A Review of Agricultural P-dynamics in the Chesapeake Bay Watershed Model

A Workgroup Report from the Chesapeake Bay Program Scientific and Technical Advisory Committee

August 2014
STAC Publication 14-005

About the Scientific and Technical Advisory Committee

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Publication Date: August, 2014

Publication Number: 14-005

Suggested Citation:
Staver, K., P. Kleinman, S. Ator, A. Buda, Q. Ketterings, J.T. Sims, and J. Meisinger. 2014. A review of agricultural P-dynamics in the Chesapeake Bay Watershed Model. STAC Publication Number 14-005, Edgewater, MD. 20 pp.

Cover graphic from: Adrian Jones (UMCES-IAN)

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Table of Contents

Executive Summary

STAC approved an *ad hoc* workgroup of scientists following its September 2011 quarterly meeting to work with CBP modelers to investigate how phosphorus (P) transport from cropland was simulated in the CBP Watershed Model (CBWM). The CBWM is the primary accounting tool for planning nutrient reduction strategies and tracking progress toward nutrient reduction goals. The specific objectives of the workgroup were:

1. To gain an in-depth understanding of how the CBWM currently simulates P loads from cropland and whether the current simulation approach is consistent with the latest scientific consensus regarding P transport mechanisms.

2. To make recommendations regarding how the CBP modeling approach should be restructured to more accurately reflect the latest research findings regarding P transport processes and what data inputs will be needed to support calibration and corroboration of a restructured modeling approach.

The workgroup initially focused on the first objective of understanding the current P transport simulation approach. Part of addressing the first objective was identifying the greatest opportunities for improving the current modeling approach, which led to the second objective of developing a set of recommendations that would help ensure that the simulation process considered the key drivers of P transport.

The workgroup did not address whether critical input data sets used in current modeling efforts such as cropland area, animal numbers, P excretion rates, etc. were accurate, since those issues are being addressed by other groups. The workgroup did conclude that the current CBWM simulation process relies too heavily on annual P application rates to estimate cropland P losses and currently is missing the effects of critical key short and long-term drivers of cropland P losses that are the focus of most cropland P loss reduction strategies, and that are included in most recently developed field-scale P simulation models.

The two key drivers that appear to be absent or poorly represented in the current CBWM simulation process are: 1) soil P concentrations, which have the potential to contribute to watershed P losses well into the future and 2) fertilizer/manure application method, timing, rate and form (National Resources Conservation Service's (NRCS) "4Rs" of nutrient management).

The workgroup developed recommendations for better accounting for soil P and the effects of how P applications are managed in the simulation process, along with several general P modeling recommendations, and also identified future data needed to improve P transport modeling within the CBWM.

- **Modeling Recommendations Related to Soil P:**

  1. **Account for soil P reservoirs as a source of P to runoff on a segment-by-segment basis**
  2. **Track segment P balances to determine whether soil P reservoirs are increasing or decreasing**
  3. **Describe the temporal dynamics of the effects of drawdown/build-up of soil P reservoirs on P losses in runoff**

- **Modeling Recommendations Related to Management of P Inputs:**

  1. **Account for different P application methods, including whether manure is left on the soil surface, incorporated by tillage, or incorporated with low soil disturbance full-width applicators or injected in bands**
  2. **Apply manure at rates and times based on watershed or regional information**
  3. **Improve representation of practices aimed at reducing P runoff potential by adjusting the timing of P applications**
  4. **Account for P stratification that develops in soils in continuous no-till**
  5. **Account for interaction between tillage and manure application on potential for P losses as particulate and dissolved P fractions in overland and sub-surface flow**

- **General Modeling Recommendations:**

  1. **Identify the fraction of P losses associated with short versus long-term management strategies**
  2. **Model functions should be capable of scaling down to provide segment and field guidance on drivers of P**
  3. **Shift away from using model-generated values and proxy data for key input parameters**
  4. **Consider changing weather patterns associated with climate change**
  5. **Better represent and report uncertainty in data sources and model output**
  6. **Differentiate between surface and sub-surface transport pathways of P loss and account for the role of drainage intensity**

- **Future Data Needs to Support Recommended Changes in Modeling Approach:**

  1. **Baseline soil P levels**
  2. **Information on P application methods**
  3. **Spatial and temporal data on manure application**

4. **Inorganic P application rates, including those associated with high-value row and horticulture crops**
5. **More systematic storm water sampling in predominantly agricultural watersheds for use in model calibration**
6. **Improved mapping of features that restrict water infiltration and promote "saturation excess" runoff**
7. **Improved mapping of drainage intensity as an indicator of hydrologic connectivity and P delivery potential**

Workgroup Background

The Chesapeake Bay restoration effort is in its 4th decade. The primary accounting tool for planning nutrient reduction strategies and tracking progress toward nutrient reduction goals is the CBWM, which generates estimates of delivered nutrient loads to the Chesapeake Bay based on reported land use and management information and collected weather data. Discussions were initiated in Maryland in 2010 between University of Maryland (UMD) scientists, Maryland Department of Natural Resources (MD DNR) and Maryland Department of Agriculture (MDA), and the CBP modeling group regarding output from CBWM indicating major reductions in P losses from cropland on the Maryland Eastern Shore that seemed to be inconsistent with research findings and monitoring data in the region. A mechanistic narrative to explain the CBWM projected reductions was largely lacking. The primary questions put forth were what were the on-the-ground practices and how were they handled in the CBWM to generate the large reductions in P from agriculture on the Maryland Eastern Shore from 1985-2000, especially on the lower Eastern Shore (LES) where poultry production is most concentrated. Informal discussions that dealt more generally with how P loads from cropland are simulated in the CBWM continued through 2011 and resulted in a presentation to STAC in September 2011 that dealt with apparent conflicts between modeled reductions in P losses and results from field research, stream monitoring, and information on changes in known drivers of P from cropland. An outcome from the September 2011 STAC meeting was the formation of a technical workgroup early in 2012 composed of small group of scientists from throughout the Chesapeake Bay watershed. The objectives approved by STAC for this workgroup were:

1. To gain an in-depth understanding of how the CBWM currently simulates P loads from cropland and whether the current simulation approach is consistent with the latest scientific consensus regarding P transport mechanisms.

2. To make recommendations regarding how the CBP modeling approach should be restructured to more accurately reflect the latest research findings regarding P transport processes and what data inputs will be needed to support calibration and corroboration of a restructured modeling approach.

Workgroup Participants

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Workgroup Activities

The workgroup met in February 2012 for a full day with Gary Shenk, the integrated analysis coordinator of the CBP modeling effort, who gave a comprehensive presentation on the overall structure of the CBWM that included a more detailed section on how P transport from agriculture is simulated. As a result of that meeting, the workgroup developed a set of follow-up questions to the CBP modeling team for clarification. Unfortunately, the CBP modeling team was overwhelmed with the process of developing Phase II Watershed Implementation Plans (WIPs) and could not respond to the workgroup's questions until early 2013. An additional complicating factor was that the original discussions regarding CBWM simulation of P transport were based on model phase 4.3 outputs, but a full transition to phase 5.3.2 occurred during the process, changing simulated P loads and creating somewhat of a moving target for the workgroup to analyze. A final complicating factor is that as part of the 2010 Chesapeake Bay Total Daily Maximum Load (TMDL) development process, in which 2017 was set as the year when a midpoint assessment will be made of progress toward reaching the 2025 load reduction goals, an agreement was reached with the states in the watershed stating that no major changes would be made to the CBWM, which is the primary accounting tool in the TMDL process, before 2017. This agreement rendered the activities of the workgroup somewhat irrelevant in the near-term, as the current model is going to remain the primary accounting system until after the midpoint assessment in 2017 regardless of the findings of this workgroup. So, while the workgroup initially focused primarily on the first objective of understanding how the current model simulates P transport, the focus shifted to the second objective of providing science-based guidance for how P transport should be simulated after 2017.

Despite the delays and complicating factors and many protracted exchanges with the CBP modeling team, both objectives were addressed. One advantage of the slow progress of this workgroup is that since its formation, both objectives were partially addressed in several related efforts (some still on-going) in which workgroup participants were involved. These efforts include but are not limited to:

1. Chesapeake Bay Goal Line 2025 – proceedings 2012 (http://www.chesapeake.org/pubs/295_Meisinger2012.pdf)
2. STAC Lag Times Workshop – October 2012 (http://www.chesapeake.org/pubs/305_Hirsch2013.pdf)
3. Building a Better Bay Model Workshop – May 2013 (http://www.chesapeakebay.net/channel_files/20763/agwg_ams_workshop_recommendations_and_tasks_092413.pdf)
4. STAC Management Effects on Water Quality Trends Workshop – March 2014 (Report in prep.)
5. CBP Agricultural Workgroup Expert Panels – on-going

In all these efforts, the workings of the CBWM were/are a key consideration.

Background on P Transport from Cropland in the Chesapeake Bay Watershed

It was not an objective of this workgroup to attempt to review the literature on P transport. The participants in this workgroup, as well as many other researchers in the Chesapeake Bay watershed and throughout the country, have conducted extensive research on P transport processes as a result of the central role of P in driving eutrophication of surface waters. However, since the overall objective of this workgroup was to determine whether the simulation of P transport in the CBWM was adequately science-based to effectively guide agricultural management activities in the Chesapeake Bay restoration effort, it is necessary to consider the key drivers of P losses. To be a useful tool for developing strategies to reduce P losses and to accurately predict how management activities will affect P losses, a watershed model at any scale must contain the key drivers of P losses and capture the effect of management activities on those drivers.

STAC sponsored a major conference in 1998 to "examine issues related to agricultural P and water quality of the Chesapeake Bay watershed" (Sharpley 2000). A key concluding remark was: "The overall long-term goal of efforts to reduce P losses from agriculture to surface waters should aim to balance off-farm inputs of P in feed and fertilizer with P outputs as produce, along with managing soils in ways that retain nutrients and applied P resources." This remark highlights the dual drivers of P losses from cropland. The aim of strategies to balance P budgets is to stop the long-term buildup of soil P levels, which is known to increase the potential for both particulate and dissolved P losses. Several chapters in the proceedings (Coale 2000, Lanyon 2000, Sims 2000) document the buildup of soil P concentrations that have occurred during the last several decades as a result of intensification and spatial concentration of animal production. The second key driver of P losses identified in the summary statement deals with short-term field management practices that determine the risk of P losses directly associated with how both inorganic and organic P sources are applied. Historically, efforts to reduce short-term P losses focused on reducing tillage intensity and soil erosion. The development during the last several decades of reduced tillage and no-till crop production systems greatly reduced the potential for soil erosion. However, during the same time frame, the increasing water soluble P content of manure from concentrated animal production facilities has increased the potential for high dissolved P losses from cropland even where erosion has been effectively controlled.

More recently, STAC sponsored a conference in 2010 in an effort to identify agricultural nutrient management practices that will help meet the 2025 nutrient reduction targets put forth in the Chesapeake Bay TMDL. The proceedings (STAC 2012) contain a section devoted to P that reiterates and refines some of the points made at the 1998 STAC conference, and identifies supporting research, much of it in the Chesapeake Bay watershed, conducted since the 1998 conference. Key points from this conference relevant to the objectives of this workgroup are:

1. Unlike nitrogen (N), which exchanges readily with large atmospheric N pools, P additions to cropland are determined exclusively by fertilizer, manure, and sewage sludge applications. P removal from cropland occurs through crop harvest.

2. Relatively minor amounts of P are lost in runoff (both surface and sub-surface) from cropland in comparison to N, but much less P is required to drive eutrophication in receiving waters.

3. P losses occur very sporadically from cropland depending on precipitation patterns. Accurately determining P losses from fields and from larger watersheds requires intensive and expensive monitoring of storm flow.

4. Historically, P loss control strategies have focused on reducing soil erosion, but more recently have expanded to address dissolved P losses as the potential for dissolved P transport has been found to persist, even when soil erosion has been curtailed. This concern is especially acute where: 1) soil P levels have increased through repeated manure or fertilizer applications above crop removal with harvest, 2) poor nutrient management practices leave applied P vulnerable to loss in runoff, and 3) sub-surface transport of P represents a primary pathway of P transport.

5. Although erosion must be controlled, effective control of soil erosion by reducing tillage will not necessarily result in reduced P losses. Increases in dissolved P can more than offset reduction in particulate P losses, especially where manure is applied and erosion potential is low (Staver and Brinsfield 2001). On more well drained soils where no-till markedly reduces runoff volume, it can reduce total P losses (Verbree et al. 2010).

6. Elevated soil P levels increase the potential for P loss by increasing the P concentration of eroded soil and by increasing dissolved P concentrations in surface runoff (Staver and Brinsfield 2001), leachate (Maguire and Sims 2002), and shallow sub-surface storm flow (Kleinman et al. 2007).

7. Dissolved P is difficult to capture with traditional edge-of-field practices such as vegetated waterways and riparian buffers which rely primarily on slowing flow to allow settling of eroded particles (Lowrance et al. 1997). Alternative practices that use P sorbing materials to remove non-point P sources from water are rapidly becoming viable (Buda et al. 2012). Notably, work by Bryant et al. (2012) shows that flue-gas desulfurized (FGD) gypsum holds promise as a substrate in permeable reactive barriers (i.e., "gypsum curtains") to remove dissolved P from sub-surface drainage waters. This practice is now under consideration as a next generation conservation tool in the Chesapeake Bay watershed (STAC 2012).

8. Soil P levels above optimum levels for crop production occur primarily in areas of concentrated animal production and result from long-term manure applications at rates equal to or greater than what is needed to meet crop N needs (Sims and Vadas 1997, Swink et al. 2009). This problem has intensified with the increased concentration of animal production that is out of balance with local feed sources (Lanyon and Beegle 1989).

9. Water solubility of P varies in different applied P sources and determines short-term potential for P losses (Kleinman et al. 2005, 2011). Indeed, use of amendments such as alum (aluminum sulfate) has been shown to dramatically reduce the loss of P associated with surface applied manure and biosolids from soils with low erosion rates (e.g., pastures). However, managing P forms in applied sources does not affect the long-term accumulation of total P in soils if P is applied at rates greater than crop removal (Dou et al. 2009).

10. The potential for P loss has short and long-term components. The short-term component relates to field management practices that affect the availability of soluble P forms on or very near the soil surface. High P losses can occur on soils with low soil P levels when soluble P sources, either manure (Staver 2004, Verbree et al. 2010) or inorganic fertilizer

(Pote et al. 2006), are applied to the soil surface in no-till settings. Long-term potential for losses is increased by repeated surpluses in annual field P budgets, which result in a buildup of soil P concentrations (Kleinman et al. 2009).

11. P losses resulting from elevated soil P concentrations will decrease very slowly, since annual P crop removal rates are insignificant compared to soil P reserves on highly enriched sites (McCollum 1991, Kratochvil et al. 2006). The greater the antecedent soil P concentration, the longer it will take for draw-down strategies to take effect. Responsiveness of soil P levels to changes in management will increase as initial P levels decrease (Maguire et al. 2008).

12. Progress has been made on reducing P surpluses at farm and regional scales (e.g., McGrath et al. 2005) but watershed P loads will be slow to respond due to large soil or sediment P reservoirs (Jarvie et al. 2013, Sharpley et al. 2013).

13. Systematic monitoring of soil P is likely the most reliable approach for tracking long-term progress toward meeting P reduction goals and can be used to verify success of efforts to balance field, watershed, and regional P budgets. However, accessing soil testing information can be difficult given privacy protection precedents.

14. Hydrologic connectivity between field P sources and surface waters is a key factor driving the potential for P loss at a watershed scale. Factors affecting connectivity can take the form of variable source area hydrology in the uplands of the Chesapeake Bay watershed (Buda et al. 2009) or in the form of artificial drainage in the coastal plain (Kleinman et al. 2007). Better identifying areas of frequent overland flow generation is key to developing recommendations for P management in the uplands. Better mapping the intensity of drainage is key to identifying the potential for sub-surface P transport on the coastal plain.

There is consistency between the two STAC workshops in the stated need to address P losses due to field and regional surpluses in P budgets that result in buildup of soil P concentrations and the short-term problem of elevated risk of P losses associated with recent P applications. These two issues are the cornerstones of P-based nutrient management and reflected in the primary nutrient management planning tool employed by state and federal action agencies: the P Site Index (PSI) (Sharpley et al. 2003).

Most recent attempts to model P transport contain both short and long-term components. Sharpley et al. (2002) summarized the key elements of P transport modeling, and identified soil P concentrations and management of P applications as essential to model accuracy. An attempt to model the impact of various management strategies on P losses from agricultural land in the

New York City water supply identified both manure spreading methods and soil P concentrations as key components that needed to be considered (Walter et al. 2001). A recently developed P transport model that has gained interest in nutrient management evaluation is the Annual P Loss Estimator (APLE), an empirical model that also requires information on existing soil P concentration and P application methods to estimate annual soil P losses (Vadas et al. 2009, 2012). Empirical relationships used in the APLE model, along with routines aimed at better simulating event-based wash-off of applied P, have been incorporated into the Integrated Farming Systems Model (Rotz et al. 2009) and, most recently, the Soil Water Assessment Tool (Arnold et al. 1998). These updates dramatically improve representation of short-term P losses. And finally, the PSI, which has been widely implemented in some form during the last decade, is a simplified modeling approach that considers both short and long-term drivers of P loss from cropland to identify "critical source areas" of P loss (Sharpley et al. 2003). The PSI relies on soil P concentration and nutrient application rate, timing, method, and form to quantify the availability of field P sources to runoff and to determine the potential for P loss by factoring the propensity of runoff to connect that source with a surface water impact. To date, the PSI has better represented surface runoff and erosion as transport factors. Current efforts to improve the PSI in Maryland have focused upon a past weakness in representing sub-surface transport potential in artificially drained areas of the coastal plain.

In response to concerns over artificial drainage and sub-surface transport of P, a symposium was held at the 2013 meetings of the "Tri-Societies" (Soil Science Society of America, Crop Science Society of America, American Society of Agronomy). Drainage-mediated losses of P, either in the form of open ditches, tile drains, or both, are implicated in the accelerated eutrophication of the Baltic Sea, Lake Champlain, and Lake Erie, as well as tributaries of the intensively drained portions of the Atlantic Coastal Plain (including the Delmarva Peninsula's Chesapeake Bay tributaries). Sub-surface P losses are surprisingly common, and have been documented in tile drain effluent for many decades. The Tri-Society conference identified major limitations to the state of current models in representing sub-surface P loss, with no existing fate-and-transport model considered adequate in describing the macropore-dominated, quick-flow processes that drive P transport through soils, either laterally to drainage ditches, or vertically (leaching) to tile drains. P losses through tile drains may occur in both sediment-bound and dissolved forms, with fine textured soils equally or more highly prone to P leaching than moderate to coarse textured soils. Factors affecting sub-surface P transport include:

1. Intensity of artificial drainage (open ditches and tile drains) connecting field sources to waterways. Most sources of P are in relatively close proximity to drainage conduits and are activated in the hours/days around storm flow.

2. Soil physical properties influencing the architecture and continuity of macropores (biopores, shrink/swell cracks) connecting sources of P with drains. This is the major short-term concern following application of fertilizer or manure.

3. Soil P sorption/desorption properties influencing the availability of P to waters that rapidly flow to drains during storm flow. In soils with a high degree of P sorption saturation, a descending "front" of P can create sub-surface sources of P that can enrich drainage.

4. Oxidation/reduction processes can result in significant increases in dissolved P to drainage waters during periods of prolonged moisture saturation. This, along with P sorption saturation, is a primary factor influencing the effectiveness of managed wetlands in mitigating P losses.

5. Drainage management systems designed for control of N losses from agricultural lands can be adapted for control of P losses, but must be assessed to ensure that they do not inadvertently exacerbate certain processes (e.g., oxidation/reduction and timing of P release).

6. As with all areas of management, trade-offs must be considered. Decreasing overland flow may reduce associated P losses, but intensifying drainage activates sources within fields that may once have had little connection to surface waters.

In summary, research on P transport processes has identified three general concerns: 1) chronic over-application of P to cropland relative to removal in crop harvests that produces a soil P reservoir vulnerable to loss in runoff, 2) fertilizer/manure application management that affects the spatial and temporal availability of applied P to runoff, and 3) drainage management. Most management strategies are aimed at one of these three aspects of P loss, while most attempts to model field P losses have addressed the first two of these key drivers (soil P and management of applied sources of P).

Workgroup Findings

A detailed description of the workings of the CBWM is beyond the scope of this workgroup but the key components of the modeling process as they relate to meeting the two workgroup objectives were addressed. For practical purposes, the overall modeling process, including CBP Scenario Builder and the CBWM, does five basic things in simulating P loads delivered to Chesapeake Bay from agricultural land:

1. **Distributes P on the cropland** – Scenario Builder calculates P loading rates to cropland in model segments based on USDA data on animal numbers, literature values on P excretion rates, and model-generated inorganic P application rates. After assumptions are made regarding total P loadings to a segment, a second set of assumptions is used to determine the spatial and temporal patterns of P distribution within the segment, that is, P distribution rates to individual crop types in Scenario Builder and CBWM-specified land uses. Most notable in this component is that annual P losses are primarily a function of annual additions of P in fertilizers and manures (with fertilizer estimated as the difference between manure P and recommended P application rates) without consideration of existing soil P reservoirs or P application methods.

2. **Distributes P in soil and plant pools** – Crop growth is simulated and removes P from the soil. Assumptions regarding P sorption/desorption are used to partition applied P in different soil pools, and most importantly into readily transportable water soluble fractions. The fraction of P partitioned into water soluble pools is a key parameter that can be adjusted in the calibration process.

3. **Moves P with water and sediment** – Simulated hydrology driven by weather data sets moves sediment off of the land surface and water through the soil profile interacting with soil P pools to drive edge-of-field P losses.

4. **Modifies P in flow after it leaves the crop field** – Edge-of-field loads are adjusted to account for processes that may increase or decrease P in flow as it moves toward the Chesapeake Bay and becomes a delivered load. This component varies widely across the Chesapeake Bay watershed as edge-of-field P loads from Coastal Plain cropland may flow directly into tidal waters while edge-of-field losses from cropland in the northern and western headwaters are subject to extensive processing in stream, river, and reservoir systems before reaching the Chesapeake Bay. This process is a key step in calibrating the model-delivered P loads to match measured P losses, but introduces adjustments that make it difficult to reconcile model output with field management effects.

5. **Applies the effect of Best Management Practices (BMPs)** – The effect of management practices to reduce delivered P loads is applied in several different ways. The three main approaches that have been used are converting land from a higher loss land use to a lower loss land use category, reducing P application rates and simulating the effect on edge-of-field losses, and applying a percent reduction coefficient as a filter to edge-of-field losses.

Although the workgroup considered all components of the CBWM related to P transport, the focus was on the first two primary functions which relate directly to capturing the effect of P-based nutrient management activities intended to reduce P losses from agricultural land. While the effect of BMPs also relates directly to P losses from agricultural land, the effectiveness of individual BMPs has been reviewed extensively, and currently is the focus of numerous expert panels formed by the Chesapeake Bay Program Agricultural Workgroup. In addition, the workgroup focused most of its efforts on topics where there appeared to be the greatest need for improvement. Although the current modeling approach will be used through 2017, it was necessary to address objective 1, that is, to understand the current modeling approach in order to address the second objective which is to make recommendations for improvement. The workgroup did not attempt to assess whether current approaches to track land use, crop production, animal numbers, or manure nutrient loads were accurate, but stresses that an accurate accounting system for tracking nutrient flows is critical if a proxy approach is going to be used to estimate soil P concentrations. In addressing the second objective, recommendations for changes to the modeling approach after 2017 are divided into the two basic driver components of P losses that are subject to management, i.e., the long-term issue of overall soil P levels and the short-term issue of management of P applications. In addition, several general recommendations are provided, plus recommendations for future data needs to support suggested changes to the modeling approach.

Modeling Recommendations Related to Soil P:

1. **Account for existing soil P reservoirs on a segment-by-segment basis –** As soil P levels increase, desorption of soil P becomes a dominant term that can sustain P losses independent of annual P balances for many years, depending on the extent of the reservoir. Failure to account for this existing reservoir overestimates the importance of annual P inputs in modeled exports, and results in overly optimistic projections of reduced P losses as a result of adjustments in annual P inputs.

2. **Track segment P balances to determine whether soil P reservoirs are increasing or decreasing** – Since soil P can increase or decrease on decadal time scales the ultimate accounting tool for tracking the impact of nutrient management efforts is segment soil P balances.

3. **Describe the temporal dynamics of the effects of drawdown/build-up of soil P reservoirs on P losses –** Watershed modeling activities create expectations of responses that will be detected by river input and Chesapeake Bay water quality monitoring efforts. A temporal component for P losses is needed in the watershed model to reconcile management activities with monitoring data.

Modeling Recommendations Related to Management of P Inputs:

1. **Account for different P application methods, including whether manure is left on the soil surface, incorporated by tillage or incorporated with low soil disturbance full-width applicators, or injected in bands** – Most P-based nutrient management approaches encourage or require either incorporation or injection of applied P to reduce short-term losses. Current modeling efforts do not address the impact of surface applied nutrients nor do they capture the benefits of injection or incorporation.

2. **Apply manure at rates and times based on watershed or regional information –** Limited manure storage is a key problem for large animal production facilities that often are forced to field apply manure temporally disconnected with crop needs. The CBWM currently does not appear to accurately represent actual timing of applications, and therefore cannot simulate the benefits of major efforts to reduce out-of-sync manure applications. This probably is a more critical issue for modeling nitrate leaching losses but also is critical for correctly simulating the seasonality of P losses, especially where manure is not incorporated.

3. **Improve representation of practices aimed at reducing P runoff potential by adjusting the <u>timing</u> of P applications –** A key component of nutrient management (one of NRCS's "4Rs") is to reduce the risk of nutrient loss by timing applications as close to crop uptake as possible. Major resources have been committed to expanding manure storage to make field applications more in sync with crop needs. Although generally more of a focus of efforts to reduce N leaching, adjustments in timing of applications also affect potential for P losses.

4. **Account for P stratification that develops in soils in continuous no-till** – Surface runoff P concentrations are highly influenced by nutrient availability in uppermost soil horizons. Long-term no-till field management can lead to stratified soil P concentrations that lead to higher dissolved P losses that can offset reductions in losses of particulate P.

5. **Account for interaction between tillage and manure application on potential for P losses as particulate and dissolved P fractions in overland and sub-surface flow –** This point is related to recommendations 1 and 3, and underscores the need to link practices to a specific land parcel where interaction is critical rather than distribute them evenly across a segment. While no-till has potential for reducing particulate nutrient losses, manure applications on no-till fields can increase soluble nutrient losses in runoff, and it is critical to capture this effect, and efforts to minimize it.

General Modeling Recommendations:

1. **Identify the fraction of P losses associated with short versus long-term management activities –** Knowing the fraction of existing or baseline P loads due to various management activities is helpful for guiding P loss strategies and also for setting reasonable expectations for the temporal trajectory of reductions in delivered P loads. Identifying the role of storm flow transport of P stored in stream channels and reservoirs also is critical where it comprises a significant fraction of P loads delivered to the Bay. This approach sets the stage for being able to link load reductions to specific management efforts.

2. **Model function should be capable of scaling down to provide segment and field guidance on drivers of P losses –** This is a spatial corollary to recommendation 1 that supports the overall need for a mechanistic narrative at the management unit scale that makes it clear to watershed managers and farmers what factors are driving P losses and how different management options will change P losses.

3. **Shift away from using model-generated values and proxy data for key input parameters –** Several factors critical in determining nutrient losses from crop fields, such as the amount of inorganic P applied and the timing and spatial distribution of manure application, are dictated in the model rather than guided by watershed or regional information sources. It is recognized that early in the Chesapeake Bay restoration effort model-generated or proxy data may have been the only options, but opportunities now exist for use of much higher quality critical data. In addition, using the data that are actually needed in the model can reduce the need to collect and interpret proxy data.

4. **Consider changing weather patterns associated with climate change** – The increase in weather variability and the recurrence of growing season drought (affecting land cover, hence erodibility) and high intensity/duration storms (generating erosive runoff from larger areas of a watershed) have severe implications to watershed P loss. Improvements to spatial and temporal representation of P loss dynamics within the CBWM will help with developing strategies to better address these risks.

5. **Better represent and report uncertainty in data sources and model output** – Better representing the uncertainty of a model is a universal concern, one that is not restricted to the CBWM. A more accessible and transparent reporting of sources of uncertainty should be a perennial goal.

6. **Differentiate between surface and sub-surface transport pathways of P loss and account for the role of drainage intensity** – Current modeling ignores the role of ditches and drains in delivering field sources of P to tributaries of the Chesapeake Bay.

In part, this reflects lack of consideration of sub-surface P transport which is highly influenced by drainage intensity.

Future Data Needs to Support Recommended Changes in Modeling Approach:

1. **Baseline soil P levels –** Given the key role of desorption of soil P in determining P losses from cropland in the present and future, and the wide range in soil P concentrations throughout the watershed, it is critical that future modeling efforts include this component of P transport. Although such data sets are not currently available in a readily usable format, collection of information on soil P is a routine practice and opportunities exist for estimating the spatial distribution of soil P. Long-term options, with advancement of global positioning and precision agricultural data collection systems for spatial tracking of soil P concentrations, will become more feasible.

2. **Information on P application methods** – How P sources are applied to cropland is a key driver of short-term P losses and a key component of P Site Indices and recently developed P field loss models. This information is critical for understanding the relative importance of application methods in driving current P losses, the potential for reducing those losses, and progress achieved toward P loss reduction goals for cropland.

3. **Spatial and temporal data on manure and biosolid applications –** While total segment manure P loads based on animal numbers may be accurate, the distribution of P losses can be modeled more accurately and the potential for targeted management strategies increased if simulated manure applications more closely match actual application patterns. This information will become more important as P-based nutrient management drives greater distribution of manure away from animal production facilities.

4. **Inorganic P application rates –** In current simulations, inorganic P is applied to cropland any time the total annual manure P application in a segment falls below crop needs, without regard for soil P reserves. A fundamental factor for P-based nutrient management, and why soil P data are routinely collected, is that P applications are unnecessary if soil P concentrations are sufficient for optimum crop production. This makes the current simulation approach incapable of utilizing soil P reserves and capturing one of the primary impacts of P-based nutrient management.

5. **More systematic storm water sampling in predominantly agricultural watersheds for use in model calibration –** Cropland P losses occur predominantly during storm flow, which is highly variable in time and space. While low intensity or synoptic sampling strategies are useful for characterizing a major fraction of watershed N losses,

much more rigorous sampling approaches will be needed to characterize P loads with a high degree of certainty.

6. **Improved mapping of features that restrict water infiltration and promote "saturation excess" runoff** – Current Soil Survey Geographic Database (SSURGO) maps reflect historical agronomic mapping priorities and may miss important features, such as subsoil restrictive layers that perch water. Pennsylvania NRCS has developed techniques for improving mapping that can be brought into runoff modeling and better spatially represent where P losses occur.

7. **Improved mapping of drainage intensity as an indicator of hydrologic connectivity and P delivery potential –** Drainage ditches (roadside, field) and tile drain lines all serve as conduits for P loss that can bypass natural and many installed filters. Accounting for variations in drainage intensity across the watershed will help in reconciling differences between edge-of-field and monitored P loads and for identifying areas most prone to sub-surface P losses.

Comment on Estimates of 1985-2000 Reductions in P Loads

The origins of this workgroup originate from discussions about CBWM projections of major reductions (>60 %) in delivered P loads from cropland in the LES of Maryland from 1985-2000, prior to widespread implementation of P-based nutrient management and changes in poultry feed designed to reduce manure P content. Reductions in P losses from LES cropland projected with the current version of the CBWM are more modest (~40 %), but still sufficient to meet the 2017 TMDL interim goal. The 1985-2000 total P contained in poultry manure generated in LES counties is estimated to have been well in excess of annual removal rates in crop harvests (Mid-Atlantic Water Program, http://www.mawaterquality.agecon.vt.edu/) suggesting that soil P concentrations continued to increase during this period, although probably more slowly and more generally as nutrient management efforts encouraged distribution of poultry manure across more acres and inorganic P use declined. Slowing the rate of soil P increase, which probably did happen on the LES from 1985-2000, would not be expected to decrease the potential for P loss due to desorption of soil P. This leaves short-term management practices as the only possible cause of reduced P losses from LES cropland during this period. 1985-2000 also was a period of increased adoption of no-till practices, which has been shown to increase total P losses where erosion rates are low (Staver and Brinsfield 2001). Shallow storm flow of desorbed P has been shown to be a major mechanism of P loss from LES cropland with elevated soil P concentrations (Kleinman et al. 2007, Vadas et al. 2007). Improved manure storage is calculated as the cause of about half of LES P reductions from cropland in current CBWM projections. Mechanistically, it is difficult to develop a scenario in which P losses from LES cropland could have decreased from 1985-2000 to the extent projected by the CBWM. Unfortunately, there are few water quality data sets that can be used to verify changes in P loads on the Eastern Shore during that period or more recently. The workgroup did not consider the specifics of projections of past P losses from other segments in the Chesapeake Bay watershed.

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