Chesapeake Bay Program
Scientific & Technical Advisory Committee

Integrated Analysis of Chesapeake Bay Monitoring Data

A Workshop Sponsored by the
Scientific & Technical Advisory Committee
and the
Monitoring & Modeling Subcommittees of the Implementation Committee
Chesapeake Bay Program

21 – 22 November, 1996
Solomons, Maryland

STAC Publication 97-2

About the Scientific and Technical Advisory Committee

The Scientific and Technical Advisory Committee (STAC) provides scientific and technical guidance to the Chesapeake Bay Program on measures to restore and protect the Chesapeake Bay. As an advisory committee, STAC reports quarterly to the Implementation Committee and annually to the Executive Council.

STAC members come primarily from universities, research institutions, and federal agencies. Members are selected on the basis of their disciplines, perspectives, and information resources needed by the Program.

STAC publications focus on issues of importance to the Chesapeake Bay Program. Publications are supported by the U.S. Environmental Protection Agency (EPA) through cooperative agreement CB-993043-04 with the Chesapeake Research Consortium, Inc. (CRC).

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EXECUTIVE SUMMARY

Background:

There is a wealth of data available from Chesapeake Bay monitoring programs and complimentary information from a variety of basic and applied research efforts. These programs should be better integrated in order to produce and apply more fully information that could improve decision making. Strategic decision making already depends on complex scientific models of the behavior of the ecosystem. Closer collaboration in design, conduct and analysis among monitoring, research and modeling programs would greatly add value to the collective effort. A workshop of leaders in Bay monitoring, modeling, research and technical management was held on November 21-22, 1996, in Solomons, Maryland to address this need.

Objectives:

- To identify innovative approaches to the analysis of monitoring data which effectively integrate modeling predictions and research findings and address important management questions.
- To foster productive collaboration among the monitoring, modeling and research communities.

Recommendations:

Teams of participants addressed specific issues pertaining to each of four key Challenges faced in the integrated analysis of monitoring data. The detailed recommendations developed by the teams are summarized below for each Challenge:

Linking Monitoring with Predictions of the Bay Water Quality Model:

1. Because of the growing importance of predictions in the Bay restoration, a Forecast Center should be planned that would develop long-term projections to guide the effort, forecasts of seasonal or event-related responses, and assimilate real-world observations (monitoring) into predictive models.
2. The linkages between monitoring and modeling can be specifically improved by more comparisons related to events (such as floods) and spatial outputs (maps).
3. The integration of modeling and monitoring has been a challenge to the Chesapeake Bay Program. Milestones such as the periodic “reevaluations” of progress in Bay restoration are important opportunities to advance the state of the art in integration and should be planned accordingly.
4. The Water Quality Model is run to answer major questions such as how much of the Bay will be stressed by low oxygen, but in the process much detalied information is produced but not retained. Archiving this intermediate information could allow some enlightening comparisons with the more detailed monitoring results.
5. Such detailed and shorter term model results would be helpful in interpreting the status and trends in the Bay ecosystem from monitoring data.
6. As the Bay Program moves forward with new commitments for increasing wetlands and riparian buffers, it is important that the Watershed Model is refined and ground truthed to accurately reflect these improvements.

Linking Living Resources and Water Quality Monitoring:

1. Most monitoring in the Bay focuses on organisms that are important in the food chain (plankton and benthos) or provide habitat (SAV) and are readily sampled, but are not themselves resources of direct value. Monitoring of fish and shellfish should be better coordinated, and where needed expanded, in order to allow better interpretation of both their effects on the regularly monitored, smaller organisms and the consequences of changes in the food chain on the fish and shellfish.
2. Definition of habitat requirements for living resources should be refined and expanded. Specific recovery criteria should be identified.
3. New statistical and modeling techniques should be explored to improve understanding of the linkages between water quality and living resources.

Improving the Sensitivity of Monitoring Small Watersheds:

1. Monitoring of nutrient concentrations in streams draining small watersheds has often not shown a reduction in nutrient concentrations following implementation of nonpoint source controls in the watershed. This could be because of “lags” in the hydrologic system or because the practices are not as effective as thought. Scientists engaged in studies of management practices, hydrology and water quality should collectively assess the information available from research and monitoring to evaluate current understanding of the effectiveness on nonpoint source controls.
2. Much can be gained from evaluating stream monitoring results following the two large flow events that occurred during 1996, the record year of freshwater inflow into the Bay.
3. Because small watersheds in the Chesapeake Basin vary so much in terms of their natural characteristics and human land uses, it is difficult to extrapolate from the few intensively monitored watersheds to the whole region. Comparisons of studies, particularly those of different scales, would improve our ability to extrapolate.

Bridging Spatial and Temporal Scales in Monitoring and Research:

1. The rich databases from monitoring physical, chemical and biological variables in the Bay and from various research programs should be analyzed to determine the dominant scales of variability of the ecosystem in space and time.
2. The results of hypothesis-driven research should be used to tune the sampling scales of monitoring to better address the causes and consequences of observed changes.
3. Remote sensing from aircraft and satellites, continuous measurements made from buoys, and towed instruments are providing large quantities of information capable of filling in the gaps of time and space for Bay monitoring.
4. More effective linking of modeling and monitoring will improve the predictability, resolution and generality of Bay models. This can be accomplished through time-series comparisons of models and data, data aggregation techniques that reduce error, and comparisons of simpler models with the more complex Water Quality Model.

INTRODUCTION

Background:

The Chesapeake Bay Program, in consortium with participating agencies, universities and organizations, has conducted a range of physical, chemical and biological monitoring programs in tidal waters and streams, in the atmosphere, and on the land with the goal of supporting the restoration and protection of the Chesapeake Bay. These programs generally approach this goal through the fulfillment of the following objectives:

- characterization of existing conditions;
- determination of status and trends; and
- use of monitoring information to further the understanding of processes controlling water quality and the linkage with living resources.

Over the years, many analyses have been conducted and reports produced to address these objectives. They include analyses of growing sophistication in determining water quality trends, evaluating habitats, and modeling of the Bay ecosystem (including its watershed). Products range from technical reports to summary presentations included in periodic *State of the Bay* reports. Monitoring data have been widely used for management purposes and by the research community to advance understanding of this ecosystem. Yet, there is a widespread feeling that more benefit could be garnered from monitoring data if the analyses of data were better integrated with ongoing research efforts and with water quality and other predictive models.

Objectives:

The objectives of the workshop were (1) to identify innovative approaches to the analysis of monitoring data which effectively integrate modeling predictions and research findings, as well as address important management questions, and (2) to foster productive collaboration among the monitoring, modeling and research communities.

Concept for the Workshop:

There is a wealth of data available from the Bay monitoring programs and complementary information from a variety of basic and applied research efforts, including through programs such as the National Science Foundation’s Land-Margin Ecosystem Research (LMER) Program, NOAA National Sea Grant Program, the EPA-supported Multiscale Experimental Ecosystem Research Center at the University of Maryland, and NOAA=s stock assessment and multiple stressor projects. There is a growing need to integrate these programs and tap the potential information yield that could result from a closer collaboration in design and analysis of monitoring, research, and modeling programs.

A workshop was held in November 1996 to address this need. Participants included research scientists, monitoring program participants, representatives of the water quality and living resource modeling effort, and managers from within and outside of the region. The central focus of the workshop was to explore and recommend ways to more effectively extend the analysis of monitoring data by inclusion of information from research and modeling activities. Conversely, recommendations were made on how to enhance the use of monitoring data in research and modeling. While data resulting from the monitoring of water quality and living resources in the tidal waters of the Chesapeake provide the richest base of information, the workshop also explored appropriate analyses of monitoring and time-series data from non-tidal waters, the landscape, and the atmosphere.

The workshop explored opportunities and made recommendations in the following areas:

a) Applying the understanding of environmental processes gained through research and modeling to direct appropriate analyses of monitoring data.

b) Linking the broad and extended time scales used in environmental monitoring with the generally more spatially and temporally intense scales in research.

c) Applying innovative statistical analyses, mathematical modeling, and graphical displays to yield information useful in environmental and resource management.

d) Integrating data from remote sensing and continuous and real-time measurement systems to extend the results of conventional monitoring[1].

e) Establishing the necessary data management and distribution infrastructure to enhance the sharing of data between monitoring and research activities[2].

Organization:

Planning and execution of the Workshop was guided by a Steering Committee comprised of the following individuals: Raymond Alden, Peter Bergstrom, Walter Boynton, Lewis Linker, Joseph Macknis, Robert Magnien, Kent Mountford, Brandt Niemann, Marcia Olson, William Romano, Kevin Sellner, and Linda Zynjuk.

The Steering Committee was chaired by Donald Boesch of the Center for Environmental and Science, University of Maryland, who was responsible for overseeing the preparation of this report. Katrin O'Connell coordinated the Workshop, and she and Caryn Boscoe assembled the report.

The Workshop:

The workshop was held on November 21 and 22, 1996 in Solomons, Maryland. Workshop participants were oriented by plenary presentations by Robert Magnien on the Chesapeake Bay Basinwide Monitoring Strategy, Donald Pryor (White House Office of Science and Technology Policy) on efforts to develop and implement a National Framework for Integrated Environmental Monitoring and Related Research, and Donald Boesch on the goals and organization of the Workshop. Most of the Workshop was spent in discussions by four Challenge Teams, described below, with a concluding plenary, report-out session.

Challenge Teams:

Rather than organize the workshop by the above five topics, the workshop was structured around four Challenges which engaged separate Teams working in parallel. In this way, ideas, debates, and recommendations were developed around concrete issues. The four Challenges and the rationale and considerations for each were as follows:

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1 STAC is planning a separate workshop on the development and application of advanced technology sensors which can be applied in remote and *in situ* sensing. The workshop did not address the technologies but addressed how the data produced from remote and *in situ* sensing can be used in integrated analysis.

2 This was limited to consideration of appropriate linkages which promote integrated data analysis and will not attempt to design the databases themselves. The Data Center Workgroup is responsible for the fundamental issues of database structure and access.

1. **Linking Monitoring with Predictions of the Chesapeake Bay Water Quality Model**.

   Management is pursuing restoration goals, the outcomes of which are being predicted by sophisticated numerical models. How do we know that outcomes predicted by these models are actually realized? Modeling and monitoring are two powerful tools by which progress in meeting Bay restoration goals are judged: modeling prospectively and monitoring retrospectively. In the periodic evaluation of progress, however, it is often challenging to integrate the two approaches. One problem confronting the analysis of monitoring data to detect trends with respect to management goals is the fact that natural variation (annual, seasonal and shorter-term) makes the detection of long-term trends difficult. How, then, can methods be applied to normalize data for variations in natural conditions (e.g. flow, salinity, temperature) for conducting trend analysis? How can the Chesapeake Bay water quality model (linked watershed-Bay model) help in this regard? Another possible application of the model is to provide specific goals for management strategies (e.g. nutrient concentrations expected upon implementation of Tributary Strategy controls). These are just a few of many questions which need to be addressed at the interface of monitoring, modeling and research. This Challenge Team focused on identifying directions and steps to more effectively accomplish this integration using the various Bay models as the framework.

2. **Linking Living Resources and Water Quality Monitoring**.

   A key goal of the Chesapeake Bay restoration is the recovery of living resources, not just the improvement of water quality. Although strides have been made in defining water quality requirements for submerged aquatic vegetation, quantitative linkage between water quality and the broader array of living resources (including fisheries, wildlife and key species in the ecosystem) remains elusive. How can we be sure that we are achieving our ultimate goal of restoring the Bay so that it can sustain bountiful living resources? Specifically, how can we better relate water quality data and living resources data to assist in defining water quality objectives for living resources? How can these data be effectively used to target restoration and improve management of living resources? And, how can data analysis be integrated with living-resource and ecosystem modeling to enhance predictive capabilities and the ability to detect predicted trends? The second Challenge Group addressed these and more specific questions from the perspective of selected living resources in the Bay.

3. **Improving the Sensitivity of Monitoring Small Watersheds**.

   The Bay restoration will require significant reduction of non-point sources of nutrients throughout the entire catchment. However, this must be accomplished Athe old-fashioned way,≅ one watershed at a time. We must be able to confidently detect the effects of our management activities at this scale. Otherwise, we will not be able to address the ultimate effectiveness of various non-point source approaches and sort out confounding factors, such as groundwater lag time.

   Various targeted watersheds have received special attention for monitoring the effects of aggressive land management on efflux of nutrients and sediments. The results of some of these are troubling in that they do not show the predicted reductions. Is this because of the difficulties of monitoring or analysis of data, the ineffectiveness of controls, or lags in response? How can we get "smarter" in monitoring and analysis by incorporating knowledge of environmental processes and models, thereby improving the sensitivity of assessment with respect to management objectives? This Challenge Team addressed these questions from the experience of several intensely managed and monitored watersheds in the Bay catchment.

4. **Bridging Spatial and Temporal Scales in Monitoring and Research**.

   To be effective, management needs to consider the degree to which a response observed in one part of the Bay reflects the larger condition. Also, it needs to understand whether conditions observed over one or a few years reflect a trend or natural variation related to climate or other factors.

   Models, such as the 3-D Water Quality Model, are designed to predict average conditions over time steps of months and segments of miles. How do we best reconcile monitoring data, which may be instantaneous and localized, with these models? Monitoring data are produced on different spatial and temporal scales, ranging from near-continuous to once-a-year (or longer) time periods and from regional to highly local. Historical data from routine records (e.g. weather and stream flow), earlier scientific measurements (e.g. CBI surveys), and the sediment record (paleobiological and chemical indicators) can provide a longer time perspective. New technology is providing the ability to monitor on different scales of time (e.g. continuous and near-real time *in situ* measurements made by the Chesapeake Bay Observing System) and space (e.g. remote sensing of important properties such as surface chlorophyll for the entire Bay and continuous profiling by towed or under-way instruments). Furthermore, research often produces information specific to the site at which the research was conducted, or to the experimental conditions (beaker to mesocosm). How do we deal with such scale mismatches? Theory and analysis techniques are advancing in this field. For example the University of Maryland Center for Environmental Science operates an EPA-funded center for research on environmental scale. The final Challenge Group addressed innovative ways to address differences in scale in observations and predictions.

Challengers:

Each Challenge Team was led by a Challenger, who was charged with laying out the issues embodied in the Challenge, stating the driving questions, summarizing the present state of analysis, and charging the Team with specific questions that were addressed in the workshop.

Facilitators:

Experienced facilitators helped move each of the four Challenge Teams toward their goals. The facilitators were familiar with Bay Program activities and goals.

RESULTS OF THE WORKSHOP

Challenge 1
Linking Monitoring with Predictions of the Chesapeake Bay Water Quality Model

Challenge Team Members: Bob Thomann (Challenger), Dave Nemazie (Facilitator), Ray Alden, Lowell Bahner, Grace Battisto, Bill Boicourt, Walt Boynton, Joe DePinto, Dave Jasinski, Lewis Linker, Mark Meyers, Neerchal Nagaraj, Brandt Niemann, Marcia Olson, Scott Phillips, Ken Staver, Ping Wang.

***Recommendations*:**

1. Plan a Forecast Center.

In considering the outcome of the Bay Program's restoration efforts, forecasts over a variety of time scales are deemed essential for guidance and evaluation. Quantitative projections of specific management actions are required to establish the will and the resources necessary to support these actions. Toward this end, a Forecast Center (perhaps a virtual rather than physical center) should be established for the Chesapeake Bay Program. A focused workshop should be convened to address both goals and specific feasibility issues for a Forecast Center. At this stage, the following approaches are deemed worthy of implementation:

- *Long-term projections of the effects of the nutrient reduction strategy*, including realistic phase-in of nutrient controls. Nutrient controls are not anticipated to be implemented instantaneously, but brought on piecemeal over a span of years. Projections of the response of the Bay should incorporate this time dependence.
- *Short-term event-scale and seasonal-scale forecasts*, for both operational use, and for model evaluation and monitoring data interpretation.
- *Development of Akey@ or Aindex@ sites to optimize monitoring efforts***.**

In the proposed workshop, the following issues should be addressed:

- specific management questions appropriate for and amenable to forecasting;
- feasibility of forecasting of various state variables (including living resources) in time and space; and
- interactions of proposed Forecast Center with the Local Government Action Plan Center.

2. Improve monitoring-modeling linkages.

a) *Model behavior and short-term system response to event-scale forcing.* The water quality monitoring and living resource programs produce a phenomenological and long-term behavioral assessment of the Bay and tributaries. In addition, several intensive (high-frequency, small spatial scale) sampling programs have been conducted. It is recommended that high-frequency model output be dumped for model grid cells corresponding with specific, well-studied locations, including those surveyed by these intensive monitoring programs. This model product can then be used to evaluate scenario predictions with present conditions on scales relevant to living resources.

Presently, there are several caveats to performing these analyses. Modelers and monitors will have to evaluate the limitations on these kinds of comparative analyses *a priori.* For example, the model produces a diurnally-averaged calculation of biological activity, while intensive surveys may resolve processes on scales of #1 hour. Comparisons of model and monitoring output of this nature would thus be limited to daily averaged conditions.

b) *Spatial comparisons of model output and Bay data.* A second kind of comparison is the model output of high spatial resolution view of surface phytoplankton pigments (modeled as chlorophyll a) with the retrospective and on-going remote sensing analyses of surface pigments in the Bay[3]. These kinds of comparisons can evaluate the model scenario response of surface phytoplankton biomass with Baywide snapshots over decadal time scales.

3. Integrate modeling and monitoring in periodic reevaluations.

The Chesapeake Bay Program has periodic reevaluations of progress in meeting Bay restoration goals (e.g. in 1991 and 1997). These reevaluations require close interaction between the monitoring and modeling programs. The 1987 Bay Agreement calls for a 40% reduction in controllable loads of nitrogen and phosphorus, which translates into 24% and 35% reductions in the total N and P loads, respectively, delivered to the Bay. Monitoring programs capture flow and nutrient concentrations at the fall-lines for the major rivers and water quality measurements are collected regularly in the tidal rivers and the Bay. The modeling program computes the flow and nutrient concentrations using the Watershed Model for each fall-line on a daily basis (however, the calculations are computed on an hourly basis). The time-variable water quality model computes hydrodynamic behavior and water quality concentrations for the Bay and tidal tributaries, being driven by loads delivered at the fall-lines from the Watershed Model.

There is a strong need to link the Watershed Modeling scenario results back to the measured monitoring data:

a) The model results for the >1985 Conditions Base Case= scenario compute nutrient concentrations into the future with the assumption of no reduction of controllable loads. This would presumably provide a worst case trend line increasing over time.

b) The model results for the >40% Reduction Bay Agreement= scenario compute nutrient concentrations into the future with the assumption of a steady reduction of controllable loads until population increases might overwhelm those reductions. This should provide a realistic trend line decreasing over time.

c) Plotting the above time series with monitoring data should provide a framework to help interpret the effectiveness of the nutrient reduction programs.

The above analysis will be useful in several ways:

a) The plots of the model results demonstrate the anticipated improvements due to nutrient control measures being implemented now and into the future. This is required since control measures are implemented over a period of time and their impacts are not immediately evident due to differences in precipitation, ground water migration, and other environmental factors. The shortage of measured nutrient discharges from nutrient control measures (BMPs, riparian forests, etc) also hampers our ability to forecast their impact.

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3 Harding, L.W., Jr. and E.S. Perry. 1997. Long-term increase of phytoplankton biomass in Chesapeake Bay, 1950-1994. Marine Ecology Progress Series 157:39-52.

b) Plots of monitoring data have a certain amount of noise from sample to sample. Similarly, model output data have a range of noise that should mimic the noise in monitoring data. This variability may be larger than that observed due to the nutrient control measures (i.e., 20-30% reduction) which come online progressively over time. This analysis should help in demonstrating whether there is in fact a reduction trend in the monitoring data, that otherwise might not be statistically significant.

c) The data used in these analyses are useful data sets that should be captured for other analyses.

4. Assess feasibility of archiving 3-D model output in finer time and space scales.

Current model scenario runs are conducted at hourly time steps in the course of calculating Areportable≅ model results: seasonal average concentrations for model cells or coarser model segments. At present, only the final result is stored; intermediate values are not retained and thus are not available for further analysis.

The spatial and temporal scales of model segments and seasonally averaged conditions are not the most appropriate scales for the physical/chemical and biological parameters. Water quality and biological monitoring data are collected once or twice monthly and meaningful time and space scales are much finer than, or different from, those provided in the final model output. Analysts trying to link modeling output and system responses are interested in obtaining intermediate model output in as fine a resolution as is feasible and practical.

Recognizing that the accuracy or validity of intermediate estimates require qualification a study should be conducted to determine the feasibility of archiving model runs at the finest practicable scale.

5. Moderate the modeling-monitoring mismatch in determining status and trends.

There has been a great focus in interpreting status and trends in water quality and biological monitoring data throughout the Bay watershed. Data users have long been cognizant of the importance of physical processes in the interpretation of the data. However, reasonable estimates of transport, residence times, hydrodynamic lag times, and degree of stratification have not been readily available. *Ad hoc* efforts at including physical dynamics in interpreting monitoring data have been encouraging, but these estimates are simplistic relative to the features that are already included in the hydrodynamic components of the mainstem and tributary water quality model. This represents an example of a mismatch between the modeling and monitoring efforts, in that hydrodynamic information inherent in the 3-D model is not available to aid in the interpretation of monitoring data. A simpler model should be derived from the ongoing modeling effort to provide hydrodynamic information on the spatial (e.g. Bay segment) and temporal (week to month) scales that would be of use to data users interested in understanding the effects of physical dynamics on the status and trends in the monitoring data. Furthermore, the integration of physical processes into monitoring investigations should aid in the generation of ecological hypotheses and in monitoring refinement efforts. This sort of information exchange would be extremely valuable in periodic reevaluations, but implementation of this effort would be very difficult with the time and resources currently available. However, the coupling of modeling information into the interpretation of monitoring data should be approached aggressively as a short-term goal of the Bay program.

6. Improve the capability of the Watershed Model to address subsurface transport and effects of wetlands and riparian buffers.

The high degree of aggregation within the Watershed Model limits its capability to accurately reflect the effect of implementation of nutrient control strategies. Given that the Bay Water Quality Model is driven by nutrient inputs calculated within the Watershed Model, the usefulness of the Water Quality Model for projecting the effect of various nutrient control strategies will be limited by deficiencies in the Watershed Model. Currently, the Watershed Model triggers load reductions instantaneously when implementation occurs. This structure neglects the multi-year residence times for nitrogen moving through subsurface flow paths, as well as the insensitivity of soil soluble phosphorus concentrations to downward adjustments in phosphorus application rates. Neglecting the time functions of nonpoint source nutrient control techniques within the Watershed Model leads to predicted reductions in nonpoint source loads many years in advance of when they actually occur. As a result, fall line or tributary water quality monitoring data will consistently be asynchronous with model output, particularly in the short-term. In sub-watersheds where water quality problems result primarily from nonpoint source loads, the current model structure will establish expectations for improvements in water quality that are not achievable in the near term. Correcting this deficiency will require inclusion in the model of time functions for various nutrient control techniques.

A second element of the Watershed Model that needs refinement is the structure for assessing the impact of watershed components that attenuate nutrient loads between the source and point of discharge into tidal waters. Accurate assessment of effects of wetlands and riparian buffer areas is necessary to predict the impact of in-field practices on in-stream nutrient loads. Given current efforts to promote riparian buffer areas, the Watershed Model needs the capability to project resulting load reductions under differing implementation scenarios.

Challenge 2

Linking Living Resources and Water Quality Monitoring

Challenge Team Members: Peter Bergstrom and Denise Breitburg (Challengers), Jack Greer (Facilitator), Carin Bisland, Steve Brandt, Claire Buchanan, Ed Houde, Rob Magnien, Ken Moore, Kent Mountford, Derek Orner, Bob Orth, Bill Romano, Kevin Sellner.

Resources Considered:

Of the many living resources in the Chesapeake Bay, several have been the particular focus of monitoring and research activities. The Challenge Team focused its attention on the following: submerged aquatic vegetation (SAV), structure of planktonic and benthic communities, effects of low dissolved oxygen on sensitive biota, and fish energetics.

Recommendations:

In order to assess more effectively the progress in achieving its goals for restoration of living resources, the Chesapeake Bay Program should:

- expand Baywide fish monitoring and coordinate it with that for other living resources and water quality in order to address top-down controls (i.e. the effects of large predators on those populations of planktonic and benthic organisms regularly monitored);
- refine and expand the use of habitat requirements to include recovery criteria; and
- explore new statistical and modeling techniques to improve our understanding of linkages between water quality and living resources.

In addition to these general recommendations, the following specific recommendations are made:

1. **Assess top-down trophic controls.** The Chesapeake Bay Program's emphasis on nutrient reduction to achieve living resource restoration implicitly assumes that these resources are controlled through food chains from the bottom-up. However, some water quality-living resource links suggest that top-down controls (i.e., by predators) are important. Available data from programs such as winter crab dredge surveys and the Trophic Interactions in Estuarine Systems (TIES) program should be mined and analyzed to provide more information on upper trophic levels in order to establish top-down effects for use in conceptual and mathematical models.

2. **Expand and better coordinate fish monitoring.** Baywide fish monitoring should be increased and current disparate efforts better coordinated. New and existing fish monitoring should also be coordinated with monitoring of nutrients, dissolved oxygen, and lower trophic levels, with the goal of providing information needed to make ecological linkages. A particular opportunity for coordination is the documentation of the effects of the high-inflow 1996 conditions on living resources.

3. **Relate factors other than nutrients**. The effects of factors other than nutrients and dissolved oxygen on living resources should be better quantified and incorporated in living resource response models. These factors include conventional pollutants (pH, temperature, solids, BOD), toxic contaminants, and fishing pressures. For example, indices of overall toxicity could be developed against which to compare biological indicators.

4. **Develop recovery criteria for living resources.** Criteria for living resource recovery should be developed beyond the water quality requirements for persistence of established populations. This is needed to address problems that exist where habitat requirements are met but resource recovery is not occurring, for example SAV growth in the lower Patuxent and Potomac rivers.

5. **Clarify living resource management questions. L**iving resource-related management questions should be separated into those that can and cannot be addressed with CBP monitoring data alone. For example, a question that can be addressed by monitoring data is "Which areas of mainstem and tidal tributaries met most or all of the AV water quality habitat requirements?". Additional data is required to "In which of those areas can we expect SAV recovery?"

6. **Explore techniques for separating natural variability.** Analytical approaches are needed to remove the "noise" of natural variability in long-term monitoring data sets in order to identify anthropogenic signals. Flow correction is currently used to achieve this, but this may change the factors we are trying to assess.

7. **Improve linkages among Bay trophic levels.** New research and analysis techniques are needed for drawing links from nutrient loads through plankton to fish abundance or biomass. A major missing link in this chain is that between phytoplankton to mesozooplankton, the primary prey for many juvenile and adult fishes.

8. **Assess effects of aquatic habitat structure on predation.** The potential impacts of aquatic habitat structure on predator-prey interactions and growth rates of key Bay organisms should be monitored and assessed. The information is needed for use in ecosystem response models. This may require changed or new monitoring, which should be designed to mesh with Bay water quality modeling efforts.

9. **Improve monitoring of critical land habitats.** Remote sensing or other monitoring of habitats at the land-water interface (especially wetlands and riparian habitats) should be

improved. The abundance and quality of these habitats impact anadromous fish, terrestrial wildlife, and nutrient and other runoff. Furthermore, such information is important for the tributary strategies and for use in targeting and tracking habitat restoration (e.g. riparian forest buffers).

10. **Assess oyster reefs as components of Bay ecosystem.** More consideration of oyster reefs is required in monitoring, data analysis, and modeling efforts. There is a need to integrate existing and new efforts in Baywide analysis and modeling efforts.

11. **Explore composite living resource indicators.** Innovative use of existing and new indicators of the integrated condition of resources, communities, and the ecosystem, such as indices of biotic integrity (IBIs), should be promoted. These indicators should be related to each other and to controlling factors. There is a particular need for indicators of functional behavior, as most of the current IBIs reflect community structure.

12. **Assess scale and dispersal effects on SAV recovery.** Temporal and spatial scales of processes leading to SAV recovery and persistence must be considered. The importance of size and density of SAV beds to persistence and spread should be assessed, as should the importance of recruitment limitations versus water quality control and the relevance of different propagule dispersal agents, e.g. waterfowl.

13. **Assess effects of water quality variability on SAV.** The variability of SAV water quality parameters in CBP monitoring data should be analyzed, particularly in areas where most SAV habitat requirements are met. Approaches similar to those used in analysis of spatial research data at the Virginia Institute of Marine Science and University of Maryland are recommended. One would predict better SAV growth where variability is less (i.e. with fewer events of poor water quality).

14. **Revise SAV habitat requirements.** Modeling results should be used to estimate leaf surface light attenuation due to epiphytes (an important factor not currently included in the SAV habitat requirements). Results can then be tested to determine how well they predict research results, and how well they correlate with SAV growth. In any case, adoption of percent light in the habitat requirements should be considered.

15. **Confirm zooplankton-fish relationships.** The relationship between summer mesozooplankton and summer planktivorous fish has been shown by correlation, but this relationship requires verification through experimentation for different salinity regimes.

16. **Assess the quality of production.** Although much attention has focused on the relationship of nutrient supply to the quantity of primary production, the quality of phytoplankton (e.g., its nutritional value in food chains supporting important living resources) is also influenced by nutrient enrichment or reductions.

17. **Continue to confirm model predictions.** Living resource feedbacks have become an important part of the Bay Water Quality Model, however many of the responses and rates are supported by very limited information. For example, there is a need to confirm the benthic biomass assumptions of the Water Quality Model with monitoring data. There is also concern that modeled filtration times seem unreasonably high.

Challenge 3
Improving the Sensitivity of Monitoring Small Watersheds

Challenge Team Members: Harry Pionke (Challenger), Alan Taylor (Facilitator), Joe Bachman, Mark Bennett, Russ Brinsfield, David Correll, Keith Eshleman, Robert Edwards, Tom Grizzard, John McCoy, Russ Mader, Katrin O=Connell.

Opportunities:

As the Chesapeake Bay Program has increasingly emphasized control of nonpoint sources and atmospheric deposition of nutrients it has become more and more important to know (1) how watersheds work in transporting nutrients toward the Bay, and (2) how we can most effectively reduce or intercept these diffuse sources of nutrients. Yet, the watersheds of the 167,000 km^2 Chesapeake Bay basin are extremely heterogeneous and complex. Even forested watersheds vary widely in the degree to which they retain or release nutrients[4]. How, then, can we improve our ability to predict responses by models and confirm them by monitoring?

Of the five areas identified in the Introduction in which the Workshop explored opportunities, four offer distinct opportunities for improving the sensitivity of monitoring of small watersheds:

- **Processes**. Those engaged in watershed monitoring need to perceive watersheds as a collection of sources, sinks, and storages arranged in a flow network. Steady state is frequently assumed, as is the case in the Bay Program's Watershed Model, wherein an action such as a nonpoint source control is assumed to have an immediate or rapid effect. Conclusions about the lack of responsiveness in reduction in nutrient transport in the stream draining the watershed may, consequently, be either correct or incorrect. Interpretations of existing watershed monitoring results can be improved through better application of what we know about watershed processes. Furthermore, the design of watershed monitoring can also be improved by application of residence time and storage estimates in order to accommodate "lag time" effects. In this last regard, it would be particularly useful to focus more attention on those enigmatic watersheds where stream flow concentrations do not reflect nutrient reductions from concerted application of management practices. Not only is it necessary to determine the actual effectiveness of BMPs under the variety of conditions existing in the Chesapeake basin, but also to evaluate the design life of structural controls and the cumulative effectiveness of routine practices. Monitoring should be designed to answer specific management questions, but should also be based on hypotheses about how the particular watershed and the particular management practices work.

- **Scale**. More attention should be focused on areas where models can be applied and sufficient data exists for some validation. Steady-state versus dynamic predictions of the spatial extent and temporal responsiveness of watershed nutrient transport to management practices should be compared Watersheds are not aggregative but integrative, which means that processes controlling at one scale may not control at another scale. For example, denitrfication in a regional aquifer, if important, cannot be properly monitored at the upland scale. Thus, monitoring approaches must be scaled to accommodate this integration over space and time.

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4 Gardner, R.H., M.S. Castro, R.P. Morgan, and S.W. Seagle. 1996. Perspectives on Chesapeake Bay: Nitrogen Dynamics in Forested Lands of the Chesapeake Basin. Chesapeake Research Consortium, Edgewater, Maryland.

- **Analysis**. Unfortunately, there are few replications of monitored watershed and, even in those cases, no two watersheds are completely identical. Nonetheless, intersite comparisons should be used wherever possible. Also, analysis of particular time intervals or events can yield special insights on processes and elucidate controlling factors. Better analytical approaches are required for improved monitoring design, addressing such issues as: how long monitoring needs to continue for adequate characterization, and trade-offs between monitoring a few watersheds over long periods versus many watersheds with shorter records. Ultimately, an optimum network of “core” watersheds should be monitored over the long term together with a “flexible” array of watersheds monitored for specific periods and purposes.

- **Remote and continuous monitoring**. Automated stream sampling has been applied in a number of watershed monitoring studies and is capable of producing weighted estimates of flux. This is a distinct advantage over most of the approaches we have to use in monitoring the estuary. Results from near-continuous sampling, therefore, can be used to improve flux estimates of streams monitored by grab sampling. On another front, historical photographic evidence of landscape change can be compared with current satellite derived date capable of providing much larger scale images, allowing one to “scale up” historical information.

Recommendations:

1. **Evaluate the monitoring and research database on the effectiveness of land use practices**. Scientists engaged in nonpoint source management, hydrologic, and water quality studies on small watersheds in the Chesapeake Bay region should collectively evaluate the overall monitoring and research data based on the effectiveness of land use practices installed for environmental quality control, including Best Management Practices, Nutrient Management and vegetated buffers.

2. **Assess watershed responses to the two large flow events of 1996**. A task force composed of scientists and those engaged in modeling watersheds of different scales in the Bay region should evaluate available data related to: the determination of the loads of water, sediment and nutrients delivered from monitored watersheds for comparison of the measured loads, and those estimated by the Watershed Model.

3. **Examine the relationships among results from studies of watersheds of different scales**. Specifically , the examination should:

   a) evaluate the usefulness of small watershed data in the estimation of the concentrations and loads of nutrients and pollutants discharged from larger areas;

   b) examine the comparability and utility of data sets taken over differing ranges of space and time, and identify the gaps in knowledge of environmental processes; and

   c) develop recommendations for the design of small watershed studies to improve their usefulness for the characterization of larger areas and longer time periods.

Challenge 4
Bridging Spatial and Temporal Scales in Monitoring and Research.

Challenge Team Members: Tom Malone (Challenger), Joy Bartholomew (Facilitator), Mary Christman, Sherri Cooper, Bob Gardner, Usha Govindarajulu, Larry Haas, Larry Harding, Colleen Hatfield, Mike Kemp, Ganapati Patil, Elgin Perry, Mike Roman.

The Concept of Scale:

The Committee on Environment and Natural Resources (CENR) of the National Science and Technology Council recently published a proposed framework for *Integrating the Nation=s Environmental Monitoring and Research Networks and Programs*. The highest priority recommendation is to Aintegrate environmental monitoring and research programs across temporal and spatial scales and among resources.≅ What is meant by Ascale≅, why is the concept of scale important, and what are the challenges to this kind of approach?[5]

In recent years, the use of the word Ascale≅ in ecology has become ambiguous and often misleading. For the purposes of this workshop, the following definitions were used:

- **Scale** denotes both resolution within the range of a measured quantity and the range of measurements. For example, the concentration of chlorophyll-a in Chesapeake Bay could have a spatial scale resolved to 10 meters over a distance of 250 km, a temporal scale resolved to 2 weeks over 10 years, and a mass scale resolved to 100 ng over a range of 100 ng to 100 mg.
- A **scale-dependent pattern** is one that changes with either a change in the resolution or the range of measurement. In the Bay and its tributaries, variables such as the concentrations of nutrient, chlorophyll, and dissolved oxygen exhibit patterns of distribution that depend on the vertical, horizontal, and time scales of observation and analysis.
- A **scale-dependent process** is one in which the ratio of one rate to another changes with either the resolution or the range of measurement, e.g., nutrient input relative to nutrient export and phytoplankton productivity within the Bay relative to the rate of export of phytoplankton biomass to the benthos are dependent on temporal scale.

Why Scale Is Important:

The development of scaling rules and the application of multiscale analysis are of fundamental importance in environmental science and management, from predictive ecology to risk assessment. Examples that illustrate the importance of scaling approaches include: (a) changes in water quality or in the abundance of commercially valuable fish stocks that occur on scales that are large relative to the forcing event itself (e.g., episodic storms or seasonal freshets); (b) biomass and species diversity vary depending on the scales of measurement as

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5 For an introduction to the concepts of Ascale≅ and to multiscale analysis see Roughgarden et al. 1989. *Perspectives in Ecological Theory*. Princeton University Press and Schneider, D.C. 1994. *Quantitative Ecology: Spatial and Temporal Scaling*. Academic Press. For an introduction to the literature see Levin, S.A. 1992. The problem of pattern and scale in ecology, Ecology, 73: 1943-1967; Rastetter et al. 1992. Aggregating fine-scale ecological knowledge to model coarser-scale attributes of ecosystems. Ecol. Appl., 2: 55-70; and Steele, J.H. 1985. A comparison of terrestrial and marine ecological systems. Nature, 313: 355-358.

well as on natural and anthropogenic forces; (c) physical and biological variability are often correlated in time and space, suggesting the propagation of energy and information among subunits having inherently different scales (e.g., transfer of turbulent kinetic energy from large to small eddies, transfer of energy from phytoplankton to fish, phenotypic expression of genetic variability); and (d) population responses to contaminants and nutrients in an ecosystem context in nature differ from responses to contaminants in controlled experiments on smaller scales.

Technical developments over the last 10-20 years have given us the tools needed to address these and other problems of scale. These include (a) computer hardware and software that allow rapid retrieval, storage, dissemination, and visualization of large quantities of data; (b) the development of simulation models that provide the means of predicting the outcome of complex and often nonlinear interactions among components; and (c) the development of sensors and platforms that measure variables with high resolution, over long periods, and large areas. These advances are making possible important advances in our ability to predict change and resolve anthropogenic sources from natural sources of variability and change.

Challenges:

In terms of bridging spatial and temporal scales in monitoring and research, there are at least three challenges:

- *Formulating scaling rules and techniques for extrapolating results from small scale experiments in the laboratory to nature and from small to large ecosystems*. Extrapolating from small to large systems often involves predicting how populations or processes in large, complex systems are likely to respond to perturbations based on their response in smaller, less complex systems. Are there scaling rules that can be used to make such predictions with known certainty? Examples include:

  - predicting biological responses to contaminant inputs in nature based on laboratory experiments (e.g., the growth response of SAV to herbicides in Chesapeake Bay based on their response in microcosms), or responses to inputs in large systems based on the dynamics of smaller systems in nature (e.g. the response of phytoplankton to nutrient inputs in the mainstem Bay based on their response in smaller subestuaries);

  - predicting long-term trends based on the dynamics of short-term change (e.g., decadal trends in the volume of summer hypoxia based the dynamics of seasonal variability); and

  - validating ecosystem models that integrate over larger scales based on instantaneous measurements at specific points within the ecosystem.

- *Developing a predictive understanding for the propagation of variability from large to small scales*. Large scale changes are often expressed on regional to local scales. How is variability propagated from large to small scales and are there scaling rules that can be used to predict small scale change from knowledge of larger scales changes? Examples include predicting the effects of global climate change on estuarine organisms sensitive to changes in temperature or sea level, or the effects of reductions in nutrient loading of coastal waters on the frequency and magnitude of red tides.

- *Developing a predictive understanding of propagation of variability across the interfaces between ecosystems characterized by inherently different scales of variability*. Changes that occur in a given system are often transmitted to other systems that have inherently different time and space scales. How are changes in one system translated into changes in another? Examples include relating changes in patterns of land-use in a drainage basin to the eutrophication of the receiving water body, linking changes in the water column and the benthos, and evaluating the effects of seasonal changes in the pattern of phytoplankton production on fish stock recruitment.

Boundaries:

In order to bound the discussion, the group agreed to focus on the problem of nutrient enrichment in terms of three categories that embody different aspects of multiscale analysis: (a) the linkage between systems having different inherent scales of variability, e.g., land-use in the drainage basin and changes in the water quality, habitats, and living resources of estuarine systems; (b) biogeochemical processes, e.g., microbial responses to nutrient loading as they are related to changes in water quality; and (c) fisheries, i.e., time and space scales defined by the life histories and migrations of fish. Discussions emphasized the following broad goals:

- quantify scale-dependent patterns that characterize variations in the parameters of both nutrient transport from land to water, and water quality and living resources in the Bay and its subestuaries;
- explore the scale-dependence of estimates of sample means and relate sampling intensity (resolution in time and space) to these estimates as a means to evaluate the cost-effectiveness of the monitoring program;
- evaluate the utility of incorporating measures of spatial and temporal variances into indices of the health of Chesapeake Bay; and
- evaluate the utility of periodic, high resolution synoptic surveys (remote sensing) and continuous measures at selected sites of key variables as a means of amplifying and extending the sampling scales of the monitoring program. These should address the problem of quantifying anthropogenic effects in the context of the scales of climatic variability that impact the Bay.

Recommendations:

The recommendations are best catagorized in the following areas: (1) the use of data from research and modeling to quantify scales of variability of key features of the Bay and its subestuaries; (2) the use of results from research and modeling to determine the causes and consequences of variability and trends revealed by monitoring; (3) relating high resolution time series and synoptic spatial distributions to extend monitoring results for more complete, quantitative, and accurate documentation of patterns relevant to the problems of water quality and living resources; and (4) modeling, monitoring, and the problems of complexity, aggregation, resolution, and predictability. In each of these areas, priority questions and issues were identified that can and should be addressed within the next one to three years.

1. **Scales of Variability**: Given the limitations of resolution and range of measurements, what are the dominant scales of variability in time and space that characterize the following factors: inputs of freshwater and nutrients, the distributions of salinity, dissolved inorganic nitrogen, chlorophyll, dissolved oxygen, mesozooplankton biomass, and benthic biomass (deposit and suspension feeders) in the mainstem Bay and its subestuaries?

   Are patterns of variability scale-dependent and, if so, how do they affect estimates of sample means and variances?

   Do the mainstem of the Bay and the subestuaries exhibit different and characteristic scale-dependent patterns? If so, are these related to particular features such as volume, depth, fill-time, surface area to volume, and the relative importance of point and diffuse nutrient sources?

   Is there co-variance among variance spectra, and is this scale-dependent? Do scale-dependent patterns differ among the Bay=s subestuaries?

2. **Causes and Consequences of Change**: Given quantitative descriptions of spatial and temporal scales of variation, are research efforts providing the information needed to determine the causes and consequences of these changes?

   Are sampling scales of the monitoring program in tune with the scales of the natural and anthropogenic forces that impact the Bay? With the scales that are expected to characterize responses in terms water quality and living resource parameters?

   Are stock assessment and monitoring data being collected on scales that will allow changes in water quality to be related to changes in fish stocks?

   Explore the use of results from hypothesis-driven research programs[6] to quantify parameters of carbon and nutrient flows (e.g., phytoplankton-mesozooplankton-fish) for the purposes of predicting patterns of biomass variability on larger time and space scales.

3. **Temporal and Spatial Scales**: The questions addressed here relate to both of the categories discussed above. They are distinct in that they require the kinds of data generated by *in situ* (moored instruments that make continuous measurements) and remote (e.g., ODAS, SeaWiFS) sensing. These data should be used to interpolate and extrapolate monitoring station data for more complete and accurate descriptions of temporal and spatial patterns and for resolving the effects of anthropogenic and natural forcings.

   To what extent are spatial and temporal scales of variability of key properties and processes correlated? Explore space-for-time scale substitutions as a means of using current differences among tributaries to predict long-term trends in response expected decreases in nutrient loading.

   How does aggregation affect results and associated errors, e.g., interpolation error in the generation of distributions by GIS using monitoring data versus those defined using high resolution, synoptic measurements?

   What are the appropriate boundaries for aggregation, e.g., geographically fixed boundaries, salinity envelops that are variable in time and space, and frequency domains?

   Document the frequency and magnitude of high energy events and the propagation of the resulting variability through the Bay and/or it subestuaries.

   Are continuous underway measurements of *in vivo* chlorophyll fluorescence useful in these regards?

4. **Modeling and Monitoring**: In the context of discussing the linkage between time and space scales of variability and the propagation of effects from one scale to another, the related problems of predictability, resolution, and generality were addressed. Three generic approaches were discussed and recommended. They are generic in the sense that specific problems and models are not identified.[7]

   a) *Time series comparison of model(s) and data*. Compare predictions and residuals of

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6 Research programs, such as the Trophic Interaction in Estuarine Systems Program (NSF/LMER), the EPA-supported Multiscale Experimental Ecosystem Research Center, and the NOAA-support multiple stressor program, are designed to test hypotheses concerning the population dynamics and the effects of stressors on populations and processes. The governing rate processes often have time scales that are short relative to patterns of change revealed by the monitoring program and measurements are typically conducted on the small scales at which organisms interact with each other and their environments.

7 The details of the analyses will change depending on the nature of the problem selected.

time-series statistical models (ARMA) with physical and/or biological models of the Bay to test the hypothesis that distinct differences will show missing processes and scales at which these are important.

b) *Resolution, aggregation and error*. Bias in parameter values results in systematic errors in model predictions. Low resolution data and/or incomplete records of extreme events can be significant contributors to biased parameter estimates. Therefore, compare parameter estimates made from a series of data aggregations. Employ bootstrap methods to estimate parameter errors at each aggregation level and test the hypothesis that scale-dependent changes in parameter bias and variance will be revealed.

c) *Complexity, information and predictability*. Complex models are information rich, but also require a great deal of data to estimate model parameters. Biased estimates of parameters and non-linear behavior of complex models may result in serious errors when used to predict across a broad-range of temporal and spatial scales. Under these circumstances, the reliability of simpler models has been shown to be greater. Comparison of a suite of models allows the gain in information with detail to be compared against the reliability of predictions across scales. Test the hypothesis that, when predicting across broad spatial and temporal scales, the non-linear behavior of complex models may produce greater errors than simpler representations of these systems.