Implications of Phosphorus Treatment of Drinking Water for Significant Wastewater Treatment Plants in the Chesapeake Bay Watershed Portion of Virginia

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Abstract

Phosphorus, in the form of orthophosphate, is added to drinking water in approximately 40% of United States (U.S.) public water systems as a lead corrosion control inhibitor. Typical phosphorus residuals are approximately 0.2 - 1.0 mg/L as P. However, in other countries, such as the United Kingdom, roughly 90% of drinking water systems utilize phosphorus corrosion control inhibitors; with residuals nearly double those of the United States. Discussion has arisen over whether the U.S. should adopt corrosion control polices that mirror those of the United Kingdom (*i.e.*, more drinking water systems adding phosphate and residual levels doubling). However, little is known about the effects this change would have on wastewater treatment plants (WWTPs) treating the amended drinking water.

Phosphorus is a pollutant that causes eutrophication and other problems to natural water bodies. As natural water bodies have deteriorated in quality, the U.S. Environmental Protection Agency (USEPA) has restricted phosphorus discharge from WWTPs. This is especially apparent within the Chesapeake Bay watershed, where WWTPs follow some of the most stringent nutrient control policies under the 2010 Chesapeake Bay total maximum daily load (TMDL). A survey of significant WWTPs within the Virginia portion of the Chesapeake Bay Watershed was conducted to investigate the effects increased phosphorus loading to drinking water residuals of 2 mg/L as P from phosphorus corrosion control inhibitors would have on WWTP treatment and total solids disposal practices.

The most common form of advanced treatment is aluminum sulfate addition (73% of WWTPs) and landfills are the most common total solids disposal strategy (72% of WWTPs). The most common change to advanced treatment resulting from increased phosphorus loading was an increased addition of aluminum sulfate (88%), and the two most common changes to total solids disposal were an increase in the amount of total solids being disposed (83%) and an increase in the phosphorus concentration of the total solids being disposed (33%). The average annual cost increase resulting from phosphorus loading was $22,867/million gallons a day (MGD) for changes to advanced treatment and $17,164/MGD for changes to total solids disposal. Annual statewide cost increases from phosphorus loading were approximately $13.4 million from changes to advanced treatment and $10 million from changes to total solids disposal for a total annual statewide cost of approximately $23.4 million.

The large standard deviation of the costs, both current and predicted, is an indication that there is an intrinsic variability of plant costs within the WWTP industry. This highlights the importance of water systems managers conducting plant-specific analyses before making any changes to the water system, including increasing phosphorus treatment at drinking water plants. While results showed that WWTPs can treat a phosphorus increase to 2 mg/L as P without violating TMDL permit levels, there will be a cost that every WWTP must determine and find a way to fund.

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1.0 Introduction

Municipal drinking water systems, as well as private homes, throughout the U.S. have lead pipes, solder, and fixtures still in use. In order to reduce the lead exposure to the consumer, drinking water is treated at the drinking water plant in order to reduce the corrosiveness of lead. One of the more common treatments is to add orthophosphate. Increasingly strict requirements for drinking water quality have included mandates to lower the lead concentrations, and, as a result, drinking water treatment requirements have changed and become more effective. One proposed change is to increase the amount of phosphorus that drinking water plants add to the water. However, concerns have arisen over the changes necessary at wastewater treatment plants (WWTPs) to treat the increased phosphorus load and prevent it from harming receiving water bodies.

The United States (U.S.) Environmental Protection Agency (USEPA) promulgated the Lead and Copper Rules (LCR) on June 7, 1991, to control lead and copper levels in drinking water coming out of consumer's taps (USEPA, 1991). The rule created the National Primary Drinking Water Regulation (NPDWR) which established requirements for drinking water utilities to engage in a variety of practices to reduce lead exposure, including optimized corrosion control treatment (OCCT), source water treatment, lead service line replacement, and public education (USEPA, 2012). Water utilities are obligated to implement these requirements if they are over a certain size (serve over 50,000 consumers) or if they exceed the Action Levels (ALs) set by the NPDWR (the ALs for lead and copper are 1.3 and 0.015 mg/L, respectively, measured in the 90th percentile of the samples).

The LCR was revised in 2000, 2004, and 2007 with little substantive change in the fundamental rule structure (USEPA, 2000, 2004, 2007a). A fourth revision was recently made in January 2014, during which discussion occurred over how OCCT is defined and how compliance with OCCT regulations should be determined (Cope et al., 2013, see appendix A). While changes to phosphorus treatment were not included in the revisions, discussion over changing phosphorus usage has continued.

1.1 Phosphorus Corrosion Control Inhibitors

While copper regulations are not as stringent as lead, permissible lead levels are so low that small changes (such as slightly corrosive water standing in contact with a lead pipe for a short time) can create lead concentrations considered health risks. It is because of this high sensitivity of lead pipes to corrosion that drinking water plants and drinking water distribution networks (hereafter referred to as water systems), are advised to reduce lead release by use of a corrosion control inhibitor (Shock, 1999).

There are three corrosion control strategies commonly used: adjusting pH and alkalinity, developing an insoluble lead scale by maintaining free chlorine residuals throughout the distribution system, and addition of orthophosphate-based corrosion inhibitors (Brown et al., 2013). The distribution of these practices varies nationally, with approximately a third of all utilities implementing phosphate addition (Cope et al., 2013). Phosphate inhibitors are used to create a protective insoluble phosphate-compound layer on the inside of pipes to prevent lead and copper from going into solution (a lead orthophosphate layer in the case of lead pipes).

The concentration of orthophosphate initially added to the water system is two to three times higher than the normal concentration, and is known as the "passivation dose."

This creates the protective, insoluble layer on the metal pipe. The dose necessary to maintain layer is known as the “maintenance dose.” It is important that the maintenance dose be added continuously and at a steady concentration (Shock, 1999). The maintenance dose will also depend upon a variety of water system characteristics, mainly pH and dissolved inorganic carbon levels (Shock, 1999), and identified secondary impacts such as limits on phosphorous loading at WWTPs (USEPA, 2011a).

The USEPA currently recommends that a minimum residual concentration of 1 mg/L as P (approximately 3.0 mg/L as PO_4) be maintained in the distribution system (USEPA, 2003a). However, differences exist between typical residuals and the USEPA recommendation. Each water system is given an individual OCCT permit by respective state regulating agencies that are in turn regulated by USEPA. This permit accounts for the water characteristics that are unique to every water system, and prescribes an *optimal* concentration of phosphorus that reduces lead corrosion without causing more severe secondary effects. Previous studies have found typical residuals in the U.S. between 0.2-1 mg/L as P (Brown et al., 2013).

Policy makers have been discussing increasing the required residual concentration for some time, such as to levels used in the United Kingdom where approximately 95% of water utilities add orthophosphate, and minimal residuals are as high as 2 mg/L as P (Brown et al., 2013; Cope et al., 2013; CIWEM, 2011). Studies have noted that wastewater plants with required total phosphorus removal would have treatment costs affected by orthophosphate-based corrosion inhibitors at concentrations of 1-2 mg/L as P (Brown et al., 2013).

Previous studies have found that major changes to water chemistry (such as those associated with alterations to corrosion control practices) are usually immediately followed with detrimental effects, including an increase of metal release rates, turbid waters, and other problems (Shock, 1999). Changes to water chemistry are extreme when completely switching from one corrosion control program to another (for example, from pH and alkalinity control to phosphate-based corrosion control inhibitors). Water utilities, and regulating policy makers, are consequently cautious when altering corrosion control programs and tend to follow one corrosion control program once it has begun.

Therefore, if changes were made to the phosphate corrosion inhibitor regulation, it can be reasonably assumed that only water treatment plants currently employing phosphorus addition will be forced to increase their phosphorus addition. Previous studies have found that, nationally, approximately 40% of water systems utilize phosphorus addition for OCCT (Cope et al., 2013). Assuming that Virginia resembles national practices, we could assume that only 40% of the WWTPs would experience an increase in phosphorus load received. In contrast, if regulations change to mirror the U.K. and 95% of water systems utilize phosphorus addition, we could assume 95% of Virginian WWTPs will experience a change in the amount of phosphorus they receive.

1.2 WWTP Phosphorus Treatment

Elevated levels of phosphate in natural waters, especially freshwater, have been known to have deleterious effects, such as eutrophication. Phosphate can enter natural waters from wastewater treatment plants (WWTPs). The USEPA has previously reduced these effluents by decreasing the amount of phosphate entering WWTPs. Examples include the elimination of phosphorus from laundry detergents in the 1980s, and the more recent reduction of phosphorus from dishwashing detergents.

Advanced treatment methods (also known as tertiary treatments) have improved the removal of phosphorus during wastewater treatment. These techniques are employed in addition to the normal secondary treatment processes used by all WWTPs. Advanced treatment methods include enhanced biological phosphorus removal (EBPR), chemical treatment, and physical separation/filtration. EBPR includes an anaerobic tank, with bacteria particularly effective at removing phosphorus, placed before the aeration tank used in normal secondary treatment. Physical treatment involves increased filtration and physical separation of contaminants after secondary treatment. Finally, chemical treatment involves the application of additional chemicals during secondary treatment that aid in the coagulation and filtration of contaminants (USEPA, 2007b).

Advanced treatment methods are often necessary, because typical secondary treatment plants cannot reach discharge limits in areas of sensitive waters (Schuler, 1996; USEPA, 2008). A previous study conducted in USEPA Region 10, home to many sensitive freshwaters, found that when utilized, advanced treatment could consistently produce effluent with phosphorus concentrations of approximately 0.01 mg/L as P. However, the treatments are very expensive (USEPA, 2007b). The study also found that there were a number of treatment methods, as well as combinations of treatment methods, used to achieve discharges of low P concentrations; without one form of treatment dominating. However, WWTPs utilized some form of chemical treatment, normally in tandem with another advanced filtration treatment. These findings are consistent with those from a study in North Carolina that found that while advanced filtration was often necessary for discharges to meet low P concentrations, there were a number of other advanced treatments, mostly chemical treatments, used along with advanced filtration (DeBarbadillo et al., 2009).

Chemical phosphorus removal has the advantage of being much simpler than biological treatment, with a lower up-front capital cost. The two most common techniques for chemical phosphorus removal are the addition of aluminum sulfate and ferric chloride. Both are coagulants and decrease the phosphate concentrations through removing the phosphate from the mixed liquor to the wastewater sludge, as well as increasing the effectiveness of filtration. The capture of phosphorus is highly dependent upon pH, with USEPA stating that optimal pH for aluminum sulfate addition is between 5.5 to 6.5 and between 4.5 to 5.0 for ferric chloride addition (but acknowledges the latter is unrealistically low).

The costs of chemical treatment will vary from plant to plant. Upfront capital costs include pumps and chemical feeds, storage tanks, chemical treatment buildings, and various miscellaneous handling and storage equipment. The operations and maintenance costs for aluminum sulfate and ferric chloride phosphorus treatment systems were determined in 2006 for Minnesota WWTPs. These operation and maintenance costs included chemicals, power, labor, and sludge disposal. The aluminum sulfate cost ranged from $0.06 to $0.20 per pound of liquid aluminum sulfate, while ferric chloride costs ranged from $0.14 to $0.21 per pound of liquid ferric chloride as of the spring of 2005 (MPCA, 2006). Aluminum sulfate is safer and easier to handle than ferric chloride, as well as less corrosive.

The disposal of biosolids and sludge produced from WWTP treatment is regulated through the USEPA Biosolids Rule (USEPA, 1993). Biosolids are considered to be the organic solids precipitated during wastewater treatment, while sludge is the inorganic solids. These two solids are often combined, treated, and disposed of together, and the term "total solids" will be used hereafter to refer to combined biosolids and sludge. The Biosolids Rule specifies three broad categories of disposal: land application, surface disposal (most commonly landfills), and incineration. Lately, the composting of total solids has become more common. Land application involves the use of total solids to either condition soil or use as a fertilizer and is the most stringently regulated. Regulation focuses on pathogen and pollutant (which includes phosphorus) concentrations. Every site to which total solids are applied has its specific phosphorus-uptake capacity calculated, and the amount of phosphorus applied to the site must not exceed this capacity. Total solids disposal to landfills, incineration, and composting do not have phosphorus-concentration regulations.

1.3 Chesapeake Bay TMDL

With new technological advances available, USEPA has continued to constrict discharge limits in areas of sensitive receiving waters. One such sensitive area has been the Chesapeake Watershed. In 2010, a Total Maximum Daily Load (TMDL) was issued for the watershed. A TMDL is a regulatory term in the U.S. Clean Water Act that sets a permissible level of a contaminant that a body of water can receive while still meeting water-quality standards. The standards for establishing TMDLs and issuing permits were first published by the USEPA in 1992. Permits are issued by state agencies and USEPA through the National Permit Discharge Elimination System (NPDES). State agencies and

USEPA consequently used TMDLs to regulate industrial point sources of pollution. In the past decade, use of the TMDL was broadened to allow for watershed-scale efforts. These efforts have involved applying TMDLs to municipal WWTPs.

The Chesapeake Bay Watershed TMDL sets limits for phosphorus, nitrogen, and sediment, creating pollution limits necessary to meet applicable water-quality standards in the Bay and its tidal rivers and embayments. The TMDL sets a phosphorus limit of 12.5 million pounds of phosphorus per year for the Bay and its tributaries, a 24% reduction from pre-2010 levels. The phosphorus limit is split by jurisdiction and tributaries, with all having an individual TMDL. All pollution control measures are expected to be in place by 2025, with 60% of actions completed by 2017 (USEPA, 2010).

As of 2009, annual discharge of phosphorus to the Chesapeake Bay was approximately 16.4 million pounds. Moreover, Virginia dominates the phosphorus load, contributing 43% (approximately 7 million pounds per year) of the phosphorus entering the Bay. Of all the phosphorus entering the Bay, approximately 24% comes from wastewater sources. There are 483 "significant" wastewater facilities within the Chesapeake Bay's watershed – 402 are municipal wastewater facilities and 81 are industrial wastewater facilities (USEPA, 2011b). The definition of a "significant" wastewater facility varies from state to state, but approximately 95% of all wastewater discharge comes from these significant sources (USEPA, 2008). The 2009 estimate for phosphorus loads from municipal wastewater facilities was 2,604,509 lbs/yr, while industrial wastewater facilities contributed 1,270,539 lbs/yr (USEPA, 2010).

There are 101 significant municipal wastewater facilities (herein referred to simply as WTTPs) within the Virginia Chesapeake Bay watershed (USEPA, 2010). The

Virginia classification of wastewater plants as significant or non-significant is unique because, unlike any other state, there is both a spatial and temporal distinction within the size categories. Significant wastewater plants above the Fall Line (the border of the Piedmont and Tidewater regions) in Virginia are defined as those with designed flow rates above or equal to 0.5 million gallons per day (MGD), and those below the Fall Line are defined as those with designed flow rates above or equal to 0.1 MGD. Meanwhile, all facilities built after the implementation of the Chesapeake Bay TMDL simply need flow rates greater than or equal to 0.04 MGD to be designated as significant (USEPA, 2010). While there are Virginia WWTPs of similar size to the significant WWTPs described above but outside of the Chesapeake Bay watershed (these are located in southern and southwest Virginia), these are not included within the Chesapeake Bay TMDL and are not represented within this paper. For rest of the paper the use significant WWTPs will solely refer to Virginia WWTPs located within the Chesapeake Bay watershed.

1.4 Research Objective

The increased addition of phosphorus in water systems will reduce lead concentrations in drinking water. However, this benefit may come at a cost to WWTPs that have to treat the added phosphorus. To investigate what this cost to WWTPs may be, it is necessary to understand current phosphorus treatment practices and the effects an increase in drinking water phosphorus residual would have on these practices. To this end, a survey was conducted on Virginia's significant WWTPs. The survey assumed an increase of drinking water phosphorus residual to 2 mg/L as P from phosphate-based corrosion control inhibitors. It inquired about present-day phosphorus treatment and total solids disposal, as well as changes and costs to treatment and total solids disposal associated with the aforementioned increase. The results describe phosphorus treatment capabilities of Virginia's WWTPs. They also provide individual WWTPs an idea of expected treatment changes and the related costs, and inform Virginia state regulators about the statewide costs associated with regulatory changes.

2. Methods
2.1 Survey Creation and Administration

A survey was conducted in order to collect information about the operations of WWTPs. The survey consisted of two parts. The first part focused on current conditions and practices, and the second part focused on changes to these conditions and practices that would occur as a result of an increased addition of phosphate-based corrosion control inhibitors to realize a residual drinking-water concentration of 2 mg/L as P. The full survey can be found in Appendix A. The following were the main topics included within the survey:

- Whether wastewater entering WWTP is treated with phosphate-based corrosion control inhibitors.
- Current secondary treatment practices.
- Current advanced treatment methods used to remove phosphorus and associated costs.
- Current total solids disposal.

The following questions were in reference to an increase of water system residual from phosphorus-based corrosion control inhibitors to 2 mg/L as P.

- Changes to the plant's advanced treatment, and associated costs, necessary to meet TMDL.
- Total solids treatment and disposal changes, and associated costs.

All WWTPs listed as "significant" municipal wastewater plants under the Chesapeake Bay TMDL and located in Virginia (figure 2.1.) were sent an e-mail inviting participation in the survey. Only WWTPs that are within the Chesapeake Bay watershed portion of Virginia are included in this list (excluding WWTPs of similar size in southern and southwest Virginia). However, for the remainder of the paper significant Virginia WWTPs located within the watershed will simply be referred to as significant WWTPs.

Appendix Q of the Chesapeake Bay TMDL provides a list of significant WWTPs, as well as their NPDES permit numbers, coordinates, and discharge volumes (USEPA, 2010b). These NPDES numbers were then used to gather accurate contact information (phone numbers, emails, and utility ownership) from the Virginia Department of Environment Quality (VDEQ) for each significant WWTP (VDEQ, 2013). The VDEQ database did not provide complete contact information for all WWTPs and lacked any information for three WWTPs. For those that were missing emails, phone calls were made to the respective utilities or municipalities to ascertain contact information and an appropriate email address.

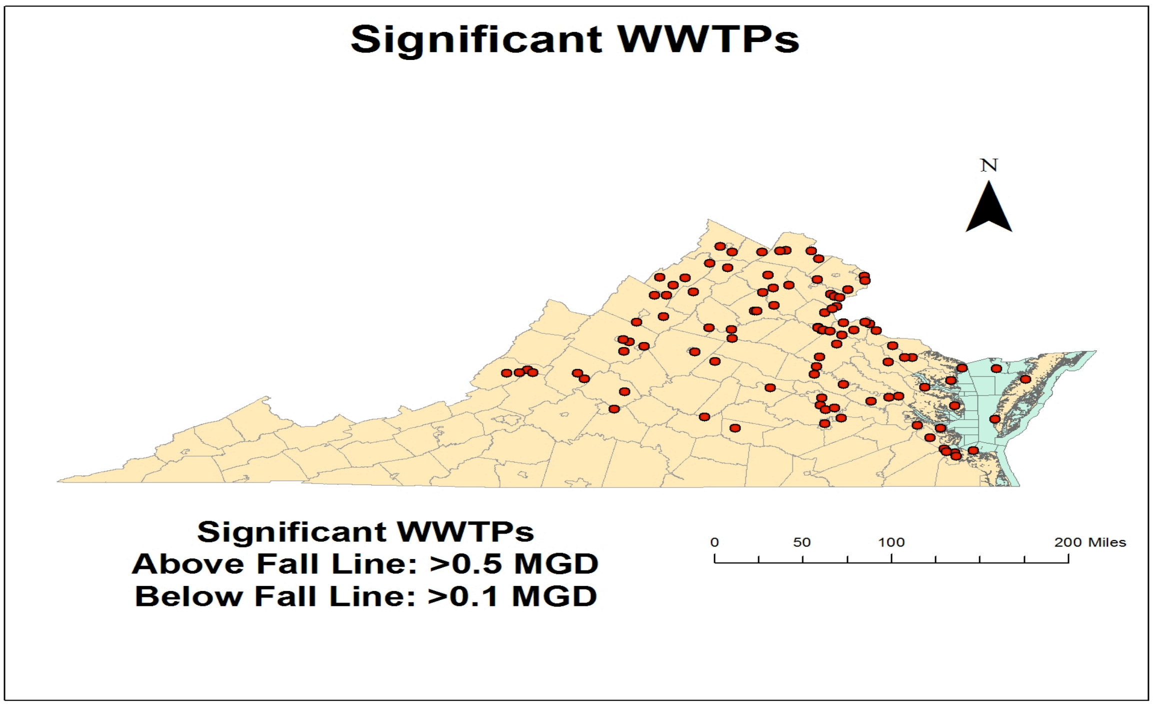

Figure 2.1. Figure shows the distribution of significant WWTPs located within the Virginia portion of the Chesapeake Bay Watershed. WWTPs included were those with coordinates available through the USEPA Chesapeake Bay TMDL, appendix Q. The coordinates were plotted via ArcGIS using the NAD83 datum and transverse Mercator projection.

The survey pool was contacted via email in December 2013 and January 2014. The email consisted of background information about the present survey, a description of the survey, and url links to both the survey on current conditions and practices and the survey on changes anticipated due to an increase in phosphorus concentrations in drinking water. Participants recorded responses by clicking the aforementioned links and going through SurveyMonkey®. Participants that did not respond within the first month (December 2013) were contacted a second time by telephone. Contact for each plant was verified and participants were reminded of the survey. A third reminder phone call was made in the middle of January for all WWTPs that had yet to respond via emails and participate in the survey, and emails were sent to those that had responded via email but had not completed the survey. The survey was closed at the beginning of February 2014, and responses were collected.

2.2 Response Analysis

The representativeness of the respondent pool relative to significant WWTPs in Virginia as a whole was examined by visually comparing frequency analyses of discharge rate among the respondent population and significant WWTPs in Virginia. Discharge magnitude was chosen because it is a good indicator of WWTP treatment processes and characteristics. The histograms of discharge sizes of Virginia significant WWTPs and survey respondent WWTPs are shown below (figure 2.2.). The distribution of the two populations approximate each other and demonstrate that the respondents of the survey are representative of Virginia significant WWTPS as a whole. Many costs were also normalized using WWTP discharge, expressed as million gallons per day (MGD). Some costs were described as negligible or minimal, and for calculation purposes were considered to be $0.00, in contrast to most costs which were thousands to hundreds of thousands of dollars.

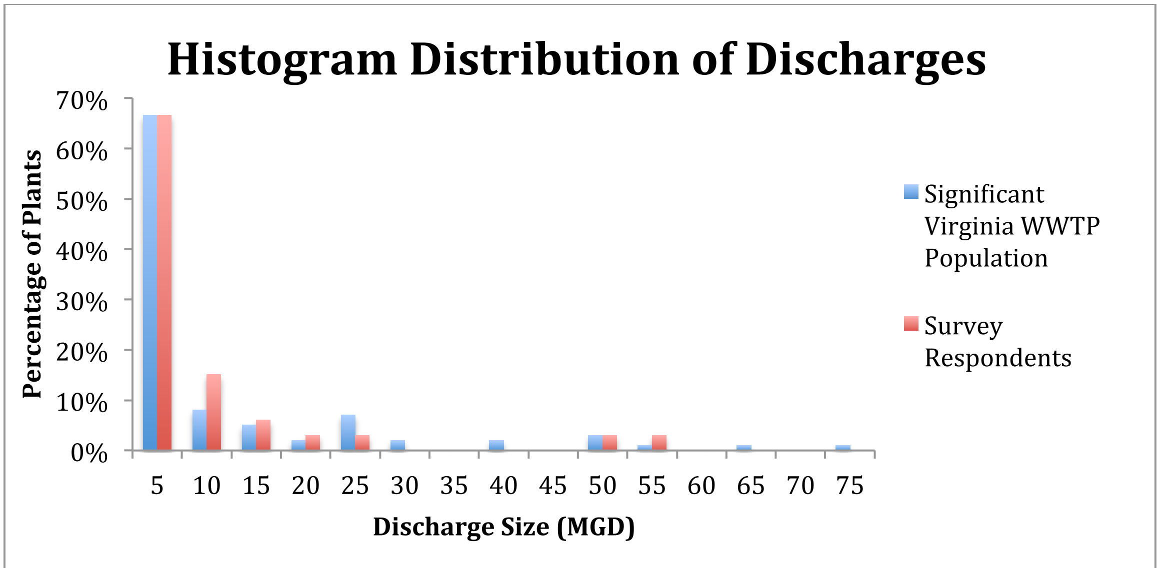

Figure 2.2. Figure shows the distribution of discharge sizes for significant Virginia WWTPs and survey respondents.

3. Results

A total of 34 WWTPs responded to the survey, representing a 34% response rate of the total population of the significant municipal WWTPs listed by USEPA in Virginia. Thirty-three WWTPs provided information on whether incoming drinking water to the WWTP is currently treated with phosphate-based corrosion control inhibitors. Eleven respondents (33%) indicated that the wastewater entering the WWTP is treated, and 22 of 30 (66%) WWTPs indicated incoming drinking water is not treated. Of the eleven WWTPs indicating incoming drinking water was treated, 6 (55%) provided information on the drinking water system residual. The average residual was 0.6 mg/L as P.

All responding WWTPs provided information on secondary treatment. Activated sludge and the addition of aluminum sulfate are the most common forms of secondary treatment (figure 3.1.). All but one responding WWTP provided information on advanced treatments usage. Aluminum sulfate addition dominated the type of advanced treatment employed (figure 3.2.). Notably, 18% of WWTPs do not have any advanced treatment.

Only 18 WWTPs provided detailed information on the up-front, installation costs of advanced treatments. Costs varied from thousands to tens of millions of dollars. The average cost was \$9.9 million with a standard deviation of \$13.8 million (table 3.1.a.). The descriptions of advanced treatment varied widely, ranging from small portions of infrastructure (e.g. “pipes and plumbing”) to specific treatment types (e.g. Aqua-disc installation) to the entire wastewater plant. Not all of the specific costs, however, were specific to phosphorus removal. Four responses included costs associated with nitrogen removal, while two responses specified that the advanced treatment was necessary for both phosphorus and other nutrients (appendix C.).

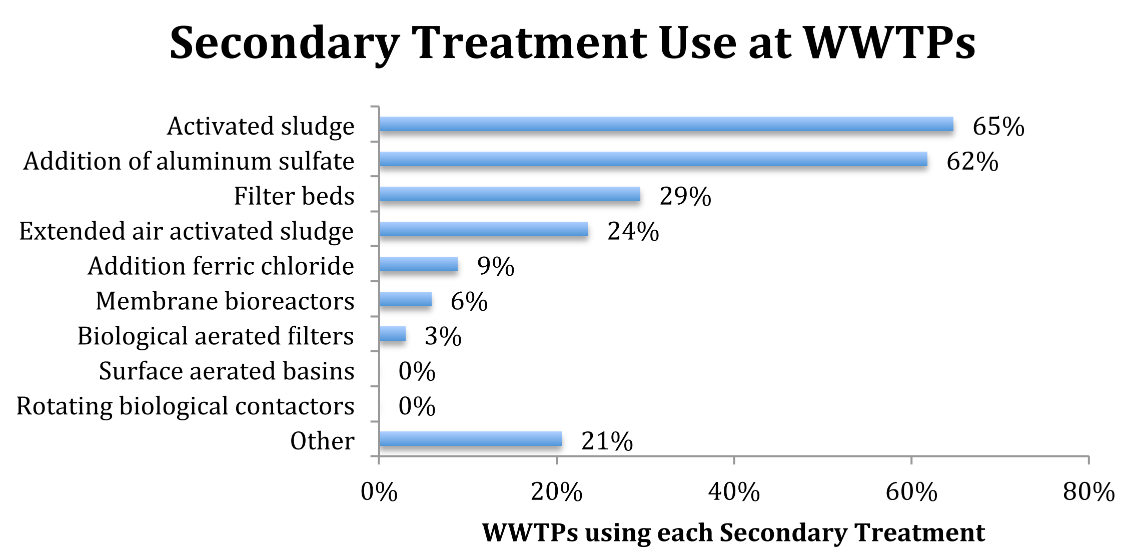

Figure 3.1. Percent usage of secondary treatment types for significant WWTPs in Virginia. A single WWTP can use multiple treatment types. Percentages based on 34 WWTP responses.

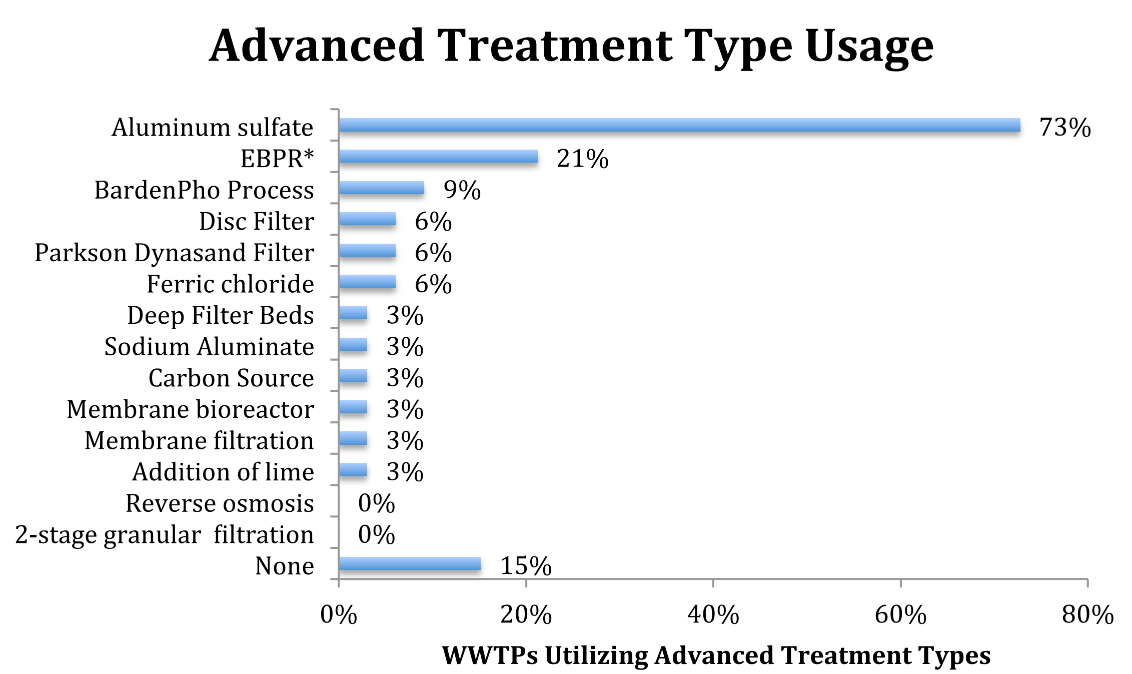

Figure 3.2. Percent usage of advanced treatment types for significant WWTPs in Virginia. A single WWTP can use multiple treatment types. Percentages based on 33 WWTP responses.

*EBPR stands for Enhanced Biological Phosphorus Removal

	Costs	
	3.1.a Current Advanced Treatment	
	Up-front/Installation	**Annual/Maintenance**
Total Cost to Individual WWTP ($)	Average: 9,928,058	Average: 113,396
	Standard Deviation: 13,592,509	Standard Deviation: 247,122
Normalized Over Daily Disharge ($/MGD)	Average: 3,018,157	Average: 32,227
	Standard Deviation: 3,447,863	Standard Deviation: 26,084
	3.1.b.Changes to Advanced Treatment	
	Up-front/Installation	**Annual/Maintenance**
Total Cost to Individual WWTP ($)	Average: 9,971,966	Average: 45,063
	Standard Deviation: 15,626,592	Standard Deviation: 82,538
Normalized Over Daily Disharge ($/MGD)	N/A	Average: 22,867
	N/A	Standard Deviation: 26,914
	3.1.c.Changes to Total Solids Disposal	
	Annual/Maintenance	
Total Cost to Individual WWTP ($)	Average: 7,366	
	Standard Deviation: 7,256	
Normalized Over Daily Disharge ($/MGD)	Average: 17,164	
	Standard Deviation: 27,721	

Table 3.1. Costs of current advanced treatment (3.1.a.), costs to advanced treatment due to an increase of phosphate-based corrosion control inhibitor dosage to 2 mg/L as P (3.1.b.), and costs to total solids disposal due to an increase of phosphate-based corrosion control inhibitor dosage to 2 mg/L as P (3.1.c.) to significant WWTPs in Virginia. Not enough respondents were available to normalize up-front charges to advanced treatment (3.1.b.). Percentages are based on 23, 20, and 15 WWTP responses for 3.1.a., 3.1.b., and 3.1.c., respectively.

Approximately half of the variation in costs can be explained by discharge size, with a coefficient of determination (r^2-value) of 0.48 between the plant discharge size and up-front/installation costs. The average normalized cost was $3.0 million/MGD, with a standard deviation of $3.4 million/MGD (table 3.1.a).

Annual maintenance costs of advanced treatment were reported by 23 WWTPs. The average was $113,396, with a standard deviation of $247,122. Reported upkeep costs were heavily dominated by the cost of aluminum sulfate addition, with 15 WWTPs listing aluminum sulfate addition as their sole upkeep cost and three additional WWTPs listing aluminum sulfate in addition to other costs. One other response simply described their upkeep cost as “chemical addition,” and this response was attributed to aluminum sulfate. So, 19 of 23 responses (83%) indicated aluminum sulfate as a significant expense (appendix C). Two of the four remaining responses gave flat upkeep costs without an explanation of costs. The other two responses stated that phosphorus was removed biologically and did not require chemical addition. Not including a cost in their response suggests that biological treatment does not include perceivable upkeep costs whereas chemical addition does. Much of the difference in annual upkeep costs can be explained by magnitude of plant discharge, with an r^2-value of 0.91. The normalized average annual upkeep cost was \$32,227/MGD, with a standard deviation of \$26,084/MGD (table 3.1.a).

Total solids disposal strategies were reported by 33 WWTPs (figure 3.3.). Disposal in landfills was the dominant strategy, used by 23 (70%) of the WWTPs. Respondents predominantly used one disposal strategy instead of multiple disposal strategies, with 28 (85%) respondents employing a sole strategy and 4 (13%) respondents using multiple strategies. Disposal strategy is not related to plant discharge size, with an r^2-value of 0.04.

A total of 28 respondents assessed whether current advanced treatment methods would meet TMDL phosphorus permit levels given an increase in drinking water residual to 2 mg/L as P due to the addition of corrosion control inhibitors. Twenty-one (72%) respondents answered yes, while eight (28%) answered no. Twenty-five respondents indicated which changes to advanced treatment would be necessary (figure 3.4.). Many WWTPs (8, or 33% of respondents) indicated that multiple changes would be necessary.

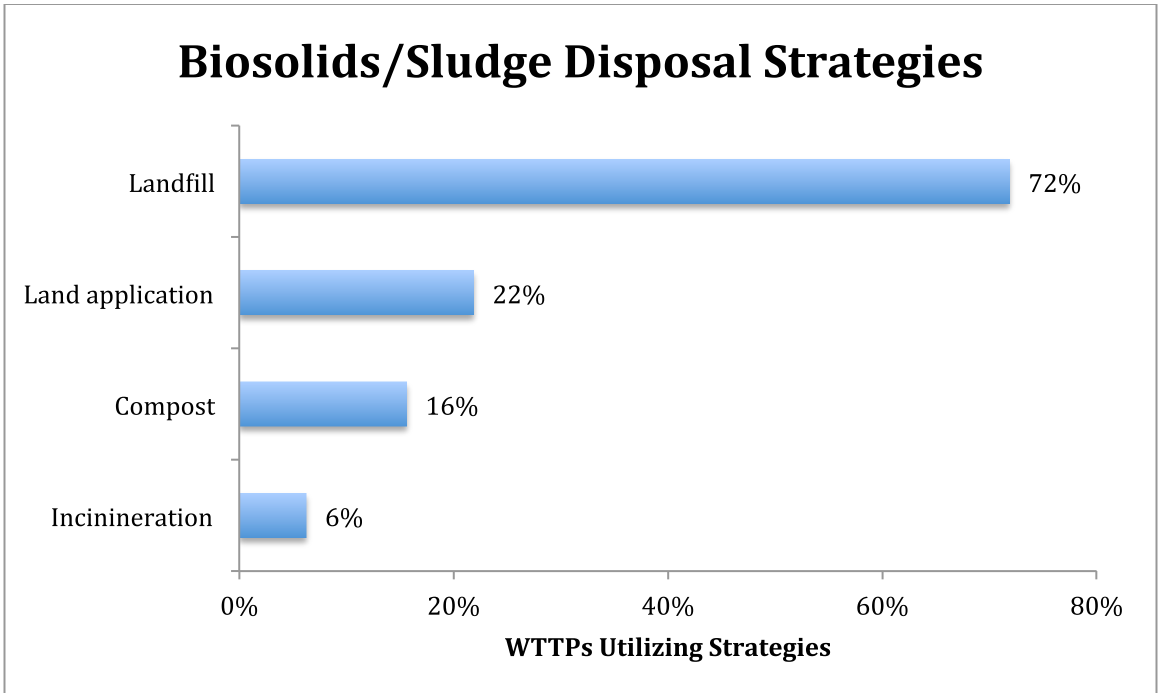

Figure 3.3. Percent usage of total solids disposal strategies by significant WWTPs in Virginia. WWTPs could use multiple strategies. Percentages based on 33 WWTP responses.

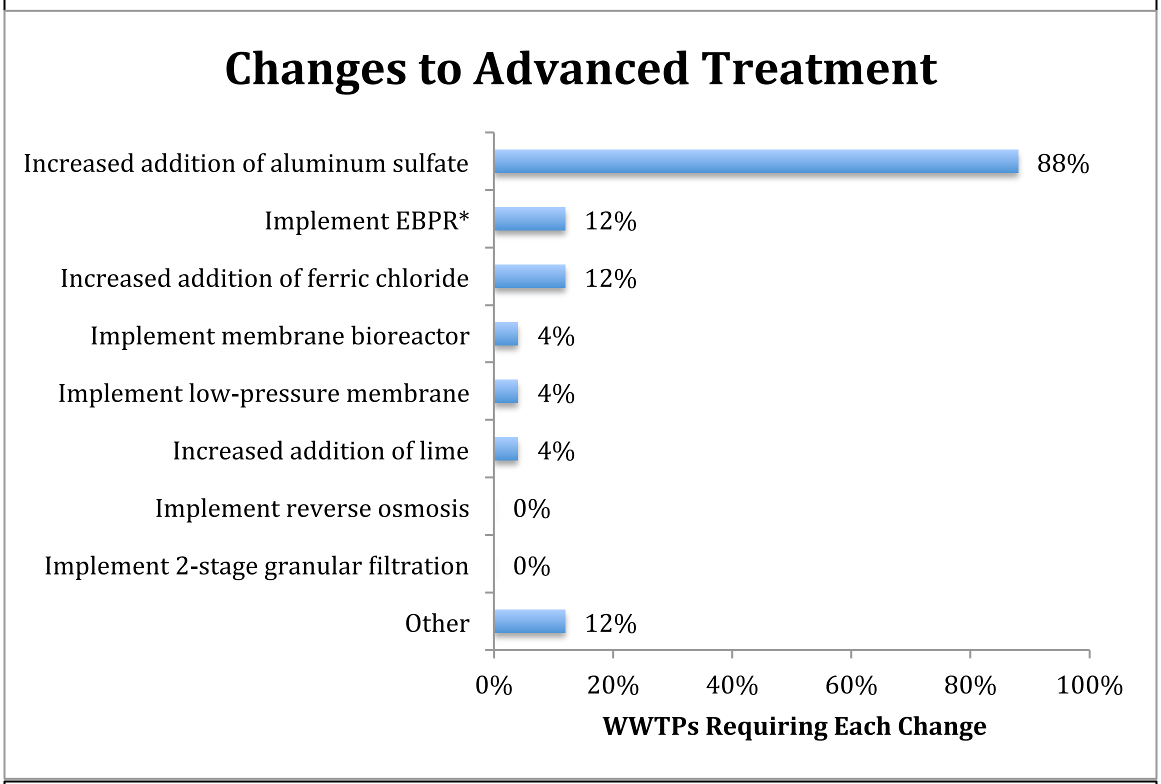

Figure 3.4. Percent advanced treatment change necessary for significant WWTPs in Virginia to still meet TMDL with and increase of phosphate-based corrosion control inhibitor dosage to 2 mg/L as P. WWTPs could utilize multiple strategies. Percentages based on 25 WWTP responses.

*EBPR stands for enhanced biological phosphorus removal

Increased addition of aluminum sulfate was the most frequent response, given by 22 (88%) of the 25 WWTPs.

A total of 23 respondents provided varying information on the costs of changes to advanced treatment (table 3.1.b.). Of the 20 responses providing cost estimates (three had reported that costs were unknown), four indicated that costs would be either negligible, minimal, or no cost at all. Of the remaining 16 WWTPs, 14 provided annual cost increases while three provided up-front capital costs (two provided both annual and up-front costs associated with advanced treatment changes). The average annual cost of changes to WWTPs was $45,063, with a standard deviation of $82,538. All of which was due to the increased annual costs associated with chemical addition (12 for increased aluminum sulfate addition and one for increased ferric chloride addition). The up-front costs associated with changes to the advanced treatment methods at three WWTPs were: $28 million for a new membrane filter, $1.6 million for a tertiary cloth disc filter, and $300,000 for new filters, respectively.

A total of 30 WWTPS commented on the changes in treatment, disposal, or cost associated with total solids disposal given an increase in drinking water residuals to 2 mg/L as P. Nineteen WWTPs (63%) expected to make some change, and 11 (37%) did not. Plant discharge size did not seem to play a large part in explaining responses, with a coefficient of determination (r^2-value) of 0.13. A total of 22 WWTPs provided information on which changes to treatment of total solids were to occur with an increase in phosphorus-based corrosion control inhibitor dosage (figure 3.5.). Increases in phosphorus concentration of total solids and in the amount of total solids produced

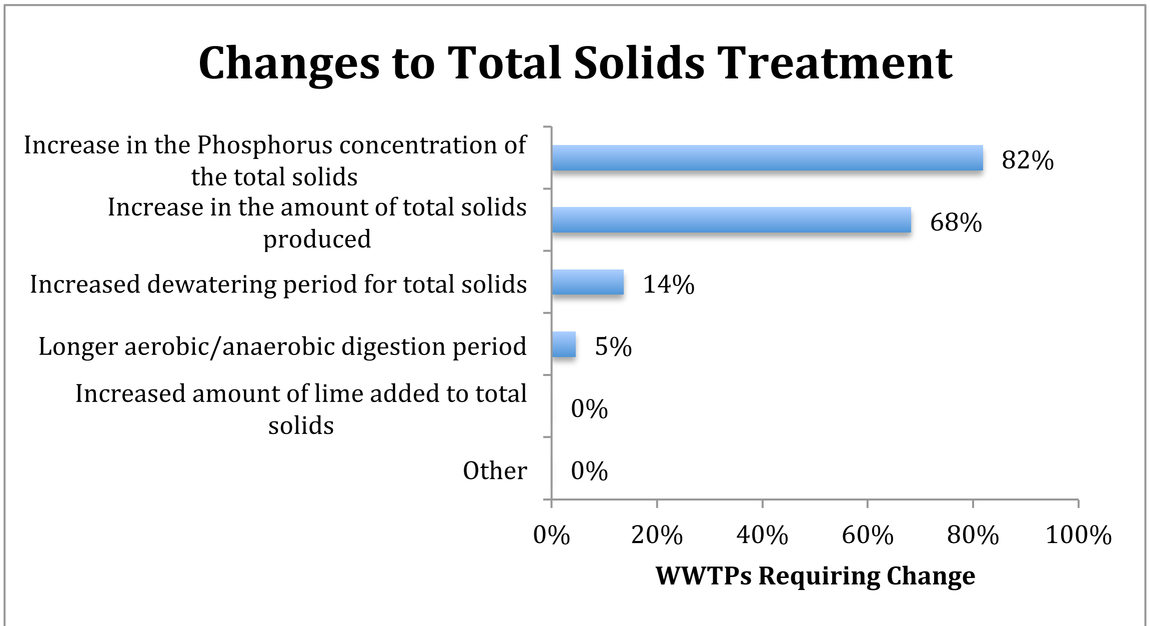

Figure 3.5. Percent of significant WWTPs in Virginia that would experience different changes to total solids treatment from an increase of phosphate-based corrosion control inhibitor dosage to 2 mg/L as P. WWTPs can experience multiple changes. Percentages based on 22 WWTP responses.

dominated the responses. Nearly half of the WWTPs, 10 (42%), indicated that there would be multiple changes. The responses about costs of changes in total solids treatment were inadequate in quantity and quality to make representative assertions. Only ten WWTPs responded. Five indicated that costs would be negligible, one was an unknown, and four indicated that costs would increase, with only two giving actual dollar amounts.

A total of 24 WWTPs provided information on the changes to total solids disposal that would occur with an increase in phosphate-based corrosion control inhibitor dosage (figure 3.6.). An increase in the amount of total solids needing to be disposed dominated the responses, with 20 (83%) of the respondents. Again, also important to note is that WWTPs were able to select multiple choices, with six (25%) of WWTPs selecting multiple choices. Of the four respondents that selected "other," two described “other” as negligible, one was unknown, and another cited a possible increase in the amount of total solids composted.

A total of 19 respondents estimated the costs associated with these changes to total solids disposal (table 3.1.c.). Four of these respondents indicated that the costs associated with disposal changes were unknown, and their responses will not be included in the following analysis. Of the remaining 15 respondents, annual costs ranged from negligible, or $0 (assumed to be the same thing for the purposes of this study), to $25,000, with an average annual cost of $7,367 and a standard deviation of $7,256. The normalized average annual cost was $17,164/MGD, with a standard deviation of $27,721/MGD.

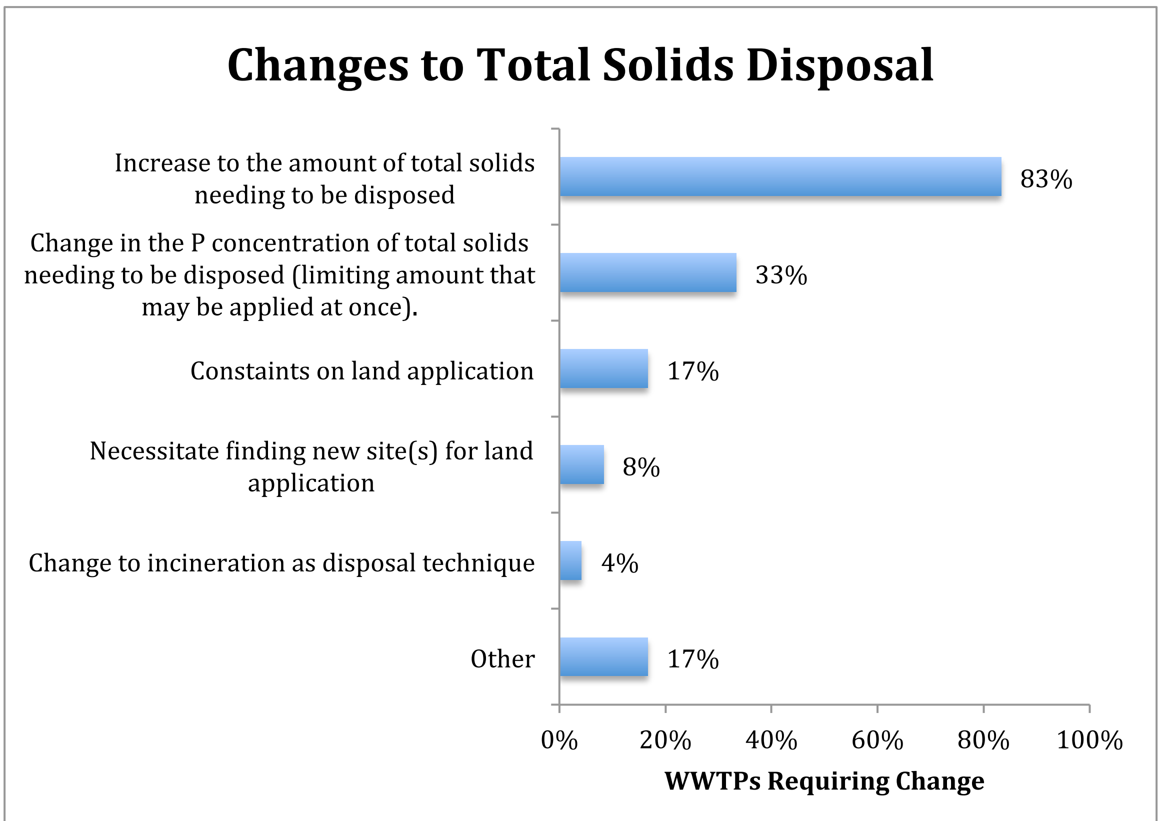

Figure 3.6. Percent of significant WWTPs in Virginia that would experience different changes to total solids disposal from an increase of phosphorus-based corrosion control inhibitors to 2 mg/L as P. WWTPs can experience multiple changes. Percentages based on 24 WWTP responses.

4. Discussion

The survey results indicate that significant WWTPs in Virginia would be able to properly treat an increase in drinking water phosphorus residual to 2 mg/L as P. It appears that most WWTPs would not alter their current treatment strategies, with 72% reporting that current advanced treatment methods could meet phosphorus TMDL permit levels given an increase in phosphorus in drinking water. Moreover, only three WWTPs reported up-front/installation costs for changes to advanced treatment due to the phosphorus increase, indicating that most WWTPs would utilize current advanced treatment practices for treating an increase in phosphorus and not be forced to initiate a new treatment process. Notably, the up-front costs of changes to advanced treatment are similar in both the mean and variability of the dollar amount to the up-front costs of current advanced treatment, indicating treatments likely to be installed are similar to those that are already in place. The majority of the phosphorus increase will be treated with the addition of aluminum sulfate, with 73% of WWTPs currently using aluminum sulfate, and 88% of WWTPs indicating an increase in aluminum sulfate as the advanced treatment solution to a phosphorus increase in the influent.

4.1 Advanced Treatment Costs

While it is clear that WWTPs can properly treat a phosphorus increase, the cost of this treatment is not as clear. For WWTPs needing to install new treatments, the expected up-front costs are almost $10 million per plant, with a standard deviation of approximately $15.6 million. However, due to the low response rate, it may be more judicious to use the installation costs of current advanced treatments. These costs are similar: approximately $10 million with a standard deviation of $13.6 million. When normalized, installation of current advanced treatments cost approximately $3 million/ MGD.

Because most WWTPs aren't expected to change treatment methods (or install new advanced treatments), annual/maintenance costs are more applicable to cost increases to advanced treatment methods. Annual/maintenance costs per plant would increase approximately 40% from a phosphorus increase (from approximately $113 thousand to $158 thousand). While there is a rather large standard deviation for changes in annual/maintenance costs per plant ($83 thousand, or 180% of the average cost), this is smaller than the current annual/maintenance cost standard deviation ($247 thousand, or 220% of the average cost). When normalized over discharge size, annual/maintenance costs per MGD will increase by approximately 72% (from $32 thousand to $55 thousand/MGD). When standard deviation of normalized costs is almost identical between anticipated changes and current costs ($27 thousand and $26 thousand, respectively).

The variability in costs associated with changes to advanced treatment from increased phosphate could be attributed to an absence of planning by WWTPs, and evidence that increased phosphate concentrations are not a concern to WWTPs. The standard deviation would be expected to decrease if WWTPs develop more in-depth analysis and plans for phosphorus treatment. While the predictions of cost increases have a standard deviation similar to that of current treatments (an indication that variability in costs is natural for the wastewater industry), current annual/maintenance cost differences are explained by WWTP discharge amount (with an r^2-value of 0.91). The variation in expected costs, however, is not explained by WWTP discharge amount (with an r^2-value of 0.01). While a large standard deviation of treatment costs may be intrinsic to the nature of the wastewater industry, it is apparent that expected costs do not fit the normal trend and are likely a result of lack of planning. This result means that it is very important for individual WWTPs to invest additional time and create tailored, comprehensive analyses prior to pursuing alterations in treatment.

4.2 Total Solids Disposal Costs

The cost increase per plant for total solids disposal is expected to be approximately \$7 thousand (only a fifth of the cost increase associated with advanced treatment), with a standard deviation of approximately \$7 thousand. While the normalized cost of solids disposal is approximately \$17 thousand (with a standard deviation of \$27 thousand), it is important to note that the increase in costs of total solids disposal is not strongly correlated with discharge size of WWTPs (with an r^2-value of 0.24). The survey also provided a weak realationship between increase in costs of total solids disposal and the disposal strategies utilized by WWTPs (with an r^2-value of 0.32). However, the representativeness of WWTPs utilizing land application was not preserved between the total population of respondents and those providing information on cost increases (with 22% of the total population and only 11% of those providing cost increases utilizing land application). Had the representativeness of the WWTPs utilizing land application been preserved, cost correlations may have been higher.

The second most common change to total solids disposal was an increase in phosphorus concentration (with 33% of WWTPs indicating this change). This change would uniquely affect the costs of land application, as nutrient concentrations must match the uptake-capability of receiving plots of land. Therefore, it would be especially important for WWTPs utilizing land application to consider changes to disposal costs following a phosphorus increase to drinking water. However, the most common change to total solids disposal was an increase in the amount of total solids requiring disposal (83% of WWTPs indicating this change). This change should not uniquely affect the cost of a single disposal strategy but increase the costs of all disposal strategies. The dominance of landfills as the most common disposal strategy and an increase in the amount of total solids produced as the most common factor affecting disposal may explain the difficulty in identifying the cause of variability in cost increases to total solids disposal. As with advanced treatment, it is important that WWTPs develop plant-specific analyses to account for this variability.

4.3 Statewide Costs

With a total statewide design flow of 585 MGD (USEPA, 2010a), the statewide annual advanced treatment costs to Virginian WWTPs from a phosphorus increase equate to approximately $13.4 million[1]. The annual costs for solids disposal are expected to increase by approximately $10 million[2]. This equates to a total annual cost of approximately $23.4 million. It is important to note that installation costs to WWTPs needing new advanced treatment capability have not been included. However, the survey indicates that this cost will be uncommon because most WWTPs have advanced treatment already in place that they will continue utilizing. It is also important to keep in mind the high standard deviation in annual costs, approaching approximately $33 million. As WWTPs continue to plan and create more accurate cost estimates, this deviation will narrow and the average cost will change.

4.4 Summary

[1] exact price was $13,377,195.
[2] exact price was $10,040,940.

Drinking water and wastewater are often seen as two disparate systems. As this paper shows, however, they are intrinsically linked. It is important to remember this connection when considering a change to any portion of a water system. Results of this survey indicate that Virginia WWTPs will be able to treat an increase of drinking water phosphorus residual to 2 mg/L as P, thereby negating the risk of nutrient pollution of the Chesapeake Bay from WWTP discharge. However, the changes in advanced treatment and total solids disposal does come at a cost. Regulators will need to weigh and balance the benefits of a reduced health risk from lead with these costs to WWTPs. The large degree of variation between WWTP costs illustrates that changes to specific WWTPs will be very individualized. Therefore, it is also important that a blanket approach not be applied to all WWTPs. Research must be conducted for every linked water-supply--wastewater system before changes are made to the drinking water.

5. References

Brown, R. A.; Nancy, M.; & Cornwell, D., 2013. Strategies for Assessing Optimized Corrosion Control Treatment of Lead and Copper. *Journal of the American Water Works Association*. Vol. 105, Issue. 5.

Chartered Institute for Water and Environmental Management (CIWEM), 2011. Lead in Drinking Water, accessed September 22, 2013.http://www.ciwem.org/knowledge-networks/panels/water-supply--quality/lead-in-drinking-water.aspx

Cope, Clayton; Via, S.; & Roberson, A. 2013. Current Water System Lead and Copper Compliance Practices. Prior to Publication. For summary of report, see Appendix A.

DeBarbadillo, C.; Levesque, S.; Maxwell, M., 2009. Strategies for Meeting Ultra-Low Phosphorus Limits: State of the Art Technologies and Case Studies. Unpublished paper presented at the North Carolina AWWA-WEA 89th Annual Conference, Raleigh, N.C.

Minnesota Pollution Control Agency (MPCA), 2006. Phosphorus Treatment and Removal Strategies. Retrieved March 3, 2006, from http://www.pca.state.mn.us/index.php/view-document.html?gid=7095

USEPA, 1991. Drinking Water Regulations: Maximum Contaminant Level Goals and National Primary Drinking Water Regulations for Lead and Copper; Final Rule. *Federal Register, 40 CFR parts 141 and 142.*Vol. 56, No. 110.

USEPA, 1993. The Standards for the Use or Disposal of Sewage Sludge. USEPA Federal Register Volume 58, Title 40 of Code of Federal Regulations, Part 503.

USEPA, 2000. National Primary Drinking Water Regulations for Lead and Copper. *Federal Register, 40 CFR Parts 9, 141, and 142*. Vol. 65 No. 8.

USEPA, 2003a. Revised Guidance Manual for Selecting Lead and Copper Control Strategies. *Report No. EPA-816-R-03-001*. USEPA

USEPA, 2003b. Lead and Copper Rule Long-term Revisions SBREFA Background Document. USEPA.

USEPA, 2004. National Primary Drinking Water Regulations for Lead and Copper: Short-Term Regulatory Revisions and Clarifications. *Federal Register, 40 CFR Parts 141.* Vol. 71, No. 137.

USEPA, 2007a. National Primary Drinking Water Regulations for Lead and Copper: Short-Term Regulatory Revisions and Clarifications. *Federal Register, 40 CFR Parts 141 and 142: 57782-57820.*

USEPA, 2007b. Advanced Wastewater Treatment to Achieve Low Concentration of Phosphorus. *USEPA, Report No. 910-R-07-002.*

USEPA, 2008. Despite Progress, EPA Needs to Improve Oversight of Wastewater Upgrades in the Chesapeake Bay Watershed*. USEPA, Report No. 08-P-0049*.

USEPA, 2010a. Chesapeake Bay Total Maximum Daily Load for Nitrogen, Phosphorus and Sediment. USEPA, Federal Register Volume 75, Number 183.

USEPA, 2010b. Appendix Q of Chesapeake Bay Total Maximum Daily Load for Nitrogen, Phosphorus and Sediment. USEPA, Federal Register Volume 75, Number 183.

USEPA, 2011a. Revised Draft: Optimal Corrosion Control Treatment Evaluation Guidance Manual for States. Prepared by The Cadmus Group (*Contract number EP-C-08-015, Work Assignment No. 3-07*).

USEPA, 2011b. Progress on Reducing Pollution from Wastewater Facilities. http://www.epa.gov/reg3wapd/pdf/pdf_npdes/WastewaterProgress.pdf

Shock, M. R, 1999. Internal Corrosion and Deposition Control. *Water Quality and Treatment, 5th addition*. McGraw-Hill Inc. New York, NY.

Schuler, Andrew,1996. Process Stability of Enhanced Biological Phosphorus Removal in Wastewater: The Effect of Varying Influent Quality. *USEPA, grant number: U914804*.

VDEQ, (2013, October 4). VPDES Individual Permits (with contact information). *VPDES Permits, Fees, and Regulations*. Retrieved October 21, 2013, from http://www.deq.virginia.gov/Programs/Water/PermittingCompliance/PollutionDischargeElimination/PermitsFees.aspx

Appendix A: Summary of Cope et al., 2013.

Cope, Clayton; Via, S.; & Roberson, A. 2013. Current Water System Lead and Copper Compliance Practices. Prior to Publication.

Report Summary

The study conducted by the first author while employed as an intern at the American Water Works Association during the summer of 2013 culminated in a report entitled *Current Water System Lead and Copper Compliance Practices.* The entire report is currently under review for publication as an article in the Journal of the American Water Works Association. The study included both a SurveyMonkey® questionnaire sent to 198 drinking water systems throughout the U.S., and telephone interviews conducted with another 16 additional drinking water systems serving above 250,000 residents. These two surveys consisted of the same 19 questions, were conducted simultaneously during June and July of 2013, and were combined into a single 214-system study.

The study focused on the current distribution and ownership of lead service lines (LSLSs), public outreach and education involved with LSL replacement, and optimized corrosion control treatment (OCCT). Of 202 respondents, 114 (56%) conducted OCCT for LCR compliance. Of these systems, 48 (37%) cited phosphate-based corrosion inhibitors as the basis for OCCT. Polyphosphate was the most common corrosion-inhibitor employed by these systems (50%), zinc orthophosphate the second (30%), and phosphoric acid the least (20%). Residual phosphate targets within the distribution systems were very system specific. The median target reported for systems using polyphosphate was 0.23 mg/L as P, and 0.33 mg/L as P for systems using both zinc orthophosphate and phosphoric acid.

Appendix B: List of questions included in SurveyMonkey® Survey

The questions were sent as two separate surveys. **The first concerned current conditions and practices:**

1. What is your NPDES permit number?
2. If you would like a summary of the survey when it is completed, please provide an email address
3. Is the wastewater that ultimately enters your WWTP treated with phosphate-based corrosion control inhibitors?
    - Yes
    - No
4. If yes, what is the phosphate residual within the distribution system (reported mg/L as P)? (If the residual concentration is unknown, please enter "unknown".)
5. Which of the following does your plant's secondary treatment consist of? (Check all that apply.)
    - Activated sludge
    - Extended air activated sludge
    - Rotating biological contactors
    - Surface aerated basins
    - Filter beds
    - Membrane bioreactors
    - Biological aerated filters
    - Addition ferric chloride
    - Addition of aluminum sulfate
    - Other
6. Please select the advanced treatment procedures that your plant utilizes to remove phosphorus. (Check all that apply.)
    - Addition of ferric chloride
    - Addition of aluminum sulfate
    - Addition of lime
    - Enhanced biological phosphorus removal (EPBR)
    - Membrane filtration
    - Membrane bioreactor
    - Two-stage granular media filtration
    - Reverse osmosis
    - Other
    - None
7. If an advanced treatment system is used at your WWTP and is not listed above, please describe below. For example, if an alternative chemical is added or an alternative filtration procedure is utilized.
8. If applicable, please indicate the year and up-front costs associated with the implementation of your advanced treatment methods selected above. This question is meant to capture the cost of installing treatments, not maintaining them.

(For example: Low-pressure membrane filtration- The installation cost approximately $$$$$.)

9. Please estimate the associated costs of up keeping any of your advanced treatment.

   (For example: Ferric chloride addition- We add 170 tons a year. This equates to an annual cost of $$$$.

   -OR-

   Membrane filtration- Annual maintenance costs are approximately $$$$)

10. Please select the mechanism(s) through which your plant's sludge/biosolids are currently disposed.
    - Land application
    - Landfill
    - Incineration
    - Compost

The second survey concerned changes associated with an increase of drinking water phosphorus residual to 2 mg/L as P:

11. Please enter your NPDES permit number.
12. If you would like a summary of the survey when it is completed, please provide an email address.
13. If phosphorus-based corrosion control inhibitors increased drinking water residuals to 2 mg/L as P, would your current advanced treatment still meet your TMDL phosphorus permit level?
    - Yes
    - No
14. If changes in advanced treatment would then be necessary to meet your phosphorus TMDL, please indicate how this might be achieved. (check all that apply.)
    - Increased addition of ferric chloride
    - Increased addition of aluminum sulfate
    - Increased addition of lime
    - Implement enhanced biological phosphorus removal (EPBR)
    - Implement low-pressure membrane filtration
    - Implement membrane bioreactor
    - Implement two-stage granular media filtration
    - Implement reverse osmosis
    - Other
15. Please estimate the associated costs with any of these changes to your advanced treatment.

    (For example: Increase in ferric chloride addition- We would need to increase the dosage of ferric chloride added by 170 tons a year. These would equate to an annual cost of $$$$$.

    -OR-

    Implementation of low-pressure membrane filtration- The installation would cost approximately $$$$$. Annual maintenance costs would be approximately $$$$)

16. If phosphorus-based corrosion control inhibitors increased drinking water residuals to 2 mg/L as P, would your sludge/biosolid treatment, disposal, or cost be affected?
    - o Yes
    - o No
17. If treatment of your sludge/biosolids were to change, please indicate which changes would most likely occur. (Check all that apply.)
    - o Increase in the amount of sludge produced
    - o Increase in the Phosphorus concentration of the sludge
    - o Increased dewatering period for the sludge
    - o Increased amount of lime added to the sludge
    - o Longer aerobic/anaerobic digestion period
    - o Other (please specify)
18. Estimate the average annual cost of these changes to sludge/biosolid TREATMENT (not disposal).

    (For example: Lime addition would increase by 165 tons a year, resulting in an annual cost of $$$$$)
19. If disposal of sludge/biosolids were to be affected please indicate which changes would most likely occur. (Select all that apply.)
    - o Increase to the amount of sludge/biosolids needing to be disposed
    - o Change in the P concentration of sludge/biosolids needing to be disposed (hence limiting amount that may be applied at once).
    - o Constraints on land application
    - o Necessitate finding new site(s) for land application
    - o Change to incineration as disposal technique
    - o Other (please specify)
20. Estimate the average annual cost of these changes to sludge/biosolid DISPOSAL (not treatment).

    (For example: Sludge production would increase by approximately 50 tons a year. This would have an annual cost increase of $$$$.)