ABSTRACT

The historical ineffectiveness of marine pollution monitoring programs is attributed to deficiencies at the most fundamental levels of program design: 1) specification of management problems and monitoring objectives; 2) identification of the detailed information needs and assessment of the value of that information; and 3) optimization of the sampling design for the temporal and spatial variability in the measurement parameters selected. In recent years a number of pollution-effects measures have been advocated by disciplinary scientists as components for pollution monitoring programs. These measurement approaches include 1) chemical analysis of suspected toxicants; 2) biochemical and physiological measures of organismic exposure and/or condition; 3) measures of community response, such as biomass and diversity; and 4) toxicity bioassays of water and sediments. Such measurements are discussed in terms of their applicability to a suite of generic monitoring objectives.

1. INTRODUCTION

In earlier papers (1-3) this author has emphasized the integral and interactive role of monitoring in overall marine pollution management strategies. The designers of scientific monitoring programs usually express concern for the statistical strength of a proposed sampling program to overcome sources of natural variability and to document cause-effect relationships (4-6), but other elements critical for management effectiveness are often overlooked. Most importantly, the management objectives and information needs from the monitoring program are frequently not specified, mainly as a result of fragmentation of jurisdictional responsibility among numerous different sectors of society and government (1,7). In a management-oriented approach to monitoring, social, economic and environmental values (e.g., human health effects, loss of resource populations, etc.) should be represented as directly as possible in the selection of indicators for monitoring. Appropriate management actions should also be indicated, at least tentatively, for different threshold levels in the monitored indicators. Such an approach is needed to define the levels of little or no concern, and to guide the design of a temporally and spatially stratified sampling program to ensure: a) that adequate statistical resolution is achieved in those areas where criteria of acceptability are being approached (i.e., where important changes are occurring), and b) that excessive effort is not placed on over-definition of trivial changes well below those criterion levels (8). Selection of monitoring parameters and sampling design should be guided by credible hypotheses of potential impact, based on understanding of causal mechanisms and inter-relationships underlying changes in indicator values. Such understanding usually relies on models derived from previous research. In some cases, initial monitoring results will not clearly indicate pollution as a cause for an observed change, and additional research (or more intensive monitoring) may be desired to strengthen the inferred causal relationships.

The foregoing general guidelines represent a hierarchical approach to monitoring, as an integral and interactive part of an overall environmental management framework that is adaptive to changes either in available information or in defined management needs (2,3,9,10).

The purposes of this paper are a) to extend the principles outlined previously by defining a suite of generic monitoring objectives pertinent to environmental management problems, and b) to examine potential measures (or environmental indicators) and sampling strategies for their potential effectiveness of contribution to the objectives.

2. MONITORING OBJECTIVES FOR MANAGEMENT

A principal management objective for monitoring of environmental quality is to ascertain that the strategies selected (for managing human activities with environmental implications) do not lead to undesired changes in environmental quality. Three categories of monitoring objectives were defined and discussed previously (1): Compliance: to ensure that activities are carried out in accordance with regulations or permit requirements implemented as part of the management systems; Hypothesis Testing/Model Verification: to check the validity of assumptions and predictions used at the permitting stage of an agreement; and
Trend Monitoring, or Surveillance: to Identify and quantify large-scale environmental changes anticipated as possible consequences of multiple activities being managed separately.

These categories can be expanded to include a number of sub-objectives, as follows:

I. Compliance: a) to confirm that contaminant releases (composition, amounts, rates, etc.) are consistent with expectation (e.g., within permitted limitations); b) to confirm that other operational requirements (geographic location of discharge, timing of discharge, equipment performance specifications, etc.) are met; c) to quantify boundary conditions for any hypothesis-testing, or research (below).

II. Hypothesis-Testing: a) to verify that the resultant scale of distribution of contaminants is consistent with any a priori management predictions (e.g., to validate accuracy of mixing zone calculations, and other dispersion models); b) to verify that the resultant magnitudes of selected contaminant-associated effects are within the expected (acceptable) bounds (i.e., to validate the dose-effect and exposure models for whatever target effects, or end points, were used in setting the applicable release limitations); c) to determine whether (and, if so, how) the scales of contaminant distribution and/or contaminant-associated effects are changing; d) to detect unexpected (or untargeted) contaminants or contaminant-related effects.

III. Trend Monitoring: a) to detect changes in contaminant concentrations and compositions occurring generally in the environment as a cumulative result of multiple sources with overlapping spheres of influence; and b) to detect changes in biological indicators that may reflect cumulative effects of multiple contaminant sources with overlapping spheres of influence.

The above suite of objectives is based on a few fundamental premises. First, contaminants have sources, and effective management necessarily and ultimately will involve controlling the nature and magnitude of those sources within some specified, acceptable bounds. Regulatory stipulations (e.g., discharge and receiving water criteria) will be designed therefore to prevent significant (or unacceptable) near-field effects either within or beyond the boundaries of a specified mixing zone, or zone of direct impact. If unacceptable outcomes, or effects, are not detectable in the near-field, it is unlikely (but unfortunately, not impossible) that far-field effects will be unacceptable. These relationships establish a hierarchy of scale, in both time and space, for the different categories of monitoring objectives, progressing from small-scale for compliance objectives to large-scale for trend monitoring (1).

Secondly, these objectives implicitly acknowledge some assimilative capacity of the environment (3,11,12) to absorb or process wastes without exceeding the specified limits, or criteria, of acceptability. With the possible exception of zero-discharge, or best-available-technology strategies, all waste-management strategies make use of an assimilative capacity concept, using selected criteria of acceptability such as water-quality criteria (13,14), sediment-quality criteria (15), or a requirement for balanced indigenous populations (16).

Finally, the various monitoring objectives fit together as an integrated management-oriented package. Properly integrated, the various hierarchical elements can represent a comprehensive and effective program of measurements, whose results address management concerns on all pertinent scales of time and space. If addressed individually and separately, however, concerns are likely to overlap considerably among different objectives much duplication of effort is probable; and maximum effectiveness of the data is unlikely to be realized. For these reasons, it has been recommended (17) that monitoring programs should be carefully integrated on a regional basis. In this regard, the National Status and Trends (NS&T) Program, now being conducted by the National Oceanic and Atmospheric Administration (18) includes an element for assessment of historic trends (19), based on earlier monitoring programs and research efforts. To date, however, few attempts have been made to coordinate the efforts of, or the information from, the many diverse near-field monitoring programs that are focused on specific development activities and sources of contamination. To make maximum use of this information would require considerable effort to standardize approaches for sampling design, methodology, analysis and reporting.

3. DESIGN CRITERIA

Bearing in mind that cost is a fundamental concern, specification of the above management-oriented monitoring objectives has strong implications for consequent monitoring design. A large portion of the overall monitoring effort clearly should be focused on concentration gradients near contaminant sources where causality is most readily demonstrable. At some distance from the source these near-field gradients of concentration or effect will become indistinguishable from the natural background characteristics. Beyond these vaguely defined boundaries, however, concerns will remain about potential broad-scale (and long-term) changes in the health or productivity of important resource populations. Cause-effect relationships are typically very elusive in such far-field, trend monitoring programs, and it may be impossible to apply knowledge about any observed environmental change effectively in subsequent management decisions (i.e., to alleviate the cause of the environmental changes). Nonetheless, some
potential changes are probably important enough to warrant managerial awareness, mainly as a basis for defining contingency research programs and action plans in the unexpected and undesired event that such changes are found to occur. Specifying the nature of these changes and defining the consequent action plans are clearly important components of monitoring design.

Spatial and Temporal Considerations

Wolfe and O'Connor (1) discussed and illustrated the strong relationship between the spatial and temporal scales pertinent to the different categories of monitoring objectives (compliance, hypothesis-testing, and trends). For compliance objectives (I.a-c. above), sampling is performed at or near the point and time of discharge, with a frequency and/or duration dictated by the nature (continuous discharge, pulsed, or distinct events) and variability of the source. Hypothesis-testing (II.a-c) requires (at least initially) intensive and short-term sampling near the sources, and especially if the resultant contaminant concentrations or effects are significant relative to regulatory standards or other criteria of acceptability (3). Once the relationships (among the source term, natural dispersive processes and the resultant scales of distribution and effects) have been established satisfactorily, then the intensity of sampling can be reduced substantially to focus on long-term changes in the scale of effects (II.c). In many areas multiple sources will be involved, and area-wide or regional sampling designs will be required instead of source-specific designs. Objective 11.d (early warning of unanticipated events) can be met (with limited success) through the use of generalized analytical techniques or observational techniques (e.g., gas-liquid chromatography-mass spectrometry) that may detect contaminants (or effects) not specifically targeted in the sampling design. Otherwise this objective can be approached effectively only through the formation of specific hypotheses and appropriate experimental sampling designs. Such hypothesized contaminant effects can be tested most effectively along established gradients of contaminant concentration.

Trend monitoring (objectives III.a,b) involves intermittent (long period and long duration) sampling to detect long-term trends in contaminant concentrations and biological effects at locations outside the influence of known sources. Samples should be pooled or composited (both in time and space) wherever appropriate to reduce small-scale and short-term variability and associated analytical costs. Locations should be selected carefully to maximize, on a cost basis, the likelihood of detecting significant trends. Information from other monitoring or research elements may provide a basis for excluding areas from consideration due either to improbability of trend detection (because of variability) or to values that are far below threshold levels of concern.

Selection of Indicators

Most of the management-oriented pollution monitoring objectives deal explicitly with the distribution of contaminants. In selecting sample media to meet the various objectives, one should consider the nature of the source contaminants (dissolved, suspended solids, etc.) and focus on appropriate dispersion processes and transport media of for compliance (I.a-b) and near-field (II.a) objectives. The focus for most other (far-field or long-term) objectives should shift to reservoirs of accumulation or contaminant sinks. Appropriate media for this purpose include sediments, tissues of sedentary organisms, or tissues of long-lived mobile organisms (e.g., marine mammals and large predatory fish, such as king mackerel or bluefish). Known sources of variability in the contaminant measures (e.g., particle size, clay composition, or organic content of sediments, and tissue type and anatomical location, age, or lipid content of organisms) should either be controlled or measured and used to normalize results.

If pollution assessment and management practices are indeed successful to some degree, then the direct biological effects of contaminants should be measurable only in the vicinity of known sources and an effective sampling plan should be stratified accordingly. That is, where source-oriented chemical analyses do not indicate significant problems of contamination, it makes little sense to implement an area-wide program of intensive effects monitoring in an effort to give early warning of small (or trivial) changes from ambient conditions. Known sources of variability in the bio-effects indicators have been proposed in recent years as appropriate components of monitoring programs (6,20). Most of these measures have proven successful (to varying degrees) in detecting gradients of contaminant effect in areas of moderate disturbance, but suffer from problems of non-specificity (i.e., to contaminants) of response and/or insensitivity (i.e., low signal-to-noise ratios) in areas of only modest contamination.

Capuzzo and Kester (6) suggested that (non-migratory) demersal fish and shellfish populations should be used as the principal target organisms in monitoring programs. They further suggested a suite of measures that included the contaminant contents (including metabolites) of tissues (relative to those in ambient sediments and interstitial waters), the activities of detoxification enzymes, the incidence of disease and histopathologies, the seasonal variations in energy reserve, and the reproductive status and recruitment of juvenile phases. With this information, potential changes at the organismal and population levels could be detected and analyzed before irreversible damage is likely to occur at the community or ecosystem level (6).
Considering the costs and statistical sensitivities of the various procedures, the intensive approach proposed above seems best suited for areas of moderate contamination where such effects are detectable (i.e., directed again at objectives II.b,c). Bioassay approaches (e.g., 21-23) for measuring toxicity (lethal or sublethal) of ambient sediments or water may similarly be most useful for establishing near-field gradients (objective II.b) or for determining changes in the scale of contamination (II.c). The associated costs for these efforts would not seem warranted, however, either in areas where both the magnitude of contaminant inputs and the resultant scale of effects are small (i.e., well below any limits of acceptability), or for trend-monitoring (objectives III.a,b) over large areas beyond the immediate effects of known sources. Focusing the measures of sublethal biological effect on areas of moderate contaminant stress will serve to strengthen the credibility of contaminant-impact hypotheses, so that these may be incorporated appropriately into improved criteria of acceptability (3) that can be applied more effectively in region-wide management.

For trend-monitoring, therefore, two categories of measurements should be emphasized. First is the measurement of contaminant concentrations and concentrations in selected environmental components and locations where this potential occurrence (or increase) is most likely to show up if it occurs, or where it would be of significant concern completely irrespective of source. Such targets might include edible tissue of food fish from open coastal or continental shelf regions, tissues of marine mammals and birds, open ocean surface waters, continental shelf sediments, and deep ocean (abyssal) organisms and sediments.

The second category of measures recommended here for trend monitoring focuses on the status of valued environmental resources that may be susceptible to large-scale pollution impacts. Usually the effects of pollutants on such resources will not be directly discernible, either from the influences of natural environmental variation or from other anthropogenic influences, such as overfishing or habitat destruction. Nonetheless, the cumulative effects of these various categories of disturbance must be known in order to gain insights about the potential significance of pollutants. Recommended measures (24) include fecundity in fish and shellfish, mortality in fish and shellfish, reproductive success in mammals and birds (and mammals), as well as fishery catch and population data. Such information has usually been gathered under the aegis of resource management programs (as opposed to environmental management, or pollution programs), and few efforts have been made to quantify the potential significance of regional pollution trends to overall resource productivity. It is essential that such information be analyzed using robust models of population dynamics to facilitate our understanding of possible pollution effects at the population and ecosystem levels (25).

4. CONCLUSIONS

Monitoring design should be oriented toward management needs. A tiered, or hierarchical, approach to monitoring is recommended, with stratification of sampling based on established (or suspected) gradients of contaminant concentration and criteria of acceptability of effect (including both nature and magnitude of a specific effect, and the scale over which it occurs). All known sources of contaminants should be monitored at a level necessary for characterization of inputs. In areas where inputs (and resultant contaminant concentrations) are low relative to criteria of acceptability, additional monitoring may be required only if the sources undergo significant change in composition or quantity. At most, only low-intensity monitoring would be required to establish trends.

In areas of moderate contamination, more comprehensive monitoring is required. In addition to source characterization, measurements are required to determine that the dispersion of contaminants in the environment is consistent with predicted scales of contaminant distribution and that the effects are within acceptable limits. Such situations also provide a testing ground to determine whether additional effects are occurring (beyond those predicted and deemed acceptable a priori), and whether on that basis, the a priori criteria of acceptability should be modified.

Finally, trend monitoring is required in areas distant from known sources of contaminants to ascertain whether undesired changes are occurring on spatial and temporal scales much greater than those addressed by the source-oriented portions of the program. Low intensity sampling and chemical analysis of organisms and sediments from selected remote locations is suggested, along with continuous surveillance and population modeling of valued resource organisms.

To be effective, the suite of monitoring objectives should be viewed and operated as a single program, probably on a regional basis. Institutional separation of different monitoring functions results in redundancy of effort, lack of inter-comparability, and incomplete interpretation of results.

5. REFERENCES


