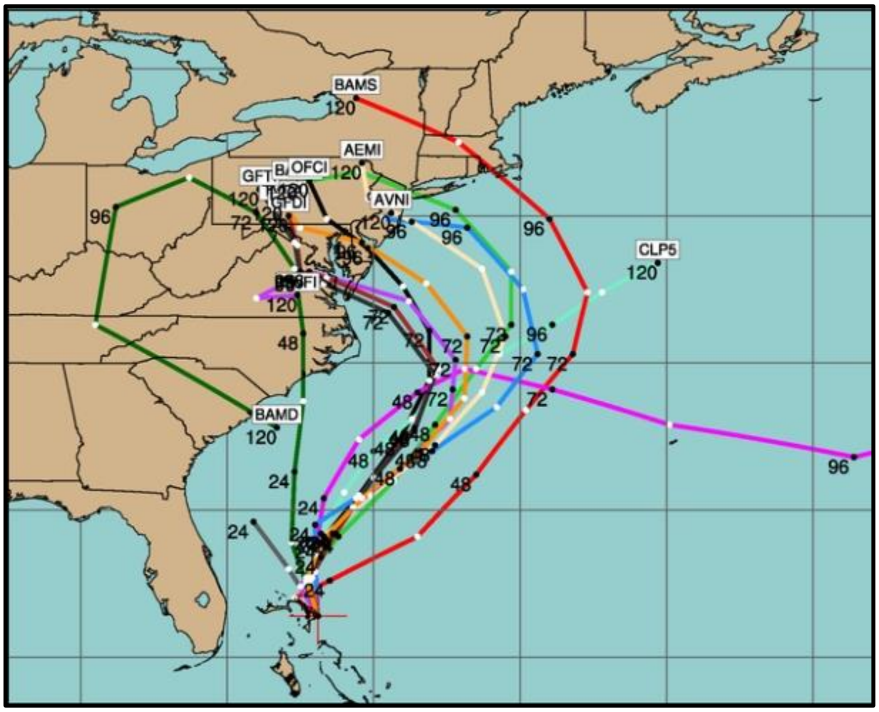
Multiple Models for Management in the Chesapeake Bay



Multiple models are already widely accepted for some issues. In October 2012, television weather broadcasts informed millions of anxious coastal residents with multiple-model projections (“spaghetti plots”) of tropical storm Sandy. The same forecasts guided critical decisions by governments and emergency managers.

STAC Workshop Report
February 25-26, 2013
Annapolis, Maryland

STAC Publication 14-004

About the Scientific and Technical Advisory Committee
The Scientific and Technical Advisory Committee (STAC) provides scientific and technical guidance to the Chesapeake Bay Program (CBP) on measures to restore and protect the Chesapeake Bay. Since its creation in December 1984, STAC has worked to enhance scientific communication and outreach throughout the Chesapeake Bay Watershed and beyond. STAC provides scientific and technical advice in various ways, including (1) technical reports and papers, (2) discussion groups, (3) assistance in organizing merit reviews of CBP programs and projects, (4) technical workshops, and (5) interaction between STAC members and the CBP. Through professional and academic contacts and organizational networks of its members, STAC ensures close cooperation among and between the various research institutions and management agencies represented in the Watershed. For additional information about STAC, please visit the STAC website at www.chesapeake.org/stac.

Publication Date: July, 2014

Publication Number: 14-004

Suggested Citation:
Weller, D. E., B. Benham, M. Friedrichs, R. Najjar, M. Paolisso, P. Pascual, G. Shenk, and K. Sellner. 2013. Multiple Models for Management in the Chesapeake Bay. STAC Publication Number 14-004, Edgewater, MD. 37 pages.

Cover graphic from: The National Weather Service

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Executive Summary

In early 2012, the Director of the Chesapeake Bay Program (CBP) asked the Program's Scientific and Technical Advisory Committee to consider how the CBP might use multiple models. That request resulted in two workshops. The first detailed a pilot multiple modeling project for the Bay's shallow waters (Friedrichs et al. 2012). The second workshop, summarized here, sought to develop more general recommendations on how the CBP could utilize multiple models in management decisions. The workshop considered case studies of multiple models in environmental regulation, the perception of multiple models by the public and decision makers, and legal issues associated with multiple modeling in regulatory settings. This report presents the Findings (factual conclusions or the consensus of workshop experts about the use and benefits of multiple modeling) and four Recommendations that the CBP could initiate to begin realizing those benefits:

Findings

1. Using multiple models offers many documented advantages over analyzing one model of an environmental system.
2. There are different ways to implement multiple models (multi-model ensembles, using other models to assess a decision model, modular community modeling, and model comparisons in pilot studies or testbed areas). The common principle is that findings are stronger when multiple lines of evidence, multiple data sets, or multiple algorithms agree.
3. Analyzing multiple models increases knowledge and understanding of underlying processes.
4. Average predictions from a set of models typically perform better than those from any single model.
5. Information from multiple models can help quantify model uncertainty, which is critical to sound science and rational decision-making.
6. Modeling is inexpensive compared to the costs of monitoring, implementation, and poor decisions.
7. Properly framed multiple models can be a legal asset rather than a liability.
8. Managers and the public are poorly informed about modeling, model uncertainty, multiple models, and the value of investments in modeling.
9. Multiple modeling can expand opportunities for additional technical experts and non-technical stakeholders to participate in modeling, fostering greater understanding and acceptance of models and the decisions based upon them.
10. Multiple models of the Chesapeake Bay and its watershed already exist and they could be integrated into CBP modeling to improve knowledge and decision-making.

Recommendations

1. The CBP should implement a multiple modeling strategy for each major decision-making model of the Bay (airshed, land use, watershed, and estuary) and analyze the output to quantify skill, advance knowledge, and inform adaptive management.
2. The CBP should exercise the multiple model systems developed under Recommendation 1 to quantify model uncertainty and confidence in key predictions used in decision-making.
3. The CBP should estimate and better communicate the appropriate levels of spending on monitoring, modeling, and research relative to the costs of implementation and the cost of poor decision-making.
4. The CBP should implement ways to better communicate modeling, uncertainty, and multiple model results to partners, decision makers, and the public.

1. Introduction

1.1 Goals and event information

Scientists have documented many advantages to analyzing more than one model of a system. Multi-model analysis can compare different conceptual models of systems, contrast the skills of different models, improve basic understanding of systems, and help quantify the level of confidence in model predictions. Despite the scientific advantages, some managers and environmental advocates are wary of multi-model approaches. The concern is that multi-model approaches cost more, and that results from more than one model may confuse the public and decision makers, provoke legal challenges, and slow the regulatory process.

The Chesapeake Bay Program's (CBP) Scientific and Technical Advisory Committee (STAC) has repeatedly recommended that the CBP use multiple model strategies to enhance modeling and decision-making regarding Chesapeake Bay restoration (Committee for the ANPC/LimnoTech Review 2011, Pyke 2011a,b, Friedrichs et al. 2011). In response, the Director of the CBP in early 2012 asked STAC to organize technical experts and CBP stakeholders to develop recommendations on how the CBP could utilize information from multiple models in CBP management decisions. That request resulted in two STAC workshops on multiple modeling. The first workshop was held April 26-27, 2012 at the Virginia Institute of Marine Science (VIMS) in Gloucester Point, Virginia. It framed a shallow water, multiple model comparison pilot project (including costs and action plan) that would provide the foundation for future modeling in the productive littoral areas of the Bay and would demonstrate the potential use of multiple models in routine CBP modeling activities (Friedrichs et al. 2012). As a result, the CBP decided to implement the recommended pilot project, and in November 2013, the Environmental Protection Agency (EPA) issued a Request for Proposals to conduct the work (USEPA 2013).

This report presents the findings and recommendations of the second workshop, which took place February 25-26, 2013 in Annapolis, MD. The goal was to gather regional and national technical experts and managers (including some with experience using multiple models in a regulatory context) to discuss their experiences and consider how multiple models could be used within the CBP. The workshop's five main objectives were to:

- Explore the scientific benefits of model comparison and multiple modeling.
- Present case studies of models in environmental regulation that highlight how the use of multiple models has helped or hindered the implementation of environmental regulations.
- Seek legal insight on whether multiple models should be used to enhance the credibility and defensibility of regulatory decisions made to implement the Total Maximum Daily Load (TMDL) program for the Chesapeake Bay.
- Gain insight from social science on how the use of multiple models might affect the perception of models and their results by decision makers and the public.

- Conduct extensive discussion to synthesize the sense of the assembled experts and participants on if and how multiple model approaches should be used by the CBP.

The results of the workshop are organized into two sections in this report. The first section on **Findings** highlights factual conclusions and the consensus of professional opinion that emerged from the workshop presentations and discussion. Those findings consider the definition, advantages, and perceived pitfalls of using multiple models in environmental decision-making, plus some observations on the current status of multiple modeling in Chesapeake Bay decision-making. The second section on **Recommendations** presents specific actions that workshop participants recommended to advance CBP's modeling program through the use of multiple modeling.

1.2 Definition of multiple modeling

The workshop began with a short introduction by Dr. Donald Weller (Smithsonian Environmental Research Center), who offered a definition of multiple modeling and outlined the possible benefits, pitfalls, and case studies that would be considered. The definitions and benefits were summarized from the literature review sections of recent papers and reports on multiple modeling in the Chesapeake region (Friedrichs et al. 2011, Bever et al. 2013, Boomer et al. 2013, Luettich et al. 2013). For the purposes of the workshop, the participants accepted the definition that **multiple modeling involves the analysis of a set of models that make some predictions in common**. Note that this definition excludes a set of models that make predictions for different parts of the system, like the airshed, watershed, and estuary model system developed by the CBP. Such a system may involve more than one model, but the models make predictions that cannot be directly compared because they are for different processes in different places.

Definitions of key terms are also listed in the Glossary (page 25).

1.3 Model comparison versus multiple modeling in decision-making

The workshop considered two possible components in multiple model analyses. A **multiple model analysis always includes some formal comparison of predictions or outputs** across the model set. Some multiple model analyses (often called model comparisons) end with that step, but the use of **multiple models can also be integrated into the decision-making process** so that decisions and regulations are formally guided by the results from more than one model. For example, a decision could be based on the average and range of predictions from a set of models, or multiple models could be used to demonstrate the skill of a single decision model.

1.4 Ways to implement multiple modeling in decision-making

There are different ways to implement multiple modeling in decision-making. In **multi-model ensembles**, **a set of models makes the same predictions, and the outputs of all the models**

would be used in decision-making. The outputs of the individual models can be compared, and differences among the models can be related to the different assumptions and approaches. Together the models provide an average prediction, and differences among the predictions can be summarized (perhaps as a range or probability distribution) to provide an estimate of the uncertainty in the model average prediction. For example, a multi-model ensemble approach could be used to define a target nutrient reduction needed to achieve a water quality standard. Multiple solutions (target nutrient reductions) would be obtained from several models and averaged to obtain the mean target nutrient reduction. The main advantage of this approach is the mean model result tends to more correct than any single model result (Reichler and Kim 2008, Bever et al. 2013, Boomer et al. 2013), and the ensemble provides a measure of uncertainty (the variability in the model solutions). The multiple solutions also provide options to select more or less conservative management targets. Weighted averaging and Bayesian methods can improve multi-model ensemble integration (Kadane and Lazar 2004, Tobias and Li 2004, Morales et al. 2006).

Alternatively, **multiple models can be used to assess a management decision model** to quantify how good the management model is compared to other models. Ideally, this would be done *before* applying the management model to guide decisions. This approach is different from multi-model ensemble modeling. It still requires a comparison of the results of the management model with other models, but the comparisons need not focus on predicting specific management endpoints (such as the target nutrient reduction mentioned above). Instead, the comparisons can be more general. For example, in evaluating an estuarine decision model, its predictions of critical ecosystem attributes (such as modeled light penetration or the concentrations of nutrient, chlorophyll, or dissolved oxygen) could be compared to those of other models to reveal the general performance of the management model. If the management model performs well compared to other models, then one can be justified in using it for management applications. This method of multiple modeling allows managers to use a single model that gives only one answer, while using the other models to assess the skill of the management model. This approach can also include models that are mechanistically simpler or that consider smaller areas, or shorter times than the decision model. The simpler models can still contribute to skill assessment where their predictions overlap with those of the decision model.

The workshop participants also learned that **many of the benefits of multiple modeling can be achieved with a modular modeling framework** in which an overall model can be run with different representations of key processes by swapping model modules representing those processes. Simulations using different modules then act much like the more distinct models described above and can potentially support the same kinds of assessments and integration across simulations. A case study detailing this kind of modular modeling is reported below.
The common principle in all the methods of multiple modeling is that multiple lines of evidence, multiple data sets, and multiple algorithms make the findings stronger.

1.5 Benefits of using multiple models

There are many advantages of using multiple models over a single model (Kadane and Lazar 2004, Reichler and Kim 2008, Bever et al. 2013, Boomer et al. 2013). **The advantages of multiple modeling include:**

- Compares hypotheses about system function.
- Identifies agreements among models (higher confidence in these results).
- Identifies disagreements (lower confidence in these results).
- Can provide model average predictions, which often perform better than single-model predictions.
- Helps quantify uncertainty.
- Helps identify deficiencies and errors in each individual model.
- Builds collaboration among groups within the modeling community.
- Fosters continual synthesis and model development to improve knowledge and predictions.

The above benefits are emphasized in the case studies presented below, and some additional benefits are also summarized. The bottom line is that **multiple modeling is good science**.

1.6 Concerns about using multiple models

Despite the recognition of the benefits of multiple modeling, some workshop participants still had **concerns about using multiple modeling in environmental management and regulation**. Some of those concerns included:

- Multiple models require more work, more staff, and more funding.
- Multiple modeling takes more time, maybe too long for tight decision timelines.
- Multiple models or predictions may provoke legal challenges.
- Multiple modeling may be incompatible with Clean Water Act (CWA) and TMDL rules.
- Multiple models highlight uncertainties by producing different predictions.
- More than one model or prediction may confuse the public and decision makers.

The workshop presenters specifically addressed the issues of cost, uncertainty, confusion, acceptance, and legal difficulties behind the concerns above. Their responses are embedded in the remainder of the report. Together, their responses show that these concerns do not preclude implementing multiple modeling to realize its many benefits.

2. Case studies of multiple models in environmental issues

2.1 Multiple modeling in climate and weather forecasting

Invited experts presented case studies to illustrate the application of multiple modeling to environmental problems. Some of the best known multiple-model applications are in the areas of weather forecasting and climate impact assessment. Dr. Raymond Najjar (Department of Meteorology, The Pennsylvania State University) reviewed these applications for the workshop.

Multiple models are commonly used in weather forecasting and climate impact assessments. **Multiple models have been used for climate impact assessments for more than two decades**, and the first prominent climate model comparison was published in 1990 (Houghton et al. 1990). An ongoing climate model comparison project includes 20 climate modeling groups from around the world (http://cmip-pcmdi.llnl.gov/cmip5/). Regional comparison projects that feature models with finer spatial resolution have recently been started, such as the North American Climate Change Assessment Program (Mearns et al. 2009). Climate models have steadily improved over the years as a result of improved representation of physical processes, higher resolution, and better computer resources (Reichler and Kim 2008).

A consistent finding of global climate model comparison projects is that **the multi-model mean is often superior to any individual climate model,** and **the spread among multiple models provides a useful estimate of uncertainty** (Reichler and Kim 2008). Studies at the regional scale, such as in the state of Pennsylvania (Shortle et al. 2009, 2013), support this finding. **Multiple models also facilitate hypothesis testing**. For example, multiple climate model simulations support the hypothesis that most of the increase in global-mean temperature over the past 100 years is a result of greenhouse gas increases (Hegerl et al. 2007). **The degree of model consensus is also a useful indicator of how strongly a conclusion can be made** about some aspect of future climate change (Meehl et al. 2007). For example, projections of temperature and precipitation change in the Chesapeake Bay watershed to the end of the 21st century unanimously agree that the watershed will continue to warm. There is less consensus that winter and spring precipitation will increase, and very little agreement regarding summer and fall precipitation change (Najjar et al. 2010). **Without multiple models, it is hard to know how much to trust any one model**.

It is hard to imagine weather and climate prediction without multiple models.

To assess the usefulness of multiple models in weather forecasting, meteorologists at the Pennsylvania State University were interviewed. Their responses unanimously confirmed the power of multiple modeling and reinforced many of the advantages noted in Section 1.5. **It is difficult to envision the fields of climate science and weather forecasting without multiple models.**

2.2 Modular model benefits in air quality analysis

Workshop participants also examined a single model approach that produced many of the benefits of multiple modeling. James Kelly (USEPA Office of Air Quality Planning and Standards) described the Community Multi-scale Air Quality (CMAQ) atmospheric chemistry and transport model and its use in regulatory impact analysis. CMAQ is a modular community model used by the EPA and state governments to inform decisions about air quality standards, regulations, and emission control plans. CMAQ simulates how weather and key chemical and physical processes affect the evolution and fate of pollutant emissions in the atmosphere. CMAQ produces three dimensional grids of the concentrations of ozone, particulate matter, and toxics in the atmosphere, as well as deposition amounts and visibility metrics. CMAQ is a single model, **but the model is modular and hosts multiple representations of key processes.** Configured with different modules and inputs, CMAQ can produce simulations that represent different concepts, algorithms, or data sets, much like the independent multi-model ensembles discussed above.

CMAQ is distributed through a group called the Community Modeling and Analysis System (CMAS). **There is a formal process for community involvement in model development and evaluation.** CMAS provides a forum for comparisons of model results with laboratory and field observations to evaluate if new or updated modules enhance model performance and to determine which representation of a process provides the best representation for a particular application. Through this forum and peer-reviewed literature, the preferred modules for use in model application to inform decision-making are identified. Most applications of CMAQ for decision-making also include a weight-of-evidence analysis to corroborate model findings by considering atmospheric observations, emission data, or additional modeling. This process yields a single model that has the understanding and backing of the community.

The example of CMAQ and CMAS shows that **properly conducted modular community modeling provides many of the same benefits as multiple models and has blurred the line between single, modular, and multiple models**. This single community model approach has broad consensus and works well within its regulatory context, which demands continual improvement, clear results, community buy-in, and quick response.

2.3 Multiple modeling in water quality management

To provide examples more relevant to the water quality management decisions faced by the CBP, three workshop presentations summarized case studies in which multiple models were used to inform policy or regulatory decisions about nutrient loadings from the land to coastal waters. Dr. Dominic DiToro (Department of Civil and Environmental Engineering, University of Delaware) presented a pioneering 1970s multiple model analysis of the effects of phosphorus loading on Lake Erie and other Great Lakes. The work was motivated by massive drops in fish catches in the 1960s and 1970s caused by eutrophication and resulting hypoxia. Five different models relating phosphorus loads to chlorophyll and bottom dissolved oxygen were analyzed to estimate the maximum phosphorus load that would still keep bottom dissolved oxygen above target levels (Bierman et al. 1975, Thomann et al. 1975, Vollenweider 1978, Chapra 1978, Bierman 1980). The analysis was used to set a target phosphorus load reduction that was accepted by Canada and the United States who share jurisdiction over the lake (Vallentyne and Thomas 1978, Phosphorus Management Task Force 1980).

Dr. Victor Bierman (LimnoTech) shared the more recent example of multi-model analysis of nutrient loading to the Gulf of Mexico. The work was motivated by negative impacts on commercial fishing and other coastal resources from hypoxia driven by high nutrient loads. Three load-response models were analyzed to estimate the maximum nitrogen and phosphorus loads that would still keep the area of the hypoxic zone at or below a target maximum of 5000 km^2 (Bierman et al. 1994, Justić et al. 1996, Scavia et al. 2003, 2004). The models together provided critical information that led to setting a goal of reducing the riverine loads of total nitrogen and phosphorus 45% in the 2008 Gulf of Mexico Action Plan (Scavia and Donnelly 2007, Mississippi River/Gulf of Mexico Watershed Nutrient Task Force 2008).

Fish kills in the Neuse River caused by hypoxia attributed to sewage and agricultural runoff motivated a multi-model analysis presented by Dr. Kenneth Reckhow (Cardno ENTRIX and Professor Emeritus at School of the Environment, Duke University). His research team applied three eutrophication models, a 2-dimensional simulation, a 3-dimensional simulation, and a Bayesian probability network model (Bayes-net). The last model provided coarser temporal and spatial resolution than the two simulation models but produced probabilistic predictions of the effects of nitrogen loading on fish and shellfish. The multi-model analysis helped support the commitment to reduce nitrogen loads to the Neuse River by 30% (Stow et al. 2002, 2003, Borsuk et al. 2003). The Bayes-net model was as also used in a participatory modeling effort (see Section 4.4.2) to identify stakeholder concerns and to provide stakeholders and decision makers with a realistic appraisal of the chances of achieving desired outcomes under alternative nutrient management strategies (Borsuk et al. 2004).

Many of the observations about multiple modeling were shared across the three examples, so they are presented in a single list, emphasizing new points beyond the general ones already listed above:

- Multiple models provide different conceptual and operational perspectives.
- Multiple models utilize available data in different ways.
- Multiple models provide multiple lines of evidence.
- Running multiple types of models can be more informative than multiple models of the same type (model diversity can be more valuable than multiplicity).
- Diverse models can range from simple empirical to highly complex.

The three water quality presentations also addressed model uncertainty and the use of models in decision-making:

- Water quality forecasting is challenging, so predicting uncertainty is high and often unknown.
- Adequacy of knowledge depends on scientific uncertainty and attitude toward risk.
- There is almost always enough information to make an informed decision.
- An optimal decision balances uncertainty and risk, but that balance cannot be achieved without quantifying uncertainty.
- The public and the courts need to understand levels of uncertainty and risk and set expectations accordingly.
- Multiple models reduce risk in management decisions.
- Management decisions should be based on weight-of-evidence and collective scientific insights from monitoring, experiments, models, and case studies in other similar systems.
- There is a need to educate the public about the meaning and utility of multiple models.

Finally, all three of these case studies considered the cost of multiple modeling:

- Each study had models that were much less expensive than the most complex model.
- Full cost accounting shows that multiple modeling is inexpensive compared to the cost of measurement programs.

3. Multiple modeling in the Chesapeake Bay system

3.1 Multiple model analyses of the Chesapeake Bay and watershed

Although multiple modeling has not been a formal tool in the CBP modeling program, academic scientists have undertaken some multiple model analyses in the Chesapeake Bay. These have been model comparisons only, so the results have not been formally used in decision-making, but they provide system-specific examples of the possibilities of multiple model analysis for the CBP.

Dr. Marjorie Friedrichs (Virginia Institute of Marine Science) presented an example of a multi-model ensemble analysis of the Chesapeake Bay. This project is part of the Coastal and Ocean Modeling Testbed (Luettich et al. 2013), funded by the NOAA - Integrated Ocean Observing System program (IOOS). This model comparison effort examined the relative performance of six coupled hydrodynamic-dissolved oxygen (DO) models for the Chesapeake Bay, including the model developed and used by the CBP in setting the current Bay TMDL (Cerco et al. 2010). The physical (hydrodynamic) components of the models were similar, but the representations of biology and dissolved oxygen dynamics differed dramatically. The project compared the relative skills of the models in predicting the mean and variability of stratification and DO levels at monitoring stations. Although specific project results were not used to make any regulatory decisions, **this testbed comparison project provided impetus for the CBP to consider multiple modeling, and**

it also provided the foundation for an upcoming shallow water multiple-model effort (USEPA 2013). Major conclusions and recommendations from the IOOS multiple model comparison included:

- Multiple hydrodynamic and DO models for the Chesapeake Bay already exist.
- The current CBP model performed well relative to the other models, and this has increased academic confidence in and support for the CBP model.
- Other models do nearly as well, especially in terms of reproducing dissolved oxygen but not as well in reproducing stratification.
- Very simple constant net respiration rate models reproduce the mean and variability of dissolved oxygen surprisingly well.
- Averaging output from multiple models provided better hindcasts of hypoxic volume than relying on any individual model alone.
- It is critically important to quantify model skill, use open-source community models, and promote collaboration on Chesapeake Bay modeling among different institutions.
- Multiple models could improve the CBP regulatory model.
- The CBP modeling program should use multiple estuarine models.

Friedrichs also summarized the results from the first STAC Multiple Models for Management Workshop (informally called "M3.1"; April 2012), which developed the plan for the shallow water pilot project (Friedrichs et al. 2012). The overall recommendation from the workshop was that a multiple shallow water model pilot project is key to the advancement of the CBP modeling program and should begin as soon as possible. M3.1 workshop participants unanimously agreed that multiple modeling efforts were critical to:

- Help determine whether the regulatory CBP model is as skillful as other models of the Bay.
- Build scientist, management, and stakeholder confidence in the model at a time when confidence in the regulatory model is low.
- Help the CBP heed recommendations in several recent STAC reports and reviews.

In addition, M3.1 workshop participants felt that a prototype multiple modeling project should be conducted specifically in the shallow waters of the Bay because the Modeling Workgroup has recently identified limitations to the existing model in the shallowest, most productive parts of the Bay and have suggested that additional modeling approaches need to be considered in these waters.

In the proposed effort, shallow water hydrodynamic-water quality modelers would be sought for participation in a 1-2 year pilot project. Each modeling team would use a common forcing data set to implement 3-5 year base case runs at specified times and sites and would provide daily distributions of variables relevant for submerged aquatic vegetation (temperature, salinity, dissolved oxygen, light, and nutrients). Each team would also provide results for specified nutrient reduction scenarios. A separate model comparison team would use state-of-the-art metrics to assess the relative skill of the participating simulations, compare the results of the modeled nutrient change scenarios, and analyze causes and impacts of differences among the models. The outcomes of the pilot project would include:

- Identify a new model for the shallow waters and/or suggested improvements to the existing model.
- Provide confidence estimates for CBP shallow water simulations.
- Demonstrate the utility of using multiple models as recommended by STAC and by the National Resource Council review of the CBP (NRC 2011).

The CBP watershed model has also been involved in some model comparisons. One recent study compared the skill of ten implementations of six watershed models at predicting observed water, nitrogen, and phosphorus losses from the Patuxent River watershed, one of the nine major tributaries to the Bay (Boomer et al. 2013). The model set included Phase 4 and 5 versions of the CBP watershed model, three implementations of the Chesapeake Bay SPARROW model, two empirical models developed by the Smithsonian Environmental Research Center, a simple loading coefficient model developed by the state of Maryland, and one spatially distributed watershed model. The major conclusions of the study were:

- There was no "best model"- no single model consistently outperformed the others across the modeled endpoints for which predictions were compared to observations.
- The average prediction across the multi-model ensemble was consistently more skillful than any single model prediction.
- The range of predictions among models helped to quantify model uncertainty.
- Watershed models were generally skillful at predicting water discharge, intermediate at predicting nitrogen loads, and poor at predicting phosphorus loads.
- The process of model comparison identified and corrected errors in every model implementation.
- None of the other watershed models could replace the CBP models in decision-making and regulation. The CBP model has unique capabilities that reflect its role in regional planning, decision-making, and environmental regulation.

The academic model comparisons summarized above highlight an important reality: **multiple models of the Chesapeake Bay watershed and estuary already exist and should be exploited to better inform management and regulation**. When alternate models are not compared and integrated into Bay Program analyses, they can be exploited in efforts to slow or stop environmental regulation. There is a recent example from the Chesapeake Bay watershed. The U.S. Department of Agriculture (USDA) developed a model system for the Chesapeake Bay watershed by integrating three USDA models and then applied the model system to estimate the nitrogen and phosphorus reductions achieved by agricultural conservation practices implemented throughout the watershed (USDA- NRCS 2011). A group representing the agricultural industry hired a consulting firm to compare the USDA model to the CBP watershed model. The consulting report identified differences between the two models and called for suspending the TMDL until those differences could be resolved (LimnoTech 2010). The report was widely cited by opponents of the TMDL in the popular press and in congressional testimony. Ultimately, independent reviews by STAC and by another watershed modeling experts concluded that the consulting report contained many errors and misinterpretations, and that the USDA model and CBP models were in fairly close agreement (Committee for the ANPC/LimnoTech Review 2011, Band 2011).

An important part of this story is the missed opportunity that it represents. The USDA is a Federal partner in the CBP and its models should have been used to inform CBP decisions. A proactive multiple modeling effort by the CBP and USDA to compare the two models could have reported their close agreement and cited that as support for the TMDL, thereby realizing some of the benefits of multiple modeling described above.

Unfortunately, a second opportunity for USDA-CBP collaboration has recently been missed. Despite the strong recommendations from STAC for proactive model comparison (Committee for the ANPC/LimnoTech Review 2011) and a formal agreement between EPA and USDA to collaborate on modeling the Chesapeake Bay watershed (Ganeson 2011), an update of the earlier USDA analysis (USDA-NRCS 2011) was recently released (USDA-NRCS 2013) with no evidence of proactive efforts to collaborate on comparing results with those from CBP modeling.

3.2 Chesapeake Bay Program modeling and perspective on multiple modeling

Mr. Gary Shenk (CBP Integrated Analysis Coordinator and lead developer of the CBP watershed model) provided a brief review of how the CBP uses its current modeling suite, what opportunities the CBP sees for multiple modeling, and how it views the advantages and disadvantages of multi-model approaches. The existing CBP modeling suite is used to set basin-wide maximum loads of nutrient and sediment pollutants, identify where watershed load reductions would yield the most benefit for the Bay, allocate the "pollution diet" of needed load reductions to states and major river basins, and help track progress in implementing load reduction practices (Linker et al. 2013, Shenk and Linker 2013). Shenk reported that **CBP managers and modelers are convinced about the scientific value of multiple modeling, but see the additional cost as the biggest obstacle to adoption**.

Shenk reported three current or planned activities of the CBP modeling approach could be considered applications of multiple modeling:

- The CBP supports the shallow water pilot multiple modeling project (see Section 3.1). Since the workshop, the CBP has issued a Request for Proposals to implement the pilot project (USEPA 2013).
- The current agricultural nutrient cycling module of the watershed model could be replaced by simpler relationships in future model versions. Those simpler relationships would be

formed from analysis of multiple models and could yield algorithms that are robust, understandable, and scalable.
- Current Best Management Practice (BMP) expert panels incorporate multiple modeling into their estimates of BMP efficiencies.

In response to workshop comments on the importance of uncertainty in decision-making, Shenk reminded the group that the Chesapeake Bay TMDL accounts for scientific uncertainty in estimating maximum loads with an implicit margin of safety (MOS). In this approach, model assumptions are kept sufficiently conservative to provide a high probability that water quality standards will be achieved despite the uncertainties.

4. Objections to multiple modeling

Workshop presentations and discussion explicitly considered four primary objections to multiple modeling. The general sense of those discussions is summarized below.

4.1 Costs more

One objection to the use of multiple models is the additional cost of running and analyzing several models. Costs for multiple models will be more than a single model, and the costs might be prohibitive if all models employed were as complex and applied over as large a region as the current CBP models. However, the case studies presented in the workshop all emphasized that **full cost accounting shows multiple modeling is inexpensive compared to the cost of monitoring**. For example, in the Gulf of Mexico study, $20-$40 million were spent on monitoring and research, and the most expensive model cost 100 times less than that. The other two models were even less costly (V. Bierman, Section 2.3). More importantly, **the cost of modeling is trivial compared to the cost of implementation or the cost of poor decisions**. Errors from a single model in either sources of pollutants or most effective practices for load reduction could result in a huge use of funds for minimal benefit in contaminant reduction (a poor decision). Additional investments in modeling to acknowledge, quantify, and reduce uncertainty can produce savings in implementation that far outweigh the additional modeling costs.

Models are cheap, data are expensive, and implementation is really expensive.

The CBP and the scientific community both need to counter the notion that all of the available funding should be spent on implementation and that additional research or modeling is not needed. These misguided attitudes are fostered when model uncertainty and areas of ignorance that demand further research are not acknowledged (Section 4.2.1) and proactively targeted. Insufficient investment in modeling and monitoring breaks the adaptive management cycle (Section 4.2.2).

Without adequately measuring outcomes and developing the best synthesis of new knowledge from past actions, it is difficult to learn from management successes and failures.

4.2 Highlights uncertainty

4.2.1 Quantifying uncertainty

Another argument against multiple modeling is that it highlights uncertainty by offering different predictions. In fact, quantifying uncertainty is a necessary part of a complete scientific description of knowledge about a process or prediction. **Quantifying uncertainty is critical to informed decision-making and to rational decisions that balance risk and uncertainty** (K. Reckhow Section 2.3, and Reckhow 2003). The current CBP modeling suite would have more scientific credibility if it could provide estimates of uncertainty (Band et al. 2005, 2008, Committee for the ANPC/LimnoTech Review 2011). However, some stakeholders and decision makers would prefer not to acknowledge or discuss uncertainty, and some believe that acknowledging uncertainty only provides ammunition to opponents of environmental management actions. Nonetheless, experts in the workshop argued that the best practices of both environmental science and decision science demand that we not ignore uncertainty, but instead work to quantify it and to educate decision makers, courts, and the public about realistic and unreasonable expectations for models and about dealing rationally with the inevitable uncertainty in model predictions.

Multiple models can help quantify model uncertainty (Sections 1-3), and they can also help us better understand the uncertainty associated with the effects of management decisions. For example, one estuarine model might predict that reducing nitrate inputs to a target load will increase DO by 10%. If two other models predict increases of 9% and 13%, then we have increased confidence that DO will in fact respond as desired, and we have a good sense that the uncertainty in the response is about 1-3% of DO.

4.2.2 Adaptive management

The proper response to uncertainty is adaptive management (Boesch 2002, Stankey et al. 2005, Williams et al. 2007). Adaptive management arose from recognizing that knowledge is never complete and uncertainty is always inherent in natural systems; therefore, **management actions should *not* be delayed by the impossible goals of complete understanding and eliminating uncertainty**. Adaptive management methods help ensure that programs progress while better information is collected. Precise prescriptions for adaptive management differ, but all involve a basic four-step cycle of synthesizing knowledge, developing plans, implementing those plans, measuring the outcome, and then repeating the cycle. The applicability of adaptive management to Chesapeake Bay restoration was explicitly considered and strongly recommended by the National Research Council (NRC) review (NRC 2011). With adaptive management, knowledge of the effects of management actions on water quality and the modeling of those effects will evolve in parallel with regulations and management actions. As discussed above, using multiple models helps reinforce confidence in some model predictions and helps identify where additional monitoring or research is needed to reduce uncertainty and increase confidence. Multiple modeling also fosters improved understanding, a key requirement of adaptive management. With these advantages, **using multiple models can improve the outcomes of adaptive management more efficiently over time than relying on a single model** (Williams et al. 2007).

4.3 May create legal issues

Another objection to using multiple models involves the possibility that multiple modeling might create legal problems by provoking or supporting legal challenges to decisions and regulations. It has been suggested that the use of multiple models might even be incompatible with the provisions of the Clean Water Act or with procedures for developing and implementing TMDLs. A panel of legal experts addressed these concerns at the workshop and sought to answer this basic question: Should multiple models be used to enhance the credibility and defensibility of regulatory decisions made to implement the TMDL program for the Chesapeake Bay? If so, how? If not, why not?

Two presenters (Ross Pifer, Penn State Law, and Chris Day, EPA) reviewed a then-ongoing legal case in which the American Farm Bureau Federation (AFBF) and other plaintiffs sought to prevent EPA from implementing and enforcing the Chesapeake Bay TMDL. In that lawsuit, AFBF claimed that EPA violated the Administrative Procedures Act (APA) by rendering an arbitrary and capricious decision based on model results that were beyond the predictive capacity of the models used. The plaintiffs also argued that EPA "fed its models flawed data," by, for example, using tillage data that differed from a USDA Natural Resources Conservation Service report and by assuming that manure on animal feeding operations flows directly into watercourses. However, Pifer and Day noted that much of the legal case was focused on issues of EPA authority and procedure, rather than on the models or even the science in general. On September 13, 2013 the legal case was decided, with the court ruling upholding both the process and substance of EPA's actions in setting the TMDL. The AFBF is now appealing that decision.

Wendy Wagner (School of Law, University of Texas) and Pasky Pascual (USEPA) considered the more general challenges that the law presents for an agency's use of computational models and how modeling and multiple models relate to the notion of "weight of scientific evidence" in a regulatory context. They concluded that **there is no legal reason to reject the use of multiple models in regulatory framework**. **In particular, there is no legal bar *per se* to using multiple models in setting a total maximum daily load for pollutant levels in the Chesapeake Bay.**

The use of models (either single or multiple) in environmental regulation is governed by the applicable statues in accordance with the Administrative Procedures Act (APA) of 1946. The APA is intended to improve governance by ensuring that regulatory agencies establish procedures for rulemaking, inform the public of rules and procedures, and allow the public to participate in rulemaking. Importantly, the APA authorizes courts to review whether regulatory agencies are complying with their statutory mandates. Under the Clean Water Act, there has been a string of court cases challenging the science underlying TMDL models, including the 2011 AFBF lawsuit challenging the Final Chesapeake Bay TMDL (see above). When reviewing such challenges, courts must determine whether a regulatory agency's decision is "arbitrary and capricious, an abuse of discretion or not otherwise in accordance with law." In *Motor Vehicle Manufacturers Ass'n of the United States v. State Farm Mutual Automobile Insurance Co.,* the U.S. Supreme Court ruled that courts can set aside a decision only if, after conducting a "searching and meaningful" review of the administrative record, they conclude that a governmental agency relied on factors that Congress did not intend, failed to consider an important aspect of the problem, or offered an explanation that ran counter to the evidence or was so implausible that it could not be ascribed to agency expertise or to a difference in view.

In reviews of EPA science, courts have consistently deferred to the Agency's scientific determinations, asserting that it is not the court's role to substitute its judgment for that of EPA, particularly when considering technical and scientific matters that fall within the Agency's expertise.

In addition to supporting the legality of multiple modeling, the legal panel considered the more strategic question of whether the use of multiple models would enhance or diminish the defensibility of regulatory decisions. A consensus emerged that **properly framed multiple models can be a legal asset, not a liability** because there are strategic benefits of multiple modeling in drafting regulations to protect water quality. Multiple modeling helps dispel the notion that there is only one, "true" model of a system. Every model is a simplified simulation of reality, replete with assumptions and uncertainties. An opponent of a regulation can always counter-propose an alternative model for every model upon which a regulatory agency relies.

Using multiple modeling would help the courts clearly see that an agency considered alternative models and evaluated their corresponding strengths and weaknesses. Secondly, **multiple modeling can increase the weight of scientific evidence.** A single model cannot lay claim to all the best datasets, the best algorithms, or the best hypotheses available. Multiple modeling facilitates the explanations of assumptions, data, and model skill, and it enhances the synthesis of various streams of data and multiple hypotheses.

Multiple models can offer more support for decisions than a single model.

The performance of a single model is often context-specific, excelling under certain conditions. Multiple modeling can integrate the results of models under a variety of possible scenarios, thereby enhancing the robustness of results and increasing the weight of scientific evidence.

In summary, courts have a long history of evaluating the regulatory use of computational models. Over this arc of history, the lesson is clear: plaintiffs are most successful in challenging regulations when they raise objections to an agency's use of a model and the agency is unresponsive to the challenge. Using multiple modeling may help a regulatory agency demonstrate that it has considered the potential weaknesses or unrealistic assumptions underlying any single model. **The use of multiple models in a regulatory framework is both possible and appropriate.**

4.4 May confuse stakeholders

Another concern about multiple modeling is its potential to further confuse the public and decision makers. **Understanding the strengths and weaknesses of quantitative models is generally weak among non-scientists, and this lack of understanding undermines confidence in models and the decisions based upon them.** Having many models instead of one may only make the situation worse. During the workshop, a panel of social scientists addressed these concerns and their broader social science context. The experts included: Christine Keiner (Department of Science, Technology and Society at Rochester Institute of Technology) and Michael Paolisso and Jeremy Trombley (Department of Anthropology, University of Maryland). The following text summarizes some of the issues they presented.

4.4.1 Misunderstanding and mistrust of quantitative models

The quantitative models used by environmental scientists are not well understood outside of a small circle of experts. Moreover, the results of quantitative environmental modeling often conflict with individual, group-cognitive, and social models. Stakeholders in the Bay watershed use their own knowledge and experience to interpret modeling and model results. Mistrust is one result, especially when policy or program actions based on model results are perceived to affect livelihoods and lifestyles unnecessarily. For example, some stakeholders believe you cannot quantify nature so they do not trust quantitative models.

Mistrust of quantitative environmental models can be viewed as a type of friction, where friction is resistance to interconnections and to overcoming the challenges inherent in integrating individuals with new technologies, practices, and data. Such friction is a normal part of change and improvement in the status of knowledge and our actions. The work of the Chesapeake Bay modeling community is a long-term, continuous effort that naturally generates friction because it produces new knowledge, involves multiple groups, and affects individuals through policies and programs.

Initially, implementing multiple modeling would be expected to increase friction. For example, policymakers and stakeholders will probably not want to accept another way of modeling because it would disrupt and change current known practices and procedures. Even though scientists and legal experts say that multiple models produce more defendable scientific findings, others may resist because of concerns about the resource costs and increased complexities in deriving management options. Multiple models may in fact provide very useful opportunities for Bay environmental stakeholder groups to improve knowledge and acceptance of what science and modeling actually does. For example, multiple modeling might reduce the false expectations among the public that science produces certainty (Section 4.2.1), and this more accurate view should help provide a platform for adaptive management (Section 4.2.2).

4.4.2 Participatory modeling

In participatory modeling, modelers, scientists, stakeholders, and decision makers work together to build and analyze models. Expanding stakeholder involvement in the modeling process is one way to increase public trust in models and model results and to decrease the intensity and number of challenges to model results. Participatory modeling can also be a tool of conflict resolution, where all participants, including scientists and modelers, are able to discuss issues of validity, reliability, uncertainty, and translation from modeling to policy implementation. Participatory modeling can involve technical education and non-technical participation. An important gain from participatory modeling is transparency. Participatory modeling would help to open the "black box" of quantitative modeling, which should increase trust and understanding of what models in general and multiple models in particular can and cannot do. Exploration of the scientific, policy, and public significance of multiple models can produce a continuum of participatory involvements, from passive information sharing and discussion to active engagement in developing model parameters and collecting data. Building a participatory framework into multiple modeling efforts would also allow cognitive and social models to be recognized and tapped for knowledge and support. Finally, integrating participatory modeling into multiple models can be an effective way to engage Bay citizens into science and management efforts for the Chesapeake Bay; however, some workshop participants were concerned about involving non-technical people in the more technical phases of model formulation, parameterization, programming, and analysis. Representatives from the CBP also reminded participants that their current and past efforts have been highly participatory, pointing out the huge number of committees, subcommittees, and other stakeholder groups that regularly have opportunities to comment on modeling results and future priorities.

4.4.3 Education and outreach

There was broad consensus in the workshop about the need for more education and outreach to help the public and decision makers better understand modeling and multiple modeling. Many people cannot make informed decisions about models because models are mysterious to them. Ignorance about modeling fosters distrust of current modeling and limits interest in possible improvements, such as multiple modeling. Modelers and managers have not successfully conveyed the strengths and limitations of models and the value of modeling. **Further efforts are needed to better inform the public and decision makers about reasonable expectations from models and about invalid expectations** (for example, problems arise when models are treated as "answer machines"). It is particularly important to inform stakeholders about the uncertainty of model predictions. **The need to convince decision makers, jurisdictions, and the public that they want to know model uncertainty is an important obstacle to multiple modeling.** However, workshop experts were clear that quantifying uncertainty is essential for generating sound environmental policy (see Section 4.2.1).

5. Findings

The steering committee has distilled the presentations and discussion in the workshop (above) into the following Findings about multiple modeling in a regulatory context.

1. **Using multiple models offers many documented advantages over analyzing one model of an environmental system.**

2. **There are different ways to implement multiple models (multi-model ensembles, using other models to assess a decision model, modular community modeling, and model comparisons in pilot studies or testbed areas). The common principle is that findings are stronger when multiple lines of evidence, multiple data sets, or multiple algorithms agree.**

3. **Analyzing multiple models increases knowledge and understanding of underlying processes.**

4. **Average predictions from a set of models typically perform better than those from any single model.**

5. **Information from multiple models can help quantify model uncertainty, which is critical to sound science and rational decision-making.**

6. **Modeling is inexpensive compared to the costs of monitoring, implementation, and sub-optimal decisions.**

7. **Properly framed multiple models can be a legal asset rather than a liability.**

8. **Managers and the public are poorly informed about modeling, model uncertainty, multiple models, and the value of investments in modeling.**

9. **Multiple modeling can expand opportunities for additional technical experts and non-technical stakeholders to participate in modeling, fostering greater understanding and acceptance of models and the decisions based upon them.**

10. **Multiple models of the Chesapeake Bay and its watershed already exist, and they could be integrated into CBP modeling to improve knowledge and decision-making.**

6. Recommendations

After synthesizing the workshop presentations and discussion, the steering committee offers the following Recommendations for applying multiple modeling within the Chesapeake Bay Program.

Recommendation 1. The Chesapeake Bay Program should implement a multiple modeling strategy for each major decision-making model of the Bay (airshed, land use, watershed, and estuary) and analyze the output to quantify skill, advance knowledge, and inform adaptive management.

The workshop considered many possible multiple model applications, but did not try to reach consensus on a shorter menu of recommended applications. Instead, we list the ideas presented, and we suggest that the CBP work with the scientific and management communities to identify, develop, and implement the most promising multiple modeling options.

In planning and implementing multiple modeling activities, the CBP should seek initial and periodic review from STAC. Some workshop participants were concerned that some CBP suggestions for future multiple modeling (such as the informal review of multiple models in expert judgments, see Section 3.2) were not consistent with scientists' definition of multiple modeling. STAC review could help ensure that proposed activities are consistent with the best scientific understanding and practices of multiple modeling.

The Shallow Water Pilot project received the strongest workshop support among the possible multiple modeling activities considered. Support for this activity was strong because of ongoing efforts by the CBP to address problems with the current treatment of shallow water, interest by the CBP modeling team in the pilot project, consistent strong recommendations from STAC to implement the pilot project (Friedrichs et al. 2011, Pyke 2011a,b, 2012), and an existing plan for the project (Friedrichs et al. 2012). After the workshop, the CBP released a request for proposals

(RFP), which was issued in November 2013 (USEPA 2013). The RFP seeks applications from interested modelers to contribute models and to conduct a comparison among models.

Other multiple modeling possibilities considered in the workshop are listed below by sector.

Watershed

The existing watershed model could be assessed in more formal comparisons with other watershed models (e.g., Boomer et al. 2013). STAC already recommended more formal comparisons of the CBP watershed model with the USDA Conservation Effects Assessment Project (CEAP) modeling effort (USDA-NRCS 2011, Committee for the ANPC/LimnoTech Review 2011), especially because the USDA model has been cited in efforts to discredit the CBP model and delay TMDL implementation (LimnoTech 2010). Other models of the entire watershed (e. g., SPARROW, Ator et al. 2011; SWAT, Meng et al. 2010; and other models, Weller and Baker in press) could also be included. It could be particularly informative to compare model predictions of the fluxes and concentrations of water, sediment, and nutrients at major river monitoring stations where data are available to assess model skill.

The watershed model could be exercised with other models in studies of particular watersheds or particular BMPs. STAC has previously recommended simulating smaller, data-rich watersheds to complement or to improve the larger modeling system for processes or places where it is not working well (Band et al. 2005, 2008). This approach could focus on research watersheds, small watersheds, or a major river basin.

The CBP watershed model could be developed and operated in a more modular way (as in the CMAQ-CMAS example, Section 2.2). This would require developing better mechanisms to engage academics and other members of the modeling community in working on modules. It would also require developing institutions and procedures for evaluating skill and selecting best options (again as in the CMAS example). STAC has recommended that the USDA Agricultural Policy Environmental Extender (APEX) model implemented for the CEAP project (USDA-NRCS 2011) could be more formally compared with the algorithms representing croplands and agricultural management practices in the CBP watershed model (Committee for the ANPC/LimnoTech Review 2011).

Estuary

Besides the shallow water project (above), multiple modeling could also build on and extend past comparisons of the many existing models for the entire estuary (Bever et al. 2013). Another opportunity would be to develop a Bayes-net model for the entire Chesapeake Bay (or for one of its major tributaries, such as the Potomac). The Bayes-net approach has been applied to model nitrogen pollution in North Carolina’s Neuse estuary (see Section 2.3). Reckhow suggests that the modeling for a Chesapeake effort could be inexpensive, possibly as little as the few years of support for a postdoctoral scholar. The Bayes-net model could be compared to the CBP model and other existing models (Bever et al. 2013). A particular advantage of the Bayes-net approach is its ability to provide uncertainty estimates for predictions. A Chesapeake Bayes-net model could provide initial uncertainty estimates for some of the important quantities predicted by the CBP models, thus filling an important gap (see Recommendation 2). As in the Neuse experience, the model could also be a vehicle for stakeholder participation (Borsuk et al. 2004).

If multiple modeling is acknowledged to provide the best science and we do not use multiple modeling, then we cannot claim to be using the best science.

Implementing the recommendation to incorporate some form of multiple modeling for every decision model will start the CBP down the path to realizing the benefits of multiple modeling (see Findings). It would also satisfy repeated recommendations from STAC to incorporate multiple modeling strategies (Band et al. 2008, Committee for the ANPC/LimnoTech Review 2011, Friedrichs et al. 2011, 2012, Pyke 2011a,b, 2012). Once multiple modeling is the standard operating procedure for the CBP, the routine comparison of output from several other models with the EPA regulatory models will help determine whether the regulatory models are as skillful as other models; enable effective adaptive management and accountability; and build scientist, management, and stakeholder confidence in the models and the decisions based upon them. Multiple modeling is essential to support the claim that CBP is exploiting the best possible science.

Chesapeake Bay Modeling Laboratory

Expanding multiple modeling is related to recent interest in creating a Chesapeake Bay modeling laboratory (CBML). The committee that reviewed the CBP for the National Research Council of the National Academy of Science first recommended establishing such a laboratory (NRC 2011). The proposed advantages of the CBML included many issues discussed in this report, such as: evaluating model uncertainty, improving predictive skill, improving model credibility, and incorporating multiple-modeling approaches (NRC 2011). Recently, a CBP-implemented committee (Modeling Laboratory Action Team) released a report that presents options for creating a CBML (Bennett et al. 2014). Although the CBML was not explicitly discussed in our workshop, the steering committee notes that establishing a CBML would provide funding, personnel, and a collaborative community environment that could help support the expansion of multiple modeling recommended here.

Caveat: The steering committee emphasizes that recommending greater use of multiple models in the CBP does not undermine the current application of the existing CBP models or provide a rationale for delaying or halting TMDL implementation.

Recommendation 2. The Chesapeake Bay Program should exercise the multiple model systems developed under Recommendation 1 to quantify model uncertainty and confidence in key predictions used in decision-making.

We should not hide from model uncertainty. . .

…instead, we must acknowledge it, quantify it, and use the information to make better decisions.

The inability to estimate uncertainty came up repeatedly during the workshop as a limitation of the current CBP modeling suite in filling its roles as a synthesis of knowledge and as a decision tool. The capability to help estimate uncertainty was repeatedly mentioned as a key advantage of multiple modeling. Balancing risk and uncertainty is critical to good decisions (Section 4.2.1), and STAC has repeatedly recommended that the CBP develop uncertainty estimates for its models (Band et al. 2008, Committee for the ANPC/LimnoTech Review 2011, Friedrichs et al. 2011, 2012). However, formal uncertainty analysis of very complex simulation models implemented over a large area remains a challenging scientific and computational problem. Multiple modeling provides an alternate way to quantify uncertainty. For TMDL purposes, quantifying uncertainty is more rigorous, informative, and cost-effective than an arbitrary margin of safety (MOS) as in the current CBP calculations (Reckhow 2003).

Recommendation 3. The Chesapeake Bay Program should estimate and better communicate the appropriate levels of spending on monitoring, modeling, and research relative to the costs of implementation and the cost of sub-optimal decision-making.

The cost of restoring the Bay is far greater than needed investments in modeling, monitoring, and research.

Without funding, multiple models will not benefit the Chesapeake Bay restoration effort. The CBP acknowledges the scientific advantages of multiple modeling, but considers the additional cost to be the biggest obstacle to implementing multiple modeling. However, small amounts of funding could support substantial progress (Friedrichs et al. 2012), and the second or third model in a multiple model set is typically much less costly than the first (DiToro, Bierman, and Reckhow; Section 2.3). Funding for more multiple

Suppose multiple models and adaptive management could provide even modest (2 to 5%) reductions in the Blue Ribbon panel's restoration cost estimate of $28 billion. How much would it be worth to have information that could save between $560 million and $1.4 billion in initial costs plus between $54 million and $135 million in annual maintenance costs thereafter?

modeling (and modeling in general) is embedded in the larger context of relative investments in new research and modeling, monitoring, and implementation. The current CBP modeling budget is approximately $2.5 million annually (Bennett et al. 2014). The monitoring expenditure from governments and other partners is roughly $10-$12 million annually (Peter Tango, CBP Monitoring Coordinator). The ultimate total cost of restoring the Bay is difficult to estimate, but has been roughly estimated as $19 billion over eight years (Chesapeake Bay Commission 2003) or $28 billion initially followed by $2.7 billion annually thereafter for operation and maintenance (Chesapeake Bay Watershed Blue Ribbon Finance Panel 2004). Both estimates are enormous compared to the cost of modeling. Additional investments in modeling and monitoring can accelerate the adaptive management cycle, and those investments are trivial relative to the cost of implementation. More importantly, additional investments in modeling to acknowledge, quantify, and reduce uncertainty can produce savings in implementation that far outweigh the additional modeling costs. A more formal analysis of the costs and benefits of modeling (and monitoring) relative to the cost of implementation will help the CBP to more effectively make the case for the value of information and the cost of ignorance.

Recommendation 4. The Chesapeake Bay Program should implement ways to better communicate modeling, uncertainty, and multiple model results to partners, decision makers, and the public.

Significant, on-going outreach is needed to explain modeling and its value if stakeholders are expected to provide funding to support modeling, to contribute effectively to developing models, and to have confidence in the model and the results. That outreach could be implemented through current outreach and education programs and through participatory modeling (Sections 2.3 and 4.4.1, and Borsuk et al. 2004). Outreach is needed to educate stakeholders about:

- The development and structure of the models used to quantify pollutant loads to the Bay and to assess the water quality in the Bay.
- The critical assumptions implicit in the models.
- The strengths and limitations of the models.
- The utility and risks of using the models as decision/management tools.
- The need to quantify uncertainties associated with the models and the modeling results.
- The need to account for those uncertainties in decision-making.
- The advantages of having multiple models contributing to an overall assessment and understanding of the Chesapeake Bay ecosystem.
- The fact that knowledge is always incomplete, so targets and recommendations may change as understanding improves.
- The value of adaptive management as a path forward in the face of incomplete knowledge and uncertainty.

An analogy

Sometimes a scenario from everyday life can help to illuminate a complex technical issue. Here is a scenario to help put the additional cost of multiple modeling in perspective.

You are undertaking a long journey that will cost tens of thousands of dollars. If you go off course or you arrive late, you will waste thousands of dollars. Selecting the best route is difficult, but you have a map that you bought for $10. It's pretty good, but you know it has some errors. A second map that corrects some of those errors would cost $2, and a third would cost $1. Should you obtain these additional maps and consult them on your journey? How does the cost of these extra maps compare to the thousands of dollars a mistake could cost?

Glossary

decision model -- in this report, this term refers to a model that guides decision makers in setting regulatory limits, allocating responsibility for meeting those limits, or selecting management actions to meet environmental goals.

management model -- a tool used to organize information and make decisions about environmental management issues, such as reducing water pollution or air pollution.

modular model -- a model that separates a complex simulation into components (modules) that each represents a specific process or set of processes. Each module can be replaced with another representation of its particular process(es) without reprogramming the rest of the simulation.

multiple modeling -- the analysis of a set of models that make some predictions in common.

model comparison -- in this report, the term refers to a formal, quantitative comparison of predictions or outputs among a set of models. This activity is most informative when models are compared to observations to assess model skill.

multi-model ensemble -- a set of models that make the same predictions and are analyzed together to examine variability among the predictions of the different models.

participatory modeling -- in this activity, modelers, scientists, stakeholders, and decision makers work together to build and analyze models.

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AGENDA

Multiple Models for Management in the Chesapeake Bay (M3.2)

Scientific and Technical Advisory Committee
Date: February 25-26, 2013
Workshop Agenda
Location: Sheraton Annapolis Hotel
http://www.chesapeake.org/stac/agendas/222_FINAL%20M3.2%20Workshop%20Agenda.pdf

(Links to on-line copies of the workshop presentations and are included below)

Day 1

Introductory Session

Overview of multiple modeling approaches; past and future multiple modeling efforts in the Chesapeake

8:30 am Welcome and Introduction - Don Weller (SERC)

- Possible approaches to multiple modeling
- Pros and cons of multiple modeling
- Genesis of this workshop
- Workshop plan

Abstract: http://www.chesapeake.org/stac/presentations/222_Weller%20Abstract.pdf
Presentation: http://www.chesapeake.org/stac/presentations/222_WellerM3.2v05a.pdf

9:00 am Multiple Model Comparisons in the Chesapeake Bay: Hydrodynamics and Dissolved Oxygen - Marjy Friedrichs (VIMS)

- U.S. IOOS Estuarine Hypoxia Testbed results
- Proposed CBP Multiple Shallow Water Model Pilot Project

Abstract: http://www.chesapeake.org/stac/presentations/222_Friedrichs%20Abstract.pdf
Presentation: http://www.chesapeake.org/stac/presentations/222_M3.2_Friedrichs_Final_Take2.pdf

9:30 am Modeling and Multiple Modeling in the CBP - Gary Shenk (EPA-CBPO)

- Describe the role of models in developing the TMDL
- Describe current ideas of the CBP modeling team for future modeling and multiple modeling activities
- Introduce CBP view of advantages/disadvantages of multiple models

Abstract: http://www.chesapeake.org/stac/presentations/222_Shenk%20Abstract.pdf
Presentation:
http://www.chesapeake.org/stac/presentations/222_2013_02_25%20M3%20in%20the%20Chesapeake%20Bay%20Program%20gshenk.pdf

Case Studies of Multiple Models in Management

Examples of past successes and failures in applying multiple models in decision-making and regulation, especially in water and water quality management.

10:00 am Single-Model Case Study: Air Quality Modeling for PM2.5 NAAQS Regulatory Impact Analysis - Jim Kelly (EPA)

The presentation will discuss a regulatory air quality modeling case study in which a single-model approach was used. The case study is the Regulatory Impact Analysis (RIA) for the recent revisions to the PM2.5 National Ambient Air Quality Standards. Key considerations for using single-model approaches in regulatory applications will be discussed. The potential use of multiple-models in typical regulatory air quality modeling applications will also be considered.

Abstract: http://www.chesapeake.org/stac/presentations/222_Kelly%20Abstract.pdf
Presentation: http://www.chesapeake.org/stac/presentations/222_JKelly_MultipleModels_22Feb13.pdf

10:30 am Break

10:45 am **Multiple models used in weather forecasting and climate impact assessments - Ray Najjar (PSU)**

This presentation will discuss how the assessment of uncertainty in weather and climate forecasts is greatly aided by the use of multiple models

Abstract: http://www.chesapeake.org/stac/presentations/222_Najjar%20Abstract.pdf

Presentation:
http://www.chesapeake.org/stac/presentations/222_multiple%20models%20in%20climate%20and%20weather.pdf

11:15 am **Great Lakes Phosphorus - Dom DiToro (University of Delaware)**

Presentation:
http://www.chesapeake.org/stac/presentations/222_DiToro_Presentation_Multiple%20Models_STAC_v1.pdf

11:45 am **Hypoxia in the Gulf of Mexico: Benefits and Challenges of Using Multiple Models to Inform Management Decisions - Vic Bierman (LimnoTech)**

This presentation will describe three different modeling frameworks for relating delivered nutrient loads from the Mississippi River Basin to the Gulf of Mexico, and their impacts on seasonal hypoxia. Results from these models were used to inform management decisions on reductions in nutrient loads that would be necessary to meet the goals in the 2001 and 2008 Action Plans for mitigating the occurrence of hypoxia. The presentation will focus on how these models were used in the process, and both the benefits realized and the challenges encountered.

Presentation: http://www.chesapeake.org/stac/presentations/222_Bierman_M3.2_02252013.pdf

12:15 pm **Lunch (Provided)**

1:00 pm **Multiple Water Quality Models to Inform TMDL Making in the Neuse River Estuary - Ken Reckhow (Cardno ENTRIX)**

Presentation: http://www.chesapeake.org/stac/presentations/222_Multiple%20Models%20-%20Neuse%20Estuary%20Experience%20-%20Ken%20R.pdf

This presentation will discuss how multiple models were used in the Neuse River Estuary to inform TMDL decision-making and what CBP can learn from the experience.

1:30 pm **Directed Whole-Group Discussion of Case Studies & Introductory Talks**

Facilitators: Don Weller (SERC) and Brian Benham (VT)

2:30 pm **Break (Provided)**

Social Science Issues

How might the use of multiple models affect the perception of models and their results by decision makers and the public?

2:45 pm **Producing Policy-Relevant Scientific Knowledge via (Multiple) Environmental Models: Challenges and Opportunities - Christine Keiner (STS, Rochester Institute of Technology)**

Abstract: http://www.chesapeake.org/stac/presentations/222_Keiner%20Abstract.pdf

Presentation: http://www.chesapeake.org/stac/presentations/222_Keiner%20STAC%20slides%20030713%20final.pdf

3:15 pm **Multiple Modeling in Human Space- Michael Paolisso (UMD)**

Abstract: http://www.chesapeake.org/stac/presentations/222_Paolisso%20Abstract.pdf

Presentation: http://www.chesapeake.org/stac/presentations/222_Multiple%20Models%20in%20Human%20Space%20-%20Paolisso.pdf

3:45 pm Multiple Modeling Practices: Making a Difference for the Chesapeake Bay- Jeremy Trombley (UMD)
Abstract: http://www.chesapeake.org/stac/presentations/222_Trombley%20Abstract.pdf
Presentation:
http://www.chesapeake.org/stac/presentations/222_JTrombley%20prezi%20M3.2%20workshop%20(2).pdf

4:15 pm Directed Whole-Group Discussion of Social Science Issues
Facilitators: Michael Paolisso (UMD) and Lucinda Power (EPA-CBPO)

5:15 pm Recess

Day 2

8:30 am Summary/Re-Cap of Day 1 Don Weller (SERC)
Presentation: http://www.chesapeake.org/stac/presentations/222_M32blogV2b.pdf

Legal Issues

Should multiple models be used to enhance the credibility and defensibility of regulatory decisions made to implement the TMDL program for the Chesapeake Bay? If so, how? If not, why not?

8:45 am Introduction - Pasky Pascual (EPA)

9:00 am Legal Challenge to EPA's Promulgation of Final Chesapeake Bay TMDL - Ross Pifer (Penn State Law)
Abstract: http://www.chesapeake.org/stac/presentations/222_Pifer%20Abstract.pdf
Presentation: http://www.chesapeake.org/stac/presentations/222_20130226%20-%20AFBF%20v%20EPA%20-%20Annapolis.pdf

On January 10, 2011, American Farm Bureau Federation (AFBF) and Pennsylvania Farm Bureau (PFB) filed suit against EPA challenging the promulgation of the Final Chesapeake Bay TMDL. In this litigation, AFBF and PFB seek to prevent EPA from engaging in any further activities related to the enforcement or implementation of this Final TMDL. This presentation will address the legal basis for the claims asserted by AFBF and PFB, EPA's legal response to the complaint, and the current procedural status of the litigation.

9:20 am Supplementary Perspective on American Farm Bureau - Chris Day (EPA)

9:35 am Questions and Answers for Pifer and Day

9:50 am Legal Challenges for Computational Models - Pasky Pascual (EPA) and Wendy Wagner (U. of Texas, Austin)

Pascual and Wagner will discuss ways that the law presents challenges for an agency's use of computational models, and explore the notion of "weight of scientific evidence" within a regulatory context. Along with Liz Fisher, both have published a series of papers analyzing the role of computational models to make regulatory decisions, as well as the various court challenges to these models.
Presentation: http://www.chesapeake.org/stac/presentations/222_multiple%20models%20conference%20final.pdf
http://www.chesapeake.org/stac/presentations/222_Pascual%20-%20Chesapeake%20Bay%2002-21-13.pdf

10: 30 am Question and Answer for Pascual and Wagner

10:45 am Break

11:00 am TMDL Opportunities - Bill Snape (Center for Biological Diversity)
Snape will take an in depth look at the Clean Water Act (and related laws), and a full vision of how an ecologically-based system could be implemented.

11: 20 am Question and Answer for Snape

11:30 am **Directed Whole-Group Discussion of Legal Issues**
Facilitator: Pasky Pascual (EPA)

12:30 pm **Lunch (Provided)**

1:00pm **Break Out Discussions**

3:00 pm **Breakout Groups Report and Whole Group Discussion**

4:00 pm **Adjourn**

Break Out Group Discussion Questions

The steering committee recommends the workshop breakout groups focus their discussion around the questions listed below.

Should the Chesapeake Bay Program (CBP) make greater use of multiple models? If no, why not? If yes, what applications of multiple models seem most productive? What would be the pros and cons of each application?

Potential applications to discuss:

- Comparing possible new models for estuarine shallow waters
- Setting TMDL target loads
- Estimating the uncertainty of TMDL target loads
- Higher resolution analyses of selected tributaries with special problems or with rich data sets (e.g., James River)
- Devising plans to meet TMDL loads
- (Other applications proposed within your breakout groups)

What are the benefits of Multiple Models for Management?

What are the pitfalls of Multiple Models for Management?

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