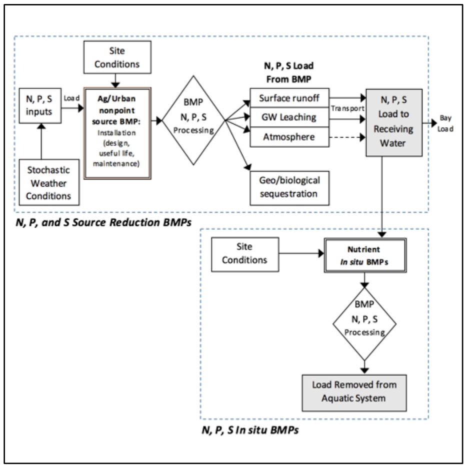
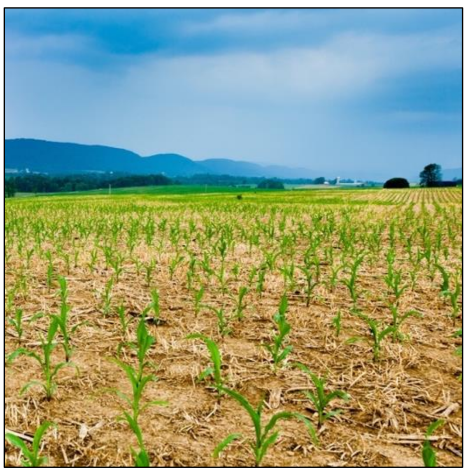
Consideration of BMP Performance Uncertainty in Chesapeake Bay Program Implementation





STAC Workshop Report
November 14-15, 2017
Fairfax, VA

STAC Publication 18-003

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 http://www.chesapeake.org/stac.

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Cover graphic (clockwise from top left): Edited version of Figure 2 in Appendix D, green roof on top of Groffs Family Funeral Home in Lancaster, Pennsylvania (Steve Droter/Chesapeake Bay Program), sea level rise in Norfolk, Virginia (Skyler Ballard/Chesapeake Bay Program), and Schrack Dairy Farm in Loganton, Pennsylvania (Will Parson/Chesapeake Bay Program).

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Executive Summary

Achieving Chesapeake Bay Program (CBP) nutrient and sediment reduction goals will require securing reductions largely from agricultural and urban nonpoint sources. While state and local governments rely largely on best management practices (BMPs) to achieve these goals, uncertainty surrounds the pollutant control effectiveness of these investments. Currently, the variation of BMP performance is not well documented or characterized in the CBP. Furthermore, knowledge gaps exist surrounding the sources and extent of the variation surrounding BMP performance. The purpose of this workshop was to make recommendations for improving the documentation and characterization of BMP performance uncertainty and to suggest how more detailed information on BMP uncertainty could be used to inform management decisions.

Through this report, the workshop participants make several recommendations for characterizing uncertainty during the process of generating BMP effectiveness estimates (BMP Expert Panel Process). These include recommendations that the Chesapeake Bay Program partnership take measures to:

1. Systematically document and represent uncertainties throughout the BMP treatment process;
2. Produce information about the distribution of removal effectiveness of each BMP;
3. Develop a method for simply and effectively communicating the degree and type of uncertainty across all approved BMPs; and
4. Provide additional guidance for how to most effectively solicit “best professional judgment” as part of the expert panel process, including best practices for structured literature syntheses, identifying and avoiding potentially inappropriate heuristics (shortcuts) and biases when obtaining expert opinion, and expert elicitation.

Introduction and Workshop Objectives

To achieve the nutrient and sediment reduction goals of the Chesapeake Bay, jurisdictions need to reduce annual nutrient loads by substantial amounts (currently established through regulation to be an additional 42 million pounds of nitrogen and 2 million pounds of phosphorus). These load reductions must come largely from agricultural and urban nonpoint sources. State and local governments primarily rely on the installation of best management practices (BMPs) to achieve these reductions. This workshop, organized by the Scientific and Technical Advisory Committee (STAC) of the Chesapeake Bay Program (CBP), focused on the uncertainty surrounding the pollutant removal effectiveness of BMPs.

The CBP utilizes a partnership-approved expert panel process for estimating the nitrogen, phosphorus, and sediment reduction effectiveness of nonpoint source BMPs. In the process, panels of experts review scientific evidence and provide estimates of the nutrient and sediment removal effectiveness for individual BMPs. These estimates are used in different ways; the CBP uses them in modeling efforts to track progress toward meeting water quality objectives, and state and local governments use them to calculate progress toward meeting Total Maximum Daily Load (TMDL) requirements.

Currently, the CBP does not explicitly address or incorporate BMP performance uncertainty in its modeling and management decisions. However, BMP performance uncertainty has important implications for the cost and risk of achieving water quality goals. Within this context, the workshop had two goals:

1. Recommend specific ways for BMP expert panels to document and characterize the uncertainties in the pollutant removal performance of BMPs; and
2. Suggest specific uses for the documented uncertainties if/when panels produce them.

Workshop Summary

Invited workshop participants consisted of individuals knowledgeable about the CBP BMP expert panel process, CBP modeling tools, state agency implementation planning and needs, as well as experts in the fields of uncertainty analysis, risk and uncertainty modeling, water quality policy, and risk assessment.

Workshop participants were briefed on the BMP expert panel process and how uncertainty has typically been addressed by BMP expert panels. As background, the output of 22 expert panels produced between 2012 and 2016 was reviewed and summarized prior to the workshop (See Appendix D). This review noted the challenges panels confront in synthesizing extant information. Substantial variation was reported in both the amount of scientific studies and field level data available to support the panels' deliberations and the processes panels used to generate final recommendations of pollutant removal performance (e.g., expert judgment, statistical analysis, and field scale modeling). The current process does not produce a consistent assessment of the magnitude of performance uncertainty across BMPs, but reviews of the 22 panel reports strongly suggested that substantial differences in performance uncertainty do exist across BMPs. In addition to recognizing this variability, workshop participants were also sensitized to:

- The extensive amount of work that is involved with each panel;
- The uniform diligence panels display in finding ways to generate recommendations; and
- The fact that panel members serve on a volunteer basis (although some resources are sometimes available in the form of CBP staff and/or to cover certain panel functions) and the number of experts within certain classes of BMPs is limited.

Workshop participants identified **four uses for more detailed information about BMP performance uncertainty estimates:**

1. More effective communication to policy makers and managers of relative certainty and confidence in pollutant removal estimates of all BMPs;
2. Modeling the range of possible aggregate pollutant load and water quality outcomes given information about BMP performance variability;
3. Enabling risk management approaches to BMP selection for Watershed Implementation Plans (WIPs); and
4. Targeted research to reduce uncertainties in the performance of key BMPs (adaptive management).

The CBP should pursue efforts to explicitly address uncertainty in modeling and management decisions. As a starting point toward achieving these benefits, workshop participants suggested that the BMP expert panels should be asked to provide additional information about BMP performance uncertainty and be given additional guidance on how to document, characterize, and report uncertainty.

Recommendations

Systematically document the types and sources of BMP performance uncertainty

Characterizing BMP performance uncertainty requires systematic identification of the factors that make outcomes variable and uncertain. BMP pollutant removal performance typically consists of multiple components, including the variability of incoming loads, site conditions, installation and maintenance, weather, types of removal processes (e.g., storage, biological transformation) and multiple loss pathways (e.g., surface runoff, groundwater leaching, atmospheric losses). The ability to observe and accurately measure pollutant control performance differs across BMPs. BMPs also vary widely in the complexity of the various factors involved in pollutant removal.

To facilitate both the identification and consideration of BMP performance uncertainty, **workshop participants recommend that all BMP expert panels take the time to develop a conceptual model (see Figure 2 in Appendix D for an example of a simple box and arrow mass balance diagram) that identifies BMP nutrient and sediment removal processes.** Such a diagram could serve several purposes. First, a diagram helps focus and organize the panel's deliberations (improved efficiency). Second, it documents the state of understanding that framed the panel's work (transparency). Third, such a diagram illustrates how uncertainty of multiple pollutant removal mechanisms can be compounded when producing a final pollutant removal performance estimate, helps identify the most critical research needs, and guides model evolution (adaptive management).

<u>Develop methods to effectively communicate BMP performance uncertainty</u>

After reviewing the practices of recent panels, workshop participants discussed methods of characterizing uncertainty. The evolution of methods used by the Intergovernmental Panel on Climate Change (IPCC) and the United States National Climate Assessment (NCA) were examined, and the value of higher or lower resolution in the characterization was discussed briefly (e.g., Moss and Schneider 2000, Manning et al. 2004, Mastrandrea et al. 2010, Moss 2011, Yohe and Oppenheimer 2011). While finer resolution in reporting degrees of uncertainty was often more satisfying for scientists developing syntheses, the nuanced distinctions in categories generally detract from effective communication to less technical audiences (see Mach et al. 2017, for example). **Given the primary objective of communicating relative uncertainty across all BMP practices to the general Chesapeake Bay Watershed community, workshop participants recommend developing a simple categorical summary characterization of BMP uncertainty as an appropriate starting point.**

<u>Identify estimates on the distribution of BMP performance for modeling outcomes and risk management</u>

The evolution of the watershed model makes analysis of multiple potential outcomes relatively straightforward. In this context, it becomes possible to consider the implications of BMP performance uncertainty by simply assuming and simulating alternative efficiencies. **Workshop participants recommend that all panels be asked to identify some basic estimates on the probability distribution of BMP performance effectiveness [e.g., first and third quartiles or one standard deviation from the panel's mean estimate, and an assessment of the shape of the distribution (skewness)].** Expert panels can use existing approaches for developing point estimates of BMP pollutant control effectiveness to derive information about the possible shape and size of a distribution of possible outcomes.

This would be sufficient to allow modelers to represent a range of outcomes from any given alternative implementation plan (e.g., probability of meeting load reduction goals). If panels provide information on the distribution of performance estimates, risk management of BMP investment decisions becomes possible. With information on the probabilities of obtaining specific levels of performance, decision-makers can evaluate BMP costs against the risks of not achieving load reduction targets.[1] Ultimately, this can better inform decisions about allocation of public resources to achieve water quality goals.

Amend CBP BMP Review Protocol process for generating panel recommendations

While there is a set of guidelines for expert panels detailing considerations and desired documentation (CBP 2015), the wide diversity in panel approaches and final products makes it clear that more explicit guidance on the definition and treatment of risk (known probabilities associated with BMP performance) and uncertainty (lack of knowledge about the probabilities) might be useful. **Workshop participants recommend the Bay Program invest the effort to expand the BMP Review Protocol so that, without being overly prescriptive, it ensures future panels will generate common elements in their reports using consistent language, descriptions, and assessments of uncertainty.**

1. Panels should be requested to use a structured review process for collecting and selecting literature to use in their work. At a minimum, this would involve providing the citation list for the entire initial literature review, and documentation of the reasons for selecting and/or disregarding items (i.e., enumeration of the salience attributes). This provides transparency for the review, and a starting point for future reviews reconsidering assigned values in light of new information.
2. Panels should be provided explicit guidance on the characterization of the information used in their analysis and the identification of the range of performance values found in the salient literature (range statistics to support alternative outcome modeling).
3. Examples of conceptual models of BMPs with identification of factor and process uncertainties should be provided to facilitate panel generation of diagrams documenting their analytical framework.
4. The protocols should provide explicit guidance on how panels can develop BMP removal effectiveness estimates in the face of uncertainty (whether and when panels should reduce estimates due to scientific uncertainties, e.g., using "conservative" estimates).

[1] The recent STAC review of the CBP Watershed Model also recommends more explicit approaches to evaluating uncertainty in the modeling process. See Easton et al. 2017. Scientific and Technical Committee Review of the Phase 6 Chesapeake Bay Watershed Model. STAC Publication Number 17-007, Edgewater, MD. 47 pp.

Beyond the expansion of the BMP Review Protocol, **workshop participants recommend the CBP move to incorporate elements of expert elicitation protocols in the panel process** (Cooke 1991, Morgan et al. 2009, EPA 2011). It is clear from the review of recent panels (presented at the workshop) that best professional judgment plays a large role in the final recommendations of many, and perhaps most, panels. Given the importance of this element, workshop participants believe it would be useful to develop guidance and/or training for panel members on the avoidance of certain heuristic shortcuts that people (including experts) commonly use and which can produce inaccurate assessments in circumstances with limited information (for examples, see Charles Yoe's workshop presentation). It would also be useful to provide facilitation training to the staff that manages and coordinates panels. Finally, **the workshop participants recommend that the CBP pilot the use of structured expert elicitation for several BMPs to assess its potential for wider application.** Expert elicitation is a formal process for developing subjective probability distributions from experts when quantitative empirical evidence is poor (Cooke 1991, Koch et al. 2015). Although a full-blown expert elicitation process can be intense and time-consuming to execute, the approach has some very real advantages when information is equivocal or limited and panel recommendations concern BMPs with potentially significant consequences in WIPs (e.g., shoreline management).

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Appendix A: Workshop Agenda

A Scientific and Technical Advisory Committee (STAC) Workshop:
Consideration of BMP Performance Uncertainty in Chesapeake Bay Program Implementation

Dates: November 14-15, 2017
Location: Northern Virginia Regional Commission, 3040 Williams Drive, Suite 200, Fairfax, VA 22031
Workshop Webpage: http://www.chesapeake.org/stac/workshop.php?activity_id=285

Workshop Goals

The objectives of the 2-day workshop are to:

1. Make specific recommendations for how to document and characterize Best Management Practice (BMP) performance uncertainty within the Chesapeake Bay Program (CBP)
2. Propose how BMP performance uncertainty might be used within the CBP's modeling, planning, and implementation efforts

Agenda

Day 1 - Tuesday, November 14

8:30 am **Breakfast (Provided)**

9:00 am **Introduction and Objectives of Workshop** – *Kurt Stephenson (Virginia Tech)*

9:20 am **Overview Summary of Role and Implementation of BMPs in the CBP** – *Gary Shenk (USGS)*

10:00 am **Uncertainty: What It Is and Why It Matters for Management** – *Carl Hershner (VIMS)*
Describe what we mean by uncertainty, illustrate definitions by referencing NPS, and briefly summarize how assessing uncertainty matters when planning implementation.

10:30 am **Uncertainty within Existing CBP Expert Panel Process** – *Kurt Stephenson (Virginia Tech)*
Describe current structure and output of the CBP BMP Expert Panels (summary of background document): How BMP efficiency estimates are generated, how uncertainty/variability is summarized, how removal effectiveness is assigned in the face of uncertainty, key areas of uncertainty in assessing performance, and qualitative comparison of levels of uncertainty across BMPs.

11:00 am **Question and Answer on CBP Expert Panel Process** – *Kurt Stephenson (Virginia Tech)*

11:30 am **Modeling Options to Investigate and Incorporate BMP Performance Uncertainty in the CBP Phase 6 Watershed Model** – *Zach Easton (Virginia Tech)*
Summary of the Phase 6 model evaluation and exploration of ways BMP performance uncertainty might be incorporated and used within the existing CBP modeling suite. The objective is to provide ideas/stimulate thought for what additional types of information

might need to be generated by the BMP expert panels or alternative methods to quantify BMP uncertainty.

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

1:00 pm **Applied Methods for Documenting, Reporting, and Assessing Uncertainty**
– Anne Grambsch (EPA)
Summary of different approaches (systematic review, evidence scaffolding, traceable accounts) used within the IPCC to characterize uncertainty. Presentation will include illustrations of each. The objective is to provide ideas/stimulate thought about output and content of the BMP expert panel reports.

2:00 pm **Facilitated Discussion** – *Erin Ling (Virginia Tech)*
Focus on workshop objective 1:

- What can be done to improve our understanding and characterization of BMP performance uncertainty?
- What types of data/information are required, and how to collect and document BMP uncertainty data?

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

2:45 pm **Facilitated Discussion** – *Erin Ling (Virginia Tech)*
What can the CBP do to improve the characterization and documenting of BMP performance uncertainty, and how would these improvements be implemented?

Individual brainstorming: Everyone please take out a piece of paper and write your top 3-5 ideas to contribute. Make sure you are specific enough that they will be understood later in the notes. (15 minutes)

Work together in groups of 4-5 people to share your ideas, and as a group, come up with a list of about 5 total ideas that your group will write on their flipchart. If there are more than 5, that is okay.
As a small group, develop and clarify your ideas with your teammates.
List any caveats or concerns. You will be sharing these with the larger group.
If ideas are relatively straightforward and easy to implement, underline them.
If ideas warrant more discussion or development, put a circle around them. (30 minutes)

Each group shares with larger group. (30 minutes)

Discussion. (45 minutes)

4:45 pm **Wrap Up**

5:00 pm **Recess**

Day 2 - Wednesday, November 15

8:00 am **Breakfast (Provided)**

8:30 am **Welcome, Summary of Day 1, Overview and Goals for Day 2**

8:40 am **Quantifying Uncertainty of Urban BMPs from the Empirical Literature**
– *Marcus Aguilar (Virginia Tech)*
Report on a project that used empirical literature to quantify cumulative levels of uncertainty of urban BMPs. The objective of this presentation is to provide ideas/stimulate thought about output and content of the BMP Expert Panels.

9:20 am **Uncertainty and Expert Opinion** – *Charles Yoe (Notre Dame of Maryland University)*
Reviews the challenges of using experts to assess uncertainty and discusses processes for soliciting such information. Illustration of assessing uncertainty of various alternatives to prevent Asian carp from reaching Great Lakes.

10:00 am **Facilitated Discussion**
Provide an overview of what emerged from the discussions yesterday.

Based on what we learned during Aguilar and Yoe's presentations, how can we further inform the recommendations that came out of yesterday's discussions?

11:00 am **Refining/Finalizing Recommendations**
What possible changes in planning and/or implementation should the CBP explore based on improved characterization of BMP performance uncertainty?

What would next steps be to get us there?

More long-term and aspirational: What should the CBP do to use improved understanding of uncertainty in management decisions?

11:45 am **Wrap Up**

12:00 pm **Lunch (Provided)**

1:00 pm **Workshop Adjourns**

Appendix B: Workshop Participants

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Appendix C: Links to Presentations

Introduction and Objectives of Workshop – Kurt Stephenson (Virginia Tech)

http://www.chesapeake.org/stac/presentations/285_Introduction%20and%20Objectives%20of%20Workshop_Stephenson.pdf

Overview Summary of Role and Implementation of BMPs in the CBP – Gary Shenk (USGS)

http://www.chesapeake.org/stac/presentations/285_Overview%20Summary%20of%20Role%20and%20Implementation%20of%20BMPs%20in%20the%20CBP_Shenk.pdf

Uncertainty within Existing CBP Expert Panel Process – Kurt Stephenson (Virginia Tech)

http://www.chesapeake.org/stac/presentations/285_Uncertainty%20within%20Existing%20CBP%20Expert%20Panel%20Process_Stephenson.pdf

Modeling Options to Investigate and Incorporate BMP Performance Uncertainty in the CBP Phase 6 Watershed Model – Zach Easton (Virginia Tech)

http://www.chesapeake.org/stac/presentations/285_Modeling%20Options%20to%20Investigate%20and%20Incorporate%20BMP%20Performance%20Uncertainty%20in%20the%20CBP%20Phase%206%20Watershed%20Model_Easton.pdf

Applied Methods for Documenting, Reporting, and Assessing Uncertainty – Anne Grambsch (EPA)

http://www.chesapeake.org/stac/presentations/285_Applied%20Methods%20for%20Documenting,%20Reporting,%20and%20Assessing%20Uncertainty_Grambsch.pdf

Quantifying Uncertainty of Urban BMPs from the Empirical Literature – Marcus Aguilar (Virginia Tech)

http://www.chesapeake.org/stac/presentations/285_Quantifying%20Uncertainty%20of%20Urban%20BMPs%20from%20the%20Empirical%20Literature_Aguilar.pdf

Uncertainty and Expert Opinion – Charles Yoe (Notre Dame of Maryland University)

http://www.chesapeake.org/stac/presentations/285_Uncertainty%20and%20Expert%20Opinion_Yoe.pdf

Appendix D: Workshop Background Document

Consideration of BMP Performance Uncertainty in the Chesapeake Bay Expert Panel Process

Kurt Stephenson and Carl Hershner

The Chesapeake Bay jurisdictions have made significant progress toward achieving the 2025 nutrient and sediment reduction goals established in the Bay TMDL. To date, municipal and industrial wastewater treatment facilities have largely achieved their collective TMDL nitrogen and phosphorus reduction responsibilities. Chesapeake Bay jurisdictions, however, still need to achieve substantial nutrient and sediment reductions from agricultural and urban nonpoint sources. Based on current understanding and modeling, the Chesapeake Bay Program (CBP) estimates that agriculture and urban nonpoint sources (both regulated and unregulated) need to achieve an additional 35 million and 12 million pounds of nitrogen reductions, 1.3 and 0.6 million pounds of phosphorus reductions, and 941 and 594 million pounds of sediment reductions, respectively to meet TMDL goals. State and local governments and their citizens are poised to spend hundreds of millions of additional dollars to meet these goals by implementing agricultural and urban nonpoint source best management practices (BMPs).

Unlike industrial and municipal wastewater treatment facilities, it is difficult and expensive to directly quantify and verify the nutrient and sediment reduction/removal performance of installed nonpoint source BMPs. The CBP has developed a process for estimating the nitrogen, phosphorus, and sediment reduction effectiveness of nonpoint source BMPs. The process relies on panels of experts to review scientific evidence and provide point estimates of the nutrient and sediment removal effectiveness, typically expressed as a percent removal. The CBP program uses these estimates in modeling efforts to track progress toward meeting water quality objectives and to develop implementation plans to reduce nonpoint source loads.

Currently, BMP performance uncertainty is not well characterized, or incorporated within the CBP, but its importance to meeting Bay goals is well recognized. Implementing BMPs without a better understanding of the level and extent of pollutant removal uncertainty can misdirect BMP investments and jeopardize achievement of water quality goals. In fact, a recent review of the Chesapeake Bay program's (CBP) Phase 6 (P6) model, conducted by the CBP's Scientific and Technical Advisory Committee (STAC), identified quantification and incorporation of uncertainty into both the BMP expert panel process and the P6 model structure as major recommendations. As a result, STAC has convened a workshop to assess how uncertainty about BMP performance can be more explicitly evaluated and incorporated within the program. The specific objectives of the workshop are to:

1. Make specific recommendations for how to document, characterize, and communicate BMP performance uncertainty within the Chesapeake Bay Program. Possible goals of a process to assess BMP performance uncertainty include:
    a. Provide a transparent and consistent means to report uncertainty;
    b. Identify key areas of scientific uncertainty (most important information gaps);
    c. Provide a means to compare performance uncertainty across BMPs;

d. Offer a transparent way to assess risk of BMP nonperformance

2. Propose how uncertainty about BMP performance might be reported and used in watershed modeling and implementation efforts.

The purpose of this report is to describe how the CBP currently addresses uncertainty about BMP performance and uses estimates of BMP performance effectiveness. The aim is to provide workshop attendees with background material to advance workshop discussions and to facilitate discussion of recommendations. This report briefly summarizes:

- how the CBP models urban and agricultural BMPs and uses estimates of BMP performance in program implementation;
- the current protocol for developing BMP nutrient and sediment removal efficiencies through the expert panel process;
- how expert panels since 2012 have addressed observed variability and scientific uncertainty in removal effectiveness when developing recommendations.

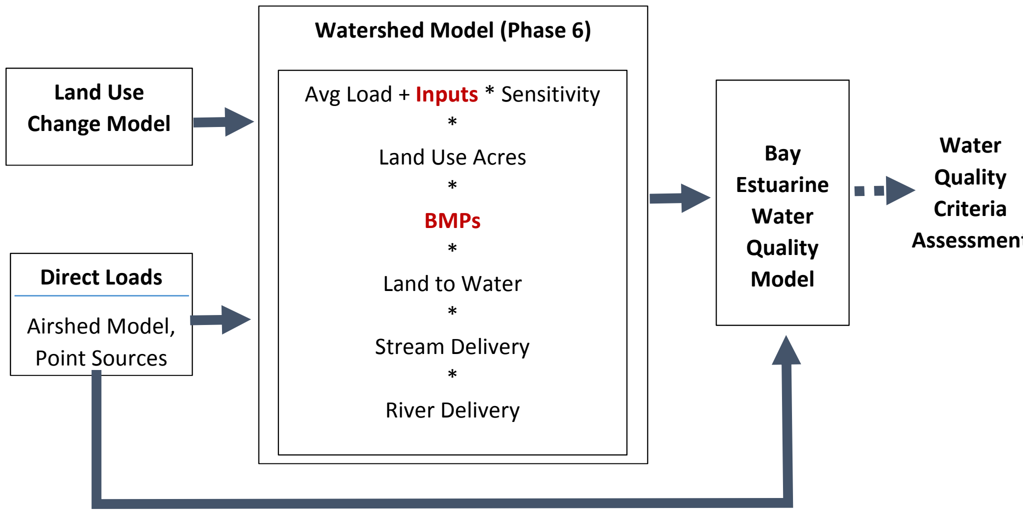
Overview of BMPs within Chesapeake Bay Program

To achieve Bay water quality standards, EPA established ambient numeric criteria for dissolved oxygen, water clarity, and chlorophyll a. The TMDL process identified nitrogen, phosphorus and sediment load goals for the Bay tributaries that would be necessary to achieve the water quality criteria in 92 segments of the Chesapeake Bay[1] (Tango and Batiuk 2013). To achieve nutrient and sediment goals, nutrient and sediment allocations are assigned to different source sectors (e.g. municipal/industrial point sources, agricultural nonpoint sources, regulated urban stormwater, unregulated urban stormwater, etc.) within the different governmental jurisdictions within the Bay watershed.

The CBP uses a suite of models to predict ambient water quality outcomes from changes in land use, air quality, and management actions that occur throughout the watershed, and to track progress toward achieving water quality criteria (see Figure 1). The P6 watershed model uses nutrient and sediment inputs from land runoff, direct discharge, and air deposition and estimates delivery through the stream and river network to the Chesapeake Bay. The Bay estuarine water quality model uses the nutrient and sediment load estimates from the watershed model to predict ambient water quality outcomes throughout the Bay. The CBP uses the estuarine model output to assess water quality status against Bay water quality criteria.

[1] Tango, P.J. and R.A. Batiuk. 2013. "Deriving Chesapeake Bay Water Quality Standards" *Journal of the American Water Resources Association*: 1-18 DOI: 10.1111/jawr.12108.

Figure 1: Chesapeake Bay Model Suite



The CBP uses the watershed model to evaluate the effectiveness of management actions to reduce nutrient/sediment loads. Conceptually, the watershed model estimates nonpoint source nutrient and sediment loads by first estimating Bay average per acre loading rates for different land uses (top line of Watershed Model box in Figure 1). Average loads are adjusted based on nutrient inputs from atmospheric deposition and fertilizer, manure and biosolid applications within a defined land segment of the watershed. This load is then multiplied by the number of acres of each land use to generate a potential exported load. Within the model, BMPs reduce nutrient and sediment loads exported from the land segment as a percent reduction in the potential exported load. The CBP typically assigns a single efficiency estimate for nitrogen, phosphorus, and sediment to each defined BMP. "Land to Water" factors add spatial variation in nutrient transmission by making adjustments to physical conditions (e.g. water absorptive capacity of soil and groundwater recharge) within the land segment. Together these factors produce total load estimates exported to the stream (< 100 cfs) and river (> 100 cfs) network. Attenuation factors are applied to land segment export loads to estimate the quantity of nutrients and sediment reaching the Bay.

The watershed model is used for both TMDL implementation planning and TMDL compliance. For example, the CBP partners participate in a watershed implementation planning (WIP) process that involves projecting possible management actions that states and local governments expect to use to achieve nutrient and sediment reduction goals. The watershed model is also used to track compliance with TMDL nutrient and sediment load reduction requirements. As states and local governments implement management actions, the changes are entered into the model to calculate progress made toward meeting nutrient and sediment reduction goals. State and local governments can only receive credit toward meeting their nutrient targets by using BMPs that have been formally evaluated and approved by the CBP and incorporated into the CBP watershed model.

The watershed model accounts for state and local efforts to reduce land-based nutrient and sediment loads in a number of ways. First, land based BMPs can be used to intercept and treat land based runoff. Examples of BMPs include agricultural cover crops and urban stormwater filtration and treatment practices (see Figure 1). Second, nutrient load reductions can also be achieved through reductions in nutrient inputs, such as reduction in agricultural and lawn fertilizer application rates and manure application ("Inputs" in Figure 1). Together, these represent the primary management tools available to state and local governments to reduce nonpoint source loads. The CBP also credits reductions from practices that directly remove nutrients and sediments from a watershed or ambient waters. These practices include stream restoration, shellfish aquaculture and algal harvest. For purposes of this report, these collective nutrient control options will be referred to as "BMPs"

The CBP uses a formal process for approving BMPs for Bay TMDL compliance. The approval process begins with convening a panel of experts at the request of the CBP. The CBP tasks experts with identifying specific nutrient and sediment reduction/removal performance estimates (typically expressed as % reduction from a baseline load condition) and to make recommendations on how performance can be verified in practice. The expert panels typically include academics, government agency staff (ex. NRCS, USGS), and consultants with relevant technical and scientific expertise. Typically, the CBP selects an acknowledged expert to chair the panel and assigns paid staff to assist with panel deliberations and report development. The panelists themselves receive no financial compensation for the time commitment. Each panel produces a technical report based on guidelines outlined in the CBP's *Protocol for the Development, Review, and Approval of Loading and Effectiveness Estimates for Nutrient and Sediment Controls in the Chesapeake Bay Watershed Model.*[2] The technical report contains a description and rationale for the panel's BMP nutrient/sediment reduction efficiency recommendation.[3]

The current *Protocol* contains limited language related to BMP uncertainty and does not formally specify how BMP performance uncertainty should be incorporated into BMP performance estimates/recommendations. The *Protocol* requires the panel to review, document, and evaluate the existing literature on BMP performance. The panel is expected to qualitatively evaluate the literature based on replication of BMP performance studies, the applicability of the existing literature to the BMP efficiency request, study location (within or outside Bay region), data collection and methods, and extent of peer reviewed literature. The panel uses the existing literature to develop the requested removal efficacy estimate. The panel also must provide a justification for the removal efficiency estimate. As part of the justification, the panel is asked to document the "uncertainties in the published literature (across and within studies)" and to explain "the approach the Expert Panel used to address scientific uncertainties and variation in

[2] http://www.chesapeakebay.net/documents/CBP_BMP_Expert_Panel_Protocol_WQGIT_approved_7.13.15.pdf
[3] For a copy and listing of BMP panel reports see: http://www.chesapeakebay.net/who/group/bmp_expert_panels

empirical findings of removal effectiveness (e.g. if 'conservative' effectiveness estimates are used to address uncertainty, provide a rationale for the estimate)" (*Protocol*, p.10)

Each Expert Panel produces a report with its recommendation. The panel's recommendation is then reviewed and approved by the CBP Working Group that requested the BMP review (e.g., Agriculture, Stormwater) and the appropriate Goal Implementation Team. These working groups are comprised primarily of state and federal officials tasked with TMDL implementation. Once approved, the pollutant reduction/removal performance estimate is incorporated into the Chesapeake Bay watershed model. Once an efficiency estimate is approved, those tasked with implementing BMPs have little incentive to consider BMP performance variability or uncertainty when selecting BMPs and making BMP investment decisions.

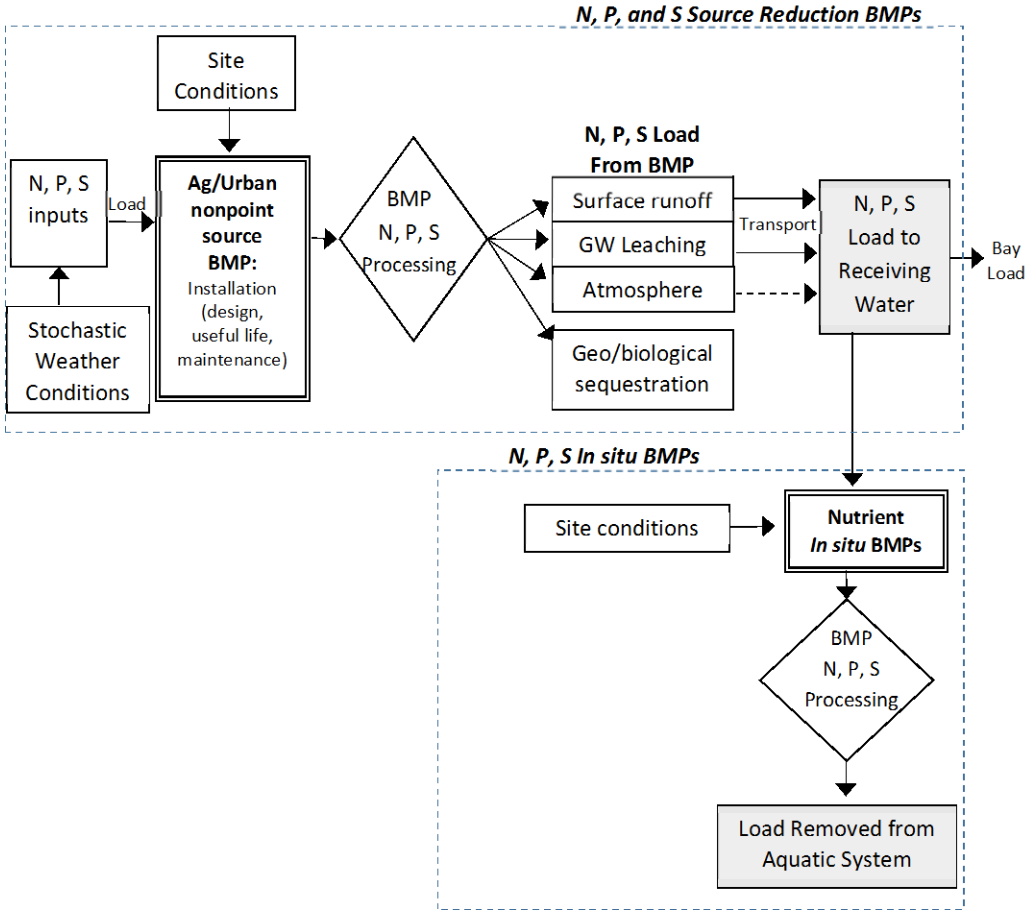
Sources of Uncertainty in BMPs Nutrient/Sediment Control Effectiveness

Uncertainty about BMP pollutant control effectiveness can be classified as coming from two primary sources: epistemic and aleatory uncertainty.[4] Epistemic uncertainty arises from lack of knowledge or data necessary to estimate probabilities. Aleatory uncertainty, in contrast, derives from the inherent randomness in the system (ex. weather-related variation).

Multiple sources of uncertainty exist within a single BMP. Figure 2 shows a simplified system material balance for a nutrient and sediment control BMP. BMPs receive N, P, and sediment inputs from a variety of sources ("Source Reduction BMPs" in Figure 2). While weather events influence these inputs, the amount and composition of those inputs may not be well-known or characterized. Variation in BMPs performance is also heavily influenced by specific site conditions (slope, soil type, surrounding vegetation, etc.). Expert panels must evaluate how these conditions alter the BMP treatment processes and confront the uncertainty surrounding BMPs performance under different conditions. Since expert panels are asked to generate average removal efficiency estimates, the panelists must decide how to aggregate performance under a wide range of variable site conditions. Once pollutants enter the BMP, a number of pollutant transformation processes treat and reduce nutrients and sediment. In general, these processes can be chemical transformation (ex. nitrification, denitrification) or bio/physical sequestration (burial, storage in plants). Pollutants can be exported from BMPs through a variety of pathways in surface runoff, groundwater leaching, or through the atmosphere (N_2, N_2O, NH_4). The extent of loss pathways may be unknown or incompletely characterized. Finally, practices must be designed, installed, and maintained. Variation in these activities may be challenging to observe and uncertainty may exist on how removal pathways respond to different design and maintenance attributes.

[4] National Research Council, 2001. *Assessing the TMDL Approach to Water Quality Management*. National Academies Press, Washington DC. Stewart, T.R. 2000. Uncertainty, judgment, and error in prediction. In *Prediction: Science, Decision Making, and the Future of Nature*. D. Sarewitz, R. A. Pielke Jr. and R. Byerly Jr., eds. Washington, DC: Island Press.

Figure 2. Nutrient/Sediment Removal Pathways



Besides reducing source nutrients/sediment, the CBP has also approved a number of practices that reduce nutrients/sediment by removing nutrients directly from the ambient aquatic environment (nutrient assimilation or *in situ* BMPs) (bottom of Figure 2). Direct ambient removal avoids uncertainty associated with fate and transport. Nutrient removal pathways include storage, bioharvest, and bioprocessing. In some cases, the removal effectiveness can be directly observed and measured (through on-site sampling), substantially reducing the uncertainty surrounding pollutant removal effectiveness.[5]

[5] Stephenson, K, and L. Shabman. 2017. "Nutrient Assimilation Services for Water Quality Credit Trading Programs: A Comparative Analysis with Nonpoint Source Credits" *Coastal Management*. 45(1): 24-43.

Consideration and Evaluation of Uncertainty within the CBP Expert Panel Process

In order to document the treatment of uncertainty in the expert panel process, we reviewed 20 BMP Expert Panel Reports produced between 2012 and 2016.[6] These BMP panel reports cover agricultural BMPs (cover crops, nutrient management, etc.), urban BMPs (filter strips, urban nutrient management, tree canopy, etc.), *in situ* nutrient assimilation practices (removal of nutrients already in source water), and other BMPs (see Table 1). The reports include both the review of new BMPs (BMPs not previously approved and used within the CBP model structure) and existing BMPs (existing BMP efficiency estimates undergoing updates). Our review begins in 2012 since this is when the more formal BMP panel review process was first implemented. We used a set of questions to systematically document how each expert panel addressed uncertainty (see Table 1).

To answer the questions in Table 2, we first read each final panel report and provided a tentative assessment for each question. To refine our understanding, we then interviewed at least one key member of each expert panel (either the panel chair or lead CBP staffer for the panel). We used a semi-structured interview process organized according to the questions in Table 2. Respondents were informed about the purpose of the workshop and were sent the questions prior to the interview. Interviews were conducted by either phone or in-person interview between September and October 2017. Interviews generally ranged 30 to 45 minutes per BMP panel report.

Summary of CBP Expert Panel Reports, 2012-2016.

A summary and comparison of the expert reports is provided in Table 3. In general, the amount of information available to the expert panels was highly variable, ranging from hundreds of studies to less than a dozen. Agricultural practices tended to have the most peer-reviewed studies available. Many of the engineered practices drew upon a fair amount of gray literature (often from purveyors). In some cases, the CBP was able to pay contractors to pull together bibliographies of the available literature for the panel experts to consider.

In almost all cases, the panels relied on a fraction of the available literature in developing a BMP effectiveness estimate. Relatively few empirical studies were designed to estimate total nutrient and sediment reduction effects of a practice. Since BMPs generally involve multiple steps/processes (see Figure 1), panels often had to combine data and insights from process-specific studies to derive an estimate for the general practice. To narrow the range of causal factors that influence performance, panels often stratified the literature based on factors such as physiographic region or research methods. Several of the panelists interviewed noted that the

[6] This list is not a complete list of all reports produced during this time period. Earlier reports that were later revised or expanded upon are not included in this review (ex. *Addition of New Cover Crop Species with Nitrogen Reduction Efficiencies for use In Phase 5.3.2. of the Chesapeake Bay Program Watershed Model* and *Continuous High Residue Minimum Soil Disturbance BMP: Recommended Sediment Reduction Efficiencies for Use in Phase 5.3.2).* Two urban stormwater reports that developed procedures to standardize removal estimates for different state practice standards (*Removal Rates for New State Stormwater Performance Standards* and *Removal Rates for Urban Stormwater Retrofit Projects)* are also excluded from this review.

bibliographies that were pulled together were challenging to work with because substantial work needed to be done to sift through information to isolate relevant studies.

Unsurprisingly given the amount of relevant literature, panels typically did not formally address or summarize the uncertainty or variability within the available data. Panels tended to qualitatively describe uncertainties within the existing literature. Panels with enough information sometimes used statistical data ranges, standard deviations, etc.) to summarize the results from a set of relevant studies. In only one case (oyster aquaculture) did panel experts collect and analyze primary data beyond what was available in the relevant literature.

The panels generally relied on best professional judgment (BPJ) to synthesize available information and generate estimates. Panelists relied on BPJ when extrapolations were required to fill in poorly understood or characterized elements of a BMP's removal process or to connect multiple lines of incomplete evidence from different studies into a conceptually coherent estimate. Panelists frequently used BPJ to generalize from site specific empirical results to the more aggregated nutrient removal estimates requested by the CBP. A few panels relied on statistical calculations (means/medians) or methods (regression) to derive an estimate (e.g. (conservation tillage, algal flow ways, oyster aquaculture). A number of the urban BMP expert panels used models to simulate Bay-relevant conditions to help generate plausible performance estimates.

Panelists were confronted with multiple gaps in scientific understanding when developing their estimates (Q6 in Table 3). Major sources of uncertainty that panelists struggled with include isolating how site conditions influenced removal effectiveness and adequately characterizing those conditions in an efficiency estimate. Significant research gaps exist for some treatment and loss pathways. For many agricultural and urban practices, far less research on the fate and transport of nutrient through groundwater/subsurface exists compared to surface runoff. Lag times in fate and transport, and performance under actual field conditions (rather than controlled experiments) are other sources of uncertainty. Several of the agricultural BMP panelists interviewed noted that experts with considerable field experience were much more confident in the relative effectiveness of different agricultural BMP practices than an absolute numerical estimate.

When confronted with uncertainty, panelists often decide on estimates that are thought to be lower than best professional estimate of the average condition. One panelist noted that disagreements among panel members were often settled by accepting the most conservative (lowest removal) estimate. Given the number of assumptions required and the complexity of removal pathways, panelists commonly made multiple "conservative" assumptions or judgments when developing an overall estimate. Some panels aimed to only provide their judgment on what would be the central tendency regarding pollutant control performance (labeled as "neutral" in Table 3). One panelist noted that their panel viewed the job as providing a credible expert judgment on effectives and scientific uncertainties, but the job of deciding how to address those uncertainties for implementation belonged to water quality managers (policy-makers). In general, the agricultural BMP panels tended to adopt a more "neutral" position in their assessments (see Table 3).

Some panels developed multiple performance estimates for a single BMP. Performance estimates differ based on the level of site specific information provided about the practice during implementation (see Table 4). In such situations, the panel would develop a "default" removal estimate based on conservative assumptions about the expected performance of a generic practice. The panel would then develop alternative removal estimates if additional BMP information such as site conditions were available. For instance, those implementing stream restoration projects can receive higher nutrient and sediment reductions if information is provided about bank conditions and connectivity to flood plains. In other cases, protocols were developed for directly measuring pollutant control outcomes (rather than practice installation). For instance, the manure treatment, algal flow-way, and oyster aquaculture panels developed protocols to directly measure nutrients removed from the aquatic system (e.g., monitored emissions or pounds of nutrients removed from harvested biomass). All other factors being equal, measurement of actual performance outcomes provides a greater level of certainty than assumptions about installation and assumed performance of a practice. By developing intentionally low default estimates, these panels, in effect, explicitly aimed to create a reward system for reducing uncertainty about BMP performance.

For most BMPs, estimated performance is based on assumptions about practice installation and maintenance. Verification of these circumstances also entails some uncertainty. Table 4 provides a summary of the verification protocols across BMPs. Verification of BMP performance can also be indirect (area wide estimation of implementation) or direct (on-site inspection or site-specific data). Frequency of verification can also be variable. Most urban BMPs must be inspected and reported at regular intervals under established permit systems. Verification of BMPs installed voluntarily or under agricultural cost share programs is typically through a sampling protocol or self-reporting.

Table 1: Chesapeake Bay BMP Expert Panel Reports Reviewed (2012-16)

BMP Expert Panel	Description of Practice	Date	Type
Agricultural BMPs			
Nutrient Management	Determine N and P reduction estimates for four Nutrient Managment elements: core, rate, timing, & placement	2016	Revised
Conservation Tillage	Determine S, N, and P reduction efficiencies for 3 levels of conservation tillage	2016	Revised
Cover Crops	Determine N, P, and S reduction efficiencies for traditional and commodity cover crops for multiple land use and cropping systems	2016	Revised
Animal Waste Mgt Systems	Estimate the nutrients that can be recovered from confined animal waste management system (loss from storage, but not volatilization)	2016	Revised
Manure Treatment Technologies	Determine the mass nutrient transfer efficiencies (% on farm, % off-farm, % volatilized) for thermochemical, compost, digester treatment technologies.	2016	New
Urban BMPs			
Runoff to Amended Soil	Determine N, P, and S reduction efficiencies for disconnecting stormwater runoff from impervious cover and routing flow to amended soils	2016	New
Erosion & Sediment BMPs	Developed sediment removal efficiencies for 3 levels of effort to prevent sediment loss from construction sites	2014	Revised
Urban Filter Strips	Developed N, P, andS removal efficiencies from stormwater treatment and runoff reductions for urban filter strips and urban riparian buffers	2014	New
Urban Tree Canopy	Estimated the N, P, and S reduction expanding the extent of urban tree canopy. Panel focused on estimating the size of canopy coverage.	2016	Revised
Urban Nutrient Management	Estimated N & P reductions from reductions in state fertilizer sales (P bans) and acres of land under defined urban nutrient management.	2013	Revised
Street/storm Drain Cleaning	Developed N, P, and S reduction credits for 2 street sweeping technologies and for removal of solids from catch basins.	2016	Revised
Elimination of Discovered Discharges to Grey Infrastructure	Development of N and P reductions from removing dry weather nutrient discharges to existing stormwater infrastructure (car washing, SSOs, sewer pipe exfiltration, etc)	2014	New
On-site Wastewater Systems	Development of N reductions before, and in, the drain field for advanced/retrofitted on-site wastewater (septic) systems	2014	New
In Situ Removal Practices			
Stream Restoration	Developed N, P, and S removal for 4 different removal pathways from stream restoration projects	2013	Revised
Wetland Restoration	Develop N, P, and S removal rates for restored, enhanced, rehabilitated, and created wetlands (not treatment wetlands) in multiple physiographic regions	2016	Revised

Algal Flow Way Technologies	Developed N, P, and S removal estimates and quantification protocols for algal biomass harvested using land based algal growing facilities.	2015	New
Oyster Aquaculture	Developed N & P removal estimates from tissue in harvested aquaculture oysters	2016	New
Other			
Shoreline Management Projects	Developed N, P, and S removal estimates for activities that prevent/reduce shoreline erosion	2015	Revised
Riparian Forest/Grass Buffers	Modest revisions to N, P, and S removal efficiencies on uplands served by forested and grass buffers in different physiographic regions	2014	Revised

Table 2: Treatment of Uncertainty in BMP Expert Panels
(1) How much information/literature (total) was available for this BMP? (Summarized as: Extensive, Modest, Limited)
(2) Of the information available in (1), how much was relevant and used to develop BMP performance estimate? (Summarized as All; Some; Very Little)
(3) What approach did the panel characterize/summarize empirical data variability within the final panel report? (Summarized as Quantitative or Descriptive)
(4) How did the panel translate existing literature/information into BMP performance (i.e., efficiency estimate)? (Summarized as "Statistical" (eg. statistical model, averaging, etc); "Model" (deterministic); or "BPJ" (best professional judgement))
(5) Did the panel explicitly address/consider uncertainty in developing final estimate? Yes or No
(6) What did the panel members consider the greatest source of uncertainty in developing their estimate (Summarized into categories shown in Figure 1).
(7) What risk position was taken by the panel when assessing uncertainty? ("conservative" or "risk neutral")

Table 3: Summary Characterization of Chesapeake Bay Expert Panel Report Content (2012-2016)

Topics of Nutrient and Sediment Control BMP Expert Panels	**(Q1)** Available Literature	**(Q2)** Literature Used	**(Q3)** Characterization of Variability	**(Q4)** Method to Derive Estimate	**(Q5)** Explicit Recognition of Uncertainty	**(Q6)** Source(s) of Greatest Uncertainty	**(Q7)** Risk Attitude
Agricultural BMPs							
Nutrient Management	Extensive	Some	Descriptive	BPJ	Yes	Implementation	Conserv
Conservation Tillage	Extensive	Some	Quantitative	Statistical	Yes	P loss pathways	Neutral
Cover Crops	Extensive	Some	Descriptive	Statistical /BPJ	No	Subsurface losses; installation methods	Neutral
Animal Waste Mgt Systems	Limited	V. Little	Descriptive	BPJ	No	Implementation	Conserv*
Manure Treatment Technologies	Limited	Some	Descriptive	BPJ	No	Implementation	Conserv*
Urban BMPs							
Runoff to Amended Soil	Extensive	Some	Descriptive	Model/ BPJ	No	Site conditions	Conserv
Erosion & Sediment BMPs	Modest	Some	Descriptive	BPJ	No	Limited data (storm events)	Neutral
Urban Filter Strips	Modest	Some	Quantitative	Model /BPJ	No	Subsurface N losses; site conditions;	Conserv
Urban Tree Canopy	Limited	V. Little	Descriptive	Model/ BPJ	Yes	Aggregation conditions	Neutral
Urban Nutrient Management	Limited	V. Little	Descriptive	BPJ	No	Implementation; lags in fate/transport	Conserv
Street/storm Drain Cleaning	Extensive	Some	Descriptive	Model/ BPJ	Yes	Research methods; fate/transport	Conserv
Elimination of Discovered Discharges to Grey Infrastructure	Modest	Some	Descriptive	BPJ*	?	Site variability	Conserv*
On-site Wastewater Systems	Extensive	Some	Descriptive	BPJ	No	Site conditions (soils)	Conserv
Nutrient Assimilation Practices							
Stream Restoration	Extensive	Little	Descriptive	BPJ	No	Source input fate/transport	Conserv*

Wetland Restoration	Extensive	Some	Quantitative	Statistical	No	Practice scope; site conditions	Neutral
Algal Flow Way Technologies	Some	Some	Quantitative	Statistical	No	Measurement method; sample size	Conserv*
Oyster Aquaculture	Some	Most	Quantitative	Statistical	No	Sample size on subset of oysters	Conserv*
Other							
Shoreline Management Projects	Extensive	Some	Quantitative	BPJ/ Statistical	No	Erosion rates	Conserv
Riparian Forest/Grass Buffers	Extensive	Some	Descriptive	BPJ	No	Site conditions; processing (flow intercept)	Conserv

*Conservative for the default estimate only. In some cases, expert panels recommended several efficiency estimates, depending on site specific information of the installed BMP (see Table 4). Panels frequently adopted a risk neutral position for BMP effectiveness estimates based on site specific data or measures of pollutant control outcomes

Table 4: BMP Quantification and Verification

	Quantification of BMP Performance		**Verification**	
BMP Expert Panel	# of BMP Quantification Protocols*	What is Measured?	Type of Verification	Frequency
Agricultural BMPs				
Nutrient Management	1	Practice	Indirect (nonvisual)	Sample
Conservation Tillage	1	Practice	Direct (visual)	Sample
Cover Crops	1	Practice	Direct (visual)	Sample
Animal Waste Mgt Systems	1	Practice	Direct (visual)	Sample
Manure Treatment Technologies	3	(1) Practice (2) Practice (3) Outcomes	(1) Indirect (nonvisual) (2) Direct (visual) (3) Direct (visual/records)	Sample Permit Schedule
Urban BMPs				
Runoff to Amended Soil	3	(1) Practice (2) Practice (3) Practice	(1) Direct (2) Direct (3) Direct	Permit Schedule
Erosion & Sediment BMPs	1	Practice	Direct	Permit Schedule
Urban Filter Strips	1	Practice	Direct	Permit Schedule
Urban Tree Canopy	1	Practice	Indirect	
Urban Nutrient Management	1*	Practice	Indirect	Annual/Sample
Street/storm Drain Cleaning	1	Practice	Indirect (records)	Annual
Elimination of Discovered Discharges to Grey Infrastructure	2	(1) Practice (2) Outcomes	(1) Direct (2) Direct	
On-site Wastewater Systems	1	Practice	Not specified	Not specified
Nutrient Assimilation Practices				
Stream Restoration	2	(1) Practice (2) Practice	(1) Direct (2) Direct	Every 5 years
Wetland Restoration	1	Practice	Direct	Variable schedule
Algal Flow Way Technologies	2	(1) Outcomes (2) Outcomes	(1) Direct (visual/records) (2) Direct (visual/records)	Annual Quarterly
Oyster Aquaculture	2	(1) Outcomes (2) Outcomes	(1) Direct (records) (2) Direct (records)	Annual Annual
Other				

Shoreline Management Projects	2	(1) Practice (2) Practice	(1) Direct (2) Direct	Every 5 years
Riparian Forest/Grass Buffers	1	Practice	Direct	Sampling

[*] Number of methods to quantify pollutant removal performance of a specific practice or technology, including a single default efficiency or an estimate based on site specific information.
[**] Identifies what the CBP uses to measure pollutant removal performance ("Practice" means the existence of the practice itself is verified and assumed to produce pollutant reductions; "Outcomes" means that indicators of pollutant reductions achieved are used as verification of pollutant removal performance)
[†] What evidence is required for verification ("Direct" means BMPs are verified by site specific information or field verification; "Indirect" means BMPs are verified through spatial sampling or aggregate secondary data).
[††] How frequently is the BMP verified?
[†††] How many Question 8, Table 2: How confident was the panel that the recommended BMP verification methods will reflect pollutant removal outcomes achieved by BMPs? (summarized High, Medium, or Low confidence).