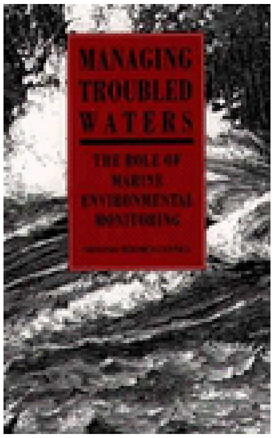

Managing Troubled Waters: The Role of Marine Environmental Monitoring

Committee on a Systems Assessment of Marine Environmental Monitoring, National Research Council

ISBN: 0-309-57173-1, 136 pages, 6 x 9, (1990)

Managing Troubled Waters

The Role of Marine Environmental Monitoring

Committee on a Systems Assessment of
Marine Environmental Monitoring
Marine Board
Commission on Engineering and Technical Systems
National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C. 1990

National Academy Press 2101 Constitution Avenue, N.W. Washington, D.C. 20418

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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The program described in this report was supported by Cooperative Agreement No. 14-12-0001-30416 between the Minerals Management Service of the U.S. Department of Interior and the National Academy of Sciences; Contract No. P-32690 with five California municipalities; and State of California Contract No. 6-213-250-0 with the California State Water Resources Control Board.

Library of Congress Catalog Card Number 89-77742
International Standard Book Number 0-309-04194-5

Printed in the United States of America

COMMITTEE ON A SYSTEMS ASSESSMENT OF MARINE ENVIRONMENTAL MONITORING

DONALD F. BOESCH, *Chairman*, Louisiana Universities Marine Consortium, Chauvin, Louisiana
JERRY R. SCHUBEL, *Vice-Chairman*, State University of New York, Stony Brook, New York
BROCK B. BERNSTEIN, EcoAnalysis, Inc., Ojai, California
WILLIAM M. EICHBAUM, Conservation Foundation, Washington, D.C.
WILLIAM GARBER, City of Los Angeles (retired), Playa Del Rey, California
ALLAN HIRSCH, Dynamac Corporation, Rockville, Maryland
A. FREDERICK HOLLAND, VERSAR, Inc., Columbia, Maryland
KENNETH S. JOHNSON, Moss Landing Marine Laboratory, Moss Landing, California
DONALD J. O'CONNOR, Manhattan College, Glen Rock, New Jersey
LISA SPEER, Natural Resources Defense Council, New York, New York
G. BRUCE WIERSMA, Idaho National Engineering Laboratory, Idaho Falls, Idaho

Staff

CHARLES A. BOOKMAN, Director
CELIA Y. CHEN, Consultant
SHEILA A. MULVIHILL, Editor
AURORE BLECK, Senior Project Assistant

MARINE BOARD

Preface

The modem age has a false sense of superiority because of the great mass of data at its disposal, but the principal advantage of mankind is rather the extent to which he knows how to form the material at his command.

Goethe Maximen und Reflexionen no. 437

BACKGROUND

From the Atlantic to the Pacific coasts of the United States, there have been increasingly frequent reports of closed bathing beaches, restricted shellfish beds, garbage washing up on shorelines, contaminated waters and sediments, oil spills, declining marine environmental quality, and ailing fisheries. The broad public perception of environmental degradation is set against a backdrop of extraordinarily complex natural ecosystem processes that are not fully understood, extensive public and private efforts to protect and restore environmental systems, and great public concern for the environment.

Environmental management efforts have included numerous marine environmental monitoring programs. More than $133 million is spent annually on monitoring programs in the United States in an effort to acquire information for marine environmental management decisions and ultimately to ensure protection of the environment. Monitoring is mandated by various federal, state, and local statutes, including the Federal Water Pollution Control Act; the Marine Protection, Research and Sanctuaries Act; the Outer Continental Shelf Lands Act; and the National Ocean Pollution Research, Development and Monitoring Planning Act. The federal agencies responsible for the implementation of these programs include the Environmental Protection Agency (EPA), the National Oceanic and Atmospheric Administration (NOAA), the U.S. Army Corps of Engineers (COE), and the Minerals Management Service (MMS) of the Department of the Interior. States, local authorities, utilities, and industries that discharge wastes into the coastal ocean conduct extensive marine environmental monitoring as well.

Despite the large expenditure of resources and broad agency participation, scientists, regulators, and monitoring practitioners agree that vast improvements are needed in the design and implementation of monitoring programs. The general perception is that the costs of monitoring programs, as currently conducted, often exceed their utility and benefit. On the other hand, there is a common vision that more appropriately designed and responsive monitoring programs would improve environmental management.

The Marine Board of the National Research Council has examined issues of the effectiveness of marine environmental monitoring in several studies over the past decade. Recognizing the growing need for national guidance on how to improve these monitoring programs, the National Research Council convened the Committee on a Systems Assessment of Marine Environmental Monitoring under the auspices of the Marine Board. Committee members were selected to ensure the wide range of expertise needed and to include a broad spectrum of viewpoints. Members represent the fields of marine environmental science, environmental management, experimental design/decision support systems, measurement systems, and public interest. (Biographies of the committee members appear in Appendix A.) The policy of the National Research Council is to include the biases that might accompany expertise vital to the study in an effort to seek balance and fair treatment.

SCOPE

The committee was asked to evaluate and make recommendations to improve the usefulness of monitoring information by reviewing current monitoring systems and technology, assessing marine environmental monitoring as a component of sound environmental management, and identifying needed improvements in monitoring strategies and practices. To develop its information, the committee commissioned three case studies, reviewed the literature, and drew upon the experience and insights of its members, managers, regulators, and practitioners involved in marine environmental monitoring. Drawing on its collective experience, the committee concentrated on the literature and experiences in monitoring the marine environment. Only selective reference is made to the voluminous literature concerning monitoring freshwater environments.

STUDY METHOD

As one of its first tasks, the committee developed a conceptual model for the design and implementation of monitoring programs and the role of monitoring in marine environmental management. (See Appendix B.) The committee then convened three panels of experts to conduct case studies on marine environmental monitoring of the Chesapeake Bay, monitoring of the Southern California Bight, and disposal of particulate wastes in the oceans. These case studies used the conceptual model in their analyses. (Participants in the case studies are listed in Appendix C.) The panel reports provided a major base of technical information on the national experience in marine environmental monitoring.*

The committee assessed the role of monitoring in environmental management, its institutional dynamics, and the details of technical design and implementation. Because both institutional and technical aspects are interrelated, they need to be considered together in developing strategies for improving the quality and usefulness of marine environmental monitoring.

ORGANIZATION OF THE REPORT

Chapter 1 provides background and justification for the study by discussing the perceived inadequacies of monitoring, identifying the objectives and major thrusts of this report, and descrying the assessment approach in detail. The second chapter discusses the role of monitoring in environmental management, including both benefits and limitations. It examines the institutional setting, the participants, and political influences. Chapter 3 discusses local, regional, and national monitoring and the need for coordination. Chapter 4 addresses the technical design and implementation of monitoring programs and describes a conceptual model for developing more effective and useful programs. The last chapter is the committee's conclusions and recommendations.

ACKNOWLEDGMENTS

The committee benefited greatly from the enthusiasm, wisdom, and hard work of many who monitor and use monitoring information. In addition to those cited as participants in or contributors to the case studies, other experts provided valuable insights along the way. They include Jack W. Anderson, Southern California Coastal Water Research Project; Gordon Beanlands, Canadian Federal Environmental Assessment Review Office;

* Copies of the case studies are available from the Marine Board, 2101 Constitution Avenue, Washington, DC 20418.

Paul Boehm, Arthur D. Little, Inc.; George Jackson, Texas A&M University; Alan Mearns, NOAA; the late Ian Morris, University of Maryland; and Jerry M. Neff, Battelle New England Marine Research Laboratory. Still others helped with early conceptual thinking: they include Donald Au-rand, MMS; Bruce L. Bandurski, International Joint Commission; John A. Calder, NOAA; Michael Champ, The American University; James Clausner, COE; Thomas Fredette, COE; Roger H. Green, University of Western Ontario; Charles W. Hummer, Jr., COE; Orie Loucks, Butler University; Alan Mytelka, Interstate Sanitation Commission; Candace Oviatt, University of Rhode Island; Thomas Patin, COE; Fred Piltz, MMS; James P. Ray, Shell Oil Company; Andrew Robertson, NOAA; Anna Shaughnessy, VERSAR, Inc.; and Kenneth Sherman, National Marine Fisheries Service. The liaisons from the sponsoring agencies were particularly lively contributors to committee discussions: Rosalind E. Cohen, MMS; Tudor Davies, EPA; Charles N. Ehler, NOAA; Robert M. Engler, COE; Susan Hamilton, City of San Diego; David Mathis, COE; John Norton, California State Water Resources Control Board; Craig Wilson, California State Water Resources Control Board; and Robert Zeller, EPA, who helped the committee to see clearly and to think practically.

Contents

Executive Summary

From the Atlantic, Gulf, and Pacific coasts of the United States come increasingly frequent reports of closed bathing beaches, restricted shellfish beds, garbage washing up on shorelines, contaminated waters and sediments, oil spills, declining marine environmental quality, and ailing fisheries. The coastal ocean contains extraordinarily productive natural ecosystems, and all its physical, chemical, and biological processes are not well understood. In addition, the anthropogenic and natural causes of change in this environment are complex and varied, and they occur over different space and time scales.

Protection and restoration of the marine environment have been the subject of intense activity over the past three decades by public officials, scientists, and citizens. Numerous statutes and regulations were adopted by federal and state governments. Billions of dollars were spent on corrective measures, and more than $133 million is spent annually to monitor the condition of the marine environment by federal, state, and local agencies; public utilities; and private corporations.

Marine environmental monitoring has been successfully employed to protect public health through systematic measurement of microbial indicators of fecal pathogens in swimming and shellfish-growing areas, to validate water quality models, and to assess the effectiveness of pollution abatement. But despite these considerable efforts and expenditures, most environmental monitoring programs fail to provide the information needed to understand the condition of the marine environment or to assess the effects of human activity on it. Further, environmental managers are often unable to assure the public that proposed protective or corrective strategies are likely to be successful. The difficulty of obtaining useful information from monitoring programs can be attributed to several factors. First, too often monitoring programs are poorly designed and the technology inappropriately applied. Second, information is rarely presented in a form that is useful in developing broad public policy or evaluating specific control strategies. (On the other hand, a number of estuarine programs directed at selected water quality problems have led to specific control strategies for waste treatment facilities.) A third factor is the very real limits on scientific knowledge and predictive capabilities. This report examines these issues in detail It proposes specific design criteria and makes recommendations about the dissemination of monitoring information. It also proposes a coherent system of regional monitoring upon which control strategies can be based and their effectiveness measured.

This report was prepared by the Committee on a Systems Assessment of Marine Environmental Monitoring of the National Research Council. Marine environmental monitoring is defined as a continuing program of modeling, measurement, analysis, and synthesis that predicts and quantifies environmental conditions or contaminants and incorporates that information effectively into decision making in environmental management.

The committee developed a conceptual model for the design and implementation of monitoring programs and the role of monitoring in marine environmental management. It then convened three panels of experts to conduct case studies on monitoring of the Chesapeake Bay, monitoring of the Southern California Bight, and the disposal of particulate wastes in the oceans. These reports provided the major base of technical information on the national experience in marine environmental monitoring. The committee evaluated the major policy and technical limitations of and opportunities for marine environmental monitoring based on the panel reports, other examples, relevant literature on monitoring strategies, and the collective experience of the members. The report conveys advice on what can be expected from marine environmental monitoring, how monitoring programs should be designed, and how they can supply information that would be more useful in decision making.

The results of marine environmental monitoring are important to a wide range of interests—beachgoers and fishermen, dischargers, engineers, government environmental managers, politicians, scientists, and private citizens. Monitoring information meets many needs:

- Monitoring provides the information needed to evaluate pollution abatement actions.
- Monitoring information can provide an early warning system, allowing for lower-cost solutions to environmental problems.

- Monitoring contributes to knowledge of marine ecosystems and how they are affected by human activity. Such knowledge allows for the establishment of priorities for environmental protection and for the assessment of status and trends.
- Monitoring information helps answer such questions as "Is it safe to swim or eat fish and shellfish?".
- Monitoring information is essential to the construction, adjustment, and verification of quantitative predictive models, which are an important basis for evaluating, developing, and selecting environmental management strategies.
- Monitoring information provides environmental managers the scientific rationale for setting environmental quality standards.
- Monitoring determines compliance with conditions set forth in discharge permits.

Monitoring would become even more useful under a comprehensive national program for documenting environmental status and trends in coastal waters and estuaries. A national program would best combine intensive regional observations and cause-effects studies with a sparser national network of observations. The latter would cover areas not included in intensive regional programs to facilitate regional comparisons and to detect broader-scale trends.

The National Oceanic and Atmospheric Administration's (NOAA) National Status and Trends Program and the Environmental Protection Agency's (EPA) National Estuary Program and proposed Environmental Monitoring and Assessment Program should cooperate to develop an effective national program. Reallocation of compliance monitoring resources could in some cases contribute to the recommended regional monitoring efforts.

Although legislative mandates for this national/regional program may already exist, the administration and Congress should review existing programs and coordinating arrangements and implement those administrative improvements or new legislative direction necessary to support the national system of long-term regional monitoring. Congress should exercise strong oversight of these efforts.

Monitoring programs also need to be better designed and monitoring methods more appropriately applied if they are to meet the expectations of all those who call for them, design them, implement them, and use or rely on the information that they can produce. Monitoring is generally not well coupled with research programs designed to improve the appropriateness of routine measurements and allow interpretation of the implications of monitoring results. Most marine environmental monitoring programs are technically sound; it is the overall design and institutional context that limits the usefulness of the information that results. Sound program design and implementation depend on the following factors:

- The goals and objectives of the monitoring program need to be clearly articulated in terms that pose questions that are meaningful to the public and that provide the basis for scientific investigation.
- Not only must data be gathered, but attention must also be paid to their management, synthesis, interpretation, and analysis.
- Procedures for quality assurance are needed, including scientific peer review.
- Because a well-designed monitoring program results in unanswered questions about environmental processes or human impacts, supportive research should be provided.
- Adequate resources are needed not only for data collection but also for detailed analysis and evaluation over the long term.
- Programs should be sufficiently flexible to allow for their modification where changes in conditions or new information suggests the need.
- Provision should be made to ensure that monitoring information is made available to all interested parties in a form that is useful to them.

In sum, the committee calls for:

- strengthening the role of monitoring in marine environmental management,
- conducting comprehensive monitoring of regional and national status and trends, and
- improving monitoring program design and making information products more useful.

The committee believes that implementation of its recommendations is vital to better protection, restoration, and understanding of the marine environment. Yet it does not wish to overstate the usefulness of monitoring programs. The marine environment is complex and variable, and it is often difficult to detect, identify, and measure anthropogenic impacts clearly. These factors, coupled with limitations to scientific knowledge, emphasize the need for realistic expectations. Environmental managers need to consider the risks and uncertainties inherent in most actions. Risk-free decision making is not possible. When well developed, applied, and used, environmental monitoring can help quantify the magnitude of uncertainty, thereby reducing but not eliminating uncertainty in decision making.

1

Introduction

THE PROBLEM

There is a growing perception that coastal ocean environments in the United States and elsewhere are deteriorating. Recent reports highlight degradation of some coastal marine environments (Office of Technology Assessment [OTA] 1987), and the broad public perception, chronicled in the popular press (Toufexis 1988; Morganthau 1988), is that this deterioration is accelerating and pervasive. The large mortality of bottle-nosed dolphins off the East Coast from the Carolinas to New England during 1987, the banning of many popular sport fisheries in the 1980s, the closure of New York and New Jersey beaches during 1988 due to stranded garbage, trash, and a small amount of medical wastes, continued controversies surrounding offshore oil and gas development, ocean outfalls off California and sewage sludge dumping off New York, extensive closures of shellfish beds around the country, the Valdez oil spill, and a host of other problems along the U.S. coasts have all heightened public concern.

Deterioration in some marine environments is fairly well documented, for example, in terms of loss of coastal wetlands and seagrass beds, contamination of bottom sediments and fish with toxic pollutants in certain harbors, and closure of substantial shellfish beds to harvesting in areas contaminated with human fecal pathogens. However, other perceptions of environmental deterioration and the relationship of certain alarming trends to human activities are not, at this point, supported by available scientific evidence. It is also the case that selected indicators of some severely degraded marine environments, such as Los Angeles-Long Beach Harbor, South San Francisco Bay, the Potomac estuary and Delaware Bay, and New York Harbor, have shown marked improvements as a result of waste control and treatment.

A formidable array of governmental regulations and programs has been set in place to protect or restore marine environmental quality and resources. But continued signs of environmental degradation in some areas point to shortcomings in the availability and use of technical information to predict or detect environmental degradation in relation to either specific or cumulative human activities. Partially as a result of these perceived shortcomings, public policies (involving either action or inaction) are frequently developed in the absence of conclusive scientific evidence relating human activities to presumed environmental effects. Conversely, public policies are sometimes developed too late to prevent widespread environmental damage.

There is a growing need for better technical information on the condition and changes in the condition of the marine environment to guide management and regulatory decisions, verify the efficacy of existing programs, and help shape national policy on marine environmental protection. Regional abatement programs, which involve control of numerous nonpoint as well as point sources, also place greater emphasis on the need for knowledge about the condition of the environment. Environmental monitoring is one approach to gathering technical information indicative of the condition of the marine environment. Monitoring is also a useful tool for judging whether protective or restorative steps are warranted or are effective.

GOALS AND OBJECTIVES OF THIS STUDY

The ultimate goal of the present study is to improve the usefulness of monitoring information. To this end, the committee sought to: review the current status of monitoring systems and technology, assess marine environmental monitoring as a component of sound environmental management, and identify needed improvements in monitoring strategies and practices.

This report is especially directed toward legislators at all levels; officers of regulatory and resource management agencies, public utilities, and industries; and technical service staff and contractors whose responsibility it is to require, specify, or design marine environmental monitoring or to interpret or apply its results. It is not a scientific review of the adequacy of marine environmental monitoring; nor is it a program-specific critique of monitoring practices. Its orientation is more forward looking than retrospectively critical. Its aim is to advise on what can be expected from marine environmental monitoring, how it should be designed, and how it can supply information more useful in decision making. Many excellent works provide advice on the design and implementation Of environmental monitoring (e.g., Holling 1978; Green 1979; Beanlands and Duinker 1983; Fritz, Rago, and Murarka 1980; Rosenberg et al. 1981). This report strives to make the best advice more widely accessible and to place its recommendations in the broad framework of environmental management and policy.

MARINE ENVIRONMENTAL MONITORING

Environmental monitoring is frequently conducted to assess the status of the marine environment, detect changes in its status, and guard against the deleterious effects of specific activities, such as waste disposal. Organizations required to conduct monitoring, regulatory agencies, the scientific community, decision makers, and public interest groups have all questioned the adequacy and usefulness of marine environmental monitoring programs. Their criticisms deal with both the technical adequacy of the monitoring per se and the usefulness of results in sound environmental management—in other words, with the entire environmental monitoring system. In view of these concerns, the Marine Board of the National Research Council established a Committee on a Systems Assessment of Marine Environmental Monitoring to assess monitoring programs as they are currently practiced and applied and to make recommendations for improving them.

Monitoring is defined in many ways (e.g., Considine 1983; Interagency Committee on Ocean Pollution Research, Development, and Monitoring 1979) and has many historical uses, usually with an emphasis on the repeated nature of the measurements (time-series). For this assessment, the committee viewed monitoring as a component of an environmental management system. This definition necessarily includes the regulatory, institutional, and decision-making aspects of environmental problems, thus focusing committee attention on the features of monitoring programs that either enhance or detract from their capability to supply information needed for environmental management. Within this context, the committee then defined "marine environmental monitoring system" as a range of activities needed to provide management information about environmental conditions or contaminants. Depending on the requirements of any particular situation, these activities could include conceptual and numerical modeling, laboratory and field research, preliminary or scoping studies, time-series measurements, data analysis, synthesis, and interpretation. What distinguishes a monitoring system from any of these activities taken alone is that a monitoring system is integrated and coordinated with the specified goal of producing predefined management information; it is the sensory component of environmental management. This broader view of a monitoring system enabled the committee to address more fully the question of how the range of available scientific and technical tools could best be used to enhance marine environmental monitoring.

Although monitoring is conducted for various purposes, it is generally intended to produce information about three broad categories of problems: (1) compliance, to ensure that activities are carried out in accordance with regulations and permit requirements; (2) model verification, to check the validity of assumptions and predictions used as the basis for sampling design or permitting and for evaluation of management alternatives; and (3) trend monitoring, to identify and quantify longer-term environmental changes anticipated (hypothesized) as possible consequences of human activities. Modeling for compliance and model verification are implicitly tied to specific management actions, whereas trends monitoring may be conducted for the less-directed purposes of surveillance (*sensu* Helawell 1978), which may be carried out in the absence of an identified need for decision making. The committee uses the term monitoring in a broad sense to include all such activities used to evaluate whether environmental management goals are being met.

Not included in the committee's operational definition of marine monitoring are continuing observations of environmental conditions for purposes other than assessing marine environmental quality, for example, measuring water levels and assessing fishery stocks for management of their exploitation.

Marine environmental monitoring is conducted by federal, state, and local agencies; waste dischargers; and researchers. At the federal level, various statutes require monitoring to be conducted. (See Table 1.1.)

Five federal agencies conduct environmental quality monitoring activities in the coastal ocean: National Oceanic and Atmospheric Administration (NOAA), Environmental Protection Agency (EPA), U.S. Army Corps of Engineers (COE), U.S. Coast Guard (USCG), and Minerals Management Service (MMS) of the Department of the Interior (DOI). Each of these agencies focuses on different space scales, ranging from effluent discharges from individual sources (point sources) and their short-term effects at a site-specific scale (e.g., EPA's National Pollutant Discharge Elimination System [NPDES] monitoring programs and COE's Dredged Area Monitoring System [DAMOS]) to measuring the far-field, long-term elects of discharges from multiple (nonpoint) sources on the coastal environment (e.g., NOAA's National Status and Trends [NS&T] Program). Both COE (dredged material disposal) and MMS (offshore oil and gas platforms) conduct monitoring for specific pollution sources.

Most agencies (e.g., EPA, COE, and USCG) conduct or require monitoring to ensure *compliance* with permit conditions specified under the authorities of the Clean Water Act (EPA), Title I of the Marine Protection, Research, and Sanctuaries Act (MPRSA) (EPA, COE, and USCG), and the Outer Continental Shelf Lands Act amendments (MMS). Others conduct long-term *trends monitoring* at different space scales (e.g., COE at the site-specific level, EPA at the regional scale through efforts such as its Chesapeake Bay and Great Lakes programs, MMS through regional environmental studies programs, and NOAA at the national level). All these agencies, except USCG, conduct field monitoring to test research hypotheses and verify models.

TABLE 1.1 Federal Mandates for Marine Environmental Monitoring

Date	Title	Number
1890	Rivers and Harbors Act	
1894	Rivers and Harbors Act (the "Refuse Acts")	
1899	Rivers and Harbors Act	
1948	Federal Water Pollution Control Act (FWPCA or the "Clean Water Act")	PL 80-845
1953	Outer Continental Shelf Lands Act (OCSLA)	PL 83-212
1956	FWPCA amendments	PL 84-660
1961	FWPCA amendments	PL 87-88
1965	FWPCA amendments	PL 89-234
1966	FWPCA amendments	PL 89-753
1970	National Environmental Policy Act of 1969 (NEPA)	PL 91-190
1970	Water Quality Improvement Act	PL 91-224
1972	Federal Water Pollution Control Act (major amendments)	PL 92-500
1972	Marine Protection, Research, and Sanctuaries Act (MPRSA or the "Ocean Dumping Act")	PL 92-532
1974	MPRSA amendments	PL 93-254
1975	Deep Water Port Act	PL 93-627
1977	MPRSA reauthorization	PL 95-153
1977	FWPCA major amendments	PL 95-217
1978	National Ocean Pollution Research, Development, and Monitoring Planning Act of 1978	PL 95-273
1978	OCSLA amendments	PL 95-372
1978	FWPCA amendments	PL 95-576
1980	Clean Water Act (FWPCA amendments)	PL 96-483
1985	Clean Water Act amendments (national)	PL 99-160
1986	Consolidated Omnibus Budget Reconciliation Act (MPRSA amendments)	PL 99-272
1987	Water Quality Act (reauthorization and amendment of Clean Water Act)	PL 100-4
1988	Ocean Dumping Ban Act	PL 100-688

SOURCE: Adapted and updated from Environmental Protection Agency (1982).

The roles and responsibilities of the agencies as they relate to marine environmental monitoring are summarized in Table 1.2.

EPA, in cooperation with other federal agencies, is required by the Federal Water Pollution Control Act to "establish . . . and maintain a water quality surveillance system for the purpose of monitoring the quality of navigable waters . . . for the contiguous zone and the oceans."

NOAA, in coordination with EPA and USCG, is required by the Marine Protection, Research, and Sanctuaries Act to "initiate a comprehensive and continuing program of monitoring and research regarding the effects of the dumping of material into ocean waters . . . or the Great Lakes."

DOI, under the Outer Continental Shelf Lands Act, is required to "monitor the human, marine, and coastal environments of such area or region (OCS [outer continental shelf] oil and gas leasing area) in a manner designed to provide time-series and data trend information which can be used for . . . the purpose of identifying any significant changes in quality and productivity of such environments, for establishing trends in the areas studied and monitored, and for designing experiments to identify the causes of such changes."

MARINE ENVIRONMENTAL MONITORING EXPENDITURES

How much is spent is not an easy question to answer because of the various sectors involved (federal, state, and local government bodies and the private sector) and because of the widely varied scope of monitoring. The committee attempted to estimate the level of expenditures for marine environmental monitoring, not to quantify these costs rigorously but to put them in context. Estimates were obtained from the following sources: annual reports prepared for Congress by NOAA on ocean pollution, monitoring, and research; annual summaries of federal programs and projects related to marine pollution (e.g., Battelle 1984); periodio inventories of nonfederally funded marine pollution research, development, and monitoring activities (e.g., Battelle 1984); and a telephone survey of federal, state, local, and private organizations known to have monitoring

TABLE 1.2 Agency Roles in Marine Environmental Monitoring

	NOAA	EPA	COE	USCG	MMS
Type of Monitoring					
Compliance		X	X	X	X
Trends	X	X	X		X
Model validation/research	X	X	X		X
Space Scale					
Local		X	X	X	X
Regional	X	X			X
National	X				

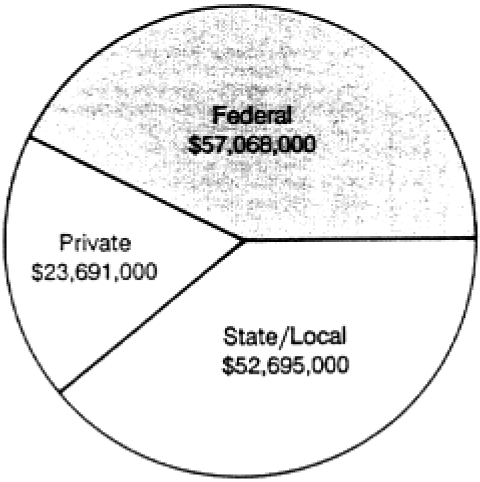

Figure 1.1
Estimated costs of U.S. marine monitoring programs.

responsibilities and programs in the coastal zone. These cost data were used to estimate average annual monitoring costs for 1985-1987 by sector and federal agency. The estimates include all types of monitoring activities (i.e., data collection, laboratory processing, data management, analysis, interpretation, and synthesis). Also included are the costs of baseline surveys designed as benchmarks for future studies.

Marine monitoring programs in the United States cost at least $133 million annually.[1] Federal agencies accounted for 43 percent of the total, state and local agencies 37 percent, and the private sector 18 percent, as shown in Figure 1.1. Within the federal sector, EPA accounted for 42 percent; other major contributors were the Department of Defense (mainly COE), MMS, NOAA, and the U.S. Geological Survey (USGS). EPA's relatively high proportion of the total federal expenditures results from its many compliance monitoring programs associated with permitting and enforcement programs. (See Figure 1.2.)

Expenditures on marine environmental monitoring vary greatly among state and local agencies. States with the largest agency expenditures are California, Florida, New York, Maryland, Washington, Texas, and Virginia;

[1] Another way of estimating monitoring expenditures is to apply certain assumptions to data on expenditures for water regulation and monitoring reported by the Bureau of Economic Analysis (BEA) of the Department of Commerce (Bureau of the Census 1987). BEA estimates that $451 million was spent nationally on water regulation and monitoring in 1985. As explained subsequently in the text, 33 percent ± 10 percent of those expenditures can be assumed to have been in coastal areas. Thus the range of expenditures for water regulation and monitoring in coastal areas in 1985 was $104 million-$194 million.

all spend in excess of $5 million annually. (See Figure 1.3.) A substantial portion of state and local efforts is directed toward the protection of public health, including measurement of contaminants and human pathogens in water, sediments, and fish and shellfish tissues. They are probably underestimates because data on the costs of many local programs were not available. As a result, the state and local (including municipal utility) expenditures are probably underestimated by a factor of at least two.

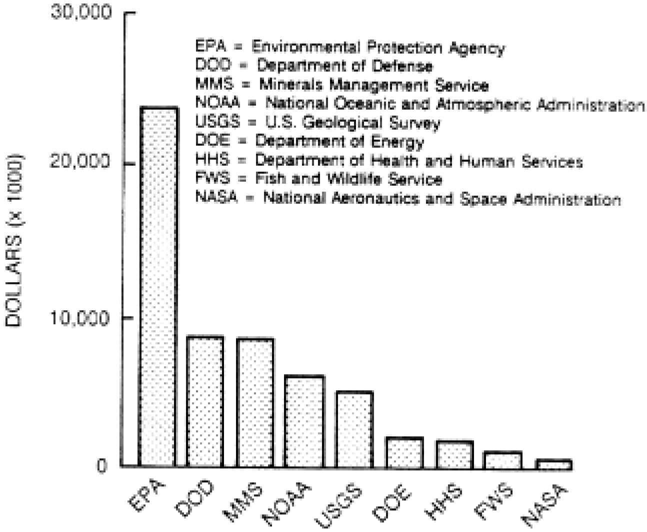

Figure 1.2
Estimated costs of marine monitoring programs, by federal agency.

Accurate estimates of private sector monitoring expenditures were not obtained for any state. These costs are poorly reported, and individuals with the information could not be identified for all industries in all states. Within the private sector, monitoring programs associated with electric power production, oil and gas development, the chemical industry, and coastal development account for most of the expenditures. Private sector monitoring expenditures are frequently on the same order of magnitude as those of state and local governments. The figures shown in Figure 1.3 are mainly associated with the electric power production industry, and even they are accurate for only a few states (i.e., California, New York, Maryland, New Hampshire, and Connecticut). No estimates of the costs of marine environmental monitoring for the oil and gas development or chemical industries could be obtained. The private sector cost estimates are therefore greatly underestimated.

Although the $133 million national expenditure minimum for marine environmental monitoring by all sectors is certainly large, it is helpful to

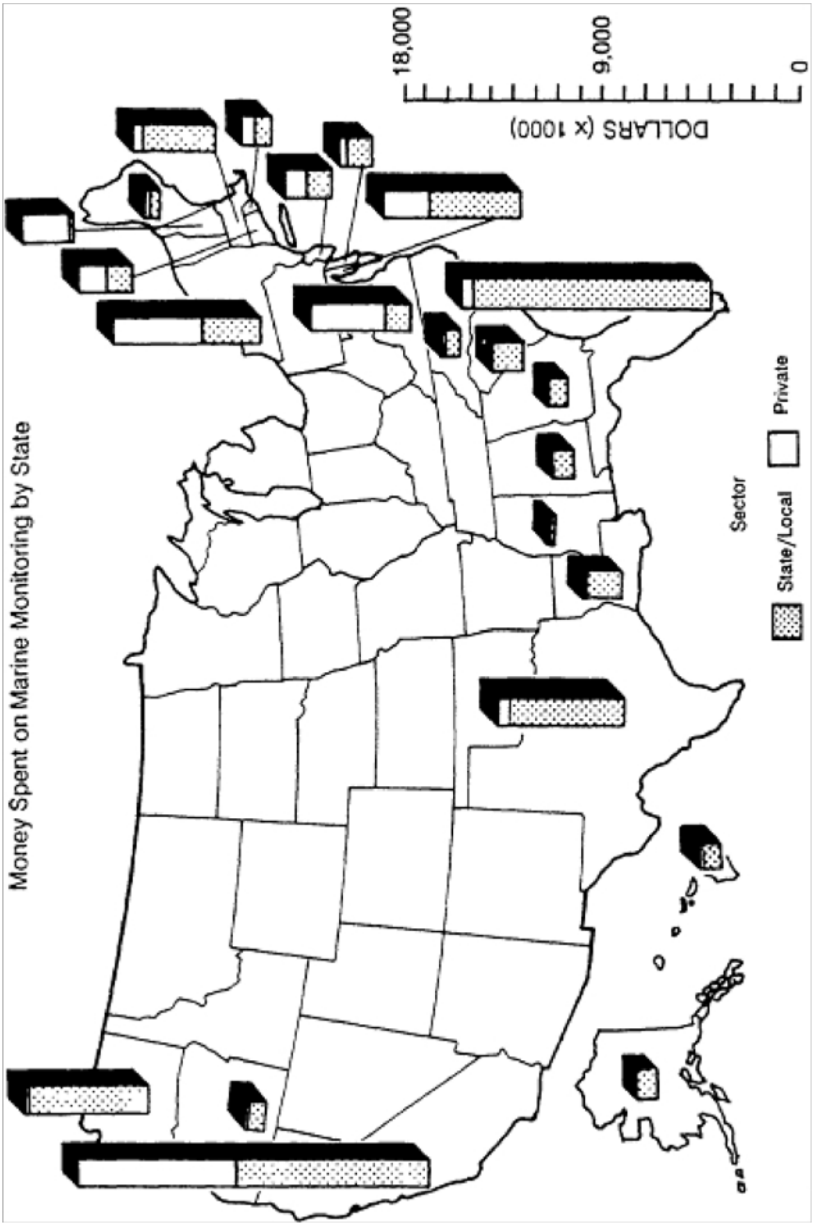

Figure 1.3
Estimated costs of marine monitoring programs, by state (for state/local governmental agencies) and the private sector.

TABLE 1.3 Pollutant Abatement Expenditures for Publicly Owned Treatment Works and Industrial Point Source Facilities, 1985

Activity'	Cost[a] ($ billion)
Publicly owned treatment works (POTWs) construction	$ 6.71
POTW operations and maintenance (O&M)	5.95
Industrial point source facility construction	2.94
Industrial point source facility O&M	5.04
Total	$20.64

[a]In constant 1982 dollars.
SOURCE: Bureau of the Census (1987), Table 340, p. 195.

this expenditure in context. Annual expenditures for pollution control are orders of magnitude larger. The Bureau of Economic Analysis estimates *national* water pollution control expenditures each year.[2] In 1985, total spending for water pollution abatement was about $20.6 billion (in constant 1982 dollars), up about 15 percent from $21.2 billion in 1982. Spending for water pollution abatement at point sources was $20.6 billion in 1985; pollution abatement at nonpoint sources was about $3.8 billion.

Almost 85 percent of all water pollution abatement expenditures were for publicly owned treatment works (POTWs) and industrial point sources. (See Table 1.3.) For a rough estimate of coastal area expenditures, it is appropriate to multiply each of the figures by 33 percent ± 10 percent.[3] The basis for doing so is the fact that about 28 percent of the POTWs with a capacity exceeding I million gallons/day (mgd) are located in coastal counties, and about 40 percent of the total wastewater flow from POTWs with a capacity greater than I mgd is from facilities located in coastal counties.

Only 9 percent of NPDES-permitted industrial point sources are located in coastal counties. However, approximately 32 percent of total industrial process wastewater discharged nationwide is within coastal counties, where many of the big water users (e.g., refineries, petrochemical plants, and pulp and paper plants) are located. Table 1.4 uses these assumptions in a first approximation of expenditures (in constant 1982 dollars) on point source pollution abatement in coastal areas. Thus, using the figures in Tables 1.3 and 1.4, one can see that the nation spends about 2 cents on monitoring out of every dollar spent on pollution abatement.

[2] Unfortunately, these estimates cannot be disaggregated by county for a comparison of coastal and non coastal expenditures; nor can they be disaggregated by state.

[3] The committee is indebted to C. N. Ehler, NOAA, for the data and assumptions that follow.

PERCEIVED INADEQUACIES OF MONITORING

Despite considerable effort and expenditures, monitoring programs have been criticized for failing not only to provide adequate information for environmental management decisions but also to resolve controversies related to specific waste discharges and to ensure environmental protection and restoration in the face of multiple impacts. The underlying issues related to these perceived inadequacies may be seen as institutional or technical or a mix of the two.

The lack of communication and coordination among the entities sponsoring or conducting monitoring and making environmental management decisions inhibits the proper design of monitoring programs and limits the usefulness of monitoring results. Inflexible regulatory requirements also limit opportunities to adapt programs to new needs. In some cases, uncertainties about institutional and financial support affect program usefulness, particularly with respect to long-term monitoring.

Major unresolved problems remain with respect to the design of technically sound sampling schemes that can detect change and separate human effects from natural variability. Further, it is frequently difficult to quantify and interpret observed effects in terms meaningful to society. Monitoring programs are usually not closely linked with research programs or other sources of contamination and disturbance information designed to identify sources and to understand the transport, fate, and effects of wastes or to elucidate natural environmental processes. Without this type of information, interpretation of monitoring results in terms that are useful to the public and decision makers is not possible.

TABLE 1.4 A First Approximation of Pollution Abatement Expenditures in Coastal Areas, 1985

Activity	Cost[a] ($ billion)
Publicly owned treatment works (POTWs) construction	$1.5-2.9
POTW operations and maintenance (O&M)	1.4-2.5
Industrial point source facility construction	0.7-1.2
Industrial point source facility O&M	1.2-2.2
Total	$4.8-8.8

[a]In constant 1982 dollars.

SOURCE: C. N. Ehler, based on the Bureau of the Census (1987), Table 340, p. 195.

Another shortcoming is that monitoring programs are often not designed to address public concerns directly or to provide information needed by management or public policy makers. Meaningful communication with, and participation of, the public and decision makers in the development of monitoring programs is rarely achieved. Results are often not reported at all; when they are, they may not be in a useful form.

ASSESSMENT APPROACH

Conceptual Model

To provide a common and comprehensive basis for evaluating marine environmental monitoring programs and generate recommendations that deal with the perceived problems of monitoring as it is practiced, the committee developed a conceptual model of the design and implementation of a marine environmental monitoring system (see Figure 1.4 and Appendix B). The conceptual model was sketched out following meetings with federal agency representatives, scientists, and engineers familiar with marine environmental monitoring programs. It included the regulatory, institutional, and decision-making interactions that affect the genesis and use of monitoring information. It was further refined by a review of the literature dealing with the philosophy and design of monitoring and collective deliberations of the committee.

Figure 1.4 depicts the ideal relationship between those who require monitoring information and those who supply it. The figure does not distinguish among the various types and purposes of monitoring (compliance, model verification, and trends) or the space and time scales over which monitoring is conducted (site-specific, regional, and national; short-term, long-term); it is generally applicable to all types and scales. The degree to which each component in Figure 1.4 has a major role in the development, implementation, and use of monitoring information and the importance of feedbacks, however, vary with the type of monitoring and the scale. All components are important for regional and national trends monitoring, whereas technical design components are more important for short-term compliance monitoring.

Deficiencies in monitoring strategies usually result from failure to consider one or more elements of the model or from considering them out of logical sequence or context. Implicit in the model is the establishment of specific objectives based on how monitoring information will be used in decision making. Also implicit is the development of a technical design significantly rigorous to provide this information. The shaded portion of the figure shows the components that are controlled by scientists and engineers developing and implementing technical designs. Use of monitoring results is reflected as a feedback loop to the institutional setting and decision-making functions. The feedback loops in Figure 1.4 describe the flow of information into higher elements of the framework. The information may influence policies, management actions, monitoring design, research, or modeling.

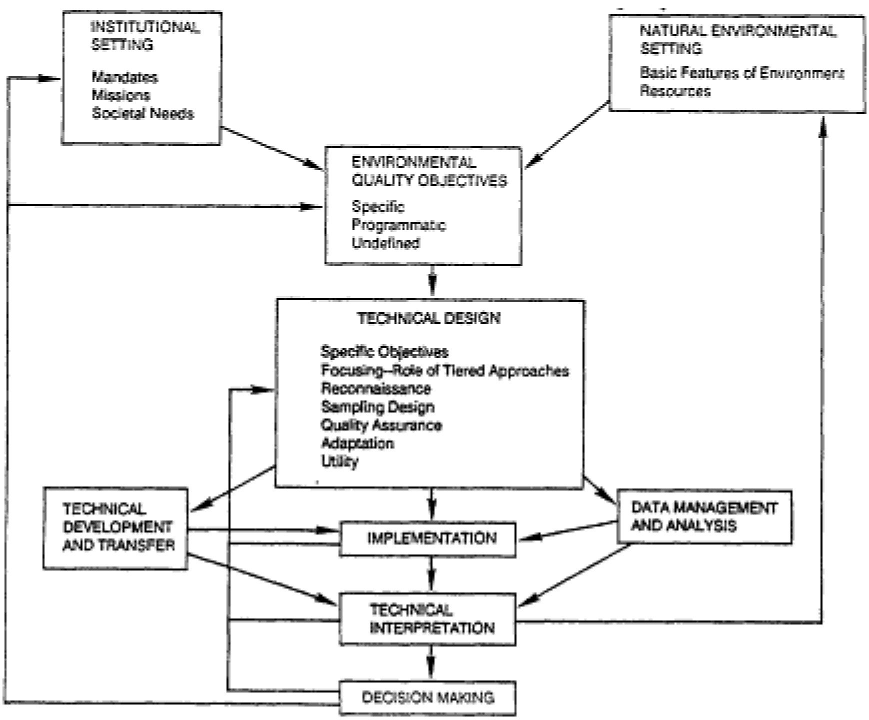

Figure 1.4
A conceptual model of marine environmental monitoring systems.

The committee considered the idealized processes shown in each box in Figure 1.4 and, specifically, the interconnections among boxes. A set of specific questions was then developed for each box. (See Appendix B.)

Case Studies

Listing all current marine environmental monitoring programs, much less evaluating them, is not possible. Instead, a case study approach was adopted to assess classes of monitoring programs in depth. The committee evaluated case study candidates on the basis of their feasibility and national significance, potential for the case study results to inspire improvements, and balance among case study types. Two of the three chosen involve important geographic regions: the Chesapeake Bay, a large estuarine system with a newly implemented regional monitoring program, and the Southern California Bight, a coastal ecosystem with extensive but uncoordinated monitoring programs. The Southern California case study allowed evaluation of whether monitoring specific activities in a region influenced by multiple human activities was adequate for detecting cumulative impacts on the region. Selecting the Chesapeake Bay allowed comparison of coordinated regional monitoring, such as exists there, with extensive source-specific monitoring programs that characterize the Southern California Bight. The third selection is not region specific; it evaluates monitoring efforts associated with the disposal of particulate wastes such as dredged material, sewage sludge, and drilling discharges in coastal environments.

Integration of Information

Within the conceptual model, the committee evaluated the major policy and technical limitations and opportunities of marine environmental monitoring based on the results of the case studies, other examples, relevant literature on monitoring strategies, and the collective experience of the members. In this report, the committee first places monitoring in the context of environmental management by answering the question "Why monitor?" and evaluating the contributions to and shortcomings of monitoring for environmental management. Next are discussed the institutional dynamics of monitoring: public perceptions, political pressures, legal constraints, and resource limitations influencing monitoring (Chapter 2). The role of and needs for monitoring at different space scales—local, regional, and national—are evaluated in Chapter 3. The technical design and implementation of monitoring are a major focus of Chapter 4, including the steps involved in the development of sampling and measurement design, from the initial management goals and objectives to technological innovation to the conversion of resulting data into information useful in decision making.

2

The Role of Monitoring in Environmental Management

THE IMPORTANCE OF MONITORING

Why Monitor?

The ultimate goal of environmental monitoring of all kinds—compliance, model validation and verification, and trends—is protection of the environment, living resources, and human health. Monitoring provides information that is useful in managing the environment, its resources, or human activities affecting them. Environmental monitoring data document existing conditions and, if collected repeatedly, chronicle changes in these conditions. Absent knowledge of prior environmental conditions, monitoring establishes a starting point for future comparisons.

Monitoring is most beneficial when it results in more effective management decisions—decisions that protect or rehabilitate the marine environment, its living resources, and uses or resources that society considers important. For example, monitoring coliform bacteria as an indicator of human fecal contamination has been an effective public health measure for decades, triggering direct management actions to close beaches to swimming or shellfish beds to harvesting or to eliminate or improve the treatment of sewage discharges. Other uses of monitoring results include:

- Providing environmental managers with a rationale for setting standards. When monitoring results show a clear change or trend, for example, a reduction in fish abundance, public confidence in the decision maker's limits on catches is enhanced.

- Constructing, adjusting, and verifying quantitative predictive models that can be the basic tool used in evaluating and selecting management strategies.
- Determining compliance with regulations and conditions set by permits.
- Providing the information needed to evaluate pollution abatement programs.
- Early warning of future problems when they can be resolved more easily and at lower cost than if left unattended. Although monitoring cannot guarantee early detection of problems, it can reduce the probability of unpleasant surprises.
- Enhancing knowledge of marine ecosystems, their variability, and society's impacts on them. With this information, managers can shift priorities and reallocate resources when necessary to match the management agency's resources with important and tractable environmental problems.
- Engendering a better understanding of the health of the marine environment. Decision makers and the public want answers to pressing questions. Is water quality getting better or worse? Are fish and shellfish increasing or decreasing in abundance? Is it safe to swim? To eat the fish? Are conditions stressful to marine organisms increasing or decreasing in frequency, extent, and duration?

The Costs of Not Monitoring

The costs of not monitoring—or of monitoring ineffectively—include failure to obtain the information needed to assess environmental conditions, to validate and verify predictive models, and to chronicle changes in the environment resulting from natural variations, management actions, and pollution impacts. In short, the cost of not adequately monitoring is a serious shortcoming in our efforts to protect and restore marine environmental quality.

The economic, social, and political costs of failing to detect and deal with environmental problems in the early stages can be enormous. Economically, correcting problems after the environment is seriously degraded adds to the costs. But some degradation may be irreparable: living resources may be so depleted and habitats so damaged that stocks of commercially and recreationally important species may never return to predegradation levels. Public health problems can arise, with attendant economic and social consequences. Public opposition and anger may increase with sudden news that beaches are unsafe for swimming or fish and shellfish are unsafe to eat. Government agencies and their officials may be blamed for neglect or short-sightedness.

Limitations of Monitoring

It is important not to overstate the usefulness of monitoring programs. The marine environment is complex and variable. In coastal regions, separating impacts of human origin from natural variability is difficult. This difficulty and others do not argue against monitoring the marine environment, but they do make the case for realistic expectations, careful and critical experimental design, periodic evaluations, and a constancy of commitment.

Often the causes of environmental problems, whether natural or human-induced, cannot be identified unequivocally even with data and information gathered from well-designed monitoring programs. A recent example of the limitations of monitoring in effectively addressing public concerns is the issue of ocean dumping in the New York Bight. During the summer of 1988, stranded wastes on beaches, unusual deaths of dolphins, diminished fish stocks, and reports of lesions on the shells of crabs and lobsters elevated public suspicion that the culprit was dumping of sewage sludge, the approved site for which had recently been relocated from 12 miles to 106 miles offshore. Despite an extensive background of studies of ocean dumping in the New York Bight and the considerable monitoring being conducted, it was not possible to say without doubt whether the observed phenomena were clue to ocean dumping or other causes. Reflecting the public's concerns, Congress acted swiftly by passing the Ocean Dumping Ban Act of 1988. Although it can be argued that an improved or more extensive monitoring program could have resolved the issue more effectively, the example points out the inherent limitations of monitoring in linking unexpected phenomena to their causes. The complexities of the problems, variability in natural systems, and the time needed to conduct research and acquire information on marine processes and systems make absolute determinations extremely difficult.

Risk-free decision making is an impossible goal. Monitoring programs can narrow uncertainty, not eliminate it. They can contribute to understanding change and to ascribing causes to these changes, and their results are useful in weighing the societal benefits of management alternatives.

The Evolution of Monitoring

Over the past two decades, several studies closely evaluated monitoring and criticized its lack of quality assurance and cohesiveness and its ability to provide information that answered decision makers' questions (e.g., Wolfe 1988; Beanlands and Duinker 1983, 1984; Walters 1986; Cairns, Dickson, and Maki 1978). Partly because of these evaluations and partly because of environmental awareness and regulation, monitoring has improved. Because they are required by law or regulation, many compliance monitoring programs now enjoy secure funding. As a result, these programs have been refined to include a high level of quality control, consistency in sampling and analytical techniques, and clearer presentations and syntheses of data and conclusions. This fact has attracted many qualified scientists to some of the larger monitoring programs.

Perhaps the best. example of this evolution is in Southern California, where compliance monitoring around wastewater outfalls began in the 1950s. Initially, the programs, implemented by municipal wastewater treatment authorities, suffered from lack of staff training, little support or recognition from funding agencies, and inadequate equipment. In 1969, the large dischargers formed the Southern California Coastal Water Research Project (SCCWRP), which introduced the concept of regionwide quality assurance. As a result, staff members from the publicly owned treatment works (POTWs) shared ideas, trained new employees, developed new and improved equipment and techniques, and worked with researchers at SCCWRP to develop technologies and approaches to synthesize and summarize findings.

Success Stories in Monitoring

The following examples of monitoring to protect public health, validate water quality models, and evaluate pollution abatement have two common characteristics. In all cases, monitoring provided clear and important input to management decisions, and it was targeted at issues that the public and decision makers recognized as important. These examples relate primarily to the impacts of point sources on estuarine water quality and the improvements effected by waste treatment facilities. They demonstrate other factors that led to successful monitoring: the specificity of the water quality problem, a relatively well-defined estuarine system, the availability of historical data, the collection of additional data relevant to the problem, and, most important, an understanding and quantification of the relation between mass emissions from human-induced and natural sources and the environmental response. For broader issues in the marine environment, many of these elements are lacking, particularly adequate historical data and an understanding of ecosystem responses.

Protecting Public Health

During the 1920s, prior to the National Shellfish Sanitation Program and the extensive monitoring of fecal coliform bacteria in shellfish-growing waters, gastroenteritis and hepatitis periodically caused significant public health problems. Besides using coliform counts for closing shellfish beds to direct harvest, the abundance of fecal coliform bacteria is also used for closing or limiting the use of bathing beaches and requiring waste treatment. There continues to be a debate over the appropriateness of the coliform standard as an indicator of the possible presence of pathogens, but outbreaks of gastroenteritis and hepatitis associated with the consumption of shellfish are now rare. Although there is need to develop methods that more directly measure the pathogens of concern rather than using an indicator organism, *Escherichia coli* , it is clear that much illness has been avoided by fecal coliform monitoring. Needed improvements in pathogen detection could allow beach-closing decisions to be more specific to local conditions, and they offer the possibility of opening shellfish beds to harvest should the coliform standards prove to be too conservative.

Validating Models: Examples from Modeling Estuarine Water Quality

One measure of successful monitoring is its contribution to better management decisions. An important use of monitoring results is to calibrate, validate, and verify mathematical models used to forecast the consequences of implementing different management strategies. Because predictive/deterministic models express our understanding of how ecosystems typically function and respond to stress, monitoring to validate models and verify predictions is essential for improving that understanding. Models validated with monitoring data may be used to select a management option.

Water quality modeling, which initially focused on biological oxygen demand (BOD), dissolved oxygen (DO), coliform bacteria, and other traditional parameters, has become increasingly sophisticated in recent decades. The original contribution of Streeter and Phelps (1926) on DO in freshwater streams was used to determine the degree of wastewater treatment required to maintain acceptable levels in the Ohio River. These basic concepts were incorporated in estuarine water analyses (O'Connor 1960; Thoman 1963; Hetling and O'Connell 1967) and subsequently extended to incorporate problems associated with eutrophication (DiToro, O'Connor, and Thoman 1971). Efforts are now directed to the transport and fate, including accumulation in food webs, of toxic substances. Application of these concepts to water quality planning was initially directed to reducing input from point sources. Increased understanding of the basic phenomena affecting water quality is now providing a basis for analyzing the effects of nonpoint sources. Monitoring has been used for water quality model validation and subsequent planning in many estuarine systems throughout the country (e.g., Boston and New York harbors, the James River, the Sacramento-San Joaquin Delta, and the Potomac and Delaware estuaries).

In Boston Harbor, a water quality model validated by monitoring data for pre- and post-treatment conditions was used to evaluate the relative impacts of treatment plant effluents, sludge discharges, and stormwater overflows. The data were collected after upgraded treatment facilities had been installed; the significant improvement in water quality with reference to bacterial concentration was consistent with model calculations. The model was then used to define the relative effects of sludge discharges and stormwater overflows. Thus the monitoring data, with the model, were a tool for assessing additional remedial measures.

New York Harbor monitoring data were used in mathematical models to forecast DO levels expected with construction of new wastewater treatment plants. These models helped in planning the upgrade and installation of treatment facilities. After the plants were in operation, the predicted improvements in DO compared well with observed conditions. The models were subsequently used in evaluating additional upgrading of the waste treatment plants and preliminarily assessing the impacts of combined sewer overflows and urban runoff on water quality. As a component of an ongoing management program that is addressing these nonpoint problems, more recent monitoring data will be used to improve the model.

Numerical models of the James River, a tributary estuary of the Chesapeake Bay, used monitoring data in support of management decisions about whether to attempt to remove kepone-contaminated sediments or to leave them in place to be buried naturally and how to conduct maintenance dredging of navigation channels.

In the Sacramento-San Joaquin Delta, estuary monitoring data were used to calibrate and verify mathematical model prediction of salinity distribution as it might be influenced by freshwater diversions from San Francisco Bay. These model results have been considered in major decisions regarding the allocation of freshwater resources in California. Similar models have been applied to Texas estuaries in freshwater resource allocation decisions.

Modeling the effects of freshwater diversion of the Sacramento River on the eutrophication of the Sacramento-San Joaquin Delta began in the early 1970s. Initial field measurements provided the data to calibrate a model of the nutrient-phytoplankton ratio, which was used to establish the monitoring program. Validation of the model with subsequent data yielded results in general accord with the observations. During the extreme drought of 1976-1977, however, the salinity level rose, disrupting phytoplankton levels and markedly affecting other levels in the food chain. These effects were not anticipated by the model because the scientific understanding of this complex physical and biological interaction was lacking.

Monitoring data supplemented by experiments helped scientists understand the changes that had occurred. Monitoring data provided the basis for introducing in the model a new variable to account for observed changes. The improved model provided a quantitative means consistent with scientific understanding of analyzing the reduced productivity under conditions of increased salinity intrusion. This example demonstrates the interaction and feedback between the research and applied elements of a program that go on as the scientific understanding of environmental phenomena increases. It further exemplifies the need for flexibility in the continuous development of monitoring and modeling with respect to the collection of field data, the design of laboratory experiments, and the synthesis of the results. This interaction is fundamental to any water quality monitoring program, as are the close cooperation and open communication among the scientists and engineers representing these areas of expertise. Both flexibility and parallel development of monitoring and modeling are needed to validate the model.

Assessing the Effectiveness of Pollution Abatement

A classic example of monitoring the effectiveness of pollution abatement in the coastal environment concerns improvements in water quality and recovery of biological populations in the Thames estuary below London (Gameson and Wheeler 1977; Thames Survey 1964). Similarly, monitoring has documented significantly improved water quality, particularly DO concentrations, due to new and upgraded wastewater plants in New York and along the Delaware River estuary. Extensive monitoring performed by municipal dischargers and other public agencies in the Southern California Bight provides other examples of the effectiveness of pollution abatement (NRC in press). Lower particulate and organic levels reduced the size of the zone of heavy sediment contamination and altered benthic communities at the Los Angeles County wastewater treatment outfall off White Point and may have contributed to the return of kelp beds off the Palos Verdes Peninsula. Lower concentrations of DDT and its metabolites in fish and shellfish have been observed following the limitations on its use (Mearns et al. 1988).

INSTITUTIONAL DYNAMICS OF MONITORING

Throw together . . . law enforcement officers, ecological researchers, . . . statisticians, policy planners, resource biologists, administrative personnel, and perhaps quite a few others. Call this a management agency. Now "interface" it somehow with its constituents, ranging from politicians worrying about the next election, to concerned conservationists, to careful business entrepreneurs, to "cowboys" out to take the biggest catch this year. . .. Finally, consider the resource itself, a complex ecological system that is too expensive to monitor thoroughly, changes unpredictably in response to environmental factors, and generally offers all sorts of conflicting signals that are open to every interpretation from imminent disaster to grand opportunity. There you have the modern management situation (Walters 1986).

As Walters's irreverent observation illustrates, environmental management —and, as a component of management, monitoring programs—operate within institutional and technological limitations. The experiences of marine monitoring professionals around the country, as well as the case studies conducted as part of this evaluation, indicate that political, legal, and bureaucratic considerations are at least as important as technical and scientific considerations in determining the success or failure of monitoring programs. Institutional interactions are discussed in the following sections. Understanding ecosystems and variability is clouded by the technical limitations of making the right measurements on the right space and time scales. This often poorly defined picture is further confused by the many expectations, viewpoints, and interpretations of the diverse parties involved, from the general public to highly qualified technical specialists.

A variety of institutions with different mandates and contributions sponsor marine environmental monitoring and use the information generated by monitoring programs.

The Principal Players Involved

Parties involved in monitoring include local, state, and federal regulatory and resource management agencies; harbor and port agencies; regulated dischargers; developers; scientists associated with consulting firms and universities; and the interested public and their elected representatives. Their responsibilities and interests, which often overlap, are described below. The following sections analyze why and how their interactions make the system work the way it does; recommendations for improving specific problems are then made.

Ideally, government agency interests in marine environmental monitoring focus on obtaining high-quality information useful to making decisions necessary to fulfill mandated responsibilities. These responsibilities include marine resource management, regulation, education, and research.

Regulated ocean dischargers and developers of ocean resources generally conduct or finance monitoring programs either because they are required to do so or because they want to provide information for decision makers and the public (or themselves) about the nature and effects of their discharges and other activities. The interests and objectives of ocean dischargers and developers include generating information that will help reduce the regulatory burden, promoting a positive public image, reducing operating costs, and aiding future decision making. All dischargers and developers share the common objectives of supplying required information at a minimal cost and seeing that the information generated is used constructively.

Scientists from government and educational or private organizations often design and implement monitoring programs. They have interests in using monitoring to increase their understanding of the patterns and processes of nature and to advance their technical capabilities.

The interested public includes a broad variety of individuals and groups, including environmental organizations, fishermen, fish-consumers, coastal and marine recreationists, and associated businesses. Their interests in monitoring range from furthering economic goals (e.g., promoting fish consumption or ocean recreation) to furthering political ends (e.g., legislation imposing stricter controls on dischargers) to concerns about human health and safety (e.g., is the water safe for swimming?) to aesthetic and philosophical concerns about the marine environment.

Elected officials and appointed members of the executive branches of government are responsible for enacting legislation, setting policy, and controlling agency finances. Elected officials mainly influence marine monitoring programs by developing and modifying legislation that requires marine monitoring activities and by controlling the budgets of agencies responsible for the monitoring programs. These officials also bring public concerns on environmental issues (e.g., the need for more or less monitoring) to the attention of high-level agency decision makers. The elected officials are influenced by both the electorates they serve and various interest groups.

Public Pressures and Perceptions

There is no shortage of good advice on why and how to monitor. But it is frequently ignored, perhaps because public pressures often create and drive environmental monitoring efforts. In the mid-1970s, for example, controversy over proposed oil and gas development on the outer continental shelf led to extensive environmental benchmark studies as a precursor to monitoring the effects of this development. As a result of public and political concerns, Congress appropriated funds for costly programs of extensive measurements, but these programs lacked clearly stated objectives and expectations (NRC 1978). Because of the criticisms, the benchmark studies concept was abandoned in favor of studies focused on leasing decisions. Now, some 12 years later, the Department of the Interior is returning to the problem of designing monitoring programs that address public concerns about environmental effects of the development that has ensued.

As is true for most public affairs, interactions between elected officials and agencies can either help or hurt monitoring activities. When elected officials' demands on agencies shift in response to shifting public and constituency group pressure, agencies often have no choice but to shift direction as well, even if their responses make little scientific or resource management sense. In particular, political demands may dictate the termination of some programs in favor of others that are of more immediate interest or concern to the public or individual constituency groups. This situation can adversely affect the quality and usefulness of monitoring programs, particularly when long-term continuous data are critical to informed decision making.

On the other hand, elected officials frequently stimulate support for monitoring. Concerns raised by Maryland officials, for example, about the lack of information needed to define the extent of pollution problems or set priorities for remediation programs were influential in obtaining state and federal funding for Chesapeake Bay monitoring programs. Without visible and active political support, the scope of these programs would have been greatly reduced, and much information about the extent of pollution problems in the bay would not have been collected. Furthermore, information derived from monitoring was an important factor in obtaining agreement on remediation strategies for Chesapeake Bay.

Conflicts between other societal needs and protection of the environment frequently arise and compromises invariably result. Findings from monitoring programs on the extent of pollution problems, the relative risks they pose to public health and environmental resources, and the success of ongoing remediation efforts are useful to elected officials in setting budgetary priorities and determining needs for additional legislation. Frequent reporting of monitoring findings to the public and political sectors is important in sustaining public and political interest needed to implement cleanup programs and keep them on schedule.

Scientists and environmental regulatory agencies have generally been successful at informing the public and elected officials about the importance of protecting the environment as a means of safeguarding public health and welfare. For example, the public has long been aware that people are receptors for many pollutants and that serious health problems result when the waste-assimilating capacity of the environment is exceeded. Scientists and agencies, however, have not made as compelling a case about the value of monitoring in defining successful and cost-effective solutions to pollution problems or in defining environmental risks to human health. As a result, many public officials and environmental protection advocates view monitoring as a way to avoid or delay costly remedial actions rather than as a technology to help identify the most appropriate and cost-effective solutions to pollution problems. For example, the Southern California case study found that some people view the 301(h) waiver[1] monitoring program

[1] Section 301(h) of the Clean Water Act, added in 1977 (P.L. 95-217), allows waivers from secondary treatment requirements for effluent discharges into coastal waters from POTWs when it can be shown that such discharges do not degrade water quality.

as a waste of money that could be used to reduce ocean waste disposal further. Indeed, this sentiment may be justified because monitoring is sometimes resorted to as an easy way out of making politically difficult decisions. The continued monitoring of acid deposition in lieu of more restrictive control of emissions in the face of overwhelming evidence of cause and effect is a frequently cited example.

Public education efforts are of little help when brochures and pamphlets are long on promotion and short on substance. Substantive monitoring information is rarely disseminated in a form understandable to most lay readers. Computer printouts are frequently the only documents produced. In addition, when technical reports are issued, they are written in a way that is incomprehensible to the average reader.

Again experience in Chesapeake Bay is an example of how general agreement within the scientific community and the involved agencies on the need for monitoring information resulted in strong political and public support for monitoring activities. The Citizens' Monitoring Program for Chesapeake Bay, working with agencies and scientists, has been successful in educating the public and officials on the uses, limitations, and findings of monitoring program results. This program is a network of citizen volunteers who live along the bay and its tributaries. They measure selected water quality variables and routinely report their results to the Chesapeake Bay data center. Citizens who are involved in the program obtain a firsthand awareness of monitoring by taking relatively simple environmental measurements. These citizens are then able to track the success of cleanup efforts closely. They become strong advocates of monitoring activities and are conduits of information from the technical community to the general public.

Failure to inform adequately and involve actively both the public and elected officials in meaningful ways is the root of many institutional problems confronting monitoring. Public and legislators' expectations about the capacity of monitoring to provide answers to important questions are often unrealistic. Monitoring program goals and decision points must be clearly stated in terms the general public can comprehend and respond to. Further, when a monitoring program is conducted or financed by dischargers or agencies that are perceived to be sympathetic to dischargers, the public is often skeptical of the results. It is important, therefore, for agencies and monitoring practitioners to inform the public and the legislators of monitoring program limitations and to exchange substantive information with interested citizens and groups openly.

Governments, public utilities, and industries can afford sustained monitoring of only a limited number of measures of environmental quality, and they must be selected or deleted through critical analysis by experienced and knowledgeable people. The public is often skeptical of proposed changes in monitoring programs, particularly when a parameter is dropped or monitoring activities are reduced in scope. For sustained public support, it is important to convey to the public the basis for selecting and sustaining a particular monitoring program.

The case studies demonstrate different degrees of monitoring program success in producing information appropriate to the needs of the groups involved. In the Chesapeake Bay Monitoring Program, for example, a good balance in the development of information products tailored to important and diverse audiences has been achieved, from managers' reports to a regular feature, "Bay Barometer," that appears in several local newspapers. In contrast, monitoring programs involving sewage discharges, stormwater runoff, and their effects on human health and living resources in the Southern California Bight have been less successful in building public awareness and confidence.

Involving the public in a meaningful way must be actively pursued if support for monitoring is to be gained and maintained and monitoring results are to shape public opinion. At the outset, a goal of major monitoring programs should be public participation in problem solving and definition as well as in helping the agency determine how best to face the dilemma at hand. Such active public participation is a component of the Environmental Protection Agency National Estuary Program, which is now developing comprehensive management plans for 12 estuaries. Similar opportunities for public review and comment are called for in California's Ocean Plan.

Once a negative attitude develops, it is difficult to change—but not always so. One public information officer associated with Southern California marine monitoring (Joseph Haworth, Jr., County Sanitation District of Los Angeles County, letter to Lisa Speer, April 1988) stated his experience:

> I've told the organizations and the people in contact with us on this issue that if they choose to be angry with us, it should be for what we're doing, not what they suspect we're doing. This has created an environment in which they are actually willing to listen to our information.

Legal and Regulatory Influences

Numerous state and federal statutes require monitoring of marine environmental parameters. Table 1.1 lists relevant federal statutes. Most coastal states have additional requirements; for example, California has more than 30 marine monitoring programs required by statute. Without statutory requirements for surveillance and monitoring, dischargers would be less likely to monitor, and agencies would have far more difficulty securing public and private funds for monitoring activities.

Legal constraints also interfere with effective monitoring. Statutory and regulatory requirements can hinder an agency's flexibility in carrying out its monitoring requirements, lead to duplication of monitoring efforts among agencies, leave important data gaps, or commit monitoring resources to irrelevant parameters or problems that are already well understood. Examples of these problems are briefly discussed below.

An example of fragmented monitoring is the existing regulatory framework in the Southern California Bight, where monitoring is carried out on a permit-by-permit basis. As a result, monitoring programs consider each regulated activity in isolation from all others. Pollutant loadings from non-point sources such as storm drains, urban and agricultural runoff, and the atmosphere are substantial; however, their impacts or loadings have not been monitored because the statutory mandates do not exist. Regional and cumulative impacts receive inadequate attention because individual programs are not responsible for measuring effects on larger spatial scales or from multiple sources.

Monitoring parameters required by regulation or permit may become irrelevant over time, but without authority or flexibility to change monitoring requirements, agencies must continue monitoring required parameters. A case in point is the County Sanitation Districts of Orange County, California, which are required as a permit condition to measure routinely a wide range of chemical contaminants—despite the fact that many of them are rarely if ever found in the effluent or sediments near the outfall (NRC in press). Dropping or shifting well-founded monitoring programs as a purely political reaction to public demands is counterproductive. However, political and bureaucratic pressures that constrain agency flexibility in developing and shifting programs as a reasonable response to societal needs and scientific objectives are also undesirable.

Statutes and regulations often state their goals in general or vague terms, making it difficult to set criteria for determining whether the goals have been met. For example, one water quality objective of the California Ocean Plan is that "the concentration of organic materials in marine sediments shall not be increased to levels which would degrade marine life" (California State Water Resources Control Board 1988). The Federal Water Pollution Control Act calls for "the protection . . . of a balanced, indigenous population of shellfish, fish, and wildlife." (See Box 2.1.) Although setting such broad goals is appropriate for legislation of a national or statewide scope and overspecification of criteria in statutes would have far worse consequences, such generalities leave the implementing agency—and the dischargers—with the difficult task of defining specific criteria meaningful for use in designing monitoring programs. Establishing these criteria is often contentious, involving arguments over whether they are meaningful with respect to the statutory or regulatory goal, are too prone to the influence of natural factors, or are adequately sensitive measures of environmental change. Once established, the criteria, which may be based on a set concentration of a contaminant in the environment or on biological variables, are often difficult to change.

BOX 2.1 STATUTORY OBJECTIVES OF MONITORING ARE OFTEN VAGUE*

Federal Water Pollution Control Act

Section 101(a)(3):

It is the national policy that the discharge of *toxic pollutants in toxic amounts be prohibited*. . . .

Under Section 316(a), states may impose effluent limitations:

that will assume the protection and propagation of a *balanced, indigenous population* of shellfish, fish, and wildlife. . . .

Outer Continental Shelf Lands Act Amendments of 1978

Section 20(b) instructs the Secretary of the Interior to:

monitor the human, marine and coastal environments . . . for the purpose of identifying any *significant changes in the quality* and productivity of such environments, for establishing trends in the areas studied and monitored. . . .

Section 20(e) requires that:

[a]s soon as practicable after the end of each fiscal year, the Secretary shall submit to the Congress and make available to the general public an assessment of the *cumulative effect of activities* conducted under this Act on the human, marine, and coastal environments.

Coastal Zone Management Act

Under Section 1456(a), grants are disbursed to further:

the prevention, reduction or amelioration of any unavoidable loss in such states' coastal zone of any *valuable environmental* or recreational resource.

* Italics added.

An example of the great influence of these criteria comes from the regulation of wastewater discharges off Southern California. Through monitoring programs, it was discovered that brittle stars (the ophiuroid *Amphioda urtica*) are highly sensitive to the deposition of particulate wastes around outfalls. Now billion-dollar decisions concerning upgrading waste treatment are being based on whether brittle stars, as representatives of a "balanced indigenous population," are found within a certain distance of an outfall. The point is not to call into question the appropriateness of this specific criterion but to highlight the public consequences of the technical interpretation of statutory or regulatory goals.

Funding and Human Resources

The effectiveness of monitoring is limited by the adequacy of financial and human resources available. The total financial investment for marine environmental monitoring by government, utilities, and the private sector in the United States is considerable. (See Chapter 1.) But expenditures are not well distributed among the types of monitoring (compliance, trends, and model validation), regions of the country, or the main elements of the technical implementation of monitoring (design, data collection, synthesis, interpretation, and reporting). In addition, many marine environmental monitoring programs suffer from the lack of continuity of support needed to define variability and trends or, at least, from frequent uncertainty about the continuity of support.

Many of the issues concerning the distribution of financial resources are exemplified by monitoring in the Southern California Bight, the most intensively monitored coastal area in the country. Annual expenditures on marine environmental monitoring there are at least $17 million per year, most of it for compliance monitoring (NRC in press). Yet the regulators, the regulated, the public, and practitioners of monitoring are dissatisfied with the resulting collection of site-specific monitoring programs, which provides inadequate information on the overall health of the ecosystem and public health and welfare risks. No comprehensive analysis has been done to ensure the appropriate allocation of the resources committed to the most serious problems. Even if the analysis had been done, under the present regulatory structure, simple reallocation of the funds spent by wastewater treatment authorities, electrical utilities, and so on to the broader purposes of regional trends monitoring would not be possible.

The Southern California case study raised another problem of resource allocation that was experienced in the other cases studied by the committee. Far too little of the available financial resources is committed to the analysis of the environmental data collected and the conversion of these data into information that is accessible and usable by decision makers. In the extreme, this situation makes the expenditures provided by taxpayers or ratepayers wasteful and, at a minimum, is frustrating to the public, regulators, and the practitioners of monitoring.

It is not just money and its allocation that limit adequate and useful monitoring. Deficiencies in the talent and experience of the practitioners of monitoring may be at least as limiting. In addition to the need for technical specialists capable of generating high-quality chemical, biological, and physical data, effective monitoring requires individuals with broad skills and experience in experimental design; data analysis, synthesis, and interpretation; communication of results; and environmental management. Dedicated guidance by one or a few broadly trained and experienced individuals is essential to the success of monitoring programs (Strayer et al. 1986). Such individuals are rare indeed and are virtually always the product of on-the-job training.

Agency Decision Making

Myth: Any good scientific study contributes to better decision making (Holling 1978).

[D]ecision makers are people who, like the rest of us, are guided partly by motives that are often not so lofty and are not spelled out clearly. . . .

There is a strong tendency in resource management to defer hard decisions as long as possible, in the hope that natural events will produce a favorable outcome. (Walters 1986)

It must be understood that monitoring, even if well designed and executed, does not eliminate risks to management decisions. There is the potential of false negatives (i.e., no indication of effects when effects may be occurring in an ecosystem component not being monitored) or false positives (i.e., effects are measured but are not generally reflected in the ecosystem) (Cairns 1988). Effective monitoring, however, may significantly reduce the uncertainty attendant upon management decisions.

Federal and state resource management, regulatory, education, and research agencies are key participants in monitoring programs. The mandates of agencies vary, but all are generally involved in protecting public health and environmental resources. Many of the agencies' mandates require monitoring information. These activities include identifying threats (past and present) to public health and environmental resources, setting priorities for the use of limited resources for pollution abatement and remediation, developing and enforcing regulations to protect public health and environmental resources, implementing remedial programs to restore and enhance damaged resources, evaluating regulations and remedial actions, and modifying agency policy.

Monitoring information, however, is but one of the elements that agencies consider when making environmental decisions or formulating policy. Other considerations are overriding statutory requirements and public policies, economic factors (e.g., the costs of alternatives), the probability of understanding the problem and its causes (e.g., the chances of solving the problem using existing information), technical factors such as whether there are engineering or other solutions to a problem, legal factors such as the burden and standards of proof (e.g., identification of who is responsible for the problem), and the political consequences of taking action or doing nothing. In this regard, Beanlands (1988) noted six questions that a senior-level decision maker or elected public official is likely to ask when faced with any problem, including problems addressed by monitoring:

1. Exactly what is the problem?
2. Who is involved and how?
3. What are my options, including doing nothing?
4. What are my chances for solving the problem?
5. What will it cost?
6. What would you advise?

The requirement to consider the institutional dimensions of technical problems means that agencies operate under constraints that can generate parallel, sometimes conflicting, objectives (i.e., to minimize expenditures, avoid controversy, foster a particular political agenda, or direct resources to issues of public concern). These constraints are often imposed by outside constituency groups, including the legislative and executive branches, regulated industries, and the public. Because conflicting objectives are often settled through a political rather than scientific process, monitoring may ultimately not do what it is supposed to do: provide information for making decisions. Public demands may result in the constant shifting of monitoring activity so that useful information is never produced.

Indeed, monitoring itself may be an outcome of decisions resulting from an interplay of these multiple elements. One example is the settlement on use of cooling water from the Hudson River estuary by power plants. Despite the great controversy over the likelihood and magnitude of the impact of the power plants on fish stocks in the estuary, it was clear that to avoid these impacts completely would require installation of costly cooling towers (Baslow and Logan 1982). Instead, a compromise was reached: the effects of larval entrainment would be monitored, and the intake of cooling water would be reduced—even if it caused power shortages—if these effects exceeded a given level.

Monitoring, on the other hand, may be an ineffective reaction to a problem with clear causes and solutions, but for which these solutions may be costly or unpopular. When the problem of floatable materials stranding on New Jersey beaches stimulated great public concern in 1988, state and federal agencies implemented various floatable monitoring programs. Yet the source of these materials, mainly from combined sewer overflows, treatment plant bypassing, and solid waste handling, was identified from studies of similar incidents along Long Island beaches 12 years earlier (NOAA 1977; Swanson, Stanford, and O'Connor 1978). Although expensive, a remedial program implemented earlier could have avoided the tremendous economic losses caused by the stranding of objectionable materials on the beaches; additional monitoring will do little to alleviate the problem.

The fact that monitoring is frequently driven by external considerations and public pressure means that the design and conduct of a rigorously scientific investigation may not be the most limiting element of a monitoring program. This situation puts those who carry out monitoring programs in the awkward position of being "expected to practice good science in a politically motivated system" (Beanlands and Duinker 1983). This difficult position may explain the conflict between agency and outside scientists over the validity of program design and results. Communication between the two groups is generally inadequate. In addition, agency monitoring program design and results are often not subject to objective technical review. The result is skepticism in the scientific community outside the agency. These conflicts exacerbate the problem of public acceptance of monitoring results.

Fragmentation of responsibility for marine environmental monitoring within agencies (e.g., among permit writers, trends assessors, and compliance personnel), among agencies, and at different levels of government leads to monitoring programs with important gaps. A case in point is activity in the Southern California Bight, where incompatible monitoring techniques and reporting make it difficult if not impossible to share information, consolidate monitoring tasks, and address regional impacts in a coordinated fashion (NRC in press). Implicit in agency decision making is a clear statement of the purpose of monitoring. Criteria to guide agency decisions regarding why, when, what, and how to monitor and why, when, and what to stop monitoring as well as guidance on when and how to integrate monitoring data into decision making need to be developed.

For the monitoring practitioner who has to work within this complex public policy and environmental management milieu, effectiveness may be best increased by improvements in the presentation of monitoring results to decision makers. It is generally true now that top-level decision makers rarely see monitoring results, let alone in a form that is useful to them. Translating data into information that is useful, synthesized, and relevant to the decisions that have to be made is a formidable challenge. Further, decision makers often require information from monitoring shortly after data are collected so that they can be considered in impending decisions. This need poses further limitations to the thorough interpretation and effective presentation of monitoring results. All three case studies found that more emphasis and resources need to be devoted to the effective conversion of data into information useful to decision makers. (See Chapter 4.)

Ten Steps to Strengthening the Role Of Monitoring in Environmental Management

The foregoing examples and discussion suggest that the role of monitoring in environmental decision making can be strengthened by addressing the following areas:

1. Clear guidance is necessary on how data are to be used and what type of decisions are to be made.
2. The goals established should be achievable scientifically, technologically, logistically, and financially.
3. The monitoring program should be integrated into the decision-making system, with decision points and feedback loops clearly established before the data are collected.
4. Where authority and control reside should be made explicit. Fiscal controls should be compatible with program controls and objectives.
5. Channels of communication among agencies and other participating individuals and groups should be identified and efforts made to ensure that the channels are interconnected and functional.
6. The monitoring program should integrate the regulatory, data, and management needs and responsibilities of the local, state, regional, and federal agencies to optimize the use of available resources.
7. Viable mechanisms should be established to involve the public and the scientific community as program participants early and often.
8. The monitoring program should include built-in mechanisms to ensure that its conclusions are communicated to decision makers and the public in terms that they can understand and act upon.
9. Monitoring programs should include mechanisms for periodic review and easy alteration or redirection of efforts when monitoring results or new information from other sources justifies a change.
10. The management action to be taken in response to both the expected results and unexpected but possible outcomes should be identified in advance.

3

Strengthening Regional and National Monitoring

CONTINUUM OF MONITORING SCALES

One of the committee's major findings is that monitoring designed principally to meet regulatory compliance needs generally does not adequately answer questions about the regional and national risks of pollutant inputs to public health, coastal environmental quality, or living resources. The reason is that compliance monitoring typically does not address potential effects removed from specific discharge points, including overall responses of the ecosystem to anthropogenic and natural stresses. Such information may not directly affect day-to-day decision making about a particular discharge, but improved knowledge on broader space and time scales of the changing environment and the status of its living marine resources is required to place site-specific regulatory decisions in a relevant context. The three case studies found that, in general, site-specific monitoring programs conducted specifically to assess the effects of specific wastewater discharges or activities were not sufficiently integrated to address questions about regional-scale problems. (See Box 3.1.)

For this reason, the committee evaluated the benefits of strengthened monitoring efforts at regional and national scales to improve understanding of broader-scale trends in marine environmental quality. However, before the findings of this assessment are presented, the scale of various monitoring activities is briefly described. Marine environmental monitoring may cover a continuum of scales. Local monitoring around a discharge site for compliance purposes generally has a characteristic scale of tens of

BOX 3.1 COMMITTEE FINDINGS ON REGIONAL MONITORING

When monitoring programs were designed principally to determine compliance with permits or were not coordinated with the organizations conducting the monitoring within a region, they were not adequate to measure broader-scale regional and national trends.

Southern California Bight

- The extensive monitoring here mainly involves sampling new specific permitted activities (e.g., a wastewater outfall, power plant, drilling rig). Many of the environmental problems, however, are much larger spatially.
- The effects of unpermitted activities (e.g., stormwater runoff, atmospheric fallout) that could have large impacts are not assessed by existing programs.
- Compliance monitoring programs could be redirected and integrated for evaluating environmental quality regionally.

Chesapeake Bay

- The Chesapeake Bay Monitoring Program, begun in 1984, is a coordinated federal/state effort to assess environmental quality trends and the effectiveness of pollution abatement efforts throughout the bay.
- The living resource component of this new program was not integrated and coordinated with the water quality component. Modifications were made in 1989 for better evaluation of status and trends in living resources.
- Sampling and analysis methods often differ among program participants, complicating the determination of areawide trends.

Particulate Wastes

- Because particulate wastes may be deposited on the seabed in coastal and shelf environments, their effects on the benthos and sediments are generally compounded by the cumulative impacts of multiple activities that are regional in scope.
- Monitoring particulate waste discharges is often confounded by natural variation (e.g., seasonal patterns) and external environmental factors (e.g., hypoxia in dredged material disposed of in Long Island Sound, discharges from offshore oil and gas activities in the Gulf of Mexico) that can be understood only when data on the major sources of variation have been quantified.

kilometers, but it often includes "control" stations farther afield. Regional monitoring can encompass areas exceeding hundreds of kilometers (e.g., Chesapeake Bay, Southern California Bight). Existing monitoring programs on a national scale (e.g., the National Oceanic and Atmospheric Administration [NOAA] National Status and Trends [NS&T] Program) have been able to collect data at stations spaced about 100 kilometers apart; thus only a few sampling sites fall within an identifiable region. Monitoring of global environmental trends, although not within the scope of this study, is being conducted at an international level to understand the interaction of physical, chemical, and biological processes that regulate the total earth system. The International Geosphere Biosphere Program (IGBP) is one of a number of ongoing global ocean monitoring programs currently planned or under way.

The effectiveness of trends monitoring, on either a regional or national scale, in quantifying meaningful changes in the marine environment and its resources depends on the selection of appropriate parameters to measure. A framework for monitoring design that encompasses selection of meaningful and sensitive parameters is provided in Chapter 4; it is beyond this study to prescribe them. However, it is clear from the committee's review that even compliance monitoring programs measure chemical and biological variables primarily because of the feasibility of monitoring them or because of a convention (e.g., inclusion on a list of priority pollutants) without regard to their relationship to environmental quality goals.

Monitoring at different scales—from site-specific to national—provides distinctly different strengths and limitations. Some of these are summarized in Table 3.1. Three points emerge from this comparison: there is no singularly appropriate scale for all objectives, integration of data from all scales is necessary for a comprehensive assessment of status and trends, and regional monitoring is especially important.

THE ROLE OF REGIONAL MONITORING

Rationale for Regional Monitoring

It is clear from Table 3.1 that monitoring programs at the regional scale have great potential to contribute information pertinent to management of the coastal marine environment and its resources; yet few regional monitoring programs exist because of important technical, institutional, and financial obstacles.

These problems are apparent in the two regional case studies commissioned by the committee. Southern California has extensive local monitoring but no coherent regional monitoring program, although regional monitoring has long been proposed. Chesapeake Bay's comprehensive monitoring program is relatively new.

TABLE 3.1 The Potential of Marine Environmental Monitoring Contributions to Management Objectives

	Scale of Monitoring Program		
Objective	Site-Specific	Regional	National
Measure effects of specific source	High	Moderate	Low
Evaluate effects of source abatement	High	Moderate	Low
Assess risks to living resources	Low	High	Low
Determine public health risks	High	Moderate	Moderate
Address public concerns	Moderate	High	Moderate
Assess cumulative effects	Low	High	Moderate
Place effects in context of natural variation	Moderate	High	Low
Set national priorities	Low	Moderate	High

Lessons from the Southern California Bight and Chesapeake Bay

Monitoring in the Southern California Bight has been conducted for many years and is predominantly organized around discharge permits. Although at least $17 million is spent to support these activities each year, a regional assessment of status and trends cannot be accomplished by synthesizing and integrating the available data. The case study (NRC in press) identified several program deficiencies regarding the relevance of monitoring activities to public concerns about human health, living resources, and ecosystem integrity, including: significant diffuse (nonpoint) sources of chemical and microbial contaminants in riverine and stormwater discharges to the bight have not been adequately quantified; no formal institutional mechanisms exist for requiring the findings from the ongoing monitoring programs to be integrated into a regional assessment of environmental quality; and no effective system exists for communicating findings of monitoring programs to the public, the scientific community, or policy makers in terms that the respective audiences can understand. As a result of these findings, the case study panel recommended development and implementation of a regional monitoring program for the Southern California Bight. The regional program should: address specific questions about the environmental condition of the bight as a whole and the resources therein; require standardized sampling, analysis, and data management methods; establish a data and information management system for all monitoring and resource data; coordinate the regulatory., management, and technical needs and responsibilities of the local, state, and federal agencies to optimize use of available resources; and involve the public and the scientific community as participants.

The Chesapeake Bay Monitoring Program encompasses an exceptionally wide array of measurements of both riverine and estuarine habitats, sediment contaminants, biological variables (including submerged aquatic vegetation, plankton, and benthos), and fisheries parameters. It is an ambitious undertaking with broad objectives and mechanisms to encourage interstate and intergovernmental coordination. The panel evaluated the program in the context of the conceptual model for marine environmental monitoring described in Chapter 1 (see Figure 1.1) using the questions reproduced in Appendix B. Despite the great strides made by the Chesapeake Bay Monitoring Program, it has some limitations.

First, the questions addressed and hypotheses tested through specific monitoring projects were not always clearly and precisely stated at the outset of their implementation. In most cases, the program implemented was not designed to establish cause-effect relationships clearly. Movement from general program goals to specific environmental quality objectives evolved along with the increased body of scientific information and understanding of the processes controlling water quality and the abundance of living resources, including pollution problems.

Second, the monitoring program design originally consisted of what is familiar and is easy and inexpensive to measure. Station locations and sampling strategies were not necessarily appropriate to answer some important systemwide questions: for example, what is the relationship between the status and trends in water quality and the status and trends in living resources? That is to say, sampling strategies for living resource and water quality management agencies were not well coordinated, and many of the data that have been collected by water quality agencies are not easily related to the available living resource data. Despite coordination efforts, jurisdictional and institutional boundaries often reduce comparability of data and impede information transfer. The Chesapeake Bay Monitoring Program now faces the common dilemma of choosing between the need for long-term consistency and the desire for flexibility in incorporating improved sampling strategies, innovative approaches, and improved coordination.

As a result, the limits to the detection of human-induced effects in a background of large natural variation were seldom stated and in most cases are not known. Sometimes sampling frequency and spatial intensity were not consistent with the scale of temporal and spatial variability of the parameters measured.

A major deficiency of the Chesapeake Bay Monitoring Program identified by the case study is that too little attention and resources were directed at the management, analysis, synthesis, and interpretation of data relative to the investment made to collect the data. In general, available funding is not adequate for regular interdisciplinary analysis, synthesis, and interpretation of data across disciplinary or jurisdictional boundaries. Bemuse of the relative simplicity of the interdisciplinary analyses that have been conducted, there is a heavy dependence on correlation among parameters for providing the information needed to develop remediation strategies. As a result, the program is not sufficiently responsive to the information requirements of decision makers; nor has it provided them with information tailored to their specific needs.

Inclusion of data from other monitoring programs in the data base is limited by the capacity of the central data management system, not by whether the data are required for specific analyses that are needed.

Although the above list of problems identified by the Chesapeake Bay case study is lengthy, the criticisms are not meant to be damning. Indeed, they are relative to the ideal monitoring program and the model discussed previously. Human, technical, institutional, and financial limitations will always adversely affect any large regional enterprise. For this reason, the findings of the case study are coupled with positive suggestions for evolutionary improvements. The Chesapeake Bay program is the nation's most ambitious regional marine environmental effort. The problems encountered in the case study are an illumination of those that will be encountered in other regional programs such as that proposed for the Southern California Bight.

The Federal Role

The federal government can and should be important in the development of regional monitoring programs. For example, federal permitting agencies (e.g., Environmental Protection Agency [EPA] regional offices) could require dischargers to participate in a regional monitoring program as a condition of obtaining discharge permits. Permitted dischargers in Southern California have expressed a willingness to participate in this type of regional monitoring program because the broader-scale assessment that would result would provide a context for the localized discharge effects that are usually found. In addition, over the long term, they feel that a regional program would document the effectiveness of their routine pollution abatement measures. The major beneficial effect of federal participation in regional monitoring efforts is to catalyze multijurisdictional efforts through active coordination and financial support, as EPA does in the Chesapeake Bay Monitoring Program.

Technical assistance in monitoring design, development of standardized sampling and analysis protocols, intercalibration and quality control of laboratories, and data and information management and interpretation are also technical areas in which regional monitoring programs would benefit from federal coordination and direct participation. For example, NOAA's NS&T Program and EPA's National Estuary Program (NEP) provide a framework around which a regional multiagency state-federal monitoring effort could be established.

THE ROLE OF NATIONAL MONITORING

Rationale for National Monitoring

In addition to strengthened regional monitoring and assessment, there is a need to provide a national overview as a broader context for evaluating trends in marine pollution and the effectiveness of pollution control policies, for determining whether observed changes are limited to certain regions or are more widespread, and for generally strengthening the early warning capability for future environmental problems. As described in Chapter 1, our nation spends more than $133 million on monitoring each year. Most is for compliance monitoring, much less for monitoring status and trends at the regional level, and still less for monitoring national status and trends. The United States needs an effective comprehensive national program for measuring and evaluating the status of marine environmental resources and trends in marine environmental quality. We presently have only the modest beginnings of such a program. The federal government participates in various regional monitoring programs through EPA's NEP and conducts a national program to monitor toxic materials in marine mollusks, bottom-feeding fish, and sediments (NOAA's NS&T Program). These projects do not individually, or in the aggregate, constitute a comprehensive national status and trends monitoring program. EPA is developing an Environmental Monitoring and Assessment Program (EMAP), to include the coastal ocean. Presently we have no authoritative scientific information to address public concerns about widespread deterioration of the oceans.

Alternate Approaches

Two fundamentally different approaches can be taken to constructing a comprehensive national marine environmental monitoring program: a fixed station national sampling design and a national program consisting of integrated regional monitoring programs.

An Independent National Fixed-Station Monitoring Program

Maintenance of a national network of fixed-point sampling stations spaced around the coasts to measure key indicators of pollution impacts using standard sampling and analysis protocols and careful quality control to ensure comparability among stations and over time is the basic concept of NOAA's NS&T Program. Its goal is "to create, maintain, and assess a long-term record of contaminant concentrations and biological responses to contamination in the coastal and estuarine waters of the United States" (NOAA 1988).

The basic NS&T station network consists of 200 sites, with an average spacing of 20 kilometers within bays and estuaries and 80 kilometers along open stretches of coastline. Samples are collected annually. There are two types of measurements. Benthic surveillance involves the collection of bottom-feeding fish and sediments at 50 sites; mussel watch involves the collection of mussels or oysters and bottom sediments at 150 sites. Both monitor trace elements, chlorinated pesticides, polychlorinated biphenyls, and polyaromatic hydrocarbons. In sediments, two measures of sewage-related contamination are included—the steroid coprostanol and spores of an indicator bacterium, *Clostridium perfringens*.

NOAA's NS&T Program is the closest current approach to a standardized national assessment of marine pollution. It illustrates both the strengths and weaknesses of the fixed-station network approach to a national monitoring and assessment framework. On the positive side, it provides for carefully controlled collection and analysis of samples and display of summary information in a way that facilitates comparisons of contamination conditions over space and time. (See Figure 3.1.) To some degree, these comparisons may be illusory, particularly the ones that suggest differences among regions. The sampling grid, however, is not dense enough to permit accurate spatial comparisons of the extent of contamination of coastal environments.

Samping sites for the NOAA program are selected to be representative of regional conditions, rather than hot spots near known sources of contamination or pristine, unpolluted sites. There is some question about how representative any isolated site can be of wider regional conditions when it is located in an area where there may be a range of pollution conditions or considerable local variability in the processes controlling the transport and distribution of contaminants. These limitations lead to the conclusion that the NS&T Program may be more useful in measuring temporal trends at individual stations than in assessing the national status of the marine environment or in comparing the extent and severity of pollution among regions in any precise way. This limitation, in turn, can lead to misinterpretation of the significance of the program's findings. For example, most of the NS&T data suggest that the coastal environment is relatively uncontaminated with pollutants. (See, e.g., Figure 3.1.) However, until the representativeness of the NOAA sampling sites is known, it is inappropriate to draw this conclusion.

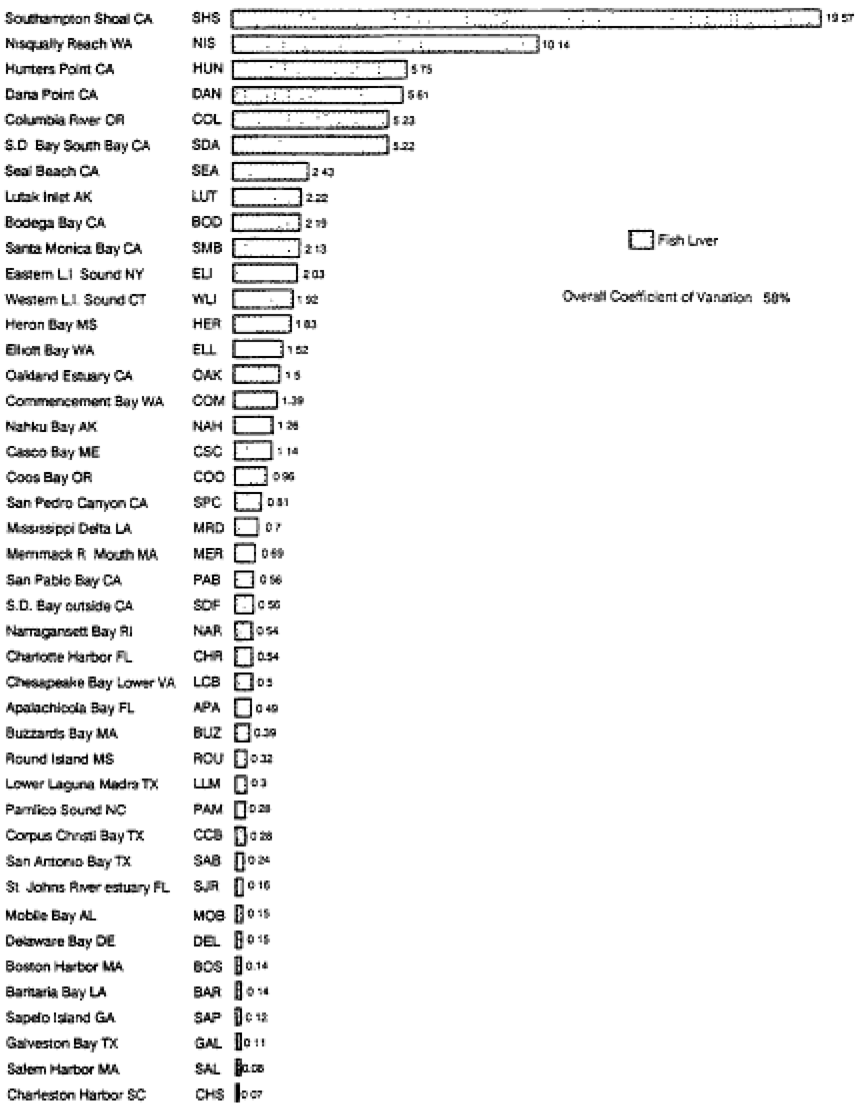

Figure 3.1
Cadmium in fish liver tissue, 1984 samples. Source: NOAA 1987, p. C-6.

With sampling only annually, the NS&T Program is designed to emphasize measurements that minimize problems associated with short-term temporal variability. Thus integrative measures such as the accumulation of contaminants in sediments and biological tissues are emphasized, rather than highly variable measurements such as water column chemistry or plankton populations. On the one hand, this emphasis is a strength of the sampling design. On the other, it reflects some inherent limitations in addressing the program's goal of providing a record of "biological responses to contamination." For example, eutrophication has been identified as a problem of growing concern in estuarine and coastal waters. Yet the annual sampling frequency of the program cannot accommodate sampling for nutrients, algal biomass, or oxygen concentrations, all of which exhibit large short-term temporal (as well as spatial) variability. Thus the program does not include a key pollution issue in its assessment of contaminant conditions. Other major pollution issues not addressed by the NOAA NS&T Program are habitat modifications, including loss of wetlands and submerged aquatic vegetation and the construction of dams, and the effects of global climate change on ecological resources.

These shortcomings reflect constraints imposed by the scope, spacing, and frequency of the sampling program that result from budgetary limitations. Of necessity, the program was designed to fit within the constraints of available funds, about $4 million annually. However, expansion of the national marine monitoring program may now be possible under the fiscal year (FY) 1990 budget proposed by the administration. This proposal provides additional resources for NOAA's NS&T Program and for EPA's EMAP. Nonetheless, even this expansion of effort is unlikely to encompass the array of sampling points and measurements needed to estimate the extent of pollution impacts given the vast extent of coastal environments.

Evaluation of the findings of water quality records from two nationwide monitoring networks designed to measure riverine water quality illustrates some of the limitations of the fixed station network approach (Smith, Alexander, and Wolman 1987). Although the data from these systems did reveal some significant trends in water quality, they were only indicative. The data collected from fixed sampling stations around the country proved inadequate to explain or validate some of these apparent trends. It was necessary to make extensive interpretations based upon other sources of information to make meaningful inferences concerning the significance of the findings.

An Integrated Network of Regional Monitoring Programs

The second broad approach to providing a national assessment of marine environmental quality is for a federal agency, NOAA or EPA, for example, to pull together, synthesize, and interpret available data from an integrated series of regional monitoring programs that have been designed to meet regional and local needs. Well-conceived regional monitoring activities would contribute meaningful information on environmental conditions in individual estuaries and coastal areas. Collectively, these initiatives could provide the basis for a national assessment of status and trends. The national contributions to such a program would consist of identification, development, and standardization of measurements; establishment of the appropriate baseline and sampling design; and compilation and integration of the findings from regional programs in a national assessment. The benefit of this approach is that it uses intensive and extensive monitoring data for individual areas. These data are more likely to be representative of environmental conditions in the regions under study and to explain cause-effect relationships with respect to observed changes.

Relying on a network approach has several shortcomings: some major estuaries or important coastal stretches may not be covered by suitably intensive studies; intensive studies may focus on short-term information needs—the "contaminant of the month" syndrome—and fail to provide the consistency in long-term sampling needed for a national assessment; and it is difficult to compare data collected by different organizations for different purposes. This element is in contrast to an independent national program such as NOAA's, in which consistency and comparability are relatively easy to ensure. EPA's proposed EMAP has many characteristics of an integrated network of regional programs.

BOX 3.2 EPA'S NATIONAL ESTUARY PROGRAM

- Established by Clean Water Act Amendments of 1987 to protect and improve water quality and enhance living resources.
- Creates a Comprehensive Conservation and Management Plan, with participation by representatives of federal, state, regional, and local agencies; affected industries; academia; and the public.
- Calls for assessing water quality and natural resources trends in the planning phase and monitoring effectiveness in the implementation phase.
- Estuary programs under development:

- -Albermarle/Pamlico Sound
- -Buzzards Bay
- -Delaware Bay
- -Delaware inland bays
- -Galveston Bay
- -Long Island Sound
- -Narragansett Sound
- -New York/New Jersey Harbor
- -Puget Sound
- -Sarasota Bay
- -San Francisco Bay
- -Santa Monica Bay

A Network of Regional Programs Coupled with a National Program

A national program that couples an independent national program with a network of regional programs and includes areas of special attention, such as the Southern California Bight, Chesapeake Bay, and other estuaries included in EPA's NEP (see Box 3.2), would overcome almost all the obstacles identified above. The sparse national array of stations in regions not the subject of intensive monitoring would be increased, and within the intensively monitored regions, sites would be selected for long-term trend assessment of common parameters. Sites within these regions would include hot spots as well as areas of intermediate and minimal contamination. The use of common protocols and intercalibration would ensure comparability of results. Cooperation between EPA's NEP and NOAA's NS&T Program would combine regional programs with a sparser national network of long-term stations and studies. These existing programs could be coordinated and enhanced to improve coverage of unmonitored areas. Another benefit of cooperation between these programs would be better data management and interpretation.

To accomplish such a union of national and regional programs, a national policy would have to provide both directives and incentives. In any case, effecting the required coordination among federal agencies, state and local agencies, and permittees is a challenge. The needs, barriers, and some opportunities for interagency and intergovernmental coordination are discussed in the following section.

COORDINATION

The Need for Interagency and Intergovernmental Coordination

Whether there is an expanded independent national status and trends monitoring program, a national monitoring program built largely from a network of regional monitoring programs, or a combination of the two, greater coordination among the various federal, state, and local agencies involved in marine environmental monitoring to adopt consistent, or at least compatible, monitoring methods and designs would clearly benefit all levels. Efforts to improve interagency coordination face formidable obstacles at both regional and national levels. Although there have been many federal efforts at coordination, the results have usually been disappointing, and many examples of overlapping, fragmentary, and unrelated monitoring efforts remain. At best, coordination task forces are able to serve as forums for information exchange and are not vehicles for modifying agency attitudes, behavior, and programs because of basic institutional and bureaucratic behavior. Monitoring to determine the conditions of well-defined coastal areas, for example, Chesapeake Bay and the Southern California Bight, may offer greater opportunities for coordination both among agency programs and between compliance monitoring and trend monitoring initiatives. In regional studies, interests shared in a geographic area may overcome the more autonomous agency interests at the national level and provide a more fertile atmosphere for coordinated efforts. In addition, technical problems that hinder coordination on national levels (e.g., what to measure) actually facilitate coordination at regional levels because it is usually easier to make decisions for specific regions.

As described earlier, NOAA is mandated under the National Ocean Pollution Research, Development, and Monitoring Act of 1978 to develop a coordinated federal program for ocean pollution research, development, and monitoring. However, this effort has largely involved information exchange and documentation of individual agency programs rather than adjustments and modifications to existing programs to achieve a truly coordinated national effort. Despite repeated recommendations calling for a more coordinated national effort (see Box 3.3), no such effort has emerged. In an attempt to remedy this deficiency, the National Ocean Pollution Program office has established the Working Group on Monitoring, cochaired by NOAA and EPA, to define the federal role in coastal ocean pollution monitoring. It may encounter similar problems unless participating agencies make a more serious commitment.

Other federal coordination arrangements are found in existing legislation (the Water Quality Act of 1987 and the Marine Protection, Research, and Sanctuaries Act, Title II, 1972) but they have not been implemented effectively. Both require critical review and possible revision if they are to improve interagency coordination.

Opportunities to Develop a Coordinated Program

There are increased potential opportunities for a coordinated national effort, provided effective federal leadership can be brought to bear. With mounting public concern about the condition of marine resources, the number of regional monitoring efforts is likely to grow. For example, EPA's NEP, authorized by the 1987 Water Quality Act, has stimulated the planning of several intensive regional monitoring programs that could contribute to a national assessment while serving more specific localized management needs. As an initial step, consideration should be given to requiring that management conferences for estuaries included in NEP make a multiyear commitment to participate in a national estuarine monitoring network. They would be requested to monitor prescribed parameters using standardized protocols and to provide data and information in standardized formats and on a prescribed schedule to a national coordinator. In turn, they would have free access to similar data contributed from other participating estuary groups. They should receive supplemental funding for the additional work required. The committee stresses, however, that any such requirements should be limited to consistency in analytical protocols, intercalibration, and formating and reporting certain information to a central point Any centralization requirement that impinges upon the flexibility needed to tailor regional programs to regional needs would be self-defeating.

BOX 3.3 PROGRAM COORDINATION: 10 YEARS OF EFFORT

The first Federal Plan for Ocean Pollution Research, Development, and Monitoring (Interagency Committee/Federal Coordinating Council 1979) recommended that a national ocean pollution monitoring plan be developed for inclusion in the second federal plan. It was to be based upon integration of existing monitoring programs.

The second National Marine Pollution Program Plan (Interagency Committee/Federal Coordinating Council 1981) stated: "The need for development of a national monitoring program has been recast in modified form. . . . [I]t is now believed that the real need is for organizing and structuring existing programs into regional monitoring networks rather than establishing a new national program for monitoring." The plan proposed "a national marine pollution monitoring network, composed of well-defined regional monitoring networks. . . ."

The fourth National Marine Pollution Program Plan (NOAA 1988) adopted as one of its six goals the documentation of trends in the status of marine ecosystems. The program recommended: "The Federal Government should promote coordination of state and regional programs, develop guidelines for use in standardizing monitoring techniques, and support useful analysis of historical and encountered data."

An Ad Hoc Working Group on Monitoring Environmental Quality of Marine Ecosystems was recently constituted to:

- establish the objectives of the federal program in this area and determine appropriate roles at the federal and state levels.
- propose a systematic strategy for developing a national monitoring capability to meet these objectives. The strategy will incorporate existing national and regional programs and will use encountered data, peer review, and information synthesis and dissemination.
- promote the development of improved indicators of ecosystem status (NOAA 1988).

In summary, the desired diagnostic national assessment of status and trends in marine environmental quality is most likely to come about through the orchestration, coordination, and synthesis of the results of well-designed local and regional studies. The inherent difficulties involved in comparing and accumulating the results of studies designed and conducted by different organizations and for different purposes are likely to be outweighed by the fact that studies tailored to specific environmental conditions and problems of an area have the best chance of yielding meaningful results. At the same time, although the committee can offer no panaceas or magic formulas, we urge continued efforts to achieve regional coordination of study protocols and parameters. Through development and demonstration of standardized approaches, such as those used in NOAA's NS&T Program, the federal government can encourage wider adoption of methods that will enhance the opportunities for development of information useful in national assessments.

4

Designing and Implementing Monitoring Programs

The technical design of monitoring programs refers to the process of deciding what to measure; how, where, and when to take the measurements; and how to analyze and interpret the resulting data. Proper analysis and interpretation of monitoring data result in information that helps scientists and managers decide whether regulatory, environmental quality, and human health objectives are being met. As emphasized in Chapter 2, when monitoring data have been converted to information in this manner, they generally provide better support for specific management actions. This chapter presents comprehensive guidance for developing the technical design of monitoring programs and describes a procedure for ensuring that the information produced meets the needs of managers and decision makers. This chapter is intended to guide those who implement monitoring programs toward better program design and improved dissemination of information gained from monitoring.

An appropriate technical design is critical to the success of monitoring programs because it provides the means for ensuring that data collection, analysis, and interpretation address management needs and objectives. To ensure that monitoring systems will produce information that is useful to decision makers, monitoring programs that address public concerns must be developed using a comprehensive methodology such as the one described here.

The committee emphasizes the importance of the following overall conclusion related to designing and implementing monitoring programs: *Failure to commit adequate resources of time, funding; and expertise to up-front* *program design and to the synthesis, interpretation, and reporting of information will result in failure of the entire program*. Without this commitment, effort and money will be spent to collect data and produce information that may be useless.

A CONCEPTUAL APPROACH TO DESIGNING MONITORING PROGRAMS

Technical design can be challenging. Variability in nature creates "noise" that often obscures the "signal" of human-induced impacts. Multiple human activities occurring within the same area or time span can interact to create complex cumulative effects. Further, choices must be made among the wide array of scientific tools that could be used and the many environmental parameters that could be measured. For example, monitoring to measure degradation in fish communities could focus on the number of species in the community, community trophic structure, the incidence of abnormalities, or many other parameters.

The committee found no shortage of good advice concerning the technical design of monitoring programs. Such useful works as Holling (1978), Green (1979), Beanlands and Duinker (1983), Fritz, Rago, and Murarka (1980), NRC (1986), Wolfe (1988), Isom (1986), Rosenberg et al. (1981), Perry, Schaeffer, and Herricks (1987), and O'Connor and Flemer (1987) provide a rich resource of ideas, strategies, and technical methods. However, a major problem revealed in the case studies is a failure to apply the appropriate design tools consistently to fulfill clearly stated monitoring objectives. The case studies and the experience of committee members indicate that too little attention is directed at deciding what measurements are required to address the priority issues defined by the public and decision makers. Such priorities provide the context for selection and application of technical design strategies.

The comprehensive methodology presented here is drawn largely from the references cited above. The goal of this synthesis is to provide a methodology for formulating clear monitoring objectives at the outset; for designing statistically sound, cost-effective sampling programs consistent with those objectives; and for synthesizing, interpreting, and reporting monitoring data.

The following sections present a design methodology that is an expansion of the central elements of the conceptual framework shown in Figure 4.1. It provides a logical and scientifically based means of linking technical decisions about monitoring design to the information needs of the decision-making process. The methodology is generic and therefore applies to most monitoring situations.

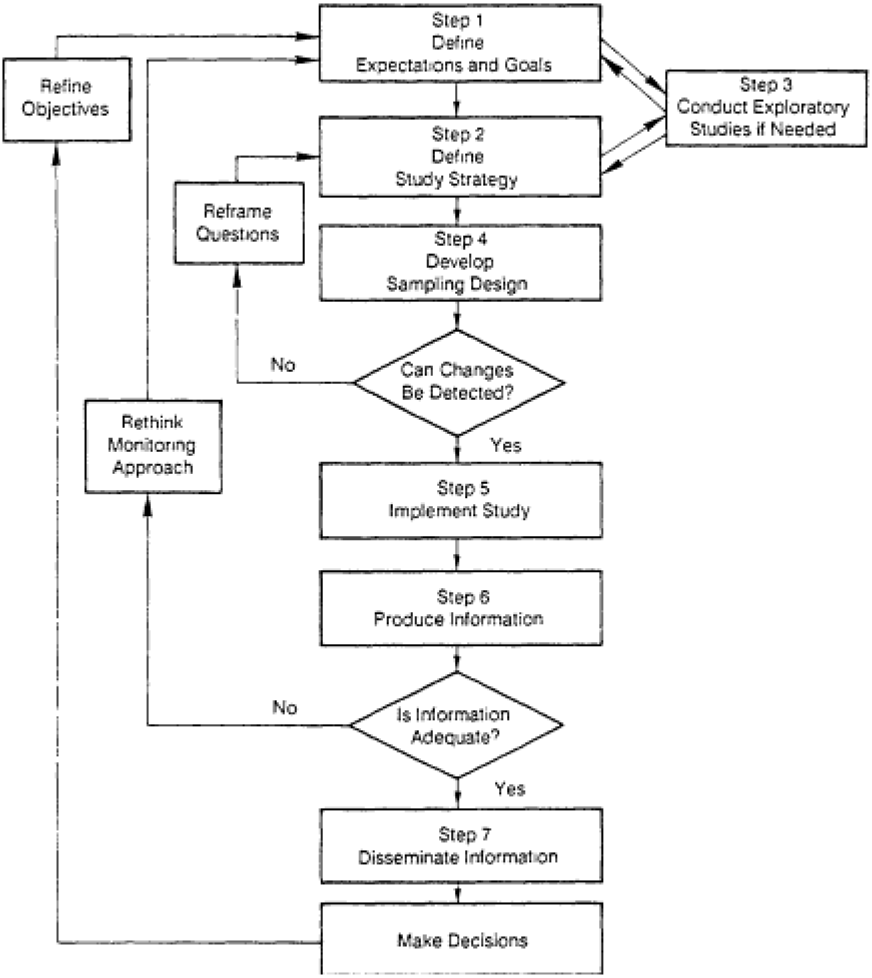

Figure 4.1
The elements of designing and implementing a monitoring program.

General Versus Specific Design Methodologies

A generic monitoring design methodology must be applicable to the various requirements of each monitoring category considered in this report—compliance, trends, and hypothesis testing. All three categories encompass a broad variety of questions about resources in many different habitats. In addition, resources, the processes that affect them, and human activities vary on diverse spatial and temporal scales. Too specific a methodology (i.e., one that specifies the exact models, parameters, sampling plans, and analyses) would be applicable only to a narrow range of situations. Conversely, a methodology that is too general will not be useful to practitioners.

The committee resolved the conflict between the needs for specificity and for generality by developing a conceptual methodology that provides guidance in producing effective technical designs for most situations. The methodology does not furnish answers to all design problems. Instead, it identifies which problems are most important and describes how they can be solved. For example, it leads practitioners through steps that convert monitoring objectives into testable questions. It provides guidance in dealing with sources of variability and uncertainty and shows how feedback mechanisms help refine questions and objectives. It demonstrates methods for linking the collection and analysis of monitoring data to the information needs of the public and decision makers. Examples are used to demonstrate how elements of the methodology would be applied to specific situations. Some steps in the methodology are more relevant to some kinds of monitoring than others.

Despite its guidance, the methodology cannot replace local or specific scientific expertise. In fact, its successful application depends on the knowledge and skill of local experts. In this respect, it reflects the decision-making approach adopted by the U.S. Army Corps of Engineers (COE) for disposal of dredged material (Peddicord et al. in press; Cullinane et al. 1986).

A Methodology for Monitoring Design

Figure 4.1 shows the main elements of the conceptual methodology, each of which is discussed in detail in subsequent sections. The methodology is based on two principles: monitoring designs must reflect cause-effect relationships while accounting for variability and uncertainty, and specific design decisions (e.g., the number of stations and replicates to be collected) can be made only after objectives and related information needs are clearly established. A lack of clarity in purpose and expectations invariably results in failure to formulate a meaningful monitoring strategy (Green 1979).

Working upward from the bottom of Figure 4.1 helps in understanding the relationships among the steps in the methodology. Information can be disseminated to decision makers (step 7) only after it has been produced (step 6). Information is produced when the results of a carefully implemented study that includes adequate data analysis and interpretation have been summarized and evaluated (step 5). For a study to be implemented successfully (step 5), it must be designed (step 4) to develop answers to important questions effectively (step 2). The focused questions that serve as the basis of a monitoring program rely on clear management objectives (step 1). Finally, preliminary studies (step 3) are often necessary to refine questions and technical aspects of the monitoring design.

Figure 4.1 also shows three important feedback points. The first, between steps 4 and 2, provides a means of reframing the study's underlying questions in light of real-world scientific, logistical, and financial constraints. As an example of such feedback, the Minerals Management Service (MMS) of the Department of the Interior evaluated historical data (Bernstein and Smith 1984) to help establish the objectives and design of a large-scale sampling program off California. The finding of this historical evaluation that natural variability made it extremely costly to detect changes in individual species helped focus the sampling program on other less variable and more sensitive parameters. The other feedback points in Figure 4.1 (encompassing steps 6, 7, and 1) allow program designers to review and modify monitoring objectives in light of actual monitoring information about the effectiveness of specific management actions and technological advances that occur during the study.

The above, and other, feedback points at more detailed levels of the methodology permit information that results from monitoring to be used to refine the sampling design. Throughout the more detailed description of the methodology that follows, feedback loops emphasize the point that information developed at one stage must be used to refine previous stages in an iterative process. For example, as scientific understanding and predictive ability increase, feedback mechanisms can be used for redirecting resources toward unanswered questions and away from issues that have already been addressed adequately. When such feedbacks are not used, monitoring loses its effectiveness for controlling and understanding human impacts on the environment. For example, electric utilities in Southern California continue to monitor for detrimental effects of thermal discharges from coastal power plants, even though nearly 20 years of monitoring have documented the limited consequences and spatial extent of thermal effects.

STEP 1: DEFINE EXPECTATIONS AND GOALS

As outlined in Chapter 2, the ultimate goal of monitoring is to produce information that is useful in making management decisions. Therefore two-way communication between scientists responsible for designing monitoring programs and the users of monitoring information is essential. These interactions give decision makers and managers an understanding of the limitations of monitoring and at the same time provide the technical experts who design monitoring programs with an understanding of what questions should be answered. Step 1 of the methodology (see Figure 4.2) is designed to ensure that this communication takes place in a structured context.

Such communication is important because anticipated population growth and continued development of the coastal zone will increase the demand for monitoring information to support environmental decision making (EPA 1987; Champ, Conti, and Park 1989). If monitoring programs are to meet these demands, their objectives must integrate public concerns and expectations with the legal and regulatory framework through the use of scientific understanding to identify the relevant questions to be addressed.

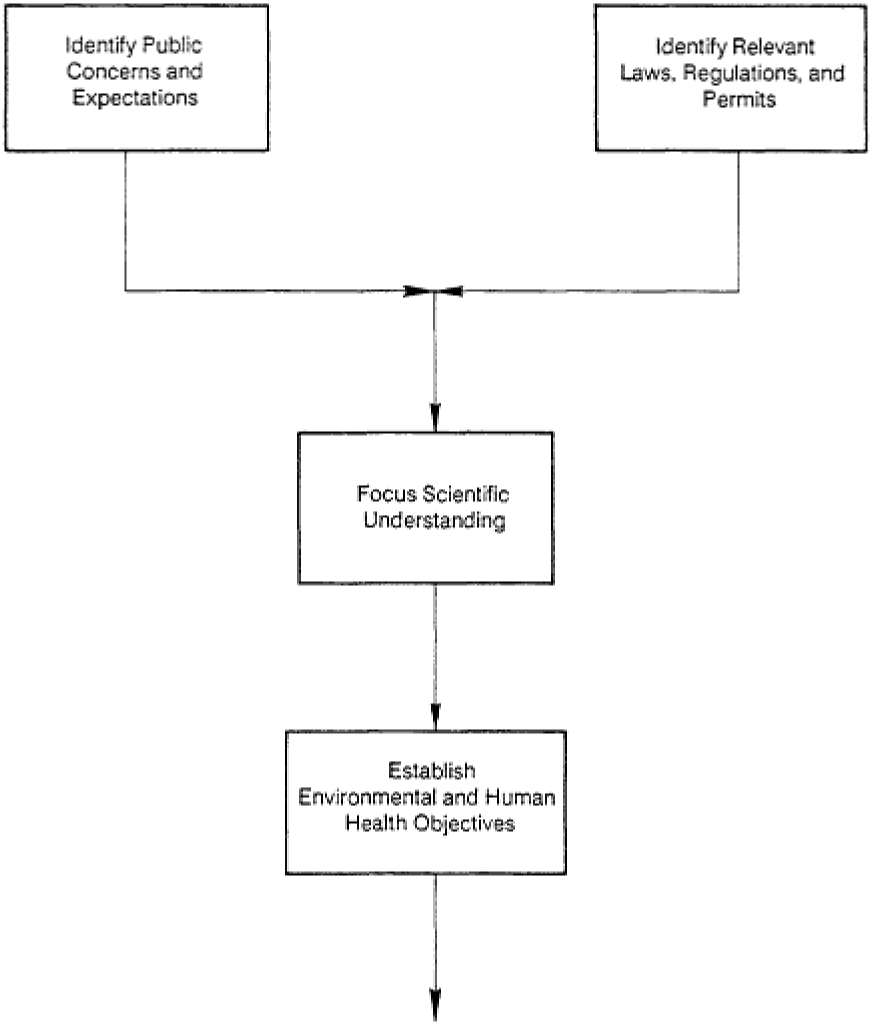

Figure 4.2
Step 1: define expectations and goals of monitoring.

BOX 4.1 A TECHNICAL DESIGN THAT MEETS MANAGEMENT NEEDS

DAMOS—the Disposal Area Monitoring System—collects only those data that can be shown, beforehand, to be useful in making management decisions or resolving technical problems (Fredette et al. in press). The DAMOS program clarifies and updates its definition of information needs through its technical advisory committee of independent scientists and through periodic public symposia. Although DAMOS has been criticized for not addressing larger-scale issues, such as the added stress of dredged material disposal on regional oxygen depletion, it has successfully addressed most important questions related to dredged material disposal. Most important, monitoring is fully integrated into the decision-making process, with active and on-going interaction between those responsible for monitoring and those responsible for making decisions.

Just as the creation of useful information depends on clear monitoring objectives, these objectives depend on unambiguous statements about what constitutes useful management information (Cowell 1978). As Bernstein and Zalinski (1986) point out when talking about useful information, one must answer the questions "Information about what?" and "Useful to whom, and in what way, specifically?" Stating clear monitoring objectives involves answering these questions as precisely and unambiguously as possible.

The three case studies identified many instances in which the development of clear objectives helped translate monitoring data into information that supported management actions. An outstanding example is the DAMOS (Dredged Area Monitoring System) program carried out by the COE New England District to guide decisions about the disposal of dredged material (Fredette et al. in press; Engler and Mathis 1989). (See Box 4.1.)

In another instance, "tiered" monitoring (Fredette et al. in press; Zeller and Wastler 1986), exemplified by the monitoring plan for the 106-mile dumpsite off the East Coast (Werme et al. 1988), is structured to yield information that can answer a hierarchy of questions. Monitoring within the site concentrates on specific questions about the dispersal of disposed material. A finding that material has spread beyond the site boundary triggers a management action: more comprehensive monitoring to answer a higher tier of questions about environmental effects.

The Southern California Bight case study highlighted real-world impediments to developing clearly stated monitoring objectives. In the bight, multiple point and nonpoint sources of contaminants are in close proximity, and effects on a variety of important marine resources overlap. Marine resources in the bight are also affected by regionwide natural disturbances (e.g., E1 Niños, storms, and population blooms of organisms) that complicate the assessment of changes from human sources. It is much more difficult to document such cumulative effects than it is to measure those from single isolated sources or events. In addition, natural variation of resources and contaminants in the bight frequently occurs on spatial and temporal scales that confound the results of monitoring programs. The limited scientific understanding of how all these processes interact makes it difficult to find clear answers to many of the questions asked by decision makers and the public. All such impediments must be identified and considered when developing objectives for monitoring programs because they affect whether it is possible to fill the information needs identified in the definition of objectives.

Many approaches to defining issues and establishing monitoring objectives (see Figure 4.2) within the constraints imposed by the scientific knowledge base and resources (availability of time, money, and personnel) are possible (e.g., Adamus and Clough 1978; Capuzzo and Kester 1987; Gilliland and Kisser 1977; Walker and Norton 1982; Wiersma et al. 1984; Cairns, Dickson, and Maki 1978)). Results of one approach (Clark 1986) that was found by the Southern California Bight case study to be especially useful are summarized in Figure 4.3. This cumulative assessment approach presents a synoptic picture of natural and human sources of disturbance and impacts and their effects on natural resources. Conducting this kind of analysis requires making decisions about which resources are valued and/or vulnerable. It also requires synthesizing available scientific information about how they are impacted. A particularly useful aspect of this approach is the identification of multiple and cumulative impacts. Further, it includes information about the limits of scientific certainty associated with potential impacts. This procedure provided a framework for synthesizing available scientific information on the Southern California Bight in a way that could be used by scientists, environmental decision makers, and the public to begin establishing realistic monitoring objectives.

Even though the analysis underlying Figure 4.3 was qualitative and was based on incomplete understanding, it helped participants in the Southern California Bight case study identify potential effects not addressed by ongoing monitoring programs. Figure 4.3 was especially valuable as a tool for synthesizing the available information into a conceptual model of system interactions. This model thus provides an effective starting point

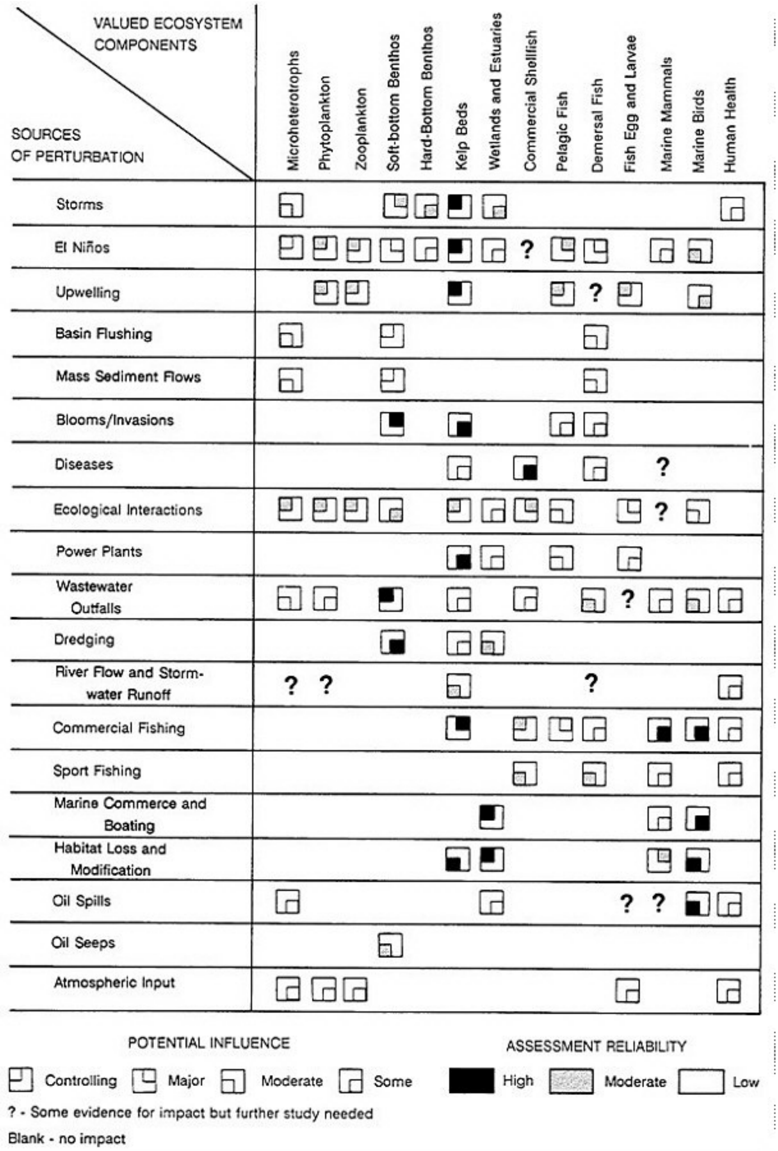

Figure 4.3
Impacts on the marine environment of the Southern California Bight. Note: Individual matrix cells illustrate the presumed relative impact of each source on each component, along with the associated scientific certainty. Columns represent cumulative impacts on individual components; rows represent the effects of individual perturbations on all components. This figure was used to summarize and investigate ways of identifying and ranking impacts in the Southern California Bight.
Source: Adapted from Clark 1986.

for developing monitoring objectives, including the selection of specific resources, impacts, and changes that should be monitored.

STEP 2: DEFINE STUDY STRATEGY

Figure 4.4 shows the elements of defining a monitoring strategy and developing specific questions to be answered. These questions guide subsequent steps in the technical design process. Step 2 begins with the general monitoring objectives developed in step 1 and ends with explicit questions to be answered that are the basis for developing a sampling design. The goal of this step is to narrow the focus of monitoring from the vast number of questions and parameters that could be examined to those that will produce the specific information needed. Step 2 is essential because, without clearly stated testable questions, monitoring is often a haphazard collection of data. As Green (1979) emphasizes, "Your results will be as coherent and as comprehensible as your initial conception of the problem." Similarly, in writing about monitoring to detect power plant impacts, Fritz, Rago, and Murarka (1980) stated: "This failure [to formulate clear-cut questions] may account for the relatively inconclusive results produced in environmental assessments."

There are no simple guidelines for producing specific questions to be answered. Whatever method is used, it must be pursued with the determination to continue until specific potential impacts on specific resources in specific locations at specific times are identified (e.g., Bain et al. 1986). To be useful, testable questions need not be complex-, DAMOS managers were concerned about whether hurricanes would erode dredged material disposal mounds and contribute to the transport and dispersal of contaminants contained in the dredged material (SAIC 1986). Their concern led to the question "Within the detection limits of seabed profiling technology, are disposal mounds in Long Island Sound smaller after a hurricane than they were before the hurricane?" In contrast, the monitoring conducted around oil platforms in the Gulf of Mexico was not based on specific questions designed to meet specific information needs, lacked any operational definition of impact, implicitly assumed that impacts would be easily distinguishable from natural variation, and failed to use an appropriate sampling design. (See Box 4.2.)

In their study of impact assessment methods, Beanlands and Duinker (1983) provide a particularly good example of the difference between useful and nebulous questions. The original nebulous question "What would be the impacts of a proposed dam on the fish resources of the river?" failed to help focus the sampling design because it did not ask "What impacts and which fish resources are of concern?" Beanlands and Duinker explain how this original question was refined to provide the specific information needed to make a decision. The refined question was: "What percentage of the Arctic char spawning habitat would be lost given a 0.5 meter reduction in the water level of the river during the month of September?"

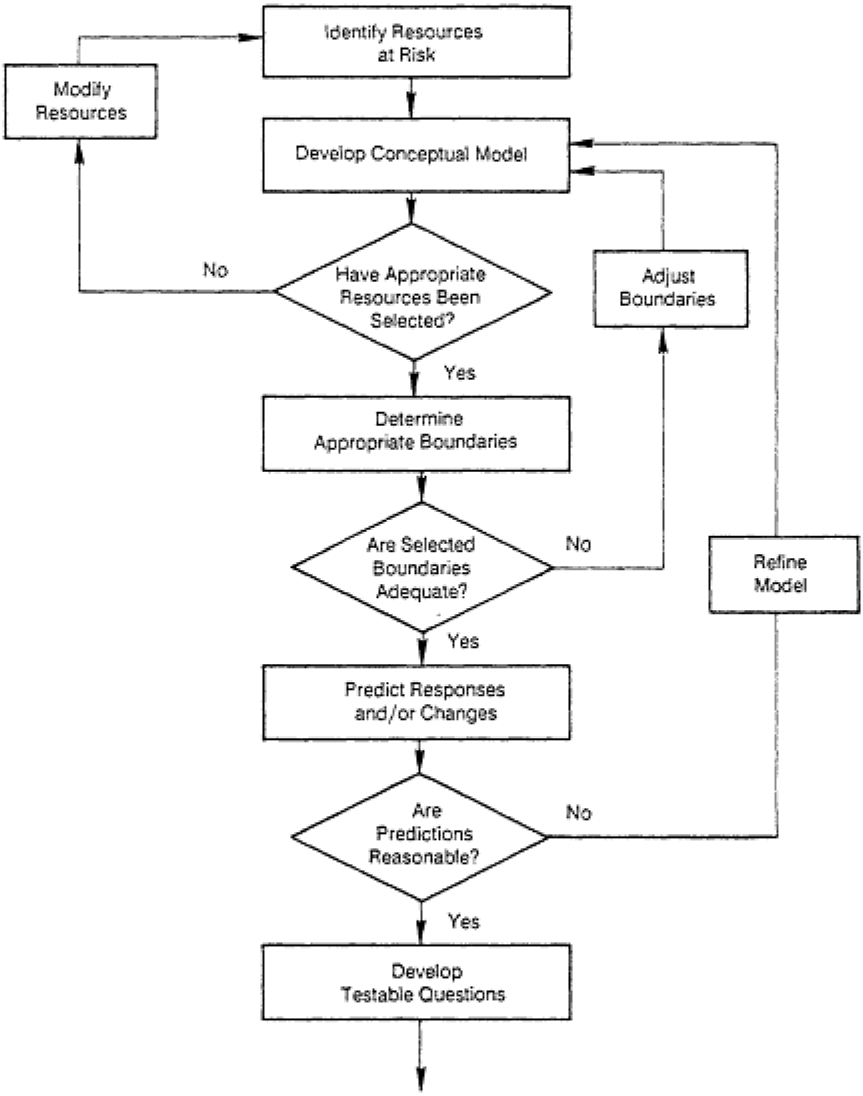

Figure 4.4
Step 2: Define study strategy.

As shown in Figure 4.4, several steps are involved in progressing from general monitoring objectives (step 1 and Figure 4.3) to specific questions to be answered (step 2 and Figure 4.4). They include: identifying

BOX 4.2 THE EFFECTS OF OFFSHORE PETROLEUM ACTIVITIES

The environmental effects of offshore oil and gas exploration and production activities have engendered much concern since national policy promoted expansion of Outer Continental Shelf (OCS) development as a response to the Arab oil embargo and threats to U.S. energy security. These concerns focused not only on oil spills but on the effects of operational discharges—drilling fluids and cuttings and produced waters.

Few long-term monitoring programs have dealt with the effects of OCS development activities; several field assessments, although not continued for long periods, share a basic purpose and many design considerations with environmental monitoring. They include several studies in the Gulf of Mexico, which has experienced offshore oil and gas development since the 1940s, and monitoring studies in the Mid-Atlantic Bight, on Georges Bank, and, more recently, in central California.

Carney (1987) reviewed the design of these studies, conducted from 1972 to 1984 and sponsored by industry (off Louisiana and in the Mid-Atlantic Bight), the Environmental Protection Agency and National Oceanic and Atmospheric Administration (off Texas), and the Minerals Management Service of the Department of the Interior (off Louisiana and on Georges Bank).

Carney concluded that the three Gulf studies could not detect long-term impacts because they lacked an operational definition of impact, implicitly assumed that any impact would be easily distinguishable from natural variation, and failed to use design techniques afforded by population survey statistics. He characterized them as the "survey and explain" approach. Although the Mid-Atlantic and Georges Bank studies showed more thoughtful design, the Mid-Atlantic study had to abandon its statistical design because the model was ecologically unrealistic.

Carney concluded that OCS monitoring could be improved by concisely stating the problem, carrying out preliminary sampling, verifying the appropriateness of the sampling unit and estimating replication needed to obtain required precision, selecting and adhering to the adopted design and the results obtained, adopting a stratified random approach in the presence of large-scale environmental variation, taking randomly allocated replicates within each combination of controlled variables, and using replication to estimate variability.

the environmental components or resources at risk, establishing the links (direct and indirect) among ecosystem attributes, particularly the resources at risk and human and natural causes of change, establishing boundaries for spatial, temporal, biological, and physical/chemical aspects of the system (including defining scales of spatial and temporal variations in both human and natural causes of change); and projecting, either quantitatively or qualitatively, human and natural changes in resources and the interactions between them. These steps help define the cause-effect relationships (i.e., a quantitative or qualitative conceptual model) that determine potential responses of the resources at risk to human activities.

An essential part of developing a sampling design and study strategy is ensuring that sufficient feedbacks are incorporated so that the questions to be answered are refined to reflect the best information available, including new information that results when a study is implemented. The evolution of the sampling design of the San Onofre kelp bed monitoring program (see Box 4.3) is a good example of a typical situation in which information acquired during the technical design stage modified the original understanding of the system and thus the monitoring objectives. The example

BOX 4.3 SAN ONOFRE KELP BED MONITORING

How are testable questions developed, and how do real-world constraints affect technical design? An example should help.

The Southern California Edison Co. (SCE) San Onofre Nuclear Generating Station (SONGS) discharges cooling water (6,274 cubic meters per second) from offshore diffusers. The diffuser flow entrains 10 times the initial volume to create a plume that extends offshore, upcoast, or downcoast depending on local currents. SCE and the California Coastal Commission's Marine Review Committee (MRC) carried out extensive predictive and monitoring studies.

Preliminary studies (tank tests, numerical modeling, and field verification) showed that, at times, the plume would enter the nearby San Onofre kelp bed (*identify resources at risk*).* Further plume modeling and preliminary experiments on kelp reproductive processes (*preliminary studies*) showed that the plume's turbidity could affect light levels in the kelp bed and reduce reproductive success and that this change might reduce the size and long-term viability, of the kelp bed.

These preliminary studies led to development of the *conceptual model*. It defined a causal link between power plant operation and kelp bed change, but it did not specify the extent and frequency of impacts (*spatial and temporal boundaries*). *Making predictions* about the extent and frequency of the potential impacts required integrating additional ecological information about kelp reproduction with further plume model results. Natural year-to-year variability in kelp recruitment was large, suggesting that monitoring should continue over several years so that natural factors controlling reproductive success could be identified and quantified. Plume models indicated that only the portion of the kelp bed nearest the diffusers would be affected. In addition, reduced light levels due to the plume were estimated.

Predictions from the *conceptual model* and results from *preliminary studies* and other research were integrated to produce the following *specific questions* to be answered:

- Would the diffusers create a turbid plume that would enter the San Onofre kelp bed?
- Would a turbid plume reduce near-bottom irradiance?
- Would reduced near-bottom irradiance reduce successful kelp recruitment compared to areas not influenced by the plume?
- Would a succession of poor recruitment events reduce the
- size of the kelp bed?
- Would a smaller kelp bed be less viable over the long term?

Field studies validated numerical models of plume behavior and kelp reproduction. Compliance monitoring of the thermal plume documented plume behavior. Trends monitoring of kelp recruitment and kelp bed size tested hypotheses about both short- and long-term plume effects.

Several important points about step 2 of the technical design framework are shown here. The *specific questions* to be answered were more precise than merely asking "Does the SONGS power plant affect the San Onofre kelp bed?" To produce precise questions, SCE and MRC integrated preliminary. studies with research and monitoring information on kelp bed ecology. Arriving at *specific questions* to be answered required refinement of the conceptual model and several iterations of modeling, research, and prediction. The first version of the conceptual model was verbal and qualitative and guided subsequent design efforts. Later versions incorporated ecological knowledge, quantitative predictions from numerical models, and subjective judgments.

* Italicized phrases indicate specific framework elements (Figure 4.4).

also demonstrates how preliminary studies can provide information crucial to developing and refining the specific questions to be answered.

Conceptual Models and Predictions

A description (i.e., a conceptual model) of the cause-effect links between human activity and anticipated environmental change is the central feature in developing specific questions to be answered. It is the conceptual model that is the means of predicting environmental change and the results of management action—predictions that efficiently direct and focus monitoring efforts. (See Box 4.4.)

A conceptual model describes links among the resources at risk; the physical, chemical, and biological attributes of the ecosystem; and human and natural causes of change. The understanding that results permits testable questions to be clearly stated and ultimately evaluated. By providing a context for organizing existing scientific understanding, a conceptual model also identifies important sources of uncertainty. As the San Onofre kelp bed example demonstrates (see Box 4.3), conceptual models can be qualitative or quantitative, depending on the state of knowledge, and they should be refined during a monitoring study.

Boundaries

Many workers (Cooper and Zedler 1980; De Angelis 1980; Dooley 1979; Fritz, Rago, and Murarka 1980; Hilborn, Holling, and Walters 1980; Beanlands and Duinker 1983; Green 1979; Holling 1978) emphasize the importance of establishing boundaries in monitoring and environmental assessment studies. These boundaries affect the kinds of questions that monitoring can answer. Suitable boundaries ensure that monitoring is relevant to both natural processes and the environmental quality and human health objectives established early in the technical design. For example, a major finding of the Southern California Bight case study was that the assortment of individual monitoring programs in Southern California was not adequate to address important potential regional and cumulative environmental effects. The Particulate Waste case study found that the site-specific monitoring programs in Long Island Sound could not easily relate changes at individual sites to regional hypoxic events. In both instances, the boundaries of the monitoring programs reflected site-specific rather than larger-scale questions.

Adequate boundaries make it more likely that all events and processes seriously affecting the system will be included. For example, water quality in the upper Chesapeake Bay is affected by the volume of freshwater input from rivers (Holland, Shaughnessy, and Hiegel 1986). Freshwater input,

BOX 4.4 CONCEPTUAL MODELS

The term "conceptual model" is sometimes misunderstood. In the technical design methodology, conceptual models refer to descriptions of causes and effects that define how environmental changes are expected to occur. Conceptual models may incorporate disparate elements (e.g., numerical models, natural history information, ecological theory, and subjective judgment) (Holling 1978; Goodall 1977; Pielou 1981; Saila 1979). Deciding just what tools to use depends on monitoring objectives, available technical knowledge, and the degree of precision required.

A wide variety of conceptual models is currently used to structure marine monitoring practice because the best representation of a specific system depends on the nature of the perturbation and the resources at risk (Beanlands and Duinker 1983; NRC 1986). The examples below show some of the approaches.

Monitoring in the San Onofre kelp bed (see Box 4.3) was based on a conceptual model that included kelp physiology and physical transport processes. When entrainment of fish eggs and larvae and impingement of adult fish by coastal power plants is a concern, conceptual models are based on population dynamics and circulation patterns that control larval transport (Barnthouse, DeAngelis, and Christensen 1979; Barnthouse and Van Winkle 1981; Boreman, Goodyear, and Christensen 1981; Polgar, Summers, and Haire 1980; Polgar, Turner, and Summers 1988).

Monitoring toxic effects of discharged chemicals is typically based on a source-receptor conceptual approach (e.g., Wiersma and Otis 1986; Wiersma et al. 1984; Behar et al. 1979; Eberhardt et al. 1976; Pickett and Whiting 1981). The ultimate receptor in such a source-receptor model could be a physical ecosystem compartment, a particular species, or an organ (e.g., the liver) within a species.

In all these approaches, the conceptual model began as a qualitative description of causal links in the system. Based on available technical knowledge, it was then expanded to include quantitative elements, such as analytical or numerical models. Sometimes the conceptual model includes more than one kind of numerical model (e.g., in the kelp bed example, plume dispersion and light attenuation models).

in turn, varies with major storms and with seasonal patterns of rainfall in the watersheds around the bay. Given this information, it is clear that the monitoring program boundaries needed to include surrounding watersheds.

Setting boundaries is not typically separate of the monitoring program's other elements. Boundaries are implicitly set when environmental quality and human health objectives are established and resources at risk identified. Additional boundaries are set when a conceptual model of linkages among ecosystem components is constructed. Walters (1986) points out that the defined boundaries of the system and the specific questions that can be asked are interdependent. The initial questions help define the system boundaries, but changing the boundaries also affects the questions that can be asked. Thus Walters suggests varying boundaries deliberately during planning, offering a valuable opportunity to examine a given situation from several perspectives. Even though boundary setting is part of several steps in the methodology, it is so important to the overall effectiveness of monitoring that explicit evaluation of boundaries is shown as a separate activity. (See Figure 4.4.) This step ensures that boundaries will result from conscious decisions rather than from unstated assumptions.

Several approaches to establishing study boundaries have been proposed; three of them, which are described below, illustrate the factors that should be considered. No one approach or one set of boundaries is best for all problems.

Beanlands and Duinker (1983) identified four types of boundaries that contribute to the sampling design of a monitoring program: (1) administrative boundaries deriving from political, social, or economic factors; (2) project boundaries deriving from the spatial and temporal extent of the project or perturbation under study; (3) ecological boundaries deriving from the nature of physical, chemical, and biological processes; and (4) technical boundaries deriving from limits on capabilities to predict or measure ecological change and/or ecosystem processes. The final study boundaries that are established should be consistent with these classes of boundaries and with study objectives. Walters (1986) discusses four dimensions to consider when establishing boundaries: the breadth of factors considered, the depth of analysis, the spatial scale of variables, and the time scale or horizon. Figure 4.5 shows another, visual, method for identifying the relative space and time scales of important ecosystem components and processes that are relevant for establishing study boundaries.

Establishing appropriate space and time boundaries is particularly important in developing the sampling design for monitoring studies for several reasons. First, the majority of parameters that could be measured by monitoring programs vary on space and time scales. No one set of boundaries is adequate for all parameters. Second, events that occur over large areas typically occur over long periods and vice versa (e.g., Chelton, Bernal, and

McGowan 1982; Haury, McGowan, and Wiebe 1978). And third, spatial and temporal variability in the marine environment can easily confound the interpretation of monitoring results (Botkin and Sobel 1976; Livingston 1982; Pearson and Barnett 1987; Holland, Shaughnessy, and Hiegel 1986). Establishment of appropriate boundaries ensures consideration of all events and processes that affect the questions being asked and thus the sampling design.

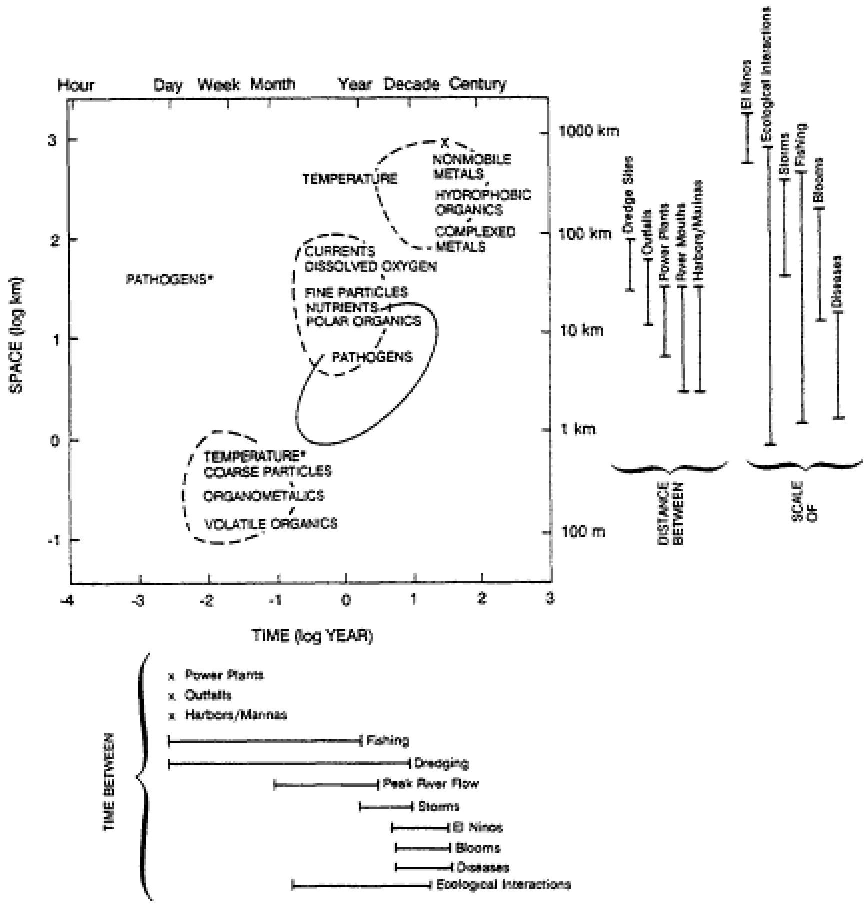

Figure 4.5
Characteristic temporal and spatial scales of the movement of marine constitue nts
and the processes of sources of perturbation. Source: Adapted from Clark 1986.

Predictions and Uncertainty

It is important to recognize that the sampling designs of all monitoring programs are based on assumptions and predictions about likely responses to perturbation. In addition, management actions are taken with the expectation that they will mitigate an impact or protect a resource. Ideally, all such predictions should be made explicitly. For example, decisions about waste load allocations in the New York Bight were based on numerical models that predicted the effects of alternative management actions (Hazen and Sawyer and Hydroscience 1978). More often, predictions are not made explicitly, but even then, the assumptions implicit in the choice of one alternative over others constrain monitoring and management actions just as though they had been made explicitly (Beanlands and Duinker 1983; Bernstein and Zalinski 1986; Holling 1978). For example, monitoring once a year precludes monitoring seasonal patterns, just as though it was assumed that seasonal patterns do not significantly affect year-to-year trends. Similarly, monitoring only benthic infauna precludes identifying impacts on other fauna; the implicit assumption is that benthic infauna are the best indicators of impacts.

In general, two types of predictions are important: those about how a particular environmental perturbation will affect a monitored parameter and those about how a specific management action will affect an important resource. Predictions should be based on a conceptual mode that specifies cause-effect relationships, and they should be stated clearly. Implicit assumptions should be avoided because their consequences are frequently not evident either to the designers or to the users of monitoring data.

Numerical models are often used to make predictions for monitoring design and management because they systemize knowledge and produce quantitative predictions. However, it is important to recognize that numerical models are not infallible. When they are wrong, the mismatch between prediction and experience affords an opportunity to improve understanding.

As one example, water quality models were used to predict the effects of proposed freshwater diversions on productivity in San Francisco Bay (e.g., Hydroscience 1974). The drought of 1976-1977 tested these predictions; it mimicked the reduced flow due to diversions. The altered salinity regime affected benthic communities, resulting in a new assemblage. This new assemblage cropped phytoplankton at an increased rate, resulting in much lower plankton productivity than predicted (Nichols 1985b).

As another example, the 1976 impoundment of a Manitoba lake (Lehman 1986) revealed serious flaws in models of reservoir dynamics. Unforeseen physical effects led to extreme biological changes, and higher water levels melted permafrost and led to severe erosion. Increased turbidity affected productivity in unexpected ways, and the commercial whitefish fishery collapsed. Mercury released during erosion was mobilized biologically, and tissue levels in walleye and northern pike rose above Canadian standards.

Uncertainty associated with assumptions and predictions varies in kind and degree (Holling 1973, 1978; NRC 1986; Walters 1986; Wolfe 1988; Freudenburg 1988; Eberhardt 1976; Paine 1981). Indeed, were there no uncertainty about environmental effects, monitoring would be unnecessary. Identifying the sources and consequences of uncertainty is sometimes more valuable than predicting the impacts (NRC 1986). Uncertainty stems from many sources (e.g., model error, measurement error, natural variability, incomplete scientific understanding) and takes many forms. At one extreme, uncertainty in well-understood systems is mainly a result of measurement error. At the other extreme, it may be difficult or impossible to predict whether an assumed effect will occur at all. In many cases, the nature of effects is clear, and only their timing, extent, or severity is uncertain. For example, the effects of organic enrichment on benthic communities are well documented (e.g., Pearson and Rosenberg 1978; Greene and Sarason 1974; Greene and Smith 1975; Stull et al. 1986; Pearson 1987; Norton and Champ 1989; Swartz et al. 1986). But the actual severity and extent of changes that will occur in any specific instance are not predictable.

The lack of clear predictions is probably the single greatest weakness of most monitoring programs. In spite of its difficulty, basing the monitoring design on explicit predictions results in discernible benefits. It provides an unambiguous statement of the assumptions underlying monitoring and management actions and increases the likelihood that all important processes and interactions will be considered adequately. It ensures that monitoring will be focused on expected changes that are relevant to management objectives. Further, explicit predictions of the kinds and amounts of change expected provide the basis for a statistically rigorous sampling, measurement, and analysis design.

STEP 3: CONDUCT PRELIMINARY STUDIES AND RESEARCH

Figure 4.1 shows that preliminary studies (step 3) support the development of both specific questions to be addressed (step 2) and the sampling designs (step 4). Such studies help refine measurement techniques, result in the development of new methods or models, estimate the magnitude of natural variability, or otherwise lay the groundwork for developing a monitoring design.

Preliminary studies have supported development of the technical design of many monitoring programs. In the kelp bed example (see Box 4.2), preliminary studies included numerical and physical modeling of the diffuser plume, physiological studies of kelp reproduction and recruitment, and field measurements of natural kelp distribution, growth, and mortality. In Chesapeake Bay, research to characterize and understand natural variability in benthos and field experiments to validate their responses to predation by fish and crabs and the estuarine salt gradient (Holland 1985; Holland, Mountford, and Mihursky 1977; Holland, Shaughnessy, and Hiegel 1986) supported development of the long-term benthos monitoring program.

An important category of preliminary studies is the measurement of important parameters under different hydrological regimes to calibrate and validate water quality models. Such preliminary studies have been carried out in the New York Bight to assess the potential impacts of nutrient fluxes through the Sandy Hook transect (O'Connor, Mancini, and Guerriero 1981; Stoddard and Walsh 1988). Intensive monitoring in New York Harbor, especially during periods of high rainfall (Hazen and Sawyer and Hydroscience 1978), was used to develop mathematical models for a water quality management plan. Both projects provided the bases for development of larger-scale models for a water quality management plan of the combined New York-New Jersey Harbor and New York Bight. Similar studies, including both modeling and monitoring, have been performed in the James, Delaware, Patuxent, and Potomac estuaries. A significant feature of such studies is that monitoring focuses on variables used in modeling as well as on resources at risk.

These examples illustrate the fact that monitoring and research are interdependent, and that their frequent separation is more arbitrary than real. Rigidly separating monitoring and research decreases the chances that monitoring will benefit from new knowledge. Relevant research and other preliminary studies should be integrated throughout a monitoring program to resolve uncertainties and focus monitoring on test questions. Such an iterative sequence of planning, modeling, data collection, and research can result in highly effective monitoring programs. The experience in integrating these approaches is more extensive in freshwater environments (e.g., Cairns, Dickson, and Maki 1978).

STEP 4: DEVELOP SAMPLING/MEASUREMENT DESIGN

Linking Testable Questions to Useful Information

Step 4 uses the information produced in steps 1-3 to develop a sampling or measurement design that states what variables will be measured and where and when the measurements will be taken. (See Box 4.5.)

The steps outlined in Figure 4.6 ensure that sampling and measurement designs will be appropriate to the questions upon which the monitoring is based. The feedbacks ensure that the evolving sampling/measurement design will produce information needed to answer the specific questions to be addressed. The elements of step 4 include: identifying the kinds and amounts of change that are meaningful; identifying and quantifying the sources of variability that may obscure or confound responses; deciding what to measure, in light of logistical constraints and limitations on scientific knowledge; developing a sampling design that provides the logical structure for the measurement program by specifying how variability will be partitioned; specifying statistical models that are the basis for selecting the kinds and numbers of measurements that should be taken; performing optimization and power analyses to determine whether the monitoring design can measure meaningful levels of change; defining data quality objectives; and developing the sampling/measurement design that incorporates all the above elements.

BOX 4.5 DIFFERENT QUESTIONS, DIFFERENT SAMPLING DESIGNS

A simple example using sewage outfall effects will clarify the relationships between questions and the technical requirements of monitoring programs. If the focus is on differences in and outside the zone of initial dilution (ZID) boundary at one point in time, the sampling design will include stations in and outside the ZID at that one time. But if the focus is instead on changes over, say, five years, then these stations would be sampled periodically over the five years rather than just once. Year-to-year variability is not important in the first sampling design, but it is in the second.

Defining Meaningful Change

The goal of a monitoring sampling design should be the detection of specific kinds and amounts of change in the resources at risk, in surrogate variables related to them, or in parameters involved in model validation or increasing the understanding of important natural processes (e.g., Fredette et al. 1986).

The definition of "meaningful change" is based on the testable questions developed in step 2. (See Box 4.6.) All kinds and levels of change are not equally important. It is therefore not possible to decide what parameters should be measured and when, where, and how measurements should be made until a determination is made about what kinds and levels of change are meaningful. When a decision about meaningful change has not been made, "monitoring programs run the risk, on the one hand, of having little or no chance of detecting anything but catastrophic change, or, on the other, of sampling far in excess of what is necessary. . . ."(Bernstein and Zalinski 1983).

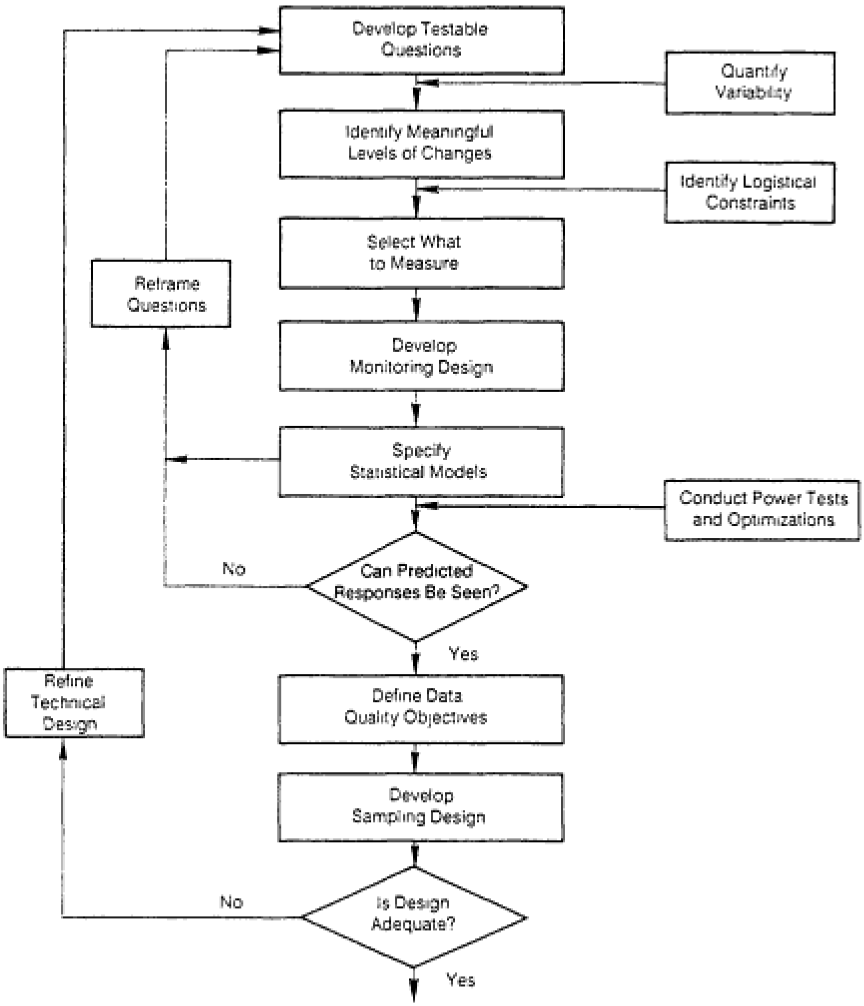

Figure 4.6
Step 4: Develop sampling/measurement design.

Deciding what kinds and amounts of change are meaningful (and to whom) is neither simple nor easy. Beanlands and Duinker (1983) note that statistical, scientific, project-specific, and wider societal concerns all contribute to the definition of meaningful changes. The benefits of defining how much change is meaningful cannot be overstated. This determination not only allows the designers of monitoring programs to focus resources more efficiently but also provides managers and decision makers with higher-quality information with which to make decisions. For example, the Marine Review Committee of the California Coastal Commission (1989) determined that an average decrease of 50 percent in population levels of certain plankton would indicate an impact from the San Onofore Nuclear Generating Station (SONGS) 3 kilometers away. A monitoring program was then designed with a specific probability of detecting this change. In the 106-mile dumpsite monitoring plan (Werme et al. 1988), the detection of any contaminants at the site boundary triggers another tier of monitoring activities. This decision criterion is based on the judgment that far-field effects are likely only if contaminants spread beyond the site boundary.

BOX 4.6 MEANINGFUL VERSUS SIGNIFICANT CHANGE

Attempts to define meaningful amounts of change are confused by meanings of "significant" (Sharma, Buffington, and McFadden 1976; Christensen, Van Winkle, and Mattice 1976; Zar 1976). Significant means "having meaning . . .; having or likely to have influence or effect" (Merriam-Webster Inc. 1986), but it also refers to the statistical difference, at a specified probability level, between or among two or more sampling distributions. The California Ocean Plan (California State Water Resources Control Board 1983) prohibits activities causing "significant" change, defined in strictly statistical terms.

How large a change is important? One that is statistically significant is not necessarily meaningful. Virtually any change can be statistically significant, depending in part on the sampling effort. Thus a monitoring program with a small sampling effort will detect only large changes, but one with an intensive sampling effort could find even miniscule changes statistically significant. Whether changes in the environment are statistically significant has no bearing on the extent to which the changes may be either meaningful or important (i.e., have ecological or human consequences).

The definition of meaningful change is not static. It can shift with changing boundary conditions or new information. For example, a short-term one-time change in a water quality parameter or contaminant level should probably be viewed differently than the same degree of change in the long-term average.

The Influence of Natural Variability

Natural variability creates a background of change that may make it difficult to quantify environmental responses to human activity (Nichols 1985a). Thus defining meaningful change depends in part on identifying and accounting for natural sources of variability. For example, E1 Niños and occasional large winter storms in Southern California can destroy kelp bed canopies and prevent the detection of subtle impacts of human activities on the kelp beds. Seasonal changes in the abundance of the benthos in Chesapeake Bay affect population dynamics in ways that can also obscure benthic responses to human impacts (Holland, Shaughnessy, and Hiegel 1986). Similarly, large-scale climate-related shifts in fish distributions can make it difficult to identify and measure the effects of harvesting (Sherman and Alexander 1986).

Natural variation affects sampling design in two major ways. First, natural changes may be so large that they mask changes of human origin. Second, random or periodic variations not accounted for in the sampling design can result in noise or false signals that make it difficult to determine the response of the ecosystem (Christie 1985; Coull 1985; Lie and Evans 1973).

Understanding variability aids development of a sampling design in several ways: it helps construct a conceptual model that includes key natural processes and linkages that affect the resources being monitored, it helps partition variability by collecting data on appropriate space and time scales (Livingston 1987; Kerr and Neal 1976), and quantitative measures of variability provide input to the optimization and power analyses that predict whether the monitoring design can detect meaningful levels of change (Cohen 1988).

Characterizing variability can be difficult because of its many sources and scales in the marine environment. Natural spatial and temporal variability can reflect simple gradients in the physical environment (e.g., depth, salinity, and temperature), or it may reflect more complex processes such as succession and ecological interactions among ecosystem components (Levin 1978; Pearson and Rosenberg 1978; Nichols 1985b; Holland et al. 1986; Holling 1978). In addition to these natural kinds of variability, human activities and their impacts vary in space and time, and they can interact with natural processes to create intricate and sometimes perplexing patterns. (See Box 4.7.) As Wolfe et al. (1987) point out, cycles of temperature, light, and other factors interact with tidal cycles, seabed topography, and processes such as evaporation, turbulent diffusion, ion exchange, respiration, growth, and predation. Failure to understand fully such factors affecting the resources at risk can make it difficult or impossible to design monitoring programs that produce useful management information.

BOX 4.7 INTERACTIONS BETWEEN HUMAN ACTIVITY AND NATURAL PROCESSES

Impacts of human origin and natural processes sometimes vary together in ways that make determination of the causes of environmental change difficult. Events in the Southern California Bight between 1973 and 1977 are an example. There was a massive influx of the echiuran worm, *Listriolobus*, into benthic communities (Stull et al. 1986). This organism's burrowing, respiratory, and feeding activities aerated and reworked sediments throughout the bight. In areas of wastewater impacts (particularly around the White Point outfall in Los Angeles), these activities reduced apparent impacts. At the same time, mass emissions from the White Point outfall were substantially reduced. When the echiuran disappeared, impacts reappeared, but not to the extent seen previously. How much of the reduction in impacts was caused by the echiuran? How much by reduced discharges? It was hard, if not impossible, to say.

Each of the three uses of information about variability mentioned above (i.e., conceptual modeling, monitoring design development, and optimization and power analyses) requires somewhat different kinds of information. Building a realistic conceptual model requires a comprehensive review of all possible sources of variability. At this point in the monitoring design methodology, it is more important to have a qualitative understanding of the relationships among most or all sources of variability than a more quantitative description of a few. Failure to include an important source of variability can result in unrealistic assumptions about how impacts are created. For example, the lack of an atmospheric source term for nutrients in water quality models of Chesapeake Bay led to erroneous predictions and incomplete management strategies (Fisher et al. 1988; Tyler 1989).

Developing an adequate monitoring design depends on somewhat more quantitative knowledge about variability because the monitoring design must specify where and when measurements should be taken.

Optimization and power analyses require quantitative estimates of the major sources of variability. It is impossible to allocate limited sampling resources without such information. For example, if year-to-year variability in a particular system is much greater than seasonal variability, then proportionally more resources should be devoted to sampling additional years rather than additional seasons within years. Such decisions cannot be made without knowledge about at least the relative magnitudes of the various sources of variability.

Selecting Variables to Measure

Most monitoring programs do not have the resources to monitor all variables of concern. The limited resources available must then be focused on the system attributes that are of the greatest concern and provide the most information about system status or changes in status. Thus actual sampling may not focus directly on the resources at risk but on surrogate variables. Surrogate variables include resources of intrinsic importance (e.g., economically important species, endangered species), early warning indicators (e.g., variables that respond rapidly to the stress of concern), sensitive indicators (e.g., variables that have a high degree of specificity to stress), process indicators (e.g., variables that provide insight into the effects of stress on complex system interactions, and variables with high information redundancy (i.e., those that are generally representative of the behavior of a number of important parameters). The rationale for monitoring surrogate variables is that they might provide clearer or simpler information than the resources would. This statement may not always apply (Wolfe and O'Connor 1986; O'Connor and Demling 1986; Bryan and Gibbs 1987), and specific criteria need to be applied to the selection of surrogate variables on a case-by-case basis. For example, diversity indices are often used to provide summary information about impacts on communities containing many species. However, much important information can be discarded in the calculation of these indices (May 1985). In addition, changes in diversity can be ambiguous, particularly when the study assemblage is exposed to more than one source of disturbance (NRC 1986). Criteria that should be used to select surrogate variables include sensitivity to the stress of concern, reliability and specificity of responses, ease and economy of measurements, and relevance of the indicator to specific concerns (NRC 1986).

Two important issues are involved in the choice of variables to monitor. The first relates to the depth of knowledge about a particular system (e.g., specificity and reliability of responses) and the second to the statistical efficiency of sampling alternative variables (e.g., the signal-to-noise ratio). A prime consideration for any monitored variable is that it should be tied directly to the specific questions to be answered and the resources at risk. In other words, changes in the status of the selected variable must unambiguously reflect changes in the resources at risk. How much they can be tied together depends largely on the depth of knowledge about the system and process being monitored. In well-understood systems, it will be clear which variables to measure and how to draw conclusions about the state of resources from them. For example, understanding the processes leading to oxygen depletion and eutrophication has focused modeling and monitoring on nutrient levels (Hydroscience 1974; HydroQual 1986). When a system is less well understood, it may not be apparent which variables will indicate meaningful changes in resources. Then the conceptual model should be used to determine whether a particular variable can be linked to the specific questions to be answered with cause-effect statements. When crucial gaps in scientific understanding occur, research or modeling may be initiated to help determine what measurements should be made. In addition, the available information should be used to make an informed decision about what to monitor now. The kelp bed example described earlier (see Box 4.3) shows how research and modeling provided data that improved the conceptual model. This improved understanding was then used to focus monitoring on quantifying the response of kelp recruitment to power-plant-induced changes in near-bottom irradiance.

BOX 4.8 VARIABILITY AFFECTS SELECTION OF VARIABLES

Dischargers in the Southern California Bight monitor the levels of contaminants in the tissue of fish collected around wastewater outfalls.

But two potentially large and poorly understood sources of variability make it difficult to interpret these data. First, different species of fish are sampled at different outfalls (NRC in press). In other words, different variables (i.e., different species) are being sampled. Second, sampling is conducted at different times around the same outfall. However, contaminant levels in fish vary seasonally as a function of reproductive status (Cross et al. 1986). These two sources of variability may interact because of differences in the timing of reproductive cycles and in tissue chemistry among species, resulting in data that provide ambiguous information about the impacts of discharges on contaminant levels in fish or about the risk of contaminant discharge to the people who eat the fish.

A second major consideration in selecting monitored variables is their statistical distributions and characteristics (e.g., signal-to-noise ratio). Monitored variables should provide the most accurate and precise estimates for the smallest required sampling effort, thus maximizing information return per sampling effort expended. Variables with high variability or unknown distributions (see Box 4.8) impair the ability to draw conclusions from monitoring data. Such variables are not appropriate for routine monitoring programs.

The Sampling Design and Its Statistical Basis

The sampling design is the central element in step 4 of the design methodology. (See Figure 4.6.) It provides the logical structure of the study (Cochran 1977; Fisher 1954) because it specifically defines how questions will be evaluated and how variation associated with different sources (e.g., spatial and temporal as well as human-induced variation) will be measured. For example, the kelp bed study (see Box 4.3) was structured around comparisons of characteristics of kelp beds located in the thermal plume against unaffected kelp beds located in reference areas far removed from the thermal plume. Several reference kelp beds were sampled to estimate natural variability among them. This structure defined the type of comparisons that would be used to detect impacts. In addition, the design consisted of sampling for several years before and several years after the power plant began operating to provide a background of natural temporal variability against which to measure changes in conditions that occurred once power plant operations began.

In many monitoring and assessment programs, it is not possible to collect preoperational data or to establish baseline conditions before an impact has occurred. Statistical comparisons in such cases are limited to comparing distributions among locations of concern to distributions at sites that are assumed to be appropriate reference areas (Green 1979). Selection of appropriate reference areas is always problematic. It is a particularly difficult problem in estuaries, where a natural salinity gradient that may vary in location from year to year generally requires broad regional sampling and application of estimation techniques to assess conditions that may occur at any particular location (Holland, Shaughnessy, and Hiegel 1986).

A poorly thought out sampling design usually results in testing of inappropriate questions, incomplete evaluation of questions, inability to separate change due to natural processes from change clue to multiple activities, relatively low ability to detect change (low statistical power), and poor use of resources due to oversampling (e.g., Gore, Thomas, and Watson 1979; Hurlbert 1984; Stewart-Oaten and Murdoch 1986; Green 1979; Thomas 1978; Bernstein and Zalinski 1983; Toft and Shea 1983; Trautmann, McCulloch, and Oglesby 1982; Skalski and McKenzie 1982; Millard and Lettenmaier 1986). A well-planned sampling design, however, provides a logical basis for evaluating questions and a clear definition of a meaningful level of change, proper matching of variables with questions, quantification and partitioning of background variability, and proper assignment of sampling units among conditions or treatments.

Once a sampling design has been developed, it becomes the basis for a statistical model, which is a formal mathematical statement of the specific questions to be tested. By structuring how questions will be asked and by formally describing and partitioning sources of variability, the statistical model furnishes an objective method for allocating sampling or measurement resources. Two statistical tools that aid in the fine-tuning and refinement of the sampling design are optimization and power analyses. When sampling resources are limited, optimization techniques help decide how to make trade-offs needed to control for several sources of variability (e.g., Gunnerson 1966). Power analysis is a procedure for determining the level of change a given sampling design will detect (Cohen 1988; Trautmann, McCullough, and Oglesby 1982). These analyses can be conducted before samples are taken, after part of the samples have been collected, or after the program has ended. This knowledge can be invaluable in determining whether the resources available for monitoring are likely to produce useful information before a program is initiated. If power analyses show that meaningful levels of change cannot be detected with the available resources, then the monitoring program can be redirected before these resources are wasted on trying to answer unanswerable questions. They also provide scientists and decision makers with an estimate of the level of uncertainty and thus the degree of confidence they should place in a given analysis result at the conclusion of a program.

QUALITY ASSURANCE: AN IMPORTANT ELEMENT OF MONITORING PROGRAM DESIGN AND IMPLEMENTATION

A quality assurance program is a system of activities undertaken to ensure that the type, amount, and quality of data collected are adequate to meet study objectives; it is a critical element of all monitoring programs (Taylor 1985; EPA 1979; EPA 1984a). Quality assurance consists of two separate but interrelated activities: quality control and quality assessment (Taylor 1985).

Quality control includes activities to ensure that the data collected are of adequate quality given study objectives and the specific hypotheses to be tested (steps 1-4). Quality control activities frequently undertaken within monitoring programs include standardized sample collection and processing protocols and requirements for technician training (EPA 1984b). The goals of quality control procedures are to ensure that sampling, processing, and analysis techniques are applied consistently and correctly; the number of lost, damaged, and uncollected samples is minimized; the integrity of the data record is maintained and documented from sample collection to entry into the data record; the data are comparable with similar data collected elsewhere; and study results can be reproduced.

Quality assessment activities are implemented to quantify the effectiveness of the quality control procedures. They ensure that measurement error is estimated and accounted for and that bias associated with the monitoring program can be identified and, if practical, eliminated. Quality assessment consists of both internal and external checks, including repetitive measurements, internal test samples, interchange of technicians and equipment, use of independent methods to verify findings, exchange of samples among laboratories, use of standard reference materials, and audits (Taylor 1985; EPA 1980, 1984c).

To be effective, quality assurance must begin with planning the monitoring program. Thus the level of uncertainty associated with obtaining the required information can be balanced against the cost of obtaining the data (EPA 1984b). Steps 1-5 activities for defining what to measure and how, where, and when to take measurements are all part of the quality assurance process. Quality assurance must continue to be an integral component of monitoring systems from implementation through information dissemination. Activities for converting the data into useful information (steps 6-7) and the feedback loops shown in Figure 4.1 must also be taken into account in designing the quality assurance program. These later activities provide mechanisms for using quality assessment information to modify and improve monitoring.

The need for quality assurance programs increases with the complexity of the measurement program and the number of organizations involved (Taylor 1978, 1985). Experience shows that chemical monitoring programs that involve a number of laboratories measuring concentrations of chemical substances are particularly subject to quality assurance problems (Taylor 1985). For example, during the early stages of the Chesapeake Bay Monitoring Program, nutrient data were collected and analyzed by three regional laboratories, all using different protocols for processing samples. As a result, the data were not comparable and could not be used to depict nutrient distributions accurately (Martin Marietta Environmental Systems 1987). As is often the case, because of the haste to initiate the collection program, the laboratories' methods and equipment were not evaluated (Taylor 1985).

Another important quality assurance issue associated with monitoring systems is maintaining the integrity of large data sets (Packard, Guggenheim, and Bernstein 1989). Two general data management problems must usually be resolved: (1) correction or removal of erroneous individual values and (2) inconsistencies that damage the integrity of the data base. Many erroneous individual values can be identified, validated, and corrected using range checks, filtering algorithms, and comparison to lists of valid values. Entering data twice using different data entry operations and then checking for nonmatches are a particularly effective method for identifying and correcting key-punch errors. Subtle errors that affect the integrity of multiple data entries are much more difficult to identify and correct. For example, errors that affect the relationships among data entries are particularly difficult to identify and correct, especially in large regional monitoring data bases. Although some data base management systems protect against such errors, others require rigorous cross-checking during data entry to identify and correct these errors. Experience shows that the most effective way to avoid corruption of a data base is to select a data management system that protects against internal inconsistencies and to design the data entry process to minimize the occurrence of errors (Packard, Guggenheim, and Bernstein 1989). Data entry screens should be simple, and they should mimic the layout of raw data sheets. Typographical errors can be minimized by users selecting from a list of valid values (using lookup tables) rather than typing in the actual values.

Quality assurance activities ensure that the goals and objectives of the monitoring program are achieved and that the data that result are adequate for use in making the anticipated decisions. The final and perhaps most important component of quality assurance for a monitoring system is the external review process. Expert reviews should be conducted before samples are taken, at various logical interim phases during a program, and following the analysis and interpretation of the data.

STEP 6: CONVERT DATA INTO USEFUL INFORMATION

The raw data collected in a monitoring program frequently do not directly address public concerns or the information needs of decision makers. Data are individual facts, and information is data that have been processed, synthesized, and organized for a specific purpose. Drucker (1988) described the difference between data and information: "Information is data endowed with relevance and purpose. Converting data into information thus requires knowledge." A useful monitoring program provides knowledge or, more specifically, mechanisms to ensure that knowledge is used to convert data collected into information.

For example, measurements of contaminant concentrations in the water or sediments near a discharge in and of themselves are not useful information. Contaminant concentration data must be analyzed and mapped to describe patterns and trends. They must then be combined with additional data (e.g., background levels, transport processes, and flux rates) to define exposure. Ultimately, to assess environmental impacts, exposure information must then be combined with the results of studies of pollutant transport and effects research (e.g., bioassay experiments) to assess the risks to and consequences for receptors and processes. Conversion of monitoring data into information, therefore, involves a range of activities, including data management, statistical analysis, predictive modeling, and fate and effects research. Each of these activities is discussed below.

Data Management

The major function of data management activites is to provide easy access to the collected data and related information (e.g., historical trends data, research data, model outputs, data summaries). Because of the amount and complexity of the data that are collected by most monitoring programs and the variety of reports and analyses that are produced, a computer-assisted data management system is usually essential. To define and select the appropriate data management system, managers should first determine the volume of data, the long-term uses of the data, existing data management capabilities, the number and background of and relationships among users of the data, the major types of analyses to be conducted, and quality assurance/quality control and reporting requirements. This information ensures a system with the required capacity and degree of access.

Monitoring data can be stored in a central location. They can also be accessed through a distributed data management system. In either case, monitoring data and relevant model results should be included in both raw and summarized form to eliminate costly reanalysis. In addition, information on study characteristics, information on the institution responsible for data collection and storage, and a brief description of sampling methods, data format, quality control procedures, and how to access the data should be readily available for each data set.

Data management activities are as important to the success of monitoring programs as the collection of data. Therefore they should be funded as a continuing core program element, and reports that summarize the types, volume, and quality of data accessible through the system should be prepared and distributed to potential users frequently. Unfortunately, monitoring data are frequently not incorporated into a data management system until most data collection is complete. At this point in many programs, there may not be enough time or money to create an adequate system. This situation lessens the utility of monitoring data to scientists within and outside the program.

Data Analysis and Modeling

The goals of analysis activities are to summarize and simplify the collected data, test for change and differences, generate hypotheses, determine the consequences of observations, and evaluate the uncertainty associated with conclusions drawn from the data. Analysis programs should be developed prior to data collection. This development should include both statistical testing and modeling to ensure that the analysis approach is appropriate to the sampling design and the sampling methods.

Successful analysis programs cut across institutional and media boundaries; partition spatial and temporal variations into their major sources (natural and human induced); are based on an understanding of linkages among physical, chemical, and biological attributes; use standard verified modeling approaches, statistical packages, and analysis/data management packages; state and determine the consequences of assumptions inherent in the sampling design and analysis approach; evaluate the sensitivity of analyses to assumptions; and summarize analysis results using easily understood graphs, maps, and tables.

Statistical analysis helps characterize the data, determine the uncertainty associated with measurements, classify the data into appropriate spatial and temporal strata, and test for spatial and temporal change. Generally, many statistical tests are appropriate for any particular situation. Selection of the most appropriate test depends upon data characteristics and the specific question being asked. Numerous publications are available to help scientists and nonscientists identify, the most appropriate test, conduct the test, and interpret the results (e.g., Green 1979).

As discussed earlier, forecasting the responses of complex marine systems to human activities and assessing their status and trends with reliability are a difficult problem. Simulation models are an assessment tool that can be used to describe environmental complexities while allowing these complexities to be used in forecasting the consequences of environmental change. Simulation models are based on essential system attributes.

Research is a basic element in the development of predictive models and the interpretation and synthesis of monitoring data and model outputs. It is the major process for establishing cause-effect relationships. Correlations and relationships identified during the analysis of monitoring data (e.g., Cairns, Dickson, and Maki 1978; Smith, Bernstein, and Cimberg 1988; Holland, Shaughnessy, and Hiegel 1986) can be an important source of ideas for future experiments and measurements. The Southern California Bight case study found that monitoring programs had benefited greatly from their close association with ongoing research programs designed to understand the fate of discharged wastes and assess sublethal effects. The Southern California experience also shows that the results from separately managed and funded research programs can be transferred effectively.

Resource allocations for analysis activities are frequently not commensurate with those for data collection. For example, the Chesapeake Bay case study found that far too little attention and resources were directed at data analysis and synthesis relative to the investment made to collect the data. Data should not be collected unless a commitment is made at the outset that support for analysis activities will be commensurate with that for data collection.

One way to address the above problem is to use a phased analysis approach. In such an approach, the data collected early in the monitoring program are used to develop and refine routine analysis methods, classify the data into spatial and temporal components, determine the adequacy of the sampling design and methods, define the status and its relationship to historical conditions, and develop a preliminary understanding of links between components and processes. Interdisciplinary analyses can follow later in the program.

STEP 7: DISSEMINATE RESULTS

The results of monitoring programs, especially regional programs, should be disseminated to a range of audiences and at several technical levels. Monitoring programs that produce only technical reports summarizing data and scientific findings are not likely to show the public or decision makers that they provide information essential to better environmental protection or management decisions. In fact, management information is produced only when it is delivered to managers and decision makers in a usable, accessible form. Many monitoring programs, especially status and trends studies, extend over years. Interim results of these studies should be disseminated regularly, allowing users to determine whether the type and volume of data that they need are being obtained. If the needed information is not being obtained, midcourse adjustments can then be made. A phased analysis and reporting approach similar to that used by the Maryland Department of the Environment (see Box 4.9) keeps target audiences informed about what the information being collected means, what data remain to be collected, what analyses remain to be completed, and why additional data collection and analyses are needed.

REALISTIC EXPECTATIONS

While acknowledging the importance and utility of monitoring information, one must not overstate the utility of monitoring information. The marine environment is complex and variable, and it is often difficult to identify and measure clearly the impacts of human origin. These factors, coupled with limitations to scientific knowledge, emphasize the need for realistic expectations. Management of the environment and the monitoring programs that are a part of that management must therefore consider the risks and uncertainties inherent in most actions. Monitoring is limited in terms of its ability to quantify changes and to identify their causes. These limitations must be forthrightly stated, understood, and incorporated in the decision-making process.

The reality of imperfect knowledge about marine systems means that monitoring should be used as an opportunity to increase and refine our

BOX 4.9 DISSEMINATION OF INFORMATION IN THE CHESAPEAKE BAY PROGRAM

The Maryland Department of the Environment (MDE) Chesapeake Bay Water Quality Monitoring Program was designed to assess water quality conditions for the Maryland Chesapeake Bay and to determine the effectiveness of actions and policies to improve and protect water quality. The program disseminates its results to the public, scientists, and decision makers. The reports described here are an example of what monitoring programs should produce.

Level I Reports

Level I reports, prepared semiannually, summarize the status of data collection activities; they include displays of spatial, seasonal, and long-term trends, analyses of results, and tabular data summaries. One of the two reports also summarizes analyses. They are distributed to all appropriate agencies and organizations.

Level II Reports

Level II reports, prepared every two years, reach the same audience as Level I reports, but they are more interpretive. Level II reports evaluate relationships among study elements, place the data in an ecological and regional perspective, and quantify the effects of major processes affecting water quality.

Level III Reports

These reports are prepared periodically for politicians, high-level decision makers, and the public. They provide an overall assessment of the status of Chesapeake Bay and changes that have occurred over defined periods. Their objectives are to identify the factors influencing environmental conditions, evaluate restoration actions, and identify management actions and policies that would improve conditions.

Executive Summaries

Program summaries, prepared annually, are short documents prepared for each major program element. They list the data being collected; describe how, when, and where collections are made; list the name, telephone number, organization, and address of the responsible principal investigator (s); describe how to obtain data summaries and/or raw data; highlight major findings, conclusions, and recommendations; and describe future plans.

Additional Documents

Periodically, MDE prepares and disseminates field and laboratory manuals, data management reports, and findings of special studies conducted to evaluate sampling and processing methods.

knowledge of them. Data and information derived from monitoring programs should be used to check, validate, and refine the assumptions, models, and understandings on which the monitoring was based. This iterative feedback increases predictive ability, reduces uncertainty, and ultimately reduces the monitoring effort needed. As discussed in Chapter 2, risk-free decision making is not achievable, and monitoring must be viewed as a way of reducing uncertainty, not of eliminating it.

Although not a necessary ingredient of every monitoring program, research on natural variability, and its causes, ecosystem function, transport and fate of materials, and biological effects of contaminants and habitat alterations is critical to the evolution of knowledge that makes monitoring more effective. At the least, regional trends monitoring should be accompanied by an ongoing research program designed to contribute to the interpretation of monitoring results. If it is not, the accumulation of data will outstrip maximum use of these data or, worse, will lead to erroneous conclusions.

In most monitoring efforts, the need to hold study methods constant for the sake of continuity must be balanced against the need to adapt methods to reflect technological advances. This dilemma cannot be resolved in any arbitrary fashion, and it must be carefully and periodically addressed in each monitoring program. Such adaptation not only includes the collection of additional data and application of new sampling techniques, but it also includes dropping obsolete measurements, reducing monitoring efforts for well-understood processes, and restructuring the entire program when fundamental assumptions are found to be flawed. As knowledge improves and new problems come to light, the resources available for monitoring must be shifted appropriately. Thus a crucial part of technical design is knowing when to stop or reduce the monitoring effort devoted to a particular problem.

5

Conclusions and Recommendations

Concern about degradation of ocean and estuarine environments and resources is increasing demand for information about these changes, their causes, and their cures. Environmental monitoring can be important in determining the health of the marine environment and the effectiveness of management policies and actions for maintaining or improving conditions. The present national effort in marine environmental monitoring is large, exceeding $130 million per year. However, this figure is modest (3 percent or less) compared with annual marine pollution abatement expenditures. Although monitoring practices have advanced, marine environmental monitoring programs are consistently hampered by poor design, inadequate resources (personnel and funds), and limited attention to changing the data into useful information that meets the needs of decision makers. Marine environmental monitoring can be made more effective by:

- strengthening the role of monitoring in marine environmental management;
- conducting more monitoring over regional and national scales; and
- improving monitoring program design and making information products more useful.

How can these objectives be reached? Specific recommendations are given below.

1. MONITORING CAN STRENGTHEN ENVIRONMENTAL MANAGEMENT

Conclusions

- Marine environmental monitoring is an effective technology for defining the extent and severity of pollution, evaluating environmental policies and actions, helping to estimate the risks and consequences of future actions, and detecting emerging problems before they become severe.
- Marine environmental monitoring is part of a broader complement of technical contributions to environmental management, which also includes fate and effects research and predictive modeling. Yet monitoring programs are seldom coupled with research and predictive modeling programs designed to support integrated decision making. Nor are many marine environmental monitoring programs effectively coordinated and related to research programs that address marine environmental quality. Monitoring activities need to be implemented in concert with other technical approaches in order to maximize the usefulness of information they provide for management decisions.
- Monitoring activities usually focus on the collection and analysis of data that are not useful to management decisions unless they are synthesized into information. Although there have been technical improvements, monitoring needs to be an integral part of an effective environmental management system in which information from monitoring is routinely used to guide and focus future actions, including regulating activities, influencing decisions, and refocusing management efforts.

Recommendations

- The effects of significant marine environmental management policies and actions (e.g., reductions in pollution loadings, discharge of potentially hazardous substances) should be monitored to evaluate the actions and to improve the ability to predict the consequences of management decisions.
- The linkages among monitoring, research, and modeling within marine environmental management systems should be improved through concerted efforts. Regional and national trends monitoring programs should include research elements or effective ties with research programs designed to provide information critical to the interpretation of monitoring results and to improve the design of monitoring programs and the collection and interpretation of monitoring data.
- Monitoring programs should be sufficiently flexible for results to be used to redesign and eliminate monitoring components that have not produced or are not likely to produce useful information.

- Agencies charged with environmental management responsibilities should provide for periodic systematic reviews of the results of their monitoring programs. To improve program effectiveness, such reviews should assess the consequences of the findings in management terms and identify needed revisions or improvements.

2. COMPREHENSIVE MONITORING OF REGIONAL AND NATIONAL TRENDS IS NEEDED

Conclusions

- The present array of compliance monitoring programs, regional monitoring programs (e.g., the Chesapeake Bay), and the National Oceanic and Atmospheric Administration (NOAA) National Status and Trends (NS&T) Program is inadequate to establish patterns and trends in the quality of the nation's coastal ocean and estuaries or to determine the effectiveness of environmental policies and regulations.
- Most resources spent on marine environmental monitoring are for monitoring compliance with specific permit conditions. Much less is allocated to assessing the regional and national extent of pollution problems or evaluating actions (past and future) to improve them.
- Compliance monitoring programs meet limited, specific objectives and are not designed to address broader public concerns about whether the marine environment is being degraded or about what such degradation means in terms of human health and ecological values.
- To address public concerns and assess the threat of the cumulative impacts of human activities on the marine environment more effectively, regional status and trends monitoring is needed. Regional monitoring information also provides a context for interpretation and evaluation of site-specific compliance monitoring.
- It may be possible to change the objectives of some compliance monitoring programs (e.g., the Southern California Bight program) in such a way that results in reallocation of resources and in adequate regional status and trends information without additional effort or cost. However, compliance monitoring cannot always be reduced prudently, and additional resources and effort are needed to meet the needs for regional status and trends monitoring.

Recommendations

- The Environmental Protection Agency (EPA) and NOAA should cooperate to develop a more effective national program to monitor environmental status and trends in the coastal ocean and estuaries. The program should combine regional programs with a sparser network of long-term stations and studies including some in natural areas not heavily influenced by human activities. The regional programs should emphasize intensive studies to develop understandings of cause-effect relationships and support and evaluate management decisions. The network would provide a basis for regional comparisons and detection of broader trends.

- The nucleus for this network should be developed through NOAA's NS&T Program and EPA's National Estuary Program (NEP) and its related coastal water activities.
- To facilitate establishment of effective, coordinated regional programs, new legal authority or regulatory policies should be instituted, allowing some resources devoted to compliance monitoring conducted by a permittee to be reallocated to a regional status and trends monitoring program. This change might be effected by requiring major dischargers to participate in a regional program or by levying fees (as a condition of permits) to support the monitoring activities of a public body.
- Other federal, state, and interstate regional monitoring programs should be strongly encouraged to participate in regional efforts by adopting compatible protocols that are consistent with their own missions and needs. However, centralized requirements should not impinge on the flexibility required to tailor regional programs to regional needs.
- Those responsible for managing estuaries included under Section 320 of the Water Quality Act of 1987 (i.e., NEP) should be required to develop and implement a status and trends monitoring program. Regional monitoring should be designed as an integral part of the particular estuarine management strategy that is developed. It should also meet certain minimum requirements and protocols to ensure coherence and compatibility with the national monitoring network.
- NOAA's NS&T Program, in concert with EPA's proposed Environmental Monitoring and Assessment Program (EMAP), revised and modified as necessary, should serve as the basis for the network component of the national program, through which regional programs can be linked and compared.
- Federal funding for national status and trends monitoring should be significantly increased for the NS&T Program and NEP to provide incentive and seed funding for the development of regional programs, enhance monitoring in areas not covered by regional programs, and support data management and interpretation activities.
- Adequate legislative mandates to undertake a national program such as the one recommended here exist, but they have not been implemented effectively. To ensure the necessary coordination for an effective interagency program, the administration and Congress should critically review existing coordination arrangements under the Water Quality Act of 1987, Title II of the Marine Protection, Research, and Sanctuaries Act of 1972,

and the National Ocean Pollution Research, Development, and Monitoring Planning Act of 1978 and revise them if they are found to be inadequate. The coordination of marine pollution research and monitoring programs among the federal agencies authorized by the 1978 legislation should be critically evaluated. Necessary administrative and statutory changes should be implemented to improve definition of responsibilities, interagency coordination, and overall effectiveness. Statutory or administrative provisions needed to ensure a more coordinated effort should be implemented, and Congress should continue to exercise strong oversight on the effort.

- NOAA should take the lead, in cooperation with EPA, in preparing a report to Congress every three years. It would synthesize the results of the national monitoring program, document the status of the coastal ocean, and evaluate management actions to protect and improve the health of the coastal ocean. This report should define the extent and severity of pollution problems, place priorities on health and environmental risks based on the extent and severity of pollution, identify emerging problems, assess regional trends in marine environmental quality, indicate important topics for research and development, and identify policies and programs needed to restore, maintain, or enhance marine environmental quality.

3. IMPROVED PROGRAM DESIGN AND INFORMATION PRODUCTS WILL MAKE MONITORING RESULTS MORE USEFUL

Conclusions

- Many monitoring programs are ineffective because they devote too little attention to the formulation of clear goals and objectives, technical program design, and the translation of data through analysis and synthesis into information that is relevant and accessible to decision makers and the interested public.
- Effective marine environmental monitoring programs must have the following features: clearly defined goals and objectives; a technical design that is based on an understanding of system linkages and processes, is directed at testable questions and hypotheses, and is subjected to peer review; methods that employ statistically valid observations and predictive models; and the means to translate data into information products tailored to the needs of their users, including decision makers and the public.

Recommendations

- Regional and national status and trends monitoring programs, monitoring for model validation, and major compliance monitoring programs should incorporate a rigorous design methodology such as that developed by the committee and presented here.

- New and existing compliance monitoring programs for major activities should be carefully reviewed by the regulatory agencies requiring the monitoring to ensure that they meet the criteria outlined in the committee's design methodology.
- EPA, in cooperation with NOAA, should prepare guidance documents on the design of compliance and regional monitoring programs for use by its regional offices, state regulatory agencies, and permittees. Adequate resources should be allocated to data analysis and integration as well as to data collection.
- NOAA, in cooperation with EPA, should promote the development of new techniques and technical protocols for use in regional and national monitoring programs to ensure compatibility and comparability of data.

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Appendixes

A

Biographical Information

DR. DONALD F. BOESCH received a B.S. in biology from Tulane University and a Ph.D. in marine science from the College of William and Mary. He was a Fulbright-Hays Fellow at the University of Queensland, Australia. He is currently Executive Director of the Louisiana Universities Marine Consortium and Professor of Marine Science at Louisiana State University. He is an Adjunct Professor at the University of New Orleans, the University of Southwestern Louisiana, and the College of William and Mary. His active research interests are in marine ecology, particularly benthic ecology, coastal oceanography, and the environmental effects of coastal and offshore oil and gas extraction. He served on the Marine Board of the National Research Council and the Marine Board's Committee on Fates and Effects of Drilling Discharges in the Ocean and chaired advisory committees to the National Science Foundation and the Department of the Interior's Outer Continental Shelf Program.

DR. JERRY R. SCHUBEL is Director of the Marine Sciences Research Center at the State University of New York at Stony Brook and until recently was the university provost. A former NIH fellow at Scripps Institution of Oceanography and faculty member and research scientist at The Johns Hopkins University's Chesapeake Bay Institute, Dr. Schubel has more than 25 years' experience as an educator and academic administrator. He received a B.S. in physics and mathematics from Alma College, an M.A.T from Harvard University, and a Ph.D. from The Johns Hopkins University.

He has published extensively on sediment transport and deposition processes and the effects of suspended sediments on estuarine environments. He has served on numerous advisory and research panels charged with environmental inquiries in the coastal and marine environments, including the Committee on National Dredging Issues of the Marine Board of the National Research Council.

DR. BROCK B. BERNSTEIN is a partner of EcoAnalysis, Inc., a consulting firm specializing in data-base systems design, data management, and data analysis of environmental, fisheries, and marine biological research. He has more than 15 years' experience in marine research and environmental studies. He is a graduate of Claremont Men's College, where he majored in English literature, and Scripps Institution of Oceanography, where he received a Ph.D. in biological oceanography. A recipient of a Killam Postdoctoral Research Fellowship from Dalhousie University, he spent four years in Nova Scotia researching kelp bed ecosystems. A special research interest of Dr. Bernstein's is the application of statistical and experimental design principles to environmental projects carried out under real-world constraints.

MR. WILLIAM M. EICHBAUM is an environmental lawyer. Currently Senior Fellow at the Conservation Foundation, he has been the Undersecretary, Executive Office of Environmental Affairs, for the Commonwealth of Massachusetts and was Assistant Secretary for Environmental Programs for the Maryland Department of Health and Mental Hygiene. Mr. Eichbaum also served as general counsel and deputy secretary for the Pennsylvania Department of Environmental Resources and Associate Solicitor for Surface Mining for the U.S. Department of the Interior; he was a guest scholar of the Woodrow Wilson Center of the Smithsonian Institute. He has served on many environmental boards and commissions and is currently a member of the Chesapeake Critical Area Commission, the National Environmental Enforcement Council, the Environmental Protection Agency Administrator's State/EPA advisory committee, and the Environmental Law Institute. He received a B.A. from Dartmouth College and an LL.B. from Harvard Law School and has published numerous articles on environmental law.

MR. WILLIAM GARBER is Permanent Secretary of the Ocean Disposal Specialist Group of the International Association on Water Pollution Research and Control. He retired in 1985 from the City of Los Angeles Bureau of Sanitation after 34 years' service. He began his tenure there as Director of the bureau's laboratories and later became Assistant Chief Engineer of the Sewage Treatment Division. Later he served as Assistant Director of the Los Angeles Bureau of Sanitation, where he helped establish California's first municipal sewage treatment monitoring program.

He is currently involved in monitoring related research at the Southern California Coastal Water Research Project. Since retiring, Mr. Garber has maintained an active consulting practice that includes such companies as Southern California Edison and other ocean dischargers. He also serves as Co-Secretary of the Specialist Group on Computer Control of Wastewater Treatment Plants. Mr. Garber is active in the Marine Technology Society and organized the Ocean Disposal Symposium at the 1985 meeting. Mr. Gather has a B.S. in chemistry from the University of California at Berkeley and is a registered civil engineer. He has presented numerous papers on a wide variety of topics, including regulatory and scientific issues in monitoring and wastewater treatment technology.

DR. ALLAN HIRSCH is President of Dynamac Corporation. A former Fulbright Scholar, he holds B.S. and M.S. degrees in zoology from Michigan State University and a Ph.D. in conservation from the University of Michigan. Dr. Hirsch spent 20 years in the federal government, serving in various environmental and natural resource management posts, including the Environmental Protection Agency (EPA), the Department of the Interior, the National Oceanic and Atmospheric Administration, and the U.S. Public Health Service. He was responsible for program and policy planning, legislative analysis, and management in the areas of pollution control, water resource planning, wetlands protection, and marine and oceanographic programs, among others. He is a recipient of EPA's Silver Medal Award, which recognizes outstanding leadership and distinguished service.

DR. A. FREDERICK HOLLAND is Director of the Ecological Sciences and Analysis Division of VERSAR Inc., where he is responsible for the design, analysis, and interpretation of the effects of perturbations on aquatic biota. A major emphasis of these programs has been quantification of cumulative and long-term impacts of human activities on the Chesapeake Bay ecosystem. He has a B.S. in biology from The Citadel and an M.S. in biology and Ph.D. in marine science from the University of South Carolina. In addition to his position at VERSAR, he is an Adjunct Associate Professor at the Center for Environmental and Estuarine Studies at the University of Maryland.

DR. KENNETH S. JOHNSON is a graduate of the University of Washington, with B.S. degrees in chemistry and oceanography, and Oregon State University, with a Ph.D. in oceanography. He is currently Professor of Oceanography at the Moss Landing Marine Laboratory and was on the research faculty of the University of California at Santa Barbara from 1979 to 1988 as an Associate Research Oceanographer. His research has covered various areas of chemical oceanography, and he is currently working on developing analytical tools for trace metal and in situ chemical analyses in seawater and ways to apply them to chemical distributions around hydrothermal vents and ocean frontal areas. He has participated in numerous research cruises and published many articles. In addition to his academic work, Dr. Johnson serves on the Oceanographic Technical Advisory Panel of the California Regional Water Quality Control Board.

DR. DONALD J. O'CONNOR is Professor of Environmental Engineering and Science at Manhattan College. He received a B.C.E. from Manhattan College, an M.C.E. from the Polytechnic Institute of Brooklyn, and an Eng.ScD. from New York University. He has 40 years' experience in higher education teaching and research. His research areas include mathematical analysis of water pollution in all natural water bodies. He is a member of the National Academy of Engineering, the American Geophysical Union, the American Society of Limnology and Oceanography, and the American Society of Civil Engineers.

MS. LISA SPEER is Senior Staff Scientist for the Natural Resources Defense Council's Coastal Project, which monitors implementation of the federal Coastal Zone Management Act, the federal offshore oil leasing program, and other federal and state programs affecting coastal and marine resources. She has a B.A. from Mount Holyoke College and a Master of Forest Science from Yale University. A member of the Board of Directors of the Coast Alliance, Ms. Speer has worked for the National Wildlife Federation, the Environmental Protection Agency (EPA), and the National Audubon Society in various capacities.

DR. G. BRUCE WIERSMA is Director of the Center for Environmental Monitoring and Assessment at the Idaho National Engineering Laboratory, working on the development of new and advanced environmental monitoring and assessment techniques. Dr. Wiersma holds a B.S. from the University of Maine, a Master of Forestry from Yale University, and a Ph.D. in ecology from the State University of New York at Syracuse. He spent 10 years with the Environmental Protection Agency, directing environmental programs in the areas of pollutant monitoring in remote pristine areas, pathways and effects of pollutants in biological systems, and pesticide monitoring for soil, human tissue, estuaries, air, water, and oceans. His experience includes work with the United Nations on environmental projects in Chile and the U.S.S.R. and memberships on many government and professional organization advisory panels and editorial boards, including founder and currently Editor of the peer-reviewed journal *Environmental Monitoring and Assessment*.

B

A Conceptual Model of Marine Environmental Monitoring

The Marine Board has developed a conceptual model of marine environmental monitoring as a tool for assessing monitoring systems. (See text Figure 1.1.) The model consists of elements that, ideally, one should consider in the optimum design of a marine environmental monitoring program. Deficiencies of monitoring strategies are usually the result of failure to consider one or more of these steps or of considering them out of logical sequence. The Marine Board will focus on the technical components and linkages in the figure but will consider them within the overall conceptual model. The questions specified below elaborate on this model and are an aid in conducting a consistent evaluation of monitoring within the framework of the conceptual model.

The model and the supporting questions were used by the committee in conducting its case studies of marine environmental monitoring.

Institutional Setting

Each case study examined how institutional conditions in the case study area have affected the design and conduct of the monitoring studies conducted there. This examination encompassed review of specific laws, the regulatory implementation of laws, court orders or the threat of court orders, management agency responsibilities, self-interest, public concerns, and scientific and technical developments. Issues included the following:

- What are the federal, state, and local statutes and regulations pertaining to monitoring?
- What, if any, are the institutional or statutory constraints on monitoring program design or technical efficiency? How do they vary across relevant agency and jurisdictional lines?
- What monitoring programs have existed and how have they evolved?
- How do public perceptions and pressures affect monitoring?
- What do the institutions (agencies, etc.) and the public expect monitoring to accomplish? Are public expectations regarding monitoring programs realistic? What can be done to increase public appreciation of the prospects and limitations of marine environmental monitoring?

Natural Environmental Setting

Each case study evaluated the degree to which the physical and biological properties and processes of the study area were considered in the initial program conception and design. Each study also considered the degree to which these programs adapted to improved understanding of environmental properties—the depth, water circulation and dilution potential, sedimentary regimes, characteristics of the biota, and living marine resources. Issues addressed included:

- To what extent was an environmental baseline established and natural variability considered in its establishment?
- What special concerns need to be considered for the various environments considered by the case study?

Environmental Quality and Human Health Objectives

Each case study evaluated the degree to which environmental quality objectives were clearly stated at the outset of the existing monitoring programs and the extent to which they are environmentally meaningful. These objectives may have been general and programmatic, they may have been defined by specific criteria and standards, or they may have been left undefined. On the one hand is a need to define carefully the parameters to be used to detect changes. On the other is the concern that the parameters, although quantitatively measurable, may not be sensitive or interpretable in terms of environmental health. Specific issues considered were:

- What were the environmental quality objectives at the onset of the environmental monitoring programs?
- To what degree were the programs designed to detect some a priori change related to an environmental quality objective?

- If measurable changes were observed in contaminant or population levels, how were they interpreted in terms of changes to the ecosystem, economy, or human health?
- What are the characteristics of monitoring programs that respond to different environmental quality objectives (e.g., compliance monitoring versus environmental trends monitoring)?

Technical Design

Each case study evaluated the depth and rigor of design considerations used in past and ongoing monitoring of the study area. Among the issues addressed were:

- What spatial and temporal requirements were considered in designing the monitoring systems? Is there documentation of the design?
- What components of the marine ecosystem and contaminants were monitored? How were they selected?
- What methodologies were used? Why were they selected?
- To what extent were the monitoring programs designed to test hypotheses?
- How do monitoring objectives and strategies differ among different monitoring applications (e.g., point source versus regional, continuous versus pulse effects, etc.)?
- What was the relative emphasis among research, monitoring observations, and data analysis and synthesis? Were these approaches well integrated?
- Were cumulative and indirect effects accounted for in the technical design?
- In the evolution of the monitoring program, what steps were taken to ensure maximum value of the entire data set to chronicle changes in the environment?
- Was the monitoring designed to establish pollutant source and receptor relationships?
- Was the technical design modified as a result of monitoring results, and was the design adaptable to such changes?
- Was the design of the monitoring program constrained or influenced by actual or anticipated modeling efforts?
- Was quality assurance a functional component of the design?

Implementation

A review of the implementation of the monitoring systems according to the technical design would require an examination of the organization of personnel and flow of activity required to accomplish the identified environmental quality objectives. Examples of important issues include the following:

- Were objective procedures followed in going from the monitoring program designed to that which was implemented?
- How did the cost and time limitations affect the implementation of the design program, and how did any effects influence statistical confidence?
- What mechanisms exist for logistical coordination of monitoring programs? Were they effectively used? How might they be improved?
- How was the quality assurance program included in the program design that was implemented?

Technical Interpretation

Each case study evaluated the technical interpretation of monitoring and made recommendations for improving it. Specific issues addressed included the following:

- Were the conclusions supported by the resulting data, and were they consistent with the limitations of the design? Was the ability to detect differences adequately considered?
- What was the potential for missing subtle, indirect, or cumulative effects of multiple or long-term activities?
- What was the relevance of observed effects to human, resource, or ecosystem health?
- Were relationships between sources and receptors established for monitored pollutant loadings and contaminant levels found in the environment?

Technology Development and Innovation

Each case study determined the critical technological needs for monitoring in the study area. Specifically, areas of mathematical modeling, remote sensing, in situ instrumentaion, sampling systems, etc. were reviewed to improve the reliability, efficiency, and timeliness of interpretation of the results. Examples of important issues are:

- What were the main technological constraints in the design and implementation of the monitoring program?
- To what extent were the monitoring systems structured to encourage innovation? How could the structure be improved?
- To what extent do improvements in monitoring depend on improvements in predictive technologies and field verification technologies such as those applicable to the quantitative description of the waste field, exposure concentrations, dose/response relationships, and food chain accumulation?

- What are the specific needs for new technology or transfer of existing technology in such areas as mathematical models, remote sensing, in situ instrumentation systems for measuring organic and biological response, sampling systems for particulates and bioavailable substances, and data analysis and management systems?

Data Management and Analysis

The case studies assessed the management and interpretation of the data sets generated by the monitoring programs. This component is critical to the eventual application of the monitoring results to management decisions. Associated issues are:

- Were the results of research integrated with the monitoring program results when they were analyzed?
- What methods were used to ensure reliable, timely, and powerful data analysis capability?
- To what extent were the data collected subjected to sophisticated analysis/synthesis techniques?
- How might data collection be automated and coupled with these emerging data management and analysis capabilities? Can automated expert systems of broad applicability be developed in marine environmental monitoring?
- What mechanisms exist or could be created for timely and effective transfer of data to products for decision-makers' needs?

Decision Making

Although the primary focus of the systems assessment of marine environmental monitoring in each study area was on technical issues, it was also necessary to consider the use of the monitoring results in subsequent management decisions. Each case study evaluated how the decision making, the activities that were managed, and the monitoring program responded to one another. The studies assessed whether the monitoring programs and results addressed regulatory needs and requirements and to what extent the requirements adapted and would adapt to the present and future capabilities of monitoring.

The following issues pertaining to decision making that were considered:

- What was the linkage between environmental monitoring and decision making? To what extent do regulatory requirements adapt to the present and future capabilities of monitoring, and to what extent did required monitoring adapt to changes in regulatory requirements?

- How were decisions made or influenced by the results of the monitoring programs?
- How did monitoring programs and results address regulatory needs and requirements?
- Were the results of environmental monitoring programs integrated functionally in decision making with other environmental assessment approaches (i.e., assessments based on existing information, predictive and conceptual environmental models, experimental approaches, and observations and measurements of environmental processes)?

C

Participants in Case Studies

Southern California Bight

William M. Eichbaum, *Panel Leader*, Conservation Foundation, Washington, D.C.

Donald Baumgartner, Environmental Protection Agency, Newport, Oregon

Brock B. Bernstein, EcoAnalysis, Inc., Ojai, California

William Garber, City of Los Angeles (retired), Playa Del Rey, California

Wesley Marx, Author, Irvine, California

Jerry M. Neff, *Rapporteur*, Battelle New England Marine Research Laboratory, Duxbury, Massachusetts

Dorothy E Soule, University of Southern California, Los Angeles, California

Chesapeake Bay

Jerry R. Schubel, *Panel Leader*, State University of New York, Stony Brook, New York

William Baker, Chesapeake Bay Foundation, Annapolis, Maryland

Paul D. Boehm, Battelle Ocean Sciences, Duxbury, Massachusetts

John Kraeuter, Rutgers University, Port Norris, New Jersey

Frederic H. Nichols, U.S. Geological Survey, Menlo Park, California

Donald W. Pritchard, State University of New York, Stony Brook, New York

Ajit Subramaniam, *Rapporteur*, State University of New York, Stony Brook, New York

Dennis Suszkowski, Hudson River Foundation, New York, New York

Jay Taft, Harvard University, Cambridge, Massachusetts

Robert Ulanowicz, University of Maryland Chesapeake Biological Laboratory, Solomons, Maryland

Particulate Wastes in the Oceans

Iver W. Duedall, *Panel Leader*, Florida Institute of Technology, Melbourne, Florida

Mary C. Barber, National Science Foundation, Washington, D.C.

Walter E Bohlen, University of Connecticut, Groton, Connecticut

Robert S. Carney, Louisiana State University, Baton Rouge, Louisiana

Dana R. Kester, University of Rhode Island, Kingston, Rhode Island

James P. Ray, Shell Oil Company, Houston, Texas

Donald C. Rhoads, Science Applications International Corporation, Woods Hole, Massachusetts

Chih-Shin Shieh, *Rapporteur*, Florida Institute of Technology, Melbourne, Florida

Robert B. Spies, University of California, Livermore, California

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