals but larvaceans are able to capture and feed on these dwarfs.

Larvaceans play a central role in ocean ecology. They are a vital link between the tiny plankton they feed on and the larger animals of the oceanic food chain, who in turn

MBARI



James King

Larvaceans build web-like "houses" around themselves that they routinely shed and rebuild. The houses act as filters for trapping plankton that the larvaceans feed on. As Bathochordaeus *illustrates (above), larvaceans appear rather ordinary when "between houses." Once the houses are built, the ordinary becomes spectacular.* Oikopleura's *house (left) is bioluminescent.* Stegasoma's *house (below) was exposed to red dye for study purposes.*

James King

feed on them. Major predators of larvaceans and their houses include the young of fish like herrings, sardines, and flounders. Young plaice, or flatfish, may consume 25 or 30 larvaceans in a day. Yellow-and-black-striped coral reef fish called sergeants major, and siphonophores, relatives of the Portuguese man-of-war jellyfish, also subsist on these ubiquitous creatures.

Larvaceans are responsible for yet one more important connection in the marine food web. When they die or spin new dwellings, their cast-off houses collapse and sink to the deep sea at rates as fast as 1,000 meters per day, contributing to marine snow (the flow of detritus from surface waters to the depths). Biologists Mary Silver of the University of California at Santa Cruz and Alice Alldredge have found that marine snow—in the form of abandoned larvacean houses—may be a primary source of food for animals living in the ocean's deepest regions. (Silver and Alldredge received the Woods Hole Oceanographic Institution's Bigelow Medal in 1992 for their work on marine snow.)

The darkness of the abyss is lit by these discarded larvacean houses. When they encounter another object, *Oikopleura* houses may glow for up to four hours—even after they've been abandoned by their occupants. Scientists once believed that this bioluminescence came from microscopic organisms such as dinoflagellates living on the houses' surfaces. But experiments have shown that *Oikopleura* houses with no light-emitting microorganisms on their surfaces can still produce light: The animals leave light-producing structures and chemicals behind in their discarded webs.

Not all larvacean houses found in the depths are empty; at least one rare larvacean dwells in the deep sea. More than 10 times larger than its shallow-water Oikopleurid relatives, *Bathochordaeus charon* spins a web that may reach the size of a pumpkin. This giant larvacean was discovered in the southeastern Atlantic Ocean by oceanographers using plankton nets during the 1898 German deep-sea *Valdivia* expedition. Between 1898 and 1991, only 17 specimens of *Bathochordaeus* were reported in the scientific literature, these from the North and South Atlantic, Indian, southwestern Pacific, and eastern Pacific oceans.

This past year with the help of *Ventana*, a remotely operated vehicle owned by California's Monterey Bay Aquarium Research Institute, marine scientists observed several of these larvaceans as deep as 700 meters in Monterey Bay. Their research shows that, rather than forming a house that completely encircles its body like other larvaceans, *Bathochordaeus* spins a fan-shaped web that floats above the animal like a huge balloon. Few of the "fiery pelagiae" glimpsed by the crew of the submarine *Nautilus* in Jules Verne's *20,000 Leagues Under the Sea* could be more eerie than giant larvaceans as they slowly whirl through the ocean's nether regions.

Cheryl Lyn Dybas is a science writer who was "brushed by the fairy wings" of Oikopleura *while scuba diving in Monterey Bay last summer. Her articles on the "underappreciated" creatures of the deeps have also appeared in* Wildlife Conservation, National Wildlife, International Wildlife, *and NSF's* Directions *magazines.*

The world is a comedy to those who think, a tragedy to those who feel.

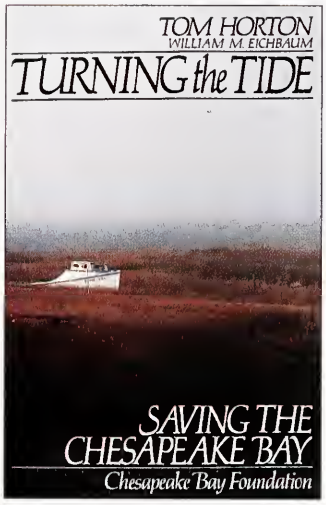
HORACE WALPOLE

We have existing images for both. . . to match your vision of the world.

CALL 304-927-2978 AppaLight FAX 304-927-3650

BOOKS REVIEWED

Turning the Tide



By Tom Horton and William M. Eichbaum, 1991. Island Press, Washington, DC; 327 pp. - $22.95 (hardback)/$14.95 (paperback).

For many people, Chesapeake Bay is the "national estuary." Indeed, efforts to "Clean up the Bay" have come to symbolize for many the nation's efforts to clean up its waters and restore the health of its coastal ocean. Award-winning author Tom Horton and William Eichbaum have written an outstanding book on Chesapeake Bay's vital signs, the status of its ecosystems, what has been done, and what remains to be done. This is an excellent book, and I recommend it for anyone wanting to know more about Chesapeake Bay or about restoring our coastal waters. The book provides an excellent description of estuarine processes and a balanced treatment of the many complex problems involved.

This story begins in 1967 when the Chesapeake Bay Foundation was organized in response to the "Save the Bay" efforts of the governors of Maryland and Virginia. Indeed much of this story takes place in the private sector.

The biggest success of the Bay cleanup is the restoration of the upper Potomac near Washington, DC, a result of massive investments in plants to treat sewage discharged into the river—10 percent of the total sewage discharge between New York City and North Carolina. One wonders if the Bay were less visible to Congress whether that investment would have been made. The good news is that state, federal, and local agencies around the Bay have formed partnerships with substantial public involvement to continue its cleanup.

The amount of damage done by humans is staggering and we are just now learning their full extent as oyster production continues to drop each year. Fish production is so low that fishing for certain species has been prohibited for several years. Even the resilient crab population undergoes wide and unexplained fluctuations in abundance. (Crabs are described as tough animals that will eat anything but have "a pissy attitude.")

The Bay has changed in the past century from a system where oysters formed large reefs and filtered the entire volume of water every five days to make the Bay the wonderful protein factory celebrated by H.L. Mencken. Now bacteria decompose most of the organic matter formed in the Bay, which depletes dissolved oxygen in bottom waters, causing massive fish kills virtually every year.

The easy part of building sewage treatment plants and prohibiting industrial discharges is behind us. The problem now is to deal with the tributaries where farm wastes flow into the Bay. In the cities, the problem has been partially solved by labelling storm drains with signs saying "Chesapeake Bay Drainage." Now we need something comparable for farms. Still more difficult is the problem of dealing with the airborne nutrients (nitrogen oxides from auto exhausts), which apparently equal the amount of nitrogen coming from sewage and from farm runoff.

Fishing is also a major part of the problem. Horton likens fishing to clear cutting the forests. Fishery management in the Bay has failed, and now both fisherman and fish are threatened. What was left of the oyster reefs after decades of overfishing is now threatened by diseases and by destruction of habitats.

But people are the principal problem. The book is persuasive that unless we deal with the problems caused by growing populations and their wastes, the outlook for Chesapeake Bay, indeed the coastal ocean, is bleak. But rather than simply crying havoc, the book ends (last third) with a citizen's guide to what can be done on a personal local and regional level.

—M. Grant Gross, Director
Division of Ocean Sciences
National Science Foundation

Coastal and Oceanographic Buoy Engineering

By Henri O. Berteaux, 1991. Published by the author, P.O. Box 182, Woods Hole, MA; 285 pp. - $58 plus postage.

Recently, a beautifully designed spar buoy (complete with multiple data sensors, computerized data storage, and radio transmission links) failed because it dragged its anchor. The anchoring system was designed to withstand certain environmental conditions and modern design practice with reasonable factors of safety; yet mother nature found another curve ball in her endless bag of tricks. Although he is not the designer of this particular spar buoy, such surprises have been common in the life's work of Henri Berteaux, the author of this book.

As a newly hired engineer in the mid 1960s, Henri participated in an oceanographic cruise that included recovery of deep-ocean, data-collection moorings. Only one in five were recovered. For the next 25 years, patient, methodical experimentation with buoys, forensic evaluation of failed components, analysis and new design brought steady progress, ultimately leading to the publication of this guidebook. His offering allows the engineer to replace guesswork with appropriate engineering analysis and rational design principles. Beginning with a review of the types and purposes of moorings, interesting designs from ocean engineering experience are described in detail.

Berteaux has compiled a good introductory primer to concepts such as buoyancy, drag forces, and both analytic and numerical modelling techniques. The theory of dynamics comes next, with an appropriately heavy emphasis on the effects of surface-ocean waves on the heave and roll of buoys. Linear models of buoy response are shown, along with an essential introduction to the concepts of added mass and hydrodynamic damping. Response in random seas is discussed at some length, with useful examples of surface and subsurface mooring systems.

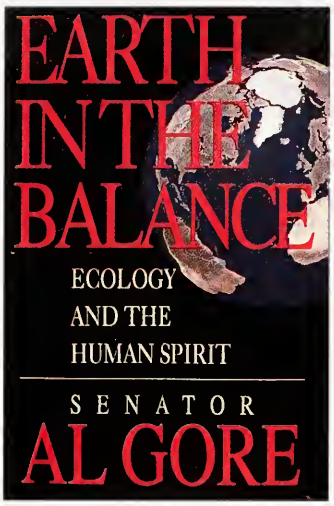
Berteaux then turns from describing the basic tools of analysis essential to understanding mooring behavior to the practical design of real mooring systems. Environmental factors, such as corrosion, icing, and fish bite, are introduced. Strumming is confronted as a serious problem in high-current applications.

Good mooring design is in the details of the materials, the fittings, and the terminations. All of these factors are carefully explained, along with valuable mechanical and material data.

The book closes with a discussion on deployment and retrieval—the two most critical moments in the life of most moorings. If you plan to throw something over the side and you want to get it back, you can greatly improve your chances by referring to this book.

—J. Kim Vandiver, Professor
Department of Ocean Engineering
Massachusetts Institute of Technology

Earth in the Balance: Ecology and the Human Spirit



By Senator Al Gore, 1992; Houghton Mifflin, Inc., Boston, MA; 407 pp. - $13.

There is universal agreement that Al Gore is one of the smartest Vice Presidents we have ever had; this would be true even if a certain someone had not immediately preceded him in the job.

While admired for his intelligence, Vice President Gore has been tarred by some pundits as wooden and unemotional. Obviously, none of them have read his book. Published last year prior to the presidential campaign, *Earth in the Balance* is written not only with a policy wonk's grasp of the facts but with the passionate gusto of a father who has made a personal—a deeply personal—commitment to change the world for his children and children everywhere.

Interspersing the wisdom of everyone from Yogi Berra to Winston Churchill, Gore has produced a solid historical context for grasping the enormity of our global environmental calamity and an adroit analysis of how we daily make it worse. It is a chilling achievement—and indictment—in prose. Those of us who believe we know how bad it is can still be shocked. Those—like most officials in the previous two Administrations, who seem to believe we can simply put a cork in the ozone hole or a big hat on our head—should be downright scared to death.

However, Vice President Gore, as they say, doesn't just "talk the talk;" he can "walk the walk." In an unusual twist for a book written by a politician, Gore makes detailed recommendations for a sweeping prescription for worldwide change. His "Global Marshall Plan" is built on the premise that "we must make the rescue of the environment the central organizing principle for civilization."

The Gore plan is very tough medicine, based on five strategic goals: stabilizing world population; rapid development of environmentally appropriate technologies; a new system of economics that accounts for the environmental cost of decisions; international agreements to implement the plan; and universal environmental education.

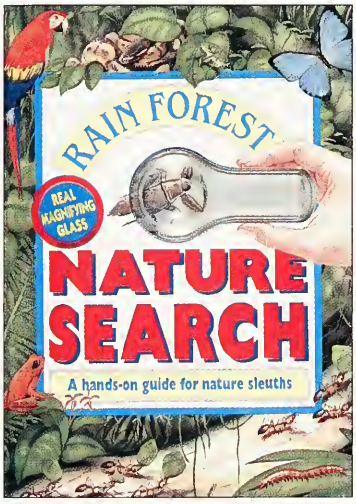
The Vice President equates the breadth of this struggle to the half-century fight against communism. It may be even harder. There is no Evil Empire to rally against. In this battle, to quote Pogo, "we have met the enemy, and he is us."

Unfortunately, failure on this battlefield will not mean the end of life as we know it, but quite simply the end of life.

Earth in the Balance was written by *Senator* Al Gore as part of a personal—and sometimes spiritual—"journey in search of a true understanding of the global ecological crisis and how it can be resolved." Feeling "called" to this challenge, a remarkable confluence of events has given *Vice President* Gore the opportunity to turn what he learned on his journey into policy. Designated our nation's environmental advocate by President Clinton, his loud, clear voice will, if we are as prescient as the author, bring Americans and all the world's citizen's together in the epic struggle for environmental sanity.

—Gerry E. Studds (D–MA), US Congress Chairman, House Merchant Marine and Fisheries Committee

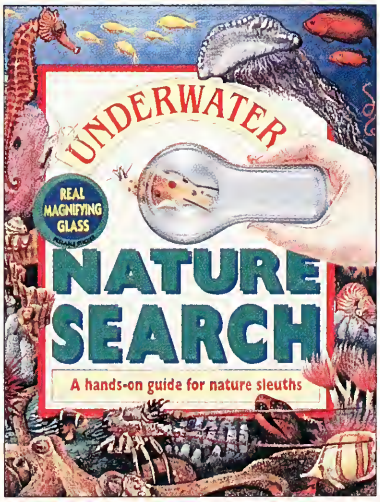
Rainforest Nature Search



By Paul Sterry and Andrew Cleave, illustrated by David Holmes, Eva Melhuish, Neil Bulpitt, and Karen Johnson.

Underwater Nature Search

By Paul Sterry and Andrew Cleave, illustrated by David Holmes, Eva Melhuish, Neil Bulpitt, and Karen Johnson.



Both are Joshua Morris Books, published by Reader's Digest Books for Children, NY. Each is 32 pp. - $14. For ages 7 to 12.

Now here's something you don't see every day: children's books about nature study that come complete with their own magnifying glasses. Those curiosity-satisfying accessories are included in two new children's books, *Rainforest Nature Search* and *Underwater Nature Search*. Though Sarah (8) and Lucy (5) enjoyed handling the magnifyers as they pored over the pages, I'm not entirely sure if the tools are absolutely essential to enjoying the books.

The books are curious hybrids of *Where's Waldo?* and more conventional, straightforward nature books. Each features luscious spreads, loaded with visually-interesting details, many of which are too small to pick out readily with the naked eye—but are revealed when the hand lens is applied to the page, provided that the detective can find the proper focal distance that allows the difficult-to-see object to be revealed, while not losing it in a blur of tiny dots that make up the printed picture.

Both books have several spreads filled with factual information about the environments they're describing, intermingled with a number of puzzle spreads. *Rainforest Nature Search* includes lots of information on creatures found in the rainforest canopy, in mid-canopy, and near bodies of water. *Underwater Nature Search* has spreads on shallow waters, the coral reef, the Sargasso Sea, a harbor, the Izu Peninsula (Japan), and the deep sea. I found that I liked the more educational spreads, while my children preferred the puzzle spreads. The pages are busy, since they are designed for hand-lens hide-and-seek, but they are well-organized.

I had some pedagogic questions about the puzzle spreads: in each book there is a spread of animals that "don't belong" in the environment the book is about: a dalmatian is depicted in the middle of the rain forest, a hippo and a penguin are shown under water at Izu Peninsula. The children are to use their hand lenses to spot these animals. To me, this went a little against logic and learning. Why have a puzzle filled with animals that "don't belong" in the middle of books that are trying to show children hundreds of animals that "do belong?"

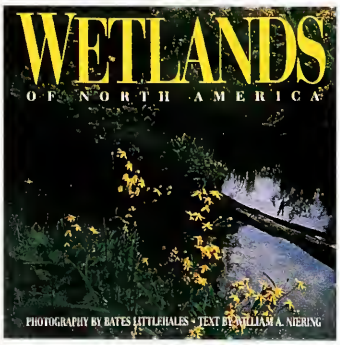
Another quibble: though I'm far from an ichthyologist, I questioned whether all of the deep-sea fish shown on pages 20 and 21 of the

undersea book would coexist at the same depth. Are flounder, giant squid and angler fish deep-sea neighbors? My uncertainty about that gave me a little bit of pause. (*Editors note:* WHOI biologist Jim Craddock suggests that this co-existence is, in fact possible, though "almost nobody" knows exactly where giant squid live, and there are many different kinds of flounder and 'angler fish'). Also, the authors of the book are British. I wondered if some Britishisms might have been inadvertently left in by the US editors. For example, the flounder mentioned above is actually referred to in the text as a "plaice."

Nonetheless, the illustrations are really quite lovely, and hunting with the magnifying glass is a lot of fun. These books do give children a more-active-than-usual peek at two fascinating regions.

—Deborah Kovacs
Author of children's literature, and Editor, *Ocean Explorer*, the newsletter for Young Associates of the Woods Hole Oceanographic Institution

Wetlands of North America



By William A. Niering and Bates Littlehales, 1991. Thomasson-Grant, Charlottesville, VA. 160 pp. - $24.95.

Illustrated nature books are often strong on photography and weak in text. This mini-coffee table book is a welcome exception. Over 138 outstanding color photographs by a former *National Geographic* photographer are framed within the solid text and scholarship of one of the nation's leading wetland ecologists.

The book is organized around four major wetland groups: freshwater marshes, coastal wetlands, swamps and riparian wetlands, and peatlands: bogs and fens. Each section includes a map showing the distribution of each wetland type in the continental US and Canada. The photographs are a mix of landscape scenes and sharp close-ups of plants and animals characteristic of each type of wetland. Readers who have not had the opportunity to see the major wetlands of this continent can rely on the landscape scenes. The selection of species for the close-ups is very good.

But there is disturbing dichotomy between the illustrations and the text. Niering discusses the functions of wetlands that are valuable to human welfare and safety and to wildlife habitat and the events that have led to loss of one-half of the original wetland acreage of the United States. But there are no author's illustrations of the ongoing activities responsible for wetland loss and long-term economic costs to the nation. Perhaps this is a conflict too difficult for commercial editors to resolve.

The title would have been more accurate had it been "Wetlands of The United States." The maps and text exclude Mexico and provide very little detail on Canada, which has 25 percent of the world's wetland area. Part of the problem is that the US and Canada have approached wetland inventory in different ways that make constructing a unified map difficult. Readers who want the first effort at a unified map and a more comprehensive continental view will turn to *Wetlands* by Finlayson and Moser (Facts on File), which is global in scope but heavier on text than is this volume.

An an introductory book for the public, for schools, and for wetland scientists who want to give legislators and their in-laws some sense of why they muck about in swamps, this is a timely and welcome publication.

—Joseph S. Larson
The Environmental Institute
University of Massachusetts

BOOKS & VIDEOS RECEIVED

MARINE POLICY

The Economics of Coastal Management: A Manual of Benefit Assessment Techniques by Edmund C. Penning-Rowsell, et al.; 1992; CRC Press, Inc., Boca Raton, FL; 380 pp - $99.95.

Diversity of Oceanic Life: An Evaluative Review edited by Melvin N.A. Peterson; 1992; The Center for Strategic and International Studies, Washington, DC; 109 pp - $14.95.

International Profiles on Marine Scientific Research by Judith Fenwick; 1992; WHOI Sea Grant Program, Woods Hole, MA; 202 pp - $5.

ENVIRONMENT

Aquatic Pollution by Edward A. Laws; 1993; John Wiley and Sons, Inc., New York, NY; 611 pp - $54.95.

Restoration and Recovery of Shallow Eutrophic Lake Ecosystems in The Netherlands edited by Louis Van Liere and Ramesh D. Gulati; 1992; Kluwer Academic Publishers, Norwell, MA; 287 pp - $164.

Use and Misuse of the Seafloor edited by K.J. Hsu and J. Thiede; 1992; John Wiley & Sons, Inc.; New York, NY; 305 pp - $80.

Saving Our Planet: Challenges and Hopes by Mostafa K. Tolba; 1992; Chapman & Hall, New York, NY; 296 pp - $25.

Coastal Stabilization: Innovative Concepts by Richard Silvester and John R.C. Hsu; 1993; Prentice-Hall, Inc., Englewood Cliffs, NJ; 578 pp - $96.

VIDEOS

Marine Detectives produced by Films for the Humanities & Sciences;1992; Princeton, NJ; 15 minutes - $89.95 (purchase)/$75 (rental).

The S.S. *United States*: From Dream to Reality produced by the Mariner's Museum; 1992; Newport News, VA; 30 minutes - $24.95.

The Private Lives of Dolphins produced by Films for the Humanities & Sciences; 1992; Princeton, NJ; 60 minutes - $89.95 (purchase)/$75 (rental).

Vanishing Lands produced by University of Maryland Foundation Lab for Coastal Research, College Park, MD; 30 minutes - $29.95 (individuals)/$69.95 (institutions).

OCEANOGRAPHY

Ocean Yearbook, Volume 10 Edited by Borgese, Ginsburg, and Morgan; 1993; The University of Chicago Press, Chicago, IL; 545 pp - 67.95.

Large Marine Ecosysystems edited by Kenneth Sherman, Lewis M. Alexander and Barry D. Gold; 1993; American Association for the Advancement of Science, Washington, DC; 376 pp - $46.95.

Submerging Coasts: The Effects of a Rising Sea Level on Coastal Environments by Eric C. F. Bird; 1993; John Wiley & Sons, Inc., New York, NY; 230 pp - $41.50.

International Geological-Geophysical Atlas of the Atlantic Ocean by Research Institute of Geology and Mineral Resources of the World Ocean; 1992; Morintech, St. Petersburg, Russia; 158 pp - $150.

Diagenesis, III edited by K.H. Wolf; 1992; Elsevier Science Publishers, Amsterdam, The Netherlands; 652 pp - $200.

GENERAL INTEREST

Celestial Navigation by Arthur E. Davies; 1992; The Redwood Press, Melksham, England; 127 pp - $29.95.

Elkhorn Slough by Mark Silerstein and Eileen Campbell; 1989; Monterey Bay Aquarium (part of the Natural History Series), Monterey, CA; 64 pp. - $8.95.

Fuzzy Thinking by Bart Kosko; 1993; Hyperion, New York, NY; 318 pp - $24.95.

Entropy and the Magic Flute by Harold J. Morowitz; 1993; Oxford University Press, New York, NY; 224 pp.—$22.

Sharks Have No Bones: 1001 Things Everyone Should Know About Science by James Trefil; 1993; Simon & Schuster, New York, NY; 305 pp - $12.

Dangerous Aquatic Animals of the World: A Color Atlas by Bruce W. Halstead; 1992; The Darwin Press, Inc., Princeton, NJ; 263 pp - $60.

The Creative Moment: How Science Made Itself Alien to Modern Culture by Joseph Schwartz; 1992; Jonathan Cape Publishers, London, England; 252 pp - £16-99.

A World Between Waves edited by Frank Stewart; 1992; Island Press, Washington, DC; 270 pp - $24.95.

Gently with the Tides: The Best of Living Aboard edited by Michael L. Frankel; 1993; R.R. Donnelley, Harrisonburg, VA; 224 pp - $14.95.

The Nature of Boats—Insights and Esoterica for the Nautically Obsessed by Dave Gerr; 1992; International Marine, McGraw-Hill, Blue Ridge Summit, PA; 448 pp - $29.95.

Big Science by Nick Downes; 1992; American Association for the Advancement of Science, Washington, DC; 120 pp - $10.95.

Chalk Up Another One: The Best of Sidney Harris by Sidney Harris; 1992; American Association for the Advancement of Science, Washington, DC; 146 pp - $10.95.

Where the Sea Breaks its Back: The Epic Story of Early Naturalist Georg Steller and the Russian Exploration of Alaska by Corey Ford; 1992; Alaska Northwest Books, Anchorage, AK; 206 pp - $12.95.

Cranks, Quarks, and the Cosmos: Writings on Science by Jeremy Bernstein; 1993; BasicBooks, New York, NY; 220 pp - $23.

The Naval War of 1812: A Documentary History edited by William S. Dudley; 1992; Naval Historical Center, Washington, DC; 779 pp - $43.

YOUNG PEOPLE

Take Action: An Environmental Book for Kids by Ann Love and Jane Drake; 1992; World Wildlife Fund, William Morrow & Co., New York, NY; 96 pp - $7.95.

World Water Watch by Michelle Koch; 1993; Green Willow Books, William Morrow & Co., New York, NY; 30 pp - $14.

Moonlight on the River by Deborah Kovacs; 1993; Viking Press, New York, NY; 42 pp - $14.95

Down in the Sea: The Jellyfish and **Down in the Sea: The Octopus** by Patricia Kite; 1993; Whitman, Morton Grove, IL; 24 pp (each) - $13.95 (each).

Broken Wings Will Fly by Mick Blackistone; 1992; Cornell Maritime Press, Inc., Centreville, MD; 30 pp - $10.95.

Animals That Glow by Judith Presnall; 1993; Watts, New York, NY; 64 pp - $12.40.

BIOLOGY

Concepts in Biological Oceanography: An Interdisciplinary Primer by Peter A. Jumars; 1993; Oxford University Press, New York, NY; $49.95.

Marine Biotechnology edited by David H. Attaway and Oskar R. Zaborsky; 1993; Plenum Press, New York, NY; 500 pp - $89.50.

Marine Pelagic Cyanobacteria: Trichodesmium and other Diazotrophs edited by E.J. Carpenter, D.G. Capone, and J.G. Rueter; 1992; Kluwer Academic Publishers, New York, NY; 357 pp - $119.

The Northern Quahog: The Biology of *Mercenaria mercenari* by Michael Rice; 1992; Rhode Island Sea Grant Information Office, Narragansett, RI; 68 pp - $7.95.

Protozoa in the Water Industry by Colin R. Curds; 1992; Cambridge University Press, New York, NY; 127 pp - $14.95.

Starfishes of the Atlantic by Alisa M. Clark and Maureen E. Downey; 1992; Routledge, Chapman, and Hall, New York, NY; 794 pp - $250.

Reef Coral Identification by Paul Humann; 1992; New World Publications, Inc., Jacksonville, FL; 240 pp - $29.95.

CETACEANS

The Whale Watcher's Handbook by David K. Bulloch; 1993; Lyons and Burford, New York, NY; 114 pp.—$13.95.

Dolphins and the Tuna Industry by the Commission on Life Sciences; 1992; National Academy Press, Washington, DC; 192 pp - $22.95.

Guardians of the Whales: The Quest to Study Whales in the Wild by Bruce Obee and Graeme Ellis; 1992; GTE Discovery Publications, Inc., Bothell, WA; 169 pp - $34.95.

DIVING

NOAA Diving Manual, Revised Edition, prepared by the National Oceanic and Atmospheric Administration; 1992; Best Publishing Company, Flagstaff, AZ; 518 pp - $65.

Great Reefs of the World by Carl Roessler; 1993; Pisces Books, Houston, TX; 126 pp - $19.95.

Shipwrecks of North Carolina from Hatteras Inlet South by Gary Gentile; 1992; Gary Gentile Productions, Philadelphia, PA; 232 pp - $20.

New Jersey Beach Diver by Daniel and Denise Berg; 1992; Aqua Explorers, Inc., East Rockaway, NY; 92 pp - $14.95.

FISHERIES

Fish for the Future by Susan Fowle; 1993; Center for Marine Conservation, Washington, DC; 142 pp - $7.95.

Surveys of Fisheries Resources by Donald R. Gunderson; 1993; John Wiley and Sons, Inc., New York, NY; 248 pp - $55.75.

Ocean Ecology of North Pacific Salmonids by William G. Pearcy; 1992; Washington Sea Grant Communications, Seattle, WA; 179 pp - $25.

The Atlantic Salmon—Natural History, Exploitation, and Future Management by W.M. Shearer; 1992; John Wiley & Sons, Inc.; New York, NY; 244 pp - $59.95.

Carp and Pond Fish Culture Including Chinese Herbivorous Species by Laszlo Harvath, Gizella Tamas, and Chris Seagrave; 1992; John Wiley & Sons, Inc., New York, NY: 158 pp - $69.95.

Fish: An Enthusiasts Guide by Peter B. Moyle; 1993; University of California Press, Berkeley, CA; 283 pp - $25.

COMING UP NEXT...

Marine Sanctuaries

Volume 36, Number 3, Fall 1993

© Ralph A. Clevenger

Tidepools of Channel Islands National Marine Sanctuary, California

This fall, *Oceanus* investigates what 20 years under the Marine Sanctuaries Act (passed in 1972 to preserve ocean areas and resources) has accomplished. Topics include conserving biological diversity, competing public and salvor interest in cultural resources, achieving integrated coastal management, educational programs in marine protected areas, and sanctuary funding in an age of deficits... and much more.

Preserving nature's gems makes the world a better place for us all. Don't miss this chance to learn more about marine protected areas!

ORDER BACK ISSUES!

What's Still Available?

- Coastal Science & Policy I
  Vol. 36/1, Spring 1993
- Marine Geology & Geophysics
  Vol. 35/4, Winter 1992/93
- Biological Oceanography
  Vol. 35/3, Fall 1992
- Physical Oceanography
  Vol. 35/2, Summer 1992
- Marine Chemistry
  Vol. 35/1, Spring 1992
- Mid-Ocean Ridges
  Vol. 34/4, Winter 1991/92
- Reproductive Adaptations
  Vol. 34/3, Fall 1991
- Naval Oceanography
  Vol. 33/4, Winter 1990/91
- DSV *Alvin*: 25 Years of Discovery
  Vol. 31/4, Winter 1988/89
- and many, many, more...

To place your order, send a check or money order (payable to WHOI) to:

Oceanus Back Issues
WHOI
Woods Hole, MA 02543

Please enclose $9.00 for each magazine ordered ($10 each for orders outside the US, Canada, and Mexico), in US dollars drawn on a US bank. Include a street address and daytime telephone number with your order. Please allow 3 to 4 weeks for delivery.

For information on other available back issues, consult the *Oceanus* editorial offices at the address listed above. Back issues of *Oceanus* are also available on microfilm through University Microfilm International, 300 N. Zeeb Road, Ann Arbor, MI 48106.

U.S. AND CANADIAN SUBSCRIBERS

❑ YES!

Please deliver *Oceanus* to me on a quarterly basis. My address is listed below. Canadian residents, please add $5 to the rates listed.

Please make checks payable to WHOI.

Name

Address

City, State, Zip

❑ Individual $25
❑ Student $20
❑ Library/Institution $35

❑ Payment enclosed

❑ New subscription
❑ Renewal

Mail this postage-paid card or call toll-free to subscribe: 1-800-825-0061

SU93 D

Oceanus

We're making waves in ocean science.

Call Now to Subscribe: 1-800-825-0061.

INTERNATIONAL SUBSCRIBERS

❑ YES!

Please deliver *Oceanus* to me on a quarterly basis. My address is listed below, and I have enclosed a check or money order in pounds sterling payable to Cambridge University Press.

Name

Street address

City, State, Country, Mail code

❑ Individual £25
❑ Student £16
❑ Library/Institution £47
❑ New subscription
❑ Renewal

SU93 I

Oceanus

NO POSTAGE
NECESSARY
IF MAILED
IN THE
UNITED STATES

BUSINESS REPLY MAIL
FIRST-CLASS MAIL PERMIT NO. 21 WOODS HOLE, MA
POSTAGE WILL BE PAID BY ADDRESSEE

OCEANUS MAGAZINE
P.O. BOX 6419
SYRACUSE, NY 13217-7980

Oceanus

Oceanus

Return this card with payment to:

CAMBRIDGE UNIVERSITY PRESS
JOURNALS MARKETING DEPT.
THE EDINBURGH BUILDING
SHAFTESBURY ROAD
CAMBRIDGE CB2 2RU
ENGLAND

MBL/WHOI LIBRARY
WH 183I -

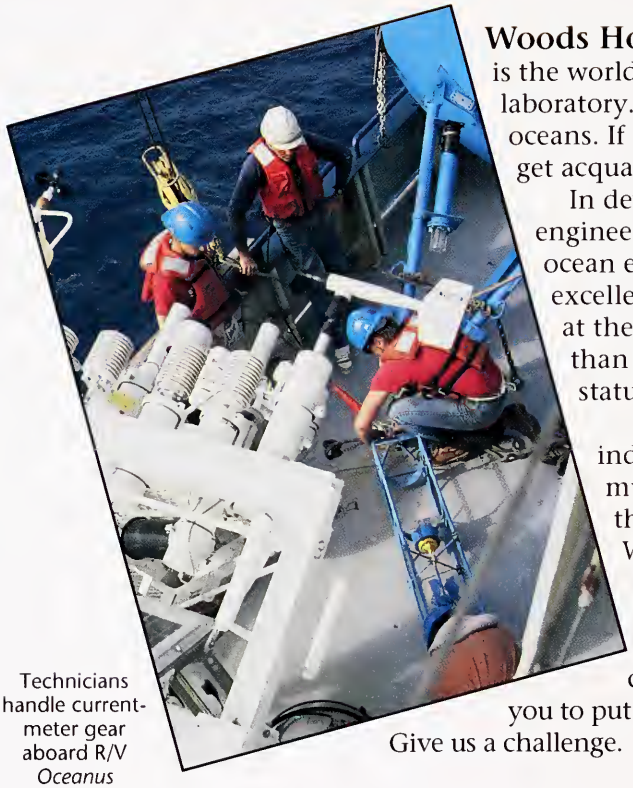
➢ R/V *Western Flyer* ➢

The most innovative of the next generation of US ocean research vessels is *Western Flyer* presently under construction for the Monterey Bay Aquarium Research Institute (MBARI) through funding from the David and Lucille Packard Foundation. The all-aluminum, twin-hull SWATH (Small Waterplane Area Twin Hull) is being built by SWATH Ocean Systems of Chula Vista, California, for January 1995 delivery. The vessel is designed principally as a mother ship for MBARI's new 4,000-meter-depth remotely operated vehicle, also under construction. With its large center well and enhanced stability, the ship should also offer a superior platform for upper-ocean research. Extensive tank tests reveal that SWATH ships are far less motion sensitive than monohulls, enhancing human endurance and the deployment of instrumentation. The ship is 117 feet long, 53 feet wide, and has 24 berths. It will have 3,000-mile transit capability. The vessel's name, *Western Flyer*, derives from MBARI's Cannery Row origins, and the rusty tub taken by John Steinbeck and Doc Rickets to the Sea of Cortez. *Western Flyer* will be outfitted with advanced communication and telemetry systems as part of MBARI's mission for technological innovation in ocean science research and education, and will be based in Moss Landing.

Peter G. Brewer
Director, Monterey Bay
Aquarium Research Institute

SCIENCE + INDUSTRY

AN OCEAN OF OPPORTUNITY



Technicians handle current-meter gear aboard R/V *Oceanus*

Woods Hole Oceanographic Institution is the world's largest independent oceanographic laboratory. Our business is understanding the oceans. If you don't know us yet, we'd like to get acquainted.

In developing oceanographic science, engineering, and operational techniques for ocean exploration, WHOI's tradition of excellence is virtually unmatched. We've been at the forefront of ocean technology for more than 60 years, thanks to our independent status and world-class staff.

Today more than ever, science and industry are relying on one another for mutual benefit. If your business involves the oceans, we'd like to hear from you. At WHOI we are encouraging more collaborations with industry, applying our experiences and talents to new and different problems. If your company can benefit from our expertise, we invite you to put our reputation on the line. Give us a challenge.

Advantages and rewards in the marketplace will go to those who understand the oceans and use them wisely. Working with the oceans is a challenge that can—and must—be met.

WOODS HOLE OCEANOGRAPHIC INSTITUTION
1930

David G. Gallo, Director
Corporate Research & Technology Program
Woods Hole Oceanographic Institution
Woods Hole, MA 02543
(508) 457-2000, ext. 3236 or 2292
fax (508) 457-2189