PROJECT NO.
4651

Forest Cover Impacts on Drinking Water Utility Treatment Costs in a Large Watershed

Forest Cover Impacts on Drinking Water Utility Treatment Costs in a Large Watershed

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Co-sponsored by:

DC Water

Fairfax Water

U.S. Endowment for Forestry and Communities

Washington Aqueduct

Washington Suburban Sanitary Commission

2018

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WRF ISBN: 978-1-60573-376-0
WRF Project Number: 4651

Prepared by Interstate Commission on the Potomac River Basin and Washington Aqueduct.

CONTENTS

TABLES

FIGURES

ACKNOWLEDGMENTS

The importance of the thoughtful participation of the project partners in the success of this project cannot be overstated. Specifically, the authors would like to acknowledge staff from the participating utilities, Project Advisory Committee, project advisors, U.S. Endowment for Forestry and Communities, and Water Research Foundation, listed below. This project was made possible by the many contributions of these individuals.

UTILITIES

- DC Water: Anjuman Islam
- Fairfax Water: Douglas Grimes, Mishelle Noble-Blair, Gregory Prelewicz, Niffy Saji, Joel Thompson
- Washington Aqueduct: Alexander Gorzalski, Anne Spiesman
- Washington Suburban Sanitary Commission: Martin Chandler, Priscilla To

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- Linda Reekie
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An in-person team meeting was held on June 9, 2017, in Rockville, Maryland, and included the organizations listed above in addition to the research team at the Interstate Commission on the Potomac River Basin, Adam Carpenter of the American Water Works Association, and Jeff Lerner of American Forests. Thank you to everyone who was able to participate. The final products of this project were significantly improved by the breadth of experience and attention to detail of the group.

The authors would like to acknowledge the contributions to this project by Tracy Mehan. Mr. Mehan was instrumental to the original concept of this project and provided ongoing support.

This project was built upon a strong data foundation. Participating utilities provided considerable withdrawal, water quality, treatment dose, and cost information. Nancy Hausrath provided information on solids handling for the City of Hagerstown, Maryland. Peter Claggett provided 2030 urban land use projections for use in model scenario development.

The Interstate Commission on the Potomac River Basin (ICPRB) gratefully acknowledges that the Water Research Foundation, U.S. Endowment for Forestry and Communities, Fairfax Water, Washington Aqueduct, Washington Suburban Sanitary Commission, and DC Water are co-funders of certain technical information upon which this report is based. ICPRB thanks these organizations for their financial, technical, and administrative assistance in funding the project through which this information was discovered.

EXECUTIVE SUMMARY

KEY FINDINGS

- This study modeled the impacts of forest protection and forest buffers on drinking water treatment costs at three treatment plants in the Potomac River basin, and whether these activities would prevent concentrations of algae, bromides, THM, and other contaminants from exceeding thresholds that might trigger significant capital costs.
- The model showed very modest impacts to water quality under the different forest protection scenarios. Treatment cost savings were estimated to be smaller than the cost of protecting forests.
- The results of this study indicate that reducing water treatment chemical costs by themselves may not be a sufficient driver for forest protection or installation of forest buffers. This conclusion would seem to be true for the water utilities involved in this study, at least over the scale and time frame examined. It would be wrong, however, to conclude it is never true for any water utility.
- It is important not to draw the general conclusion that it is not cost-effective for water utilities to fund forest conservation or the installation of forest buffers. The effectiveness of forest preservation may be a function of how much forest there is to preserve: the more forested the watershed, the more cost-effective it is to preserve forests.

OBJECTIVES

This project evaluated the relationship between forest cover and source water quality in the form of nutrients, sediments, and total organic carbon (TOC). The objectives were to:

1) Determine water quality changes near Fairfax Water, Washington Aqueduct, and Washington Suburban Sanitary Commission's (WSSC's) Potomac intakes by preserving varying degrees of existing forested lands (DC Water is a wholesale customer of Washington Aqueduct and does not have its own intake.)
2) Conduct an initial assessment of the impact of water quality changes on treatment costs, as well as a threshold-based approach to evaluating capital costs and an estimation of solids handling costs
3) Use the results to develop recommendations for source water protection activities

BACKGROUND

Many utilities currently engaged in forest protection include those with filtration avoidance permits from the U.S. Environmental Protection Agency (EPA) (e.g., New York City, Boston). Most other utilities relying on surface water have already invested in conventional treatment processes including filtration. Some have pursued advanced treatment technologies, such as ozone, granular activated carbon, and ultra-violet disinfection, which can address a host of contaminants beyond federal and state drinking water standards. Deteriorating source water quality may still impact treatment costs and cost-effectiveness evaluations for utilities with conventional treatment and even those with advanced treatment.

All utilities face financial decisions when evaluating source water protection opportunities. While source water protection is seen as an important component of a multi-barrier approach to providing high-quality water, it can be difficult to assess the financial benefits of source water protection programs. This project provides an initial evaluation of the water quality and cost benefits of protecting forested land within the Potomac River basin. Though the project focuses on the Potomac River basin, the approach is applicable to other utilities. Regardless of who ultimately pays for forest protection, the first step in such an evaluation is to conduct a rigorous and scientifically defensible study to estimate the changes in water quality from the loss of forested lands and riparian buffers, and how this may affect drinking water treatment costs.

To address these uncertainties, this project applied sophisticated watershed modeling tools and worked closely with the participating water utilities to understand the relationships between select water quality parameters and related treatment chemical doses. The results may influence how source water protection efforts are prioritized and implemented in the Potomac basin with geospatial, risk-based site identification with existing or Potomac-specific tools.

The work presented here is a first step in evaluating potential treatment cost savings resulting from forest protection. Estimates of treatment cost savings are only part of the equation for conducting a cost-benefit analysis, and this study only examined a small number of cost drivers. Future research would be needed to fully analyze operational and capital cost savings as compared to the costs of forest protection. While this study has obvious relevance for the participating utilities, developing a method for a site-specific investigation has value for other utilities that are considering source water protection implementation but are unsure about how to determine its potential value.

APPROACH

This study focuses on potential water quality impacts and associated treatment cost savings of forest protection for the four participating water utilities, Fairfax Water, Washington Aqueduct, WSSC, and DC Water. Since there is currently no acute water quality issue threatening the utilities' ability to provide clean, safe drinking water to their customers, the focus is on potential cost impacts due to water quality deterioration and the opportunities to prevent such deterioration through forest protection. Individual water quality and treatment chemical dose relationships were developed to inform each utility's source water decisions. Overall, the study provides an initial framework that utilities can utilize to understand the benefits of forest protection activities in their source water areas, and how increased forest cover could bolster risk and uncertainty protections.

In general, the research approach was to model water quality at a point just upstream of the utilities' intakes under various land use scenarios simulating varying degrees of forest protection. The water quality parameters considered in the water quality-treatment dose relationships were TOC and turbidity. These were selected as they are main drivers of treatment costs for the participating utilities. Using historic data to derive water quality-treatment dose relationships for each utility and the modeled water quality from the land use scenarios, cost savings from forest protection could be estimated. An additional effort was made to look at the relationship between forest cover and capital costs, specific to Washington Aqueduct. Means for prioritizing forest protection in the basin were summarized and future research ideas were proposed.

The specific steps of this approach included:

1) Adapting the Chesapeake Bay Program Watershed Model to output TOC loading estimates
2) Developing future land cover scenarios
3) Modeling TOC, sediment, and nutrient loadings using the watershed model for the scenarios developed in step 2
4) Developing historic water quality-treatment dose relationships for TOC and turbidity
5) Estimating future treatments costs using modeled water quality changes from step 3 and relationships from step 4
6) Summarizing current land cover conditions
7) Identifying opportunities for forest protection
8) Reviewing forest protection considerations for source water protection planning
9) Providing recommendations for future research and source water protection activities in the Potomac basin

RESULTS

Chapter 1 provides the context for this project, including a statement of research needs within the context of previous research, as well as the Potomac-specific needs.

A description of the modeling effort is given in Chapter 2, including a description of the model set-up and calibration, development of the land use scenarios, and the modeling results. The five land use scenarios developed for the year 2030 included base "business-as-usual" scenarios, two forest conservation scenarios, and two riparian buffer best management practice (BMP) scenarios. At the river reach scale, the maximum improvement in water quality conditions from the "business-as-usual" scenario (Scenario 1) was six percent for TOC concentrations, nine percent for total nitrogen concentrations, seven percent for total phosphorus concentrations, and seven percent for suspended sediment concentrations. The effects on water quality conditions are smaller, ranging from one to five percent, at the downstream-most river reaches, where the utility intakes are located (Chapter 2).

The water quality-treatment dose relationships are described by utility for selected treatment chemicals in Chapter 3. After thorough investigation of all treatment chemicals thought to be impacted by upstream forested lands (Appendix D and Appendix E), the study was narrowed to focus on coagulant at all three utilities, in addition to chlorine at Washington Aqueduct. This decision was made based on the predictive power of the water quality-treatment dose relationships and the portion of overall treatment costs explained by each treatment chemical. Application of the water quality-treatment dose relationships revealed that the largest decrease in daily treatment chemical doses from the base 2030 scenario was 1.63 percent, found for the change in average daily maximum coagulant dose at WSSC for Scenario 3, the most aggressive forest conservation scenario that conserves approximately two percent of the total forest land in the study area.

Costs are investigated in Chapter 4, including costs of selected treatment chemicals under each land cover scenario, a threshold-based approach to evaluating capital costs, and estimation of solids handling costs. Overall, the lower coagulant doses associated with the forest conservation and BMP scenarios result in lower costs. Uncertainties driven by the elements in the modeling framework, predicted river concentrations from the watershed model, and the regression relationships used to calculate concentrations at the intakes and the dosages of chemicals to treat them are at least comparable in size to the predicted reductions in treatment costs, if not larger.

Further, the relatively low magnitude of changes in nutrients and sediments in the scenarios is unlikely to trigger capital improvements. Solids handling costs were investigated for two water utilities of varying size with differing solids management practices. Increase in solids production, either due to increased source water solids loading or increased coagulant dose, would present additional costs for each utility.

Chapter 5 is an evaluation of land cover in the Potomac basin. There are 4.3 million acres of forest in the non-tidal portion of the Potomac River basin, accounting for 58 percent of total land cover. Most of these forest lands are in private ownership (70 percent), of which, 57 percent are family owned and, according to the U.S. Forest Service, less than 25 percent of private forest owners have land management plans (USDA 2013a). Furthermore, 1.3 million acres of forests are protected by conservation easements, and fewer than half of the counties in the basin protect riparian forest buffers from development through land use regulations. Methodologies for prioritizing opportunity forest lands are also discussed.

In addition to costs from treatment chemicals, infrastructure, solids handling, and implementation, utilities may consider other factors in source water protection decisions that are more difficult to evaluate economically. These could include reducing the risk (and costs) associated with impacts from fire, climate change, pests, population growth (urbanization), and land use and drinking water regulations. Each of these is discussed in Chapter 6.

Chapter 7 presents the project findings and recommendations for future action and research. The results of this project indicate a need for taking a holistic approach to source water protection in the Potomac basin that includes continued dialogue with stakeholders and upstream and downstream interests.

RECOMMENDATIONS

The results of this study indicate that reducing water treatment chemical costs by themselves may not be a sufficient driver for forest protection or installation of forest buffers. This conclusion would seem to be true for the National Capital Region (NCR) water utilities, at least over the scale and time frame examined in this study. It would be wrong, however, to conclude it is never true for any water utility: one recommendation from this study is to resist generalizations.

There are multiple reasons for conserving forests or installing forest buffers, some of which may stem from other interests of the utilities; for example, conserving forests in sensitive areas where development would make the likelihood of runoff from a transportation corridor or industrial activity more likely and thus increase the risk of spills threatening the water supply. There are also reasons that do not directly concern water supply. Forest conservation may be required to preserve local water quality. Forest buffers may be created as a result of nutrient trading to reduce the amount of retrofitting in ultra-urban areas necessary to restore water quality. Therefore, even if source water protection and treatment cost reductions do not by themselves justify forest preservation, combining them with other steps could provide justification.

In a river basin as large as the Potomac, with multiple uses and multiple interests subject to nutrient and sediment management for the restoration of Chesapeake Bay, yet still expected to grow in population, source water protection is by necessity a collaborative process. The approach to source water protection in the Potomac basin includes the need for continued dialogue with numerous stakeholders and upstream and downstream interests. By working together, common ground can be identified and strategies for moving forward can be developed. One such collaborative effort in the basin is the Potomac River Basin Drinking Water Source Protection Partnership (DWSPP). As an open forum for continued dialogue between water suppliers, state agencies, and other partners, participation in this effort will continue to encourage identification of opportunities for mutual benefit. Future research opportunities, as discussed in this report, may provide additional information for the recommended collaborative effort.

RELATED WRF RESEARCH

- Advancing and Optimizing Forested Watershed Protection (project 4595)
- Asset Management Framework for Forested Asset Protection (project 4727)
- Developing a Roadmap and Vision for Source Water Protection for U.S. Drinking Water Utilities (project 4176)

CHAPTER 1
INTRODUCTION

The Potomac River is the second largest contributor of fresh water to the Chesapeake Bay[1] and is a critical water supply source to communities in its watershed. Washington, D.C., and the surrounding National Capital Region (NCR), is the last and largest population center along the non-tidal Potomac. The Potomac basin covers 14,670 square miles (sq. mi.) stretching across Maryland, Pennsylvania, Virginia, West Virginia, and the District of Columbia (Figure 1.1). The source water area for the NCR water suppliers covers 11,560 sq. mi. of the basin. In this portion of the basin, there are approximately 4.5 million residents or about three-quarters of the basin's population. According to the U.S. Census Bureau, the total population of the basin is 6.2 million (U.S. Census Bureau 2012a) and continues to grow steadily. By 2030, the population of the entire Chesapeake Bay watershed is expected to increase by 13 percent with much of the growth anticipated in the NCR (CBP 2013).

Collectively, the main water suppliers for the NCR – the U.S. Army Corps of Engineers Washington Aqueduct Division (Washington Aqueduct), Fairfax County Water Authority (Fairfax Water), and Washington Suburban Sanitary Commission (WSSC) obtain approximately three quarters of their water from the Potomac River, relying on the river to provide, on average, approximately 520 million gallons of water every day to homes, businesses, and key government facilities. A safe and reliable water supply is essential to meeting these demands.

Fairfax Water operates the upstream-most intakes of the three utilities. Fairfax Water has two raw water intake structures on the mainstem Potomac that feed into the same plant (Corbalis): one offshore (approximately 750 feet from shore, not quite half-way across the river) and one onshore. These intakes allow Fairfax Water to identify and draw water of preferable quality. WSSC's intake is along the shoreline of the river. During certain, localized storm events, water quality at their intake is heavily influenced by the water entering the river from the heavily urbanized Watts Branch watershed, just 0.25 miles upstream. There is very little travel time between WSSC's Potomac River intake and the treatment plant, therefore no settling occurs before the water begins the treatment process. Washington Aqueduct has the last two intakes on the Potomac River, Great Falls and Little Falls. Great Falls is the preferred and most often used of the two because it relies on gravity to carry influent water, instead of Little Falls which requires pumping water up to the plant. The raw water moves from the Potomac River through the Dalecarlia Reservoir into Washington Aqueduct's water treatment plant. The settling that occurs at the Dalecarlia Reservoir provides benefits to the raw water quality. Detailed descriptions of each utility's treatment process are provided in Appendix C.

[1] The Susquehanna River is the largest contributor of fresh water to the Chesapeake Bay.

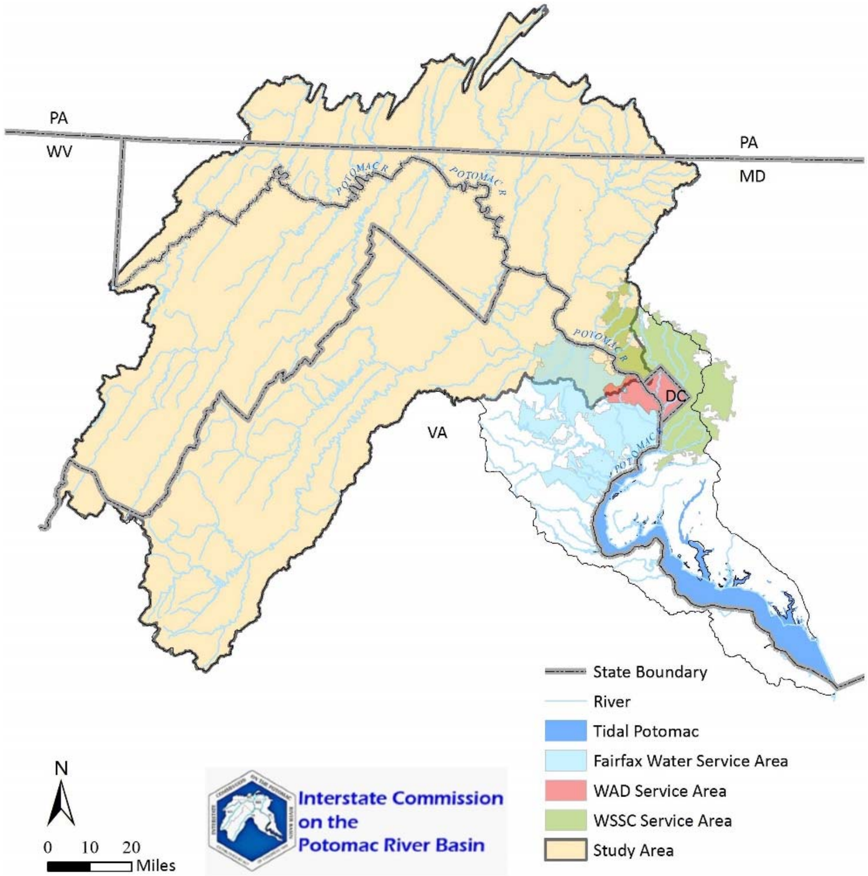


Figure 1.1 Potomac River basin and NCR water suppliers

A critical component of the Potomac's high-quality source water is that 58 percent of the basin is covered by forests. A portion of this is protected through federal, state, and local management programs or through private conservation easements. Federal land holdings, including the George Washington National Forest in the basin's headwaters, comprise about ten percent of the freshwater Potomac watershed. The George Washington National Forest is the largest federal landowner in the Chesapeake Bay watershed. There is a legacy of prioritizing forest protection for source water protection as noted in one of the initial Forest Management Plans. It states, "Insuring the purity of the water, air, and soil" as the highest priority of the National Forest (USFS 1972). While the protected lands help ensure clean water for the future, unprotected lands face development pressures.

To address changing land use in the basin, source water protection is undertaken both by individual utilities and through the Potomac River Basin Drinking Water Source Protection Partnership (DWSPP). The Potomac DWSPP is a voluntary coalition of water suppliers and regional, state, and federal agencies involved with drinking water who collaborate to protect the basin's source waters. Fairfax Water, WSSC, and Washington Aqueduct – are all active members. DC Water, serving the District of Columbia, is a wholesale customer of Washington Aqueduct and also a Partnership member. While committed to source water protection, the lack of information needed to assess the impact of forest protection on measurable water quality improvements at downstream intakes is a gap in their collective knowledge.

The importance of the Potomac River to public water supply, the current expanse of forest cover, and the projected population growth make understanding the benefits of forest protection now, as development decisions are being made for the future, critical to safe-guarding water quality.

STATEMENT OF RESEARCH NEED

Many utilities currently engaged in forest protection include those with filtration avoidance permits from the U.S. Environmental Protection Agency (EPA) (e.g., New York City, Boston). Most other utilities relying on surface water have already invested in conventional treatment processes including filtration. Some have pursued advanced treatment technologies, such as ozone, granular activated carbon, and ultra-violet disinfection, which can address a host of contaminants beyond federal and state drinking water standards. Deteriorating source water quality may still impact treatment costs and cost-effectiveness evaluations for utilities with conventional treatment and even those with advanced treatment.

All utilities face financial decisions when evaluating source water protection opportunities. While source water protection is seen as an important component of a multi-barrier approach to providing high-quality water, it can be difficult to assess the financial benefits of source water protection programs. This project provides an initial evaluation of the water quality and cost benefits of protecting forested land within the Potomac River basin, but the approach is applicable to any other utility. Regardless of who ultimately pays for forest protection, the first step in such an evaluation is to conduct a rigorous and scientifically defensible study to estimate the changes in water quality from the loss of forested lands and riparian buffers and how this may affect drinking water treatment costs.

To address these uncertainties, this project applied sophisticated watershed modeling tools and worked closely with the participating water utilities to understand the relationships between select water quality parameters and related treatment chemical doses. The results may influence how source water protection efforts are prioritized and implemented in the Potomac basin with geospatial, risk-based site identification with existing or Potomac-specific tools. Since forest protection would not occur in a vacuum, but instead in conjunction with the many efforts in the region, this study also provides an initial understanding of how source water protection efforts fit within the larger context of land protection.

The work presented here is a first step in evaluating the potential economic benefits of forest protection to water utilities. Estimates of treatment cost savings are only part of the equation for conducting a cost-benefit analysis and, further, this study only examined a small portion of cost drivers. Future research would be needed to fully analyze operational and capital cost savings as compared to the costs of forest protection. While this study has obvious relevance for the participating utilities, developing a method for a site-specific investigation has value for other utilities considering source water protection implementation but are unsure about how to determine its potential value.

Building on Previous Efforts

The Water Research Foundation (WRF) has long supported source water protection and integrated water resources management by advancing the understanding of relationships between watersheds, water quality, and utility costs and by developing tools to help utilities implement best practices. Although it is generally presumed that preserving more forested land will help maintain better raw water quality and lower treatment costs, the financial benefits associated with protecting forested lands for water suppliers are site specific. As noted in the 2012 WRF publication *Developing a Vision and Roadmap for Source Water Protection for U.S. Drinking Water Utilities* (Sklenar et al. 2012), “Before they will authorize related activities, many utility managers need to be convinced that source water protection is worth the effort and expenditures.”

Many previous WRF efforts have focused on source water protection and watershed management, but none have looked into how a utility would assess impacts of changing forest cover in its source water area on treatment costs. Some projects (LeChevallier et al. 2002, Ashbolt et al. 2005, Sturdevant Rees et al. 2006, Gullick et al. 2007, Summers et al. 2013) focus on specific water quality issues that can be addressed through source water protection such as pathogens, dissolved organic materials, and runoff from confined animal feeding operations.

Other projects such as Robbins et al. (1991), VCG (1997), and Pyke et al. (2003) are meant to help with implementation of source water protection plans. These studies could be particularly helpful in implementing on the ground source water protection activities.

The WRF-funded study, “Impacts of Major Point and Non-Point Sources on Raw Water Treatability” (Pyke et al. 2003) looked at similar issues to what is evaluated in this project, but the study’s explicit aim was to use an approach that could generalize over a wide array of watershed conditions and treatment processes rather than focusing on site-specific watershed conditions (Pyke et al. 2003).

Pyke et al. (2003) used a simple screening model to determine watershed export of total organic carbon (TOC), total suspended solids (TSS), and total phosphorus (TP) under conditions in hypothetical watersheds. The results were designed to be applicable nationwide and, therefore, the model was not site-specific. The model outputs were relative changes in annual average load from a baseline scenario. These water quality changes were in turn used in a water treatment plant model, OTTER. Equations were developed for four representative utilities, including Fairfax Water, to relate water quality changes with chemical dosages. These relationships were found to explain less than half of the variation.

The current effort attempts to build on the work done in Pyke et al. (2003) to show how site-specific information can be used to help utilities make long-term investment decisions. This type of modeling was specifically recommended by the study’s authors:

“Dynamic, site-specific receiving water modeling is required to provide a more accurate account of the effects of pollutant attenuation and transformation in the receiving water on raw water quality at the treatment plant intake. This is particularly true for sediment, phosphorus, and organic carbon. More sophisticated receiving water modeling is required to link changes in watershed export of phosphorus with water quality parameters of interest at [water treatment plants] WTPs.”

This project’s use of the Chesapeake Bay Program (CBP) Watershed Model (EPA 2010), a basin-scale, continuous simulation model, provided such “dynamic, site-specific receiving water modeling.” The Watershed Model is further discussed in Chapter 2.

This study builds on the work of Pyke et al. (2003) that is valuable for understanding the general relationship between land cover, water quality, and treatment costs to provide utilities with a model that accounts for conditions in their own source water area and model potential future land use conditions based on regional predictions. Understanding the potential future water quality conditions and associated changes in treatment costs can help utilities to invest in source water protection today. Further, the current study uses a dynamic, site-specific watershed model to provide improved information on TOC, TSS, and TP in the raw water for each of the participating utilities. While the economic analysis did not include all costs that may be incurred from deteriorating raw water quality, it provides a glimpse of what the utilities could face in the future.

RESEARCH APPROACH

This study focuses on potential water quality impacts and associated treatment cost savings of forest protection for the four participating water utilities, Fairfax Water, Washington Aqueduct, WSSC, and DC Water. Since there is currently no acute water quality issue threatening the utilities' ability to provide clean, safe drinking water to their customers, the focus is on potential cost impacts due to water quality deterioration and the opportunities to prevent such deterioration through forest protection. Individual water quality and treatment chemical dosage relationships were developed to inform each utility's source water decision making. Overall, the study provides an initial framework that utilities can utilize to understand the benefits of forest protection activities in their source water area and how increased forest cover could bolster risk and uncertainty protections.

This study's overall objectives are to:

1) estimate water quality changes near Fairfax Water, Washington Aqueduct, and WSSC's Potomac intakes as a result of preserving varying degrees of existing forested lands;
2) conduct an initial assessment of the impact of water quality changes on treatment costs; and
3) use the results to develop recommendations for future research and source water protection activities.

In general, the research approach (Figure 1.2) was to model water quality at a point just upstream of the utilities' intakes under various land use scenarios simulating varying degrees of forest protection. The water quality parameters considered in the water quality-treatment dosage relationships were TOC and turbidity. These were selected as they are main drivers of treatment costs for the participating utilities. Using historic data to derive water quality-treatment dose relationships for each utility and the modeled water quality from the land use scenarios, cost savings from forest protection could be estimated. The methodology utilized to estimate the cost of selected drinking water treatment chemicals is summarized in Figure 1.2. The figure is

Water quality-treatment dose relationships
↓
Future withdrawals
↓
Chemical doses by scenario
↓
Current cost of each chemical
↓
Daily cost of each chemical by scenario
↓
Average annual costs of each chemical by scenario
↓
Total average annual treatment chemical cost by scenario

Figure 1.2 Method for estimating treatment chemical costs by utility

provided in applicable sections of the document as a reference for the reader. An additional effort was made to look at the relationship between forest cover and capital costs, specific to Washington Aqueduct. Means for prioritizing forest protection in the basin were summarized and future research ideas were proposed.

The following report chapters detail the work completed by and conclusions of the research team:

- Chapter 1) Introduction: Provides the context for this project, including a statement of research need within the context of previous research as well as the Potomac-specific needs.
- Chapter 2) Estimated Water Quality Changes: Describes the modeling effort including the model set-up and calibration, development of the land use scenarios, and the modeling results. The modeled water quality constituents include TOC, nutrients, and sediments. The five land use scenarios developed for the year 2030 included a base "business-as-usual" scenario, two forest conservation scenarios, and two riparian buffer best management practice (BMP) scenarios.
- Chapter 3) Historic Water Quality and Treatment Dose Relationships: Provides relationships by utility for selected treatment chemicals. After thorough investigation of all treatment chemicals thought to be impacted by upstream forested lands (Appendix D and Appendix E), the study was narrowed to focus on coagulant at all three utilities in addition to chlorine at Washington Aqueduct. This decision was made based on the predictive power of the water quality-treatment dose relationships and the portion of overall treatment costs explained by each treatment chemical.
- Chapter 4) Drinking Water Utility Costs: Evaluates costs of selected treatment chemicals under each land cover scenario, a threshold-based approach to evaluating capital costs, and estimation of solids handling costs.
- Chapter 5) Using Results to Prioritize Source Water Protection: Assessed land cover conditions in the study area with particular emphasis on forested areas.
- Chapter 6) Risk Mitigation: Risks associated with other factors that may be more difficult to evaluate economically including fire, climate change, pests, population growth, and land use and drinking water regulations.
- Chapter 7) Conclusions for Source Water Protection: Presents the project findings and recommendations for future action and research.

CHAPTER 2
ESTIMATED WATER QUALITY CHANGES

The Chesapeake Bay Program Phase 5 (P5) Watershed Model (EPA 2010) was used to model TOC, TSS, TP, and total nitrogen (TN) loads for the land cover scenarios at a location on the mainstem Potomac just upstream of the utilities' intakes. As is, the P5 Watershed Model simulates TOC, although the simulation had not previously been calibrated. In order for P5 to generate TOC loads and concentrations under alternative land use scenarios, the P5 simulation of TOC had to be calibrated for the Potomac River basin. This chapter provides a brief overview of the model; details modifications made for TOC modeling; and summarizes TOC, sediment, nitrogen, and phosphorus modeling results. The modeling results were subsequently used to develop estimates of required chemical doses under the scenarios as part of the water quality-treatment dose relationships described in Chapter 3.

CHESAPEAKE BAY PROGRAM PHASE 5 WATERSHED MODEL

The Chesapeake Bay Program's Phase 5 Watershed Model (EPA 2010) provides the technical basis for linking water quality at the intakes of the three major water supply utilities of the NCR to potential changes in forest land and the implementation of forest buffers in the 11,560 sq. mi source water area. CBP is a federal-state partnership to restore and protect the water quality and ecology of the Chesapeake Bay. Among the program's partners are federal agencies, such as the U.S. Geological Survey (USGS) and National Park Service; state agencies such as the Maryland Department of the Environment and the Virginia Department of Environmental Quality; academic institutions such as the Virginia Institute of Marine Science and Penn State University; and non-governmental organizations such as Center for Watershed Protection and the Chesapeake Bay Foundation. CBP is organized in a hierarchy of workgroups, committees, and teams which allows each of the partners the opportunity to contribute their expertise to the effort of understanding the factors which determine water quality in the bay as well as to give them a voice in the decisions affecting management of the bay and its resources. At the top of the hierarchy is the Executive Council, whose members include the governors of the states in the basin, the mayor of the District of Columbia, the chair of the Chesapeake Bay Commission, and the administrator of the EPA.

The Watershed Model is one of CBP's most important tools. Its primary purpose is to help design and evaluate management scenarios for restoring water quality in Chesapeake Bay. Output from the Watershed Model is used to drive computer simulation modeling of the bay, whose output in turn can be compared to water quality standards used to measure the health of the bay. As its name suggests, P5 is the fifth in a series of models that date back to the inception of CBP in the early 1980s. It was used to help develop Total Maximum Daily Loads (TMDL) for nitrogen, phosphorus, and sediment for the Chesapeake Bay (EPA 2010); as well as for the states' Watershed Implementation Plans which spell out how the goals of the TMDLs are to be met. The final version of P5, the Phase 5.3.2 Watershed Model (referred to as the Watershed Model in this report), was used for this project. It is currently being used to track progress toward the CBP water quality goals, although a revised version of the Watershed Model, Phase 6, is expected to be adopted in the near future.

The Watershed Model is a modified version of the Hydrological Simulation Program—Fortran (HSPF), one of the most widely used watershed computer simulation models. The

Watershed Model was modified to facilitate representing time-variable land use and levels of BMP implementation over its 21-year simulation period, 1985-2005. The Watershed Model runs on an hourly time step, although the model is only calibrated at the daily scale. Like other versions of HSPF, the model used in this project simulates two types of processes: land processes and river processes. Land processes represent the flow of water through all phases of the hydrological cycle – precipitation, infiltration, runoff, percolation, and groundwater discharge – as well as the fate and transport of sediment and nutrients through the phases of the hydrological cycle and its interaction with the soil. Processes associated with agricultural activities such as plant uptake or the application of nutrients in fertilizers and manures can also be simulated. River processes, on the other hand, represent the flow of water, sediment, and nutrients through a network of free-flowing river reaches or reservoirs and impoundments. Important processes represented include the routing of flow; the scour and deposition of sediment; the exchange of nutrient species between sediment and the water column; eutrophication; and the transformation of nutrients by such processes as nitrification, denitrification or algal growth and decomposition.

The model domain is the entire 64,000 sq. mi. Chesapeake Bay watershed.[2] Both the land and rivers need to be divided into segments in order simulate them. Each segment is simulated as a unit. River processes are simulated by river reaches, which can be free-flowing streams or reservoirs. The Watershed Model simulates the rivers in the Chesapeake Bay watershed with average annual flows greater than 100 cubic feet per second (cfs), although to facilitate calibration, a few rivers with average flow less than 100 cfs were included in the model. The network of rivers with flows greater than 100 cfs were divided into river reaches at their confluences or at a USGS gaging station where simulated flows could be calibrated against observed daily average flows. There are 1,063 river reaches in the Chesapeake Bay watershed. Of these, 122 river reaches lie in the Potomac River watershed above the Atlantic Seaboard Fall Line[3]. The Fall Line and Chain Bridge are considered approximately the head of tide for the Potomac River. Flow data used in model calibration are collected at Little Falls. Water quality data, used in model calibration, are collected at Chain Bridge. River segments represent the watershed area that contributes to river reaches. Figure 2.1 shows the river segments and river reaches in the Potomac River watershed above the Fall Line.

[2] It also includes the portions of the states of Virginia, Maryland, and Delaware that lie outside the watershed, so that the entirety of these states could be represented in the model.

[3] This is the line between the Appalachian piedmont and Atlantic coastal plain, along which waterfalls and rapids are found.

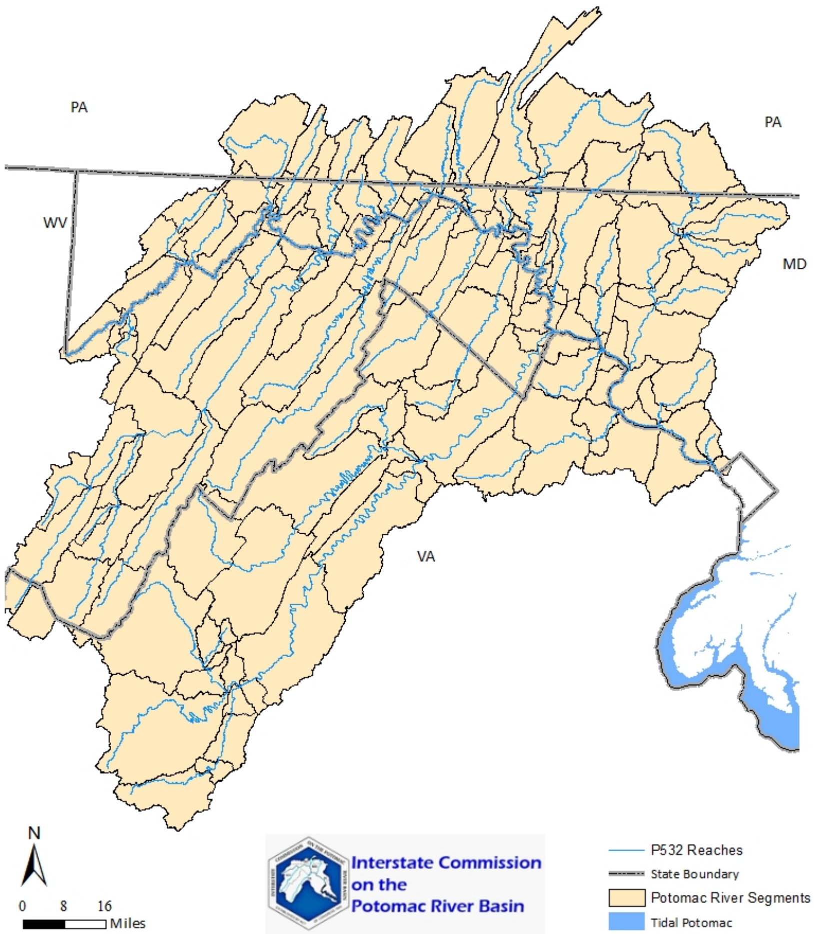


Figure 2.1 Phase 5 Watershed Model river reaches and river segments in the Potomac River watershed above the Fall Line

Land processes are simulated by land use and land segment. The Watershed Model simulates 30 different land use types, including such types as forest, harvested forest, high till cropland with applied manure, hay without applied manure, pasture, regulated pervious developed land, regulated impervious developed land, etc. Each land use type is simulated on a per acre basis. Land segments are areas within which each land use is simulated homogenously. In other words, the simulation of forest or regulated impervious developed land is the same within that land segment. Land segment boundaries usually conform to county boundaries, although some counties spanning the Piedmont, Blue Ridge, and Ridge and Valley physiographic provinces are divided at the province boundaries to capture orographic effects on precipitation. The county was chosen as the primary unit of land simulation because information on management of urban and agricultural lands was most consistently available at this scale. There are 309 land segments in the Chesapeake Bay watershed, of which 59 are in the Potomac River watershed above the Fall Line. Figure 2.2 shows the land segments in the Potomac River watershed above the Fall Line. Note that in the Watershed Model, land belonging to the federal government within a county is represented as land segment distinct from the county. These federal land segments almost double the total number of segments in the Chesapeake Bay watershed or the Potomac River watershed, but they are not included in the numbers reported here or in Figure 2.2.

Figure 2.2 Phase 5 Watershed Model land segments in the Potomac River watershed above the Fall Line

Land-river segments (LRS) are the intersection of land segments with river segments. They define what portion of a land segment contributes to an individual river reach. Since land uses are simulated on a per acre basis, the load from particular land use to a particular reach is given by the per acre load multiplied by the number of acres of that land use in a land segment. This load is adjusted to take into account the effects of BMPs and delivery factors, as is explained in more detail in Appendix A. In addition to the flow, sediment, and nutrient loads from land uses in land segments, other sources represented in the Watershed Model include municipal wastewater treatment plants; industrial dischargers; and septic systems. Diversions of water for water supply or agriculture, along with the associated nutrients and sediment, is also simulated.

The Watershed Model has been calibrated to observed conditions. While flow is primarily calibrated against USGS gage data by adjusting the simulation of land processes, other Watershed Model river constituents are calibrated against in-stream water quality data. These include:

temperature; sand, silt, and clay; ammonia, nitrate, and total nitrogen; phosphate and total phosphorus; and chlorophyll *a* (as a surrogate for algal biomass).

The entire process of model development has been subject to internal review by the CBP partnership. The CBP's Scientific and Technical Advisory Committee also organized an external peer review of the inputs and methods used in the Watershed Model (Lawrence et al. 2008), including the calibration.

Total organic carbon, a key water quality constituent impacting water supply, is conspicuously missing from the list of constituents calibrated in the river simulation. Early in the model development process, it was intended that TOC should be fully simulated and calibrated. The TOC simulation is fully functional in the Watershed Model. Observed in-stream TOC concentration data was collected for the calibration of the river simulation. Somewhere in the development process, however, the calibration of TOC was dropped, so TOC is not a calibrated parameter, although the statistics comparing observed and simulated TOC are calculated and reported.

One of the key tasks of this project was to calibrate the TOC simulation in the Potomac River watershed above the Fall Line. Appendix A describes the execution of this task and concomitantly offers additional detail on model structure. It is outside the scope of this project, however, to describe the Watershed Model or HSPF in additional detail or to document modeling results. Bicknell et al. (2000) describes the HSPF model structure in more detail. EPA (2010) provides extensive documentation of the Watershed Model. Model segmentation is discussed in Chapter 3 of the documentation, while the hydrology, sediment, and riverine simulations are discussed in Chapters 8, 9, and 11, respectively.

MODELED LAND USE SCENARIOS

The Watershed Model, as described above, was run with five land use scenarios to simulate varying degrees of forest cover in the basin. The results from the model runs were an input to the water quality-treatment dose relationships (Chapter 3) that allowed for the cost change estimates to be developed (Chapter 4).

Three land cover scenarios for the year 2030 were developed based on current and future land cover estimates and rates of forest protection. Additionally, two 2030 scenarios were developed to assess the water quality changes that could result from solely protecting forested buffers.

Scenario Development Method

In order to utilize the Watershed Model, projections were needed for all Watershed Model land use categories. Using the Chesapeake Bay Land Change Model, the CBP projects changes in pervious and impervious urban lands at the land-river segment scale for the Bay watershed (Claggett et al. 2013). Projections for other land use categories are not made by the CBP at this time. Urban land projections are available in five-year intervals from 2010 through 2030, thus why the scenarios are limited to 2030. To develop the needed data set of all land use types from the projected urban land cover, the following steps were undertaken:

1) Overlay the Watershed Model Phase 5.3.2 raster grid 2010 land use with the 2010 U.S. Census urbanized areas polygons.
2) Delineate polygons around the urban areas that are 0.5- and 1.0-mile wide.

3) Determine the forest:agriculture ratio for the land uses in each delineated polygon.
4) Multiply the impervious and pervious urban land use categories by the CBP-projected percent changes to develop acreages of those land use categories for the future year of interest (2030).
5) Adjust forest and agriculture land use categories to maintain total watershed area and calculated forest:agriculture ratio.

In general, projections of forest and agricultural land use were based on the assumption that increases in impervious and pervious developed land use would occur adjacent to existing urban areas and that existing forest and agricultural land would be converted to impervious and pervious developed land uses maintaining current proportions.

A map of urbanized areas in the Potomac basin from the 2010 U.S. Census were plotted with a map of the Watershed Model land-river segments in a Geographic Information System (GIS). One- and 0.5-mile-wide buffers were generated around each urbanized area polygon. In the GIS, these near-urban area buffers were intersected with the Watershed Model land-river segments to identify the parts of each buffer in each Watershed Model land-river segment. Using the Watershed Model Developed Land Use raster data set and the Tabulate Area built-in function in ESRI ArcMap, the acres of forest and agriculture land cover were calculated for each buffer area and a forest-to-agriculture land cover ratio in each near-urban buffer area was developed.

The total impervious and pervious land use acres were calculated from the Watershed Model 2005 land use input table. These total acres were multiplied by the projected percent change in impervious and pervious acres for 2030 from the CBP-provided land use change projection data. The acres of forest and agriculture land use categories were adjusted by the projected change in impervious and pervious land use while keeping constant the forest-to-agriculture land use area ratio calculated from the Watershed Model Developed Land Use raster data set. Also, the ratio of each land use category to the total acres of that category group was maintained. For example, the ratio of forest land use category and harvested forest land use category to total forest land use group was maintained.

The results were verified to ensure the total acres of each land-river segment remained constant between the resulting 2030 projected land use acres and the starting land use acres from the 2005 land use table. The change in total forest and agricultural land use acres compared to the change in impervious and pervious land use acres was also reviewed.

These land use projection calculations and verifications were performed using both the one- and 0.5-mile near-urban buffer areas. Ultimately, the one-mile buffer area land use projections were selected for the final 2030 land use table because it provides a more robust representation of the forest land use reduction as a result of the increase in impervious and pervious changes.

Figure 2.3 spatially shows the reduction in forest acres by land-river segment. Due to the method outlined above, the areas with the largest reduction in forest primarily occur around populated areas with the largest projected growth. The largest percent reduction is 86.3 percent in the Watershed Model land-river segment A51840PU2_4220_3900 which contains the City of Winchester, Virginia.

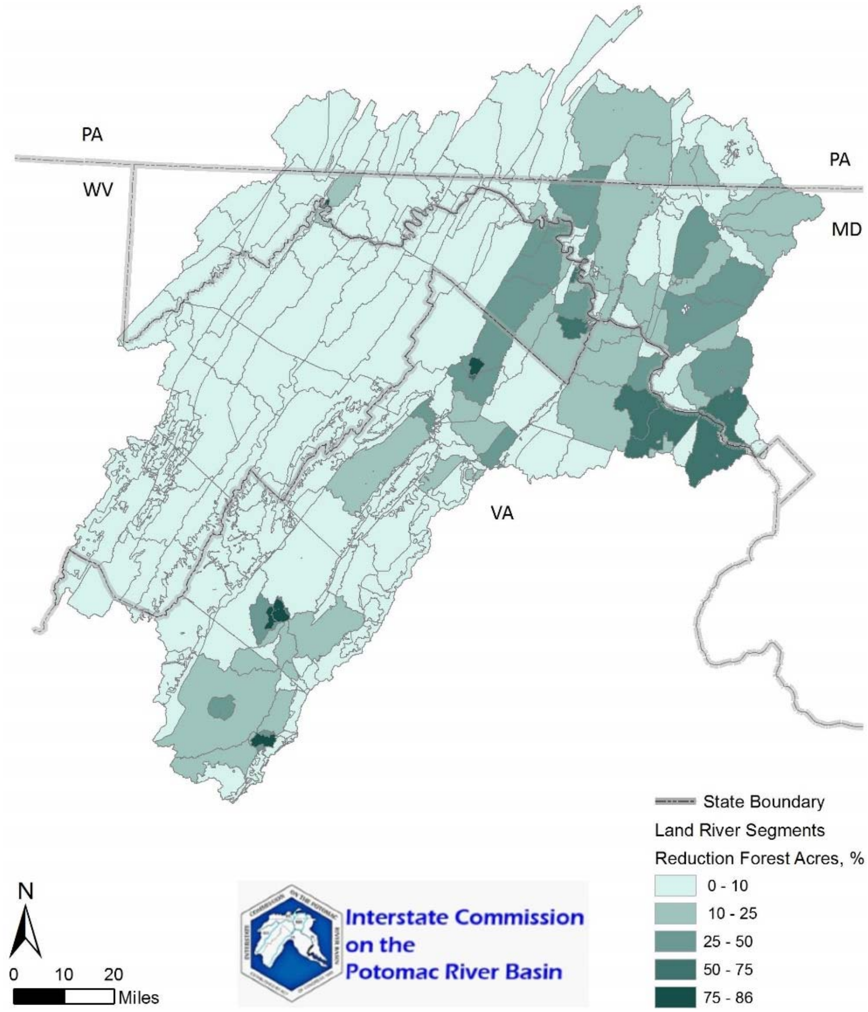


Figure 2.3 Reduction of forest land use acres by watershed model land-river segment

The scenarios developed using this method fall under two categories: land use change scenarios (Scenarios 1, 2, and 3) and BMP scenarios (Scenarios 4 and 5). Each is described in more detail in the following sections.

Land Use Scenarios

The land use change scenarios are defined by varying degrees of forest conservation. To conserve forest in these scenarios, areas of urban and/or agriculture lands are decreased to maintain the total model segment areas. A methodology was developed for assigning the agriculture and urban land use areas through review of the scientific literature related to land use changes in the Mid-Atlantic region.

The most relevant research focused on changes in resource lands (agriculture and forests) in response to urbanization in the Chesapeake Bay watershed (Jantz et al. 2005a; Jantz et al. 2005b). Specifically, the researchers found that agriculture is commonly the hardest hit in the development of the urban areas – agricultural areas are commonly consumed over twice as fast as forested areas. From this, the assumption was made that if forested lands are not available for urban expansion (through conservation efforts), the land used for the urban development will come primarily from agricultural areas. The Chesapeake Bay studies also found that best possible growth management strategies can reduce the expansion of urban areas by as much as 25 percent. To this end, the methodology used to develop the model land use scenarios is as follows:

1) Calculate the area of forests conserved for each Watershed Model land-river segment under each scenario.
2) Add this acreage to the forest land uses while keeping the proportion of forest types the same.
3) Maintain the land-river segment area by reducing agricultural areas (0.75 * river segment forest acres conserved) and reducing urban areas (0.25 * river segment forest acres conserved).
   Note: In instances where the necessary agricultural or urban acres are not available to meet these thresholds (e.g., areas where agricultural land either does not exist or does not exist in sufficient quantities to accommodate 75 percent of the forest conservation acres) the full remaining amount of acres are taken from the other land use (either agriculture or urban). In cases where the necessary agricultural and urban acres are not available to meet the required conserved forest acres, the amount of conserved forest acres is reduced to the available agricultural and urban acres.
4) The proportions of land uses within the agriculture and urban categories are maintained while achieving the necessary reductions.

The resulting land use scenarios are as follows:

- Scenario 1. Protect zero percent of the protection opportunities. The baseline scenario assumes that forest conversion will proceed as expected, with zero percent additional protection. This scenario used the calculated 2030 land use projection as-is.
- Scenario 2. Protect 50 percent of the protection opportunities. Determine the difference in forest land use between calculated 2030 and 2010 land uses. Conserve half of the lost forests by adding them back to the 2030 projection.
- Scenario 3. Protect 100 percent of the protection opportunities. Calculate difference in forest land use between 2030 and 2010 land uses. Conserve all of the lost forests by adding them back to the 2030 projection.

BMP Scenarios

Implementation of forest buffer BMPs in the Watershed Model occurs has two components. The first component includes changes to the land use input files, similar to the changes made in Scenarios 1 through 3. The second component is to apply reduction efficiencies to land uses associated with the particular BMPs. The specific BMPs applied in Scenarios 4 and 5 are agricultural riparian buffer forests and urban riparian buffer forests.

- Scenario 4. Protect forest buffers at the minimum state and county requirements. Information was compiled on forest buffer width requirements by county ordinances in the study area (Chapter 5). This information was used to calculate the total area of forested buffers required in each Watershed Model land-river segment. Some of this area, however, is already forested. To avoid double counting, the area of existing forest cover in these buffers was calculated and removed from the total buffer area to estimate the amount of forest needed to fully cover the ordinance areas. The amount of additional forest needed to fully protect the required areas was added to the forested Watershed Model land use type. The total area of the land-river segment was maintained by reducing the area of select agricultural and pervious urban land use types, following Chesapeake Bay Program BMP modeling conventions (CAST 2016; Belt et al. 2014; EPA 2010). The proportional area of the adjusted agricultural land use types was maintained in the land-river segment. The area of reduced agricultural and urban land uses was applied in the Watershed Model by applying reduction efficiencies to the specified land uses for forested buffers per Chesapeake Bay Program BMP modeling conventions.

- Scenario 5. Protect forest buffers out to 100 feet of the mainstem Potomac River and major tributaries. The major tributaries are defined as the North and South Branches of the Potomac River, Antietam Creek, Conococheague Creek, Monocacy River, and the Shenandoah River. A shapefile representing 100-foot-wide stream buffers was created and the total area of potential forested buffer within that area was calculated by Watershed Model land-river segment. Using the same methodology described in Scenario 4, the model land use inputs were updated and the reduction efficiencies were applied to land uses associated with the BMPs.

RESULTS

The Watershed Model was run for each of the five land use scenarios resulting in a 20-year time series of minimum, maximum, and average daily water quality concentrations for each river reach in the study area. The water quality-treatment dose relationships (Chapter 3) are based on conditions at Chain Bridge near the utility intakes;[4] however, it is expected that the impacts of forest conservation and BMP installation are most apparent at the local level. To this end, an evaluation was undertaken to evaluate water quality conditions for all river reaches and all scenarios. The largest differences between scenarios occurred based on localized upstream changes in land use for each scenario. The maximum improvement in water quality conditions in upstream river reaches was seven percent for TOC, nine percent for total nitrogen concentrations, seven percent for total phosphorus concentrations, and seven percent for suspended sediment concentrations.

For all scenarios, relatively minor water quality changes occur downstream near the utility raw water intakes at the study area outlet. The largest average daily reductions under the forest preservation and forest buffer scenarios near the utility raw water intakes were only three percent for TOC, five percent for total nitrogen concentrations, one percent for total phosphorus concentrations, and two percent for suspended sediment concentrations.

Daily simulated water temperatures were also used in the water quality-treatment dose relationships (Chapter 3). Temperature differences between scenarios are also quite small (less than one-tenth of one percent) over the simulation period (1984-2005) (Table 2.1).

[4] Chain Bridge is the farthest downstream river reach simulated as part of this project.

Table 2.1
Percent difference in daily and daily summer* temperatures over the simulation period (1984-2005) from Scenario 1

Scenario	Percent difference in daily temperature			Percent difference in daily summer temperature		
	Mean	Min	Max	Mean	Min	Max
2	0.01	0.04	0.02	0.01	0.02	0.01
3	0.02	0.07	0.03	0.03	0.05	0.02
4	0.00	0.04	0.01	0.00	0.00	0.00
5	0.00	0.03	0.02	0.00	0.00	0.01

*June, July, and August daily temperatures were used to calculate daily summer values

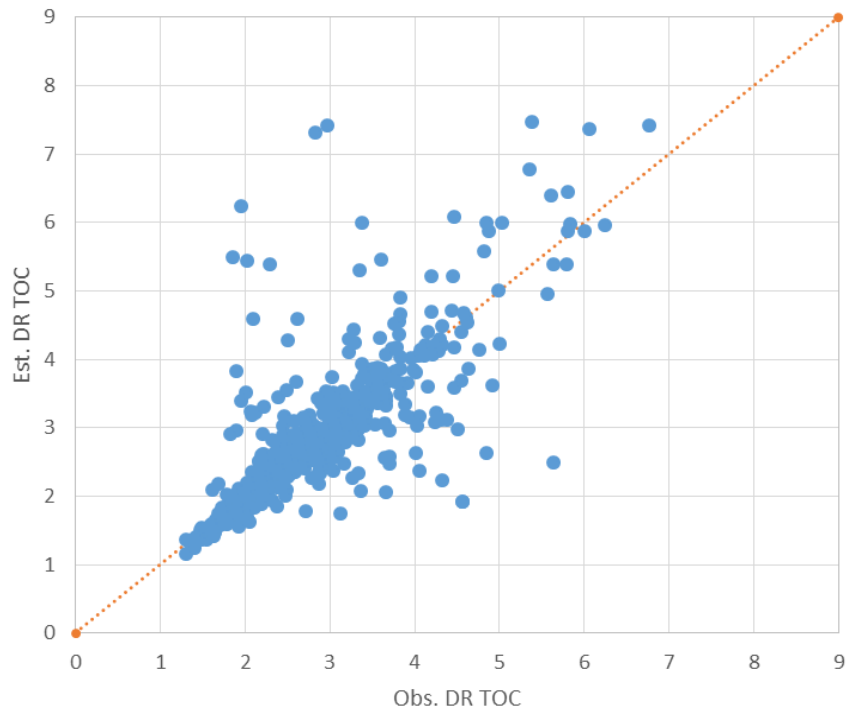
METHOD TO TRANSLATE MODELED WATER QUALITY TO UTILITY INTAKE WATER QUALITY

The Watershed Model simulates mixed reach in-stream TOC and TSS conditions (Chapter 2). That is, the model does not differentiate between concentrations within a reach of any given river segment that may be influenced by local conditions. Water quality conditions measured at the utility intakes, however, were used to develop the relationships described in Chapter 3. Conditions at an intake, under local influences, are not expected to be representative of mixed reach conditions from the model. To this end, analyses were performed to understand how to best translate modeled conditions to intake conditions for each utility.

Washington Aqueduct

Monitoring of Washington Aqueduct's raw water occurs in Dalecarlia Reservoir, not right at the intake location (see Appendix C for a more detailed description of each utility's withdrawal and treatment process). Due to reservoir settling, lower TOC and turbidity levels are expected in the reservoir than in the mainstem Potomac.

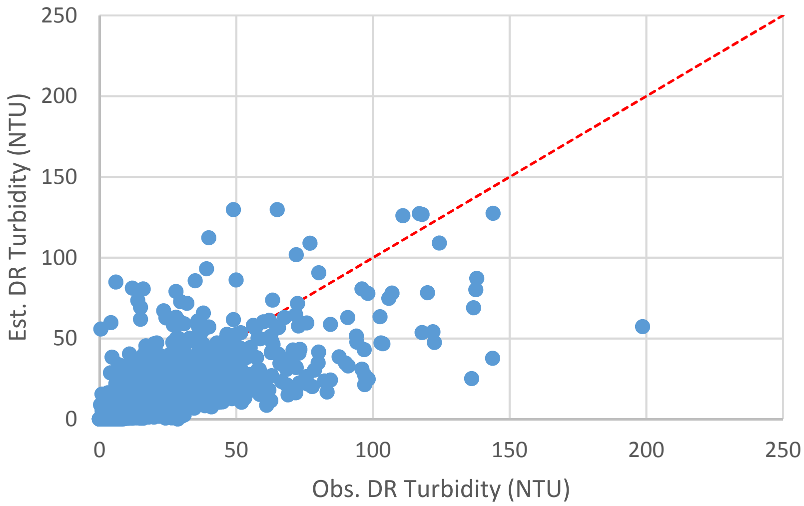
Washington Aqueduct's Dalecarlia Reservoir and Potomac River TOC concentrations, collected by Washington Aqueduct and Maryland Department of Natural Resources (MD DNR), respectively, were explored using the utility's monitoring data. A seven percent reduction in observed Great Falls TOC data, lagged two days, was observed in the available data. That is, today's Dalecarlia Reservoir TOC values can be predicted based on a seven percent reduction in observed TOC values at Great Falls two days ago. Estimated Dalecarlia Reservoir TOC values calculated using this method are compared to observed values in Figure 2.4. The R^2 for this relationship is 0.61. A verification process demonstrated the predictive power of this relationship under years with high, low, and average TOC values.



The 1:1 line, representing a perfect fit, is shown with the red dotted line.

Figure 2.4 Comparison of estimated and observed Dalecarlia Reservoir TOC values (mg/L, 2001-2015, n=697)

A similar analysis was conducted to determine turbidity changes as the raw water moves from the Potomac River through the Dalecarlia Reservoir into Washington Aqueduct's treatment plant. On average, turbidity is reduced 75 percent as the water moves through the reservoir. Estimated Dalecarlia Reservoir turbidity values calculated using this method compare to observed reservoir inflow values with an R^2 of 0.58 (Figure 2.5).



The 1:1 line, representing a perfect fit, is shown with the red dotted line.

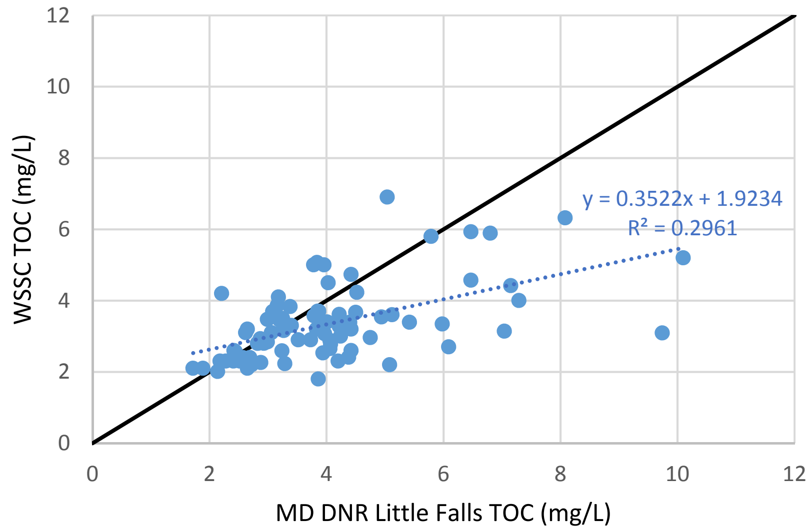
Figure 2.5 Comparison of estimated and observed Dalecarlia Reservoir turbidity values (NTU, 2001-2015, n=6,425)

Washington Suburban Sanitary Commission

The translation approach for WSSC was performed in four steps:

1) Compare the observed intake water quality conditions to the observed river water quality conditions at the MD DNR Little Falls station. The MD DNR sampling location is on the mainstem Potomac River at Little Falls, downstream of the participating utilities' intakes.
2) Develop a relationship that predicts the intake water quality condition based on the observed river water condition. Given that there was no single apparent mechanism to explain the differences between the observed river water and the utility's intake water, translation equations were developed to numerically adjust the river water to predict the utility's intake water.
3) Apply the translation relation to the river water to better match the intake water. Observed MD DNR Little Falls water conditions were translated using the translation equations developed for each utility and adjusted for the best visual agreement.
4) Compare the translated river water to the intake water by developing a plot to evaluate the translated (predicted) and observed utility intake water.

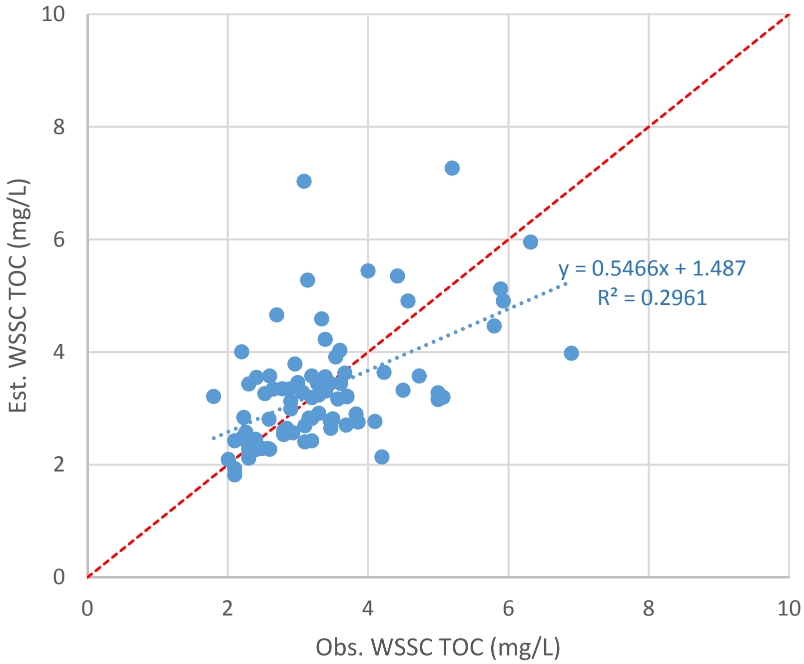
Water quality conditions at the WSSC intake are heavily influenced by the water quality of an urbanized tributary (Watts Branch). In the model, the effects of urbanization in this one location would be accounted for across the entire corresponding reach. To evaluate the effects of the tributary on intake water quality conditions, plots were developed that compare WSSC intake conditions on the y-axis and MD DNR Little Falls monitoring station conditions on the x-axis (Figure 2.6 and Figure 2.8). The data sets for these analyses are limited to dates where monitoring at both locations occurred.



The 1:1 line is shown in black. The blue dotted line, equation, and R^2 are for the regression line for the plotted data points.

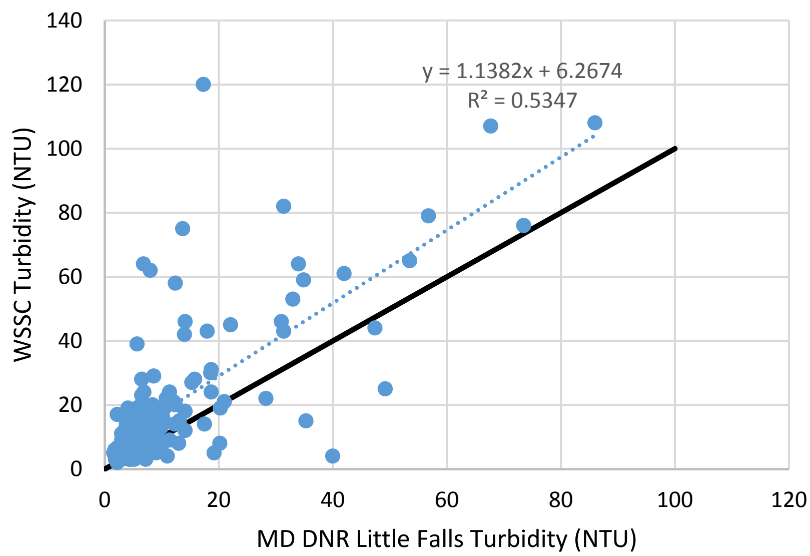
Figure 2.6 TOC at the WSSC intake versus the MD DNR Little Falls monitoring station (mg/L, 1986-2003, n=86)

A linear translator equation was developed to convert observed MD DNR Little Falls TOC data to predicted WSSC intake data - in essence moving the regression (dotted) line in Figure 2.6 closer to the 1:1 (black) line. This translator equation was manually adjusted to optimize fit. The translator equation for the estimation is: $y = 0.65x + 0.7$, where x is the observed Little Falls value and y is the estimated intake value. The data is plotted in Figure 2.7. The relationship has an R^2 of 0.3.



The 1:1 line, representing a perfect fit, is shown with the red dotted line. The blue dotted line, equation, and R^2 are for the regression line for the plotted data points.

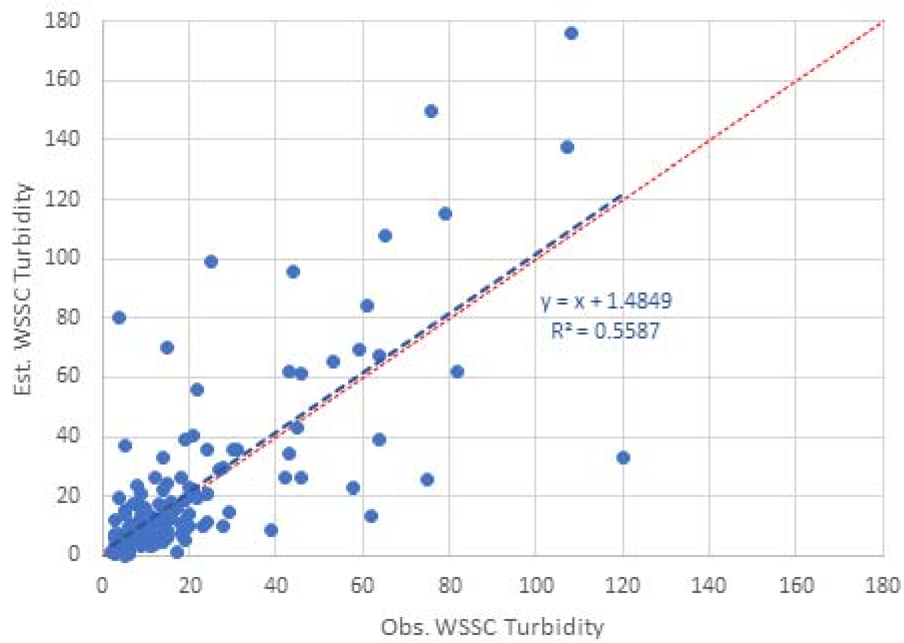
Figure 2.7 Comparison of estimated and observed WSSC TOC values (mg/L, 1986-2003, n=86)



The 1:1 line is shown in black. The blue dotted line, regression, and R^2 are for the regression line for the plotted data points.

Figure 2.8 Turbidity at the WSSC intake versus the MD DNR Little Falls monitoring station (NTU, 1999-2015, n=153)

A translator equation was also developed to convert observed Little Falls turbidity data to predicted intake data. This translator equation was manually adjusted to optimize fit. The translator equation for the estimation is $y = 2.08x - 3.3$, where x is the observed turbidity value at Little Falls and y is the estimated WSSC turbidity value. The data is plotted in Figure 2.9. The relationship has an R^2 is 0.56.



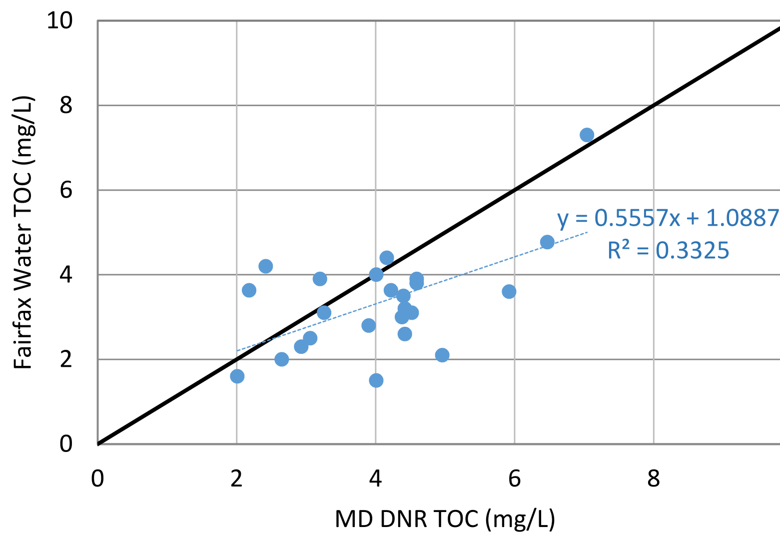
The 1:1 line, representing a perfect fit, is shown with the red dotted line. The blue dotted line, equation, and R^2 are for the regression line for the plotted data points.

Figure 2.9 Comparison of estimated and observed WSSC turbidity values (NTU, 1999-2015, n=152)

Fairfax Water

Fairfax Water has both a near-shore and mid-river intake, each with distinct water quality conditions. These conditions also vary from those that would be expected from mixed-reach conditions. Data for the entire period of interest, regardless of which intake was in use, was used to develop the water quality-treatment dose relationships (Chapter 3). The mid-river intake conditions are expected to be more representative of the model characteristics than the near-shore intake conditions. Therefore, the question becomes whether or not the combined near-shore and mid-river data require adjustment to be comparable to the model output.

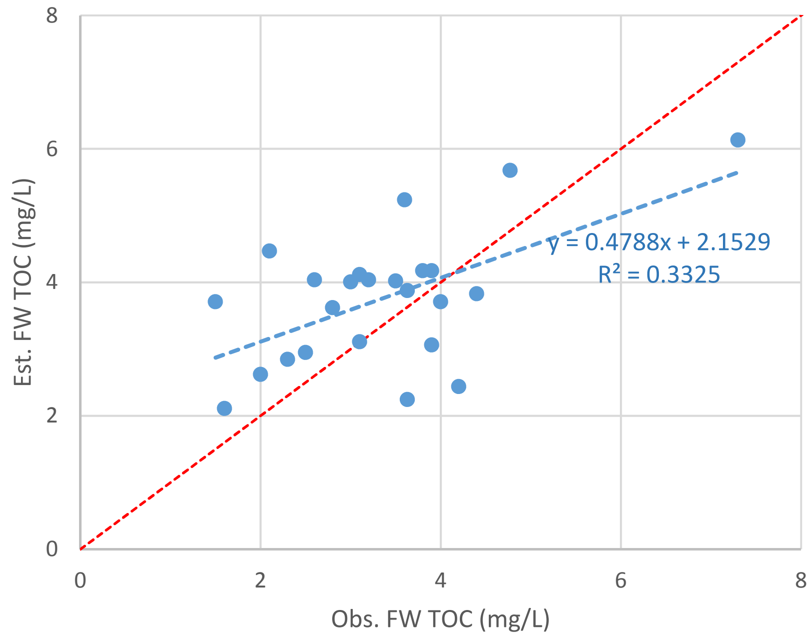
Using the same four-step translation approach that was used for WSSC, plots were developed that compare Fairfax Water intake conditions (using the data set that contains data from both intakes) on the y-axis and MD DNR Little Falls monitoring station conditions on the x-axis (Figure 2.10 and Figure 2.12). The data set sizes for these analyses are limited to dates where Fairfax Water and MD DNR monitoring occurred. In this case, the TOC comparison data set only has 24 paired samples.



The 1:1 line is shown in black. The dotted line, equation, and R^2 are for the regression line for the plotted data points.

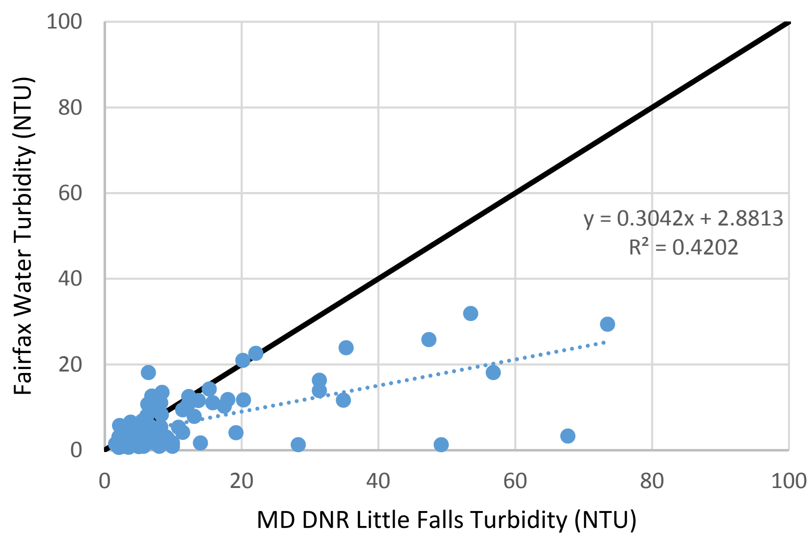
Figure 2.10 TOC at the Fairfax Water intake versus the MD DNR Little Falls monitoring station (mg/L, 1986-2001, n=24)

A translator equation was developed to convert observed Little Falls TOC data to predicted Fairfax Water intake data. This translator equation was manually adjusted to optimize fit. The translator equation for the estimation is: $y = 0.8x + 4.45$, where x is the observed Little Falls value and y is the estimated Fairfax Water value. The data are plotted in Figure 2.11. The relationship has an R^2 of 0.33.



The 1:1 line, representing a perfect fit, is shown with the red dotted line. The dotted line, equation, and R^2 are for the regression line for the plotted data points.

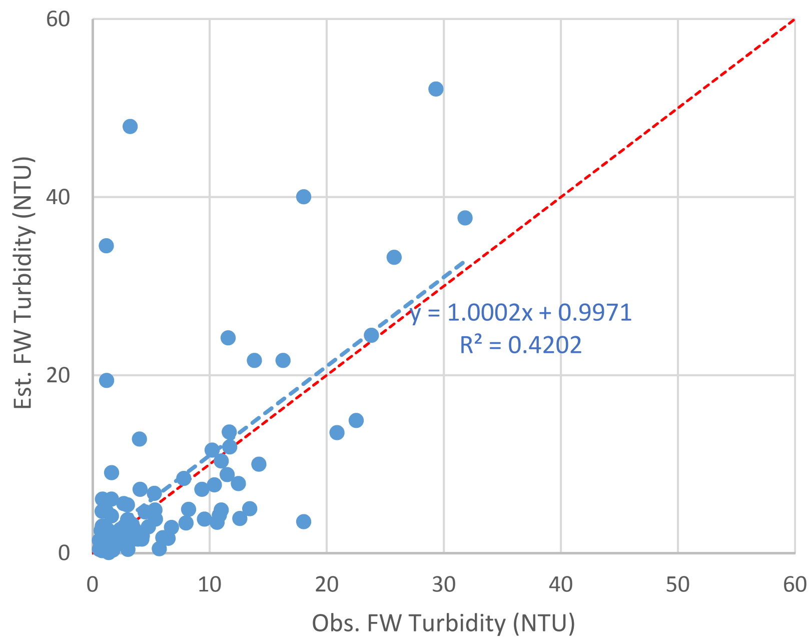
Figure 2.11 Comparison of estimated and observed Fairfax Water TOC values (mg/L, 1986-2001, n=24)



The 1:1 line is shown in black. The dotted line, equation, and R^2 are for the regression line for the plotted data points.

Figure 2.12 Turbidity at the Fairfax Water intake versus the MD DNR Little Falls monitoring station (NTU, 1999-2005, n=91)

A translator equation was developed to convert observed Little Falls turbidity data to predicted Fairfax Water intake data. This translator equation was manually adjusted to optimize fit. The translator equation for the estimation is: y = 0.724x -1.1, where x is the observed Little Falls value and y is the estimated Fairfax Water value. The data are plotted in Figure 2.13. The regression line is close to the 1:1 line despite the scatter due to the large number of points near the origin. The relationship has an R^2 of 0.42.



The 1:1 line, representing a perfect fit, is shown with the red dotted line. The dotted line, equation, and R^2 are for the regression line for the plotted data points.

Figure 2.13 Comparison of estimated and observed Fairfax Water turbidity values (NTU, 1999-2015, n=91)

CHAPTER 3
HISTORIC WATER QUALITY AND TREATMENT DOSE RELATIONSHIPS

This chapter uses the water quality modeling results presented in Chapter 2 to estimate water treatment chemical doses for the estimated turbidity[5] and TOC loads. Before the impact of forest cover on treatment cost can be estimated, the historical relationship between water quality and treatment chemical doses is needed for each utility. A relationship was derived for each utility, instead of one for all three, as each has somewhat different quality water coming into the plant and different treatment trains. Looking at each utility independently provides a relationship specific to their own circumstances.

As a first step in this process, literature linking water quality conditions and utility treatment costs was reviewed for applicability. Additionally, meetings were held with each utility to discuss their specific treatment process, water quality concerns, water quality changes that drive costs, and data availability (Appendix C). In consultation with the utilities and project advisors, this study primarily looked at TOC and turbidity because the chemicals used to treat them drive treatment costs. A decision was also made to focus on utility-specific relationships and not try to generalize across the three utilities. The hope is that this will reduce some of the variability seen in other studies (e.g., Holmes 1988, Dearmont et al. 1998).

This chapter provides a description of the method used to derive relationships and the results of the analysis. Relationships that were explored, but ultimately not used, are documented in Appendix D. Cost estimates based on these relationships are presented in Chapter 4.

RELEVANT STUDIES

An effort was undertaken to review literature related to estimating water utility chemical treatment costs based on raw water quality. The first papers reviewed were those commonly referred to in reports on estimating water treatment costs (e.g., Forster et al. 1987, Dearmont et al. 1998). The citations from these papers were then mined for additional references. Relevant papers were also identified in the TOC literature review described in Appendix B. A Google Scholar search was conducted using key words related to land use, treatment cost, and water quality. The Google Scholar "Related Articles" function was also used to identify other potentially relevant papers.

This search found that there are generally two fields of study looking at these types of relationships: economics and water resources. Examples of the different types of studies are listed below, though not all had significant findings.

- Economics, including payment for ecosystem services
    - Hedonic cost function (Holmes 1988)
    - Standard firm model (Holmes 1988)
    - Econometric model (Moore and McCarl 1987, Abildtrup et al. 2013, Fiquepron et al. 2013)
    - Bioeconomic model (Fiquepron et al. 2013)
    - Benefit transfer (Elsin et al. 2009)

[5] The Watershed Model's TSS output was translated to turbidity to match the available utility data.

- Water Resources
  - Treatment costs as function of raw water quality (Forster et al. 1987, Dearmont et al. 1998, Piper 2003, Heberling et al. 2015)
  - Raw water quality thresholds for additional treatment to estimate costs (Elias et al. 2014)

Papers deemed relevant were those that looked into the relationship between raw water quality at an intake and treatment costs. Only peer-reviewed papers were considered. Studies that linked land cover directly with treatment costs (e.g., Abildtrup et al. 2013, Fiquepron et al. 2013) were not reviewed since that is not the approach undertaken in this effort. The most relevant studies are those that look at turbidity and/or TOC and utility costs, and those that look at the relationship at a single utility. Three papers fit these needs best and are briefly summarized below.

Moore and McCarl 1987

Moore and McCarl attempted to quantify the economic costs of erosion in Oregon's Willamette Valley. One of the costs considered was sediment removal at a single water treatment plant. Costs of alum and lime dose, sediment disposal, and capital improvements were considered. The observed water quality characteristics modeled were volume treated, pH, water temperature, and turbidity. Predictive models were developed to estimate the daily alum and lime needs, and, ultimately, a cost function related to turbidity.

Their first step was to correct for first-order correlation. They then fit linear and log-linear equations, choosing those with the best R^2 values. Using these equations, daily alum and lime costs were estimated. To these costs, average costs of sediment pond cleaning and sludge disposal were added. Next, the authors developed a cost relationship between percent turbidity reduction and cost to estimate the marginal cost of turbidity. They found that for a one percent reduction in turbidity, cost would go down by approximately one-third of a percent.

Elias et al. 2014

Elias et al. (2014) assessed the value of forested land in the Converse Reservoir watershed in Mobile, Alabama. This was done by estimating future TOC loads, following urbanization in the watershed, and the additional powdered activated carbon (PAC) doses that would be needed. The authors' estimates of additional PAC needed were based on operational thresholds for removing TOC under the Stage 2 Disinfection Byproducts Rule. Equations were developed to estimate the amount of PAC needed to treat a given TOC concentration. A future estimate of PAC costs was based on historic prices. The additional PAC needed and future PAC costs were combined with a future estimate of water demand to estimate changes in daily costs.

The study found that increased monthly median TOC concentrations of 33 to 49 percent between May and October following urbanization, required "continuous additional treatment" during those same months (i.e., use PAC 100 percent of the time). This is an increase from the 47 percent of time, prior to urbanization, that additional PAC was needed.

Heberling et al. 2015

Heberling et al. developed long- and short-run relationships between water quality and treatment costs at a plant in Clermont County, Ohio. This was done using error correction models that related a dependent variable that included chemical costs (potassium permanganate, alum, polymer, total caustic, fluoride, phosphate, and chlorine), pumping, and granular activated carbon with total water produced, raw water TOC, raw water turbidity, raw water pH, pool elevation, and dummy variables for actual TOC measurements, water temperatures over 23°C, spring and summer months, calendar year, and a treatment process shutdown.

The result was a cost function that could be used with raw water turbidity and TOC to estimate future costs. The authors found that, mathematically, a one percent decrease in turbidity would lead to a 0.02 percent decrease in treatment costs, and a further 0.1 percent decrease over subsequent days. Increased TOC did not have an effect on short- or long-term costs. The treatment cost results were compared to estimated source water protection costs.

METHOD

This section describes the method used for developing water quality-treatment dose relationships and the results found (Figure 3.1). The portions of the overall method for estimating treatment chemical costs by utility described in this section are highlighted in red in Figure 3.1. These relationships are used in Chapter 4 to estimate treatment costs for each of the five modeled land use scenarios. This approach is not intended to allow for the quantification of all costs associated with raw water quality. Instead, it estimates costs of chemicals for which statistically significant relationships could be identified. Other costs, including operation and capital costs, are evaluated separately. The costs of the chemical doses, therefore, are an indicator of overall cost changes under the five land cover model scenarios. Cost estimates are discussed in detail in Chapter 4.

The following steps were implemented to use the historical, observed data from the participating utilities to derive statistically significant relationships between raw water quality and treatment doses.

Water quality-treatment dose relationships

↓

Future withdrawals

↓

Chemical doses by scenario

↓

Current cost of each chemical

↓

Daily cost of each chemical by scenario

↓

Average annual costs of each chemical by scenario

↓

Total average annual treatment chemical cost by scenario

Figure 3.1 Method for estimating treatment chemical costs by utility

Step 1. Analyze Observed Data to Develop Relationships between Water Quality and Chemical Dose

For each utility and water quality parameter (TOC and turbidity), calculate relationships between observed chemical doses and observed raw water TOC and turbidity data where:

$$\gamma_{Chem1Daily} = \beta_0 + \beta_1 x_{WQparameter1} + \beta_2 x_{WQparameter2} + \beta_3 x_{\frac{month}{season}} \ldots + \beta x_n \tag{3.1}$$

$$\gamma_{Chem2Daily} = \beta_0 + \beta_1 x_{WQparameter1} + \beta_2 x_{WQparameter2} + \beta_3 x_{\frac{month}{season}} \ldots + \beta x_n$$

$$\gamma_{Chem3Daily} = \beta_0 + \beta_1 x_{WQparameter1} + \beta_2 x_{WQparameter2} + \beta_3 x_{\frac{month}{season}} \ldots + \beta x_n$$

.

.

.

$$\gamma_{Chem3Daily} = \beta_0 + \beta_1 x_{WQparameter1} + \beta_2 x_{WQparameter2} + \beta_3 x_{\frac{month}{season}} \ldots + \beta x_n$$

The purpose of these relationships is to provide a means for predicting the daily chemical dose based on the Watershed Model output. Utility costs can then be estimated from the predicted doses utilizing the subsequent steps.

The response (dependent) variable is defined here as the daily chemical dose. Chemicals were selected from those listed in Table 3.1 based on professional judgment through ongoing conversations with the utilities and through evaluation of the statistical relationships in the observed data. Discussion of the selected chemicals follows in the next section.

Table 3.1
Chemicals considered in the development of water quality-treatment dose relationships

Chemical	Fairfax Water	Washington Aqueduct	WSSC
PACl (Polyaluminum chloride)	X		X
Sulfuric acid	X		X
Lime			X
Potassium permanganate	X		X
Alum		X	
Chlorine		X	

Predictor (independent) variables included factors available in the model outputs such as daily raw water TOC, turbidity concentrations, and temperature, month, or season. For each chemical, the appropriate independent variables were selected based on the rules governing use of the chemical at each utility (e.g., is the use seasonal, is the chemical only applied for one specific water quality condition, etc.). The parameters provided in the example equations, therefore, are simply to illustrate the possibilities, but may not all be present in each relationship. The parameter βx_n is included in the formulas to allow for the possibility of additional regression parameters, should the data demonstrate an improved relationship with such an addition.

Each regression developed using this approach was evaluated at the 95 percent confidence interval based on the:

- significance of the test statistic;
- p value of the coefficients (β_0, β_1, β_2, ... β_n);
- coefficient of determination (R^2); and
- visual interpretation.

Only statistically significant regressions were used to develop the water quality-treatment dose relationships.

Step 2. Estimate Future Withdrawals

Estimate 2030 daily withdrawals for Washington Aqueduct, WSSC, and Fairfax Water using the method developed in the Interstate Commission on the Potomac River Basin - Section for Cooperative Water Supply Operations on the Potomac's 2015 demand study (Ahmed et al. 2015). The method takes into account the simulation year (2030), month, season, weather conditions, day of week, and a daily error term based on an autoregressive integrated moving average process.

Step 3. Estimate Chemical Doses Using Simulated Water Quality Conditions for Each Scenario

Step 3a. Calculate Chemical Dose Predicted for Simulated Water Quality Conditions under the Five Scenarios

Using the regression equations outlined in Step 1 above, calculate the amount of chemicals needed to treat for the simulated water quality conditions on a daily basis at utility intakes by substituting modeled values for daily water quality conditions, month/season (since treatment approaches vary by month/season), and other predictor values.

Step 3b. Calculate Daily Quantity of Chemicals Used

The daily quantity of chemicals used is calculated using Equation 3.2:

$$Quantity_{ChemxDaily} = daily\ dose_{ChemxDaily} * projected\ daily\ withdrawal_{utilityx} \quad (3.2)$$

Daily dose is calculated in Step 3a and the projected daily withdrawal is calculated based on methods described in Step 2. For example, WSSC daily dose is predicted in mg/L; daily withdrawals can be converted to liters then multiplied by the daily dose to get total chemical quantity in mg. This quantity is calculated for each chemical under consideration.

WATER QUALITY-TREATMENT DOSE RELATIONSHIPS BY UTILITY

This section provides some background information for each utility and then presents the water quality-treatment dose relationships. For reference, descriptions of the monitoring, treatment process, and cost considerations for each utility are provided in Appendix C.

Units for all variables in the water quality-treatment dose relationships were selected to be consistent with the Watershed Model outputs. Coefficients for all variables are presented to two significant digits.

Washington Aqueduct

The two chemicals used in the treatment process at Washington Aqueduct that are expected to relate to raw water TOC and turbidity are coagulant, in the form of hydrated alum, and chlorine. The five-year period (1/1/2011 to 12/31/2015) is optimal for correlating with existing treatment practices (personal communication, Washington Aqueduct, 2/18/2016). To this end, daily data were obtained from Washington Aqueduct's Dalecarlia Water Treatment Plant for coagulant and chlorine for that five-year period. Turbidity data were obtained for Dalecarlia Reservoir, the intake point for the Dalecarlia Water Treatment Plant, for the same time period. Water temperature data were also available for this time frame and numeric indicators for season and month were developed for the daily data.[6]

Washington Aqueduct monitors for raw water TOC and UV 254 as indicators of Natural Organic Matter. Monitoring for UV 254 occurs daily and is used for plant operations such as determining chemical dosing. Monitoring for TOC occurs weekly and is used to meet regulatory obligations and fulfill other longer-term planning objectives (personal communication, Washington Aqueduct, 6/2/2016). The two parameters are closely related (Figure 3.2) and for planning purposes they can often be used interchangeably (personal communication, Washington Aqueduct, 6/1/2016). To be compatible with TOC regressions developed for the other two utilities, it was decided to develop the Washington Aqueduct regression in terms of TOC. Given the limited size of the TOC data set (n=256), the raw water UV 254 data were transformed into raw water TOC values using the equation shown in Figure 3.2 and merged with the monitored TOC data to develop a more robust "TOC+" data set from which to develop the water quality-treatment dose relationships for Washington Aqueduct.

[6] The month variable ranges from 1-12 while the season variable ranges from 1-4.

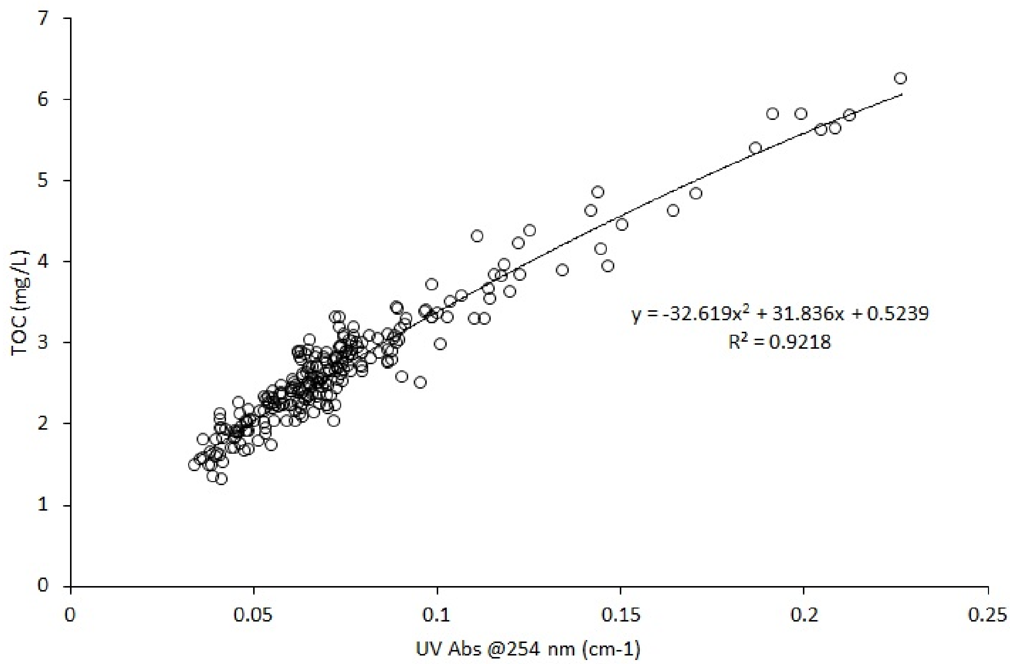


Figure 3.2 Relationship of raw water UV 254 to TOC (2010-2015)

The regressions for all combinations of independent and dependent variables are shown in Appendix E. Washington Aqueduct regressions were developed with the combined TOC+ data set, described above.

Coagulant (Hydrated Alum)

Using the last five years of data, the following relationship (Equation 3.3) was identified between hydrated alum dose, water temperature, turbidity, and TOC+ where R^2=0.58. Hydrated alum dose was converted to Al_2O_3 in (Equation 3.3) to make the equations consistent and comparable between utilities. All predictor variables, the intercept, and the overall F test statistic have p<0.0001 and are significant at a 95 percent confidence level.

$$mg/L\,Al_2O_3 = 1.5 + 0.01(°F\ Temp) + 0.01(NTU\ Turbidity) + 0.38(mg/L\ TOC) \quad (3.3)$$

Figure 3.3 is provided for visual inspection of the residual plots, line fit plots, and normal probability plot associated with this regression.

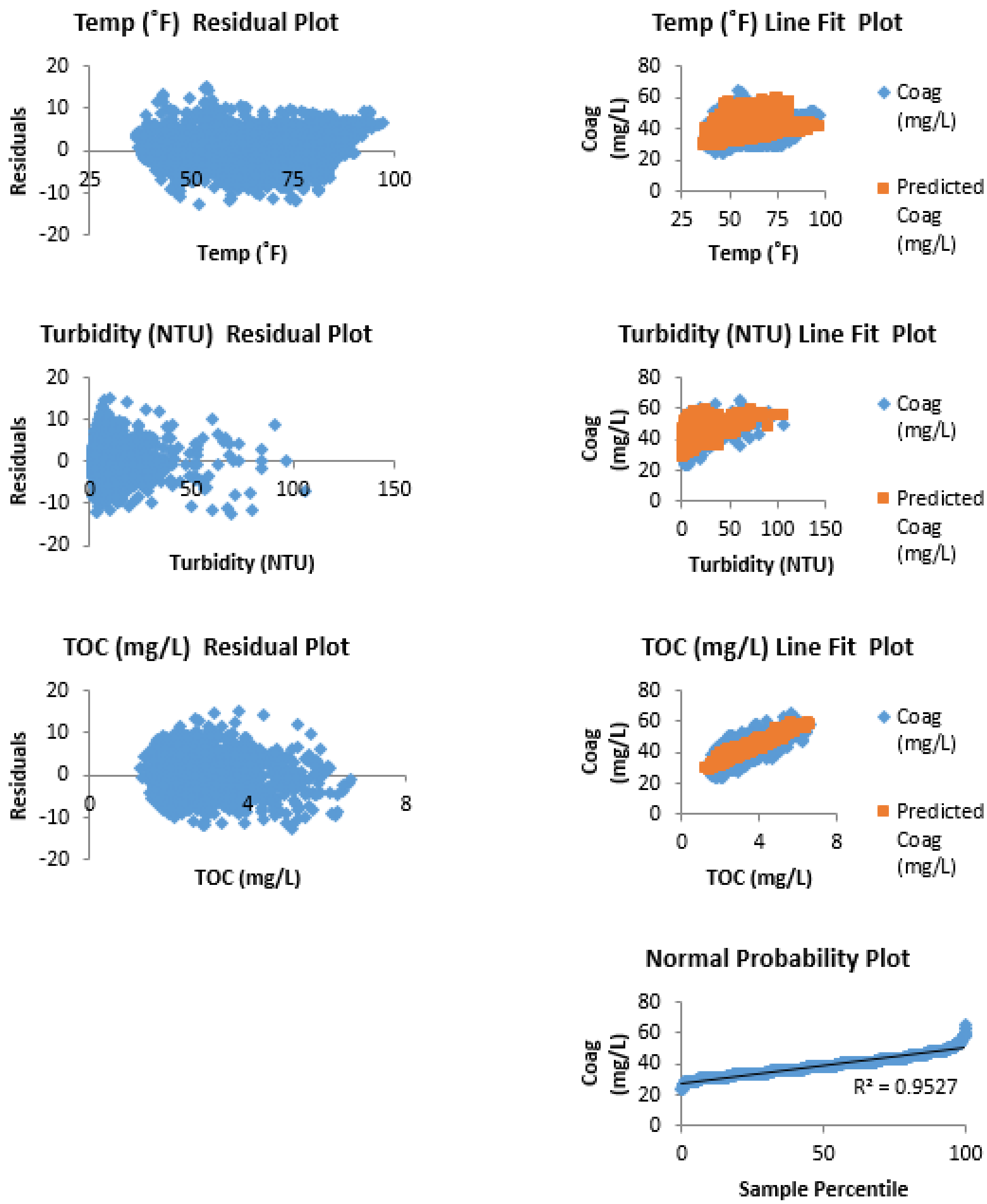


Figure 3.3 Residual plots, line fit plots, and normal probability plot for Washington Aqueduct's coagulant dose regression

A sensitivity analysis was conducted to determine the potential percent change in coagulant dose based on observed historic changes in each predictor variable. Using the developed regression equation, if the water quality-treatment dose relationship is solved twice using the average observed daily turbidity and TOC values – once with the observed maximum and once with the observed minimum daily temperature values – there is a resulting 20 percent change in predicted coagulant dose. Similarly, holding other predictor variables constant at average observed values results in a 21 percent change in predicted dose based on observed high and low turbidity values and a 62 percent change in predicted dose based on observed high and low TOC values. This is not an estimation of uncertainty or error, but rather an indication of how sensitive the regression is to each of the predictor variables.

Chlorine

Using the last five years of data, the following relationship (Equation 3.4) was identified between chlorine dose, water temperature, turbidity, and TOC+ where R^2=0.59. All predictor variables, the intercept, and the overall F test statistic have $p<0.0001$ and are significant at a 95 percent confidence level.

$$mg/L\ Chlorine = 2.5 + 0.05(°F\ Temp) - 0.01(NTU\ Turbidity) + 0.41(mg/L\ \ TOC) \quad (3.4)$$

Figure 3.4 is provided for visual inspection of the residual plots, line fit plots, and normal probability plot associated with this regression.

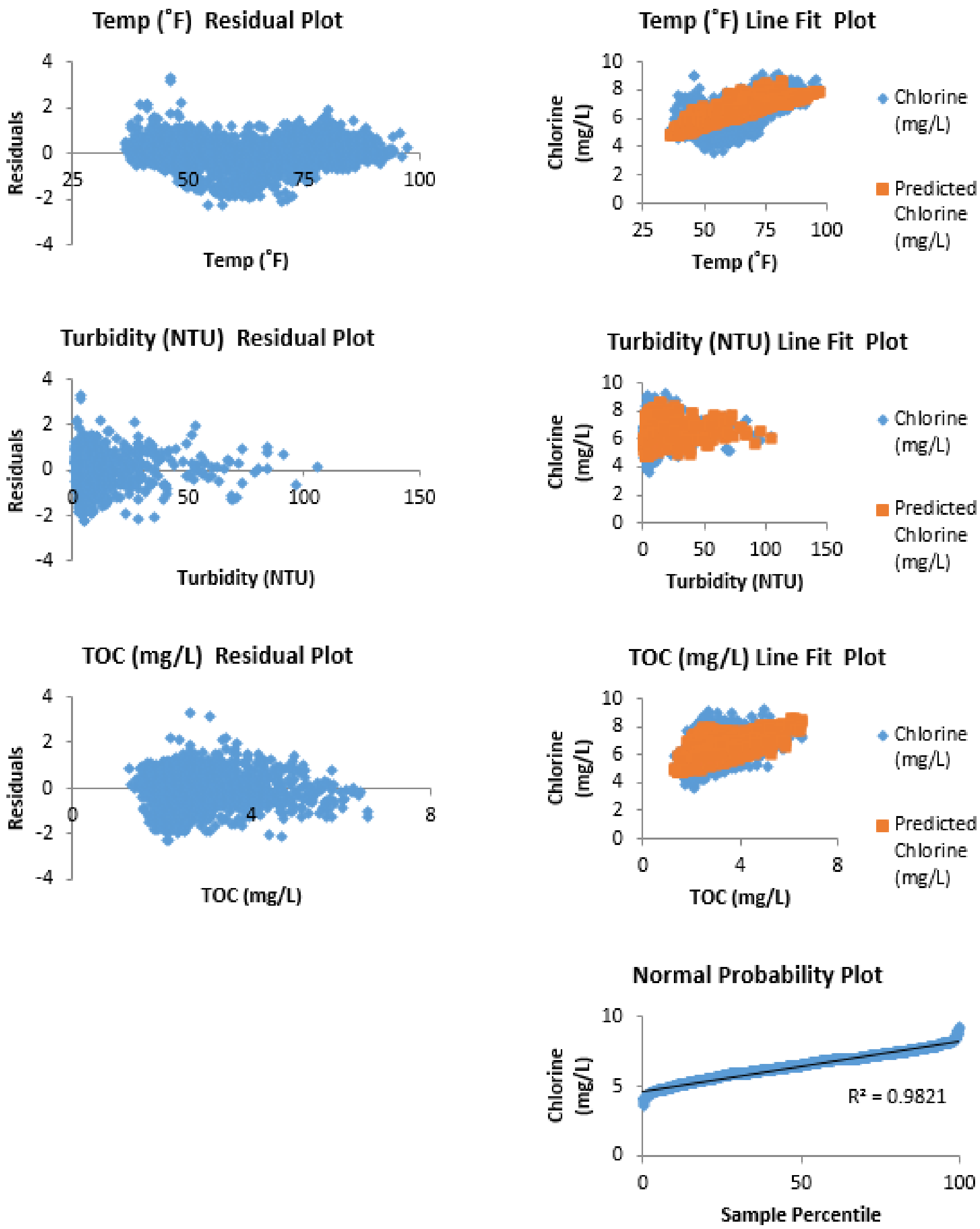


Figure 3.4 Residual plots, line fit plots, and normal probability plot for Washington Aqueduct's chlorine dose regression

A sensitivity analysis was conducted to determine the potential percent change in chlorine dose based on observed historic changes in each predictor variable. Using the developed regression equation, if the water quality-treatment dose relationship is solved twice using the average observed daily turbidity and TOC values – once with the observed maximum and once with the observed minimum daily temperature values – there is a resulting 45 percent change in predicted chlorine dose. Similarly, holding other predictor variables constant at average observed values results in a 16 percent change in predicted dose based on observed high and low turbidity values and a 32 percent change in predicted dose based on observed high and low TOC values.

Washington Suburban Sanitary Commission

Six chemicals were originally explored for relationships with raw water TOC and turbidity at the WSSC intake; namely, coagulant in the form of PACl, sulfuric acid, potassium permanganate, lime, ferric chloride, and coagulant aid. During initial evaluation, it was determined that ferric chloride and coagulant aid were not correlated with raw water TOC and turbidity particularly due to intermittent use, so they were removed from investigation at that stage of the process. Ultimately, PACl was determined to have the strongest relationship to river water quality. A discussion of the other relationships is in Appendix D.

Average daily monitoring data for treatment chemicals, turbidity, and water temperature were obtained from WSSC, as well as grab sample TOC data. In addition, a month and season variable were calculated for each day. Based on discussions with WSSC, the time period used for analysis (that represents current operating conditions) is 1/2/2007 through 2/29/2016 (personal communication, WSSC, 5/19/2016).

The regressions for all combinations of independent and dependent variables are shown in Appendix E.

Coagulant (PACl)

Using the 1/2/2007 through 2/29/2016 time period, the following relationship (Equation 3.5) was identified between coagulant dose, turbidity, and TOC where R^2=0.74. All predictor variables, the intercept, and the overall F test statistic have p<0.0001 and are significant at a 95 percent confidence level.

$$mg/L\, Al_2O_3 = 2.2 + 0.04(NTU\ Turbidity) + 0.61(mg/L\ \ TOC) \tag{3.5}$$

Figure 3.5 is provided for visual inspection of the residual plots, line fit plots, and normal probability plot associated with this regression.

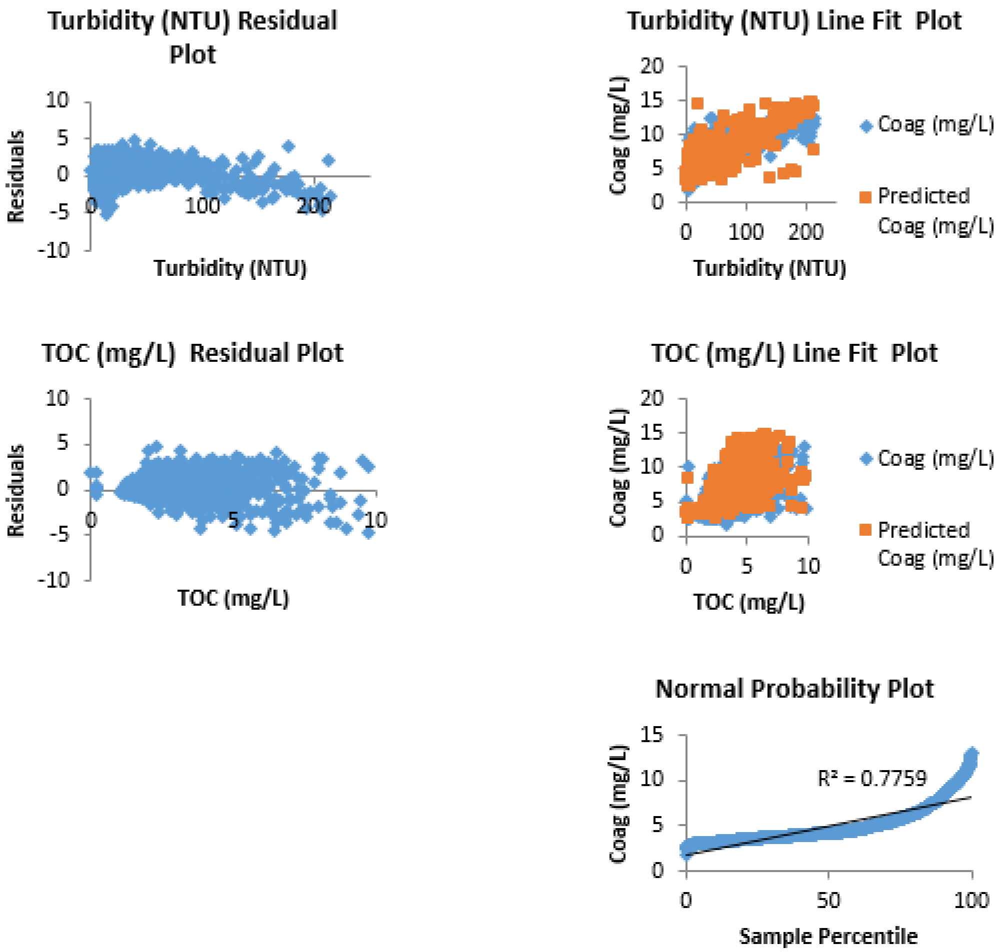


Figure 3.5 Residual plots, line fit plots, and normal probability plot for WSSC's coagulant dose regression

A sensitivity analysis was conducted to determine the potential percent change in coagulant dose based on observed historic changes in each predictor variable. Using the developed regression equation, if the water quality-treatment dose relationship is solved twice using the average observed daily TOC values – once with the observed maximum and once with the observed minimum daily turbidity values – there is a resulting 172 percent change in predicted coagulant dose. Similarly, holding turbidity constant at average observed values results in a 126 percent change in predicted dose based on observed high and low TOC values. This is not an estimation of uncertainty or error, but rather an indication of how sensitive the regression is to each of the predictor variables.

Fairfax Water

Three treatment chemicals were explored for relationships with raw water quality conditions; namely, average daily coagulant dose (PACl), average daily sulfuric acid dose, and average daily potassium permanganate ($KMnO_4$) dose. TOC and turbidity data were also obtained to represent raw water quality conditions. Similar to methods used with the other utilities' data, numeric indicators for season and month were developed for the daily data. Water temperature data were also obtained.

A ten-year time period (1/1/2006 to 12/31/15) of daily data was used in the development of relationships for Fairfax Water based on conversations about treatment process history (personal communication, Fairfax Water, 5/19/2016).

Coagulant had the strongest relationship and is discussed below. The relationships with sulfuric acid and $KMnO_4$ are covered in Appendix D. The regressions for all combinations of independent and dependent variables are also shown in Appendix E.

Coagulant (PACl)

Using the last ten years of data, the following relationship (Equation 3.8) was identified between coagulant dose, water temperature, turbidity, and TOC where R^2=0.48. All predictor variables, the intercept, and the overall F test statistic have p<0.0001 and are significant at a 95 percent confidence level.

$$mg/L\,Al_2O_3 = 2.2 + 0.01(°F\ Temp) + 0.06(NTU\ Turbidity) + 0.11\left(\frac{mg}{L}TOC\right) \quad (3.8)$$

Figure 3.6 is provided for visual inspection of the residual plots, line fit plots, and normal probability plot associated with this regression.

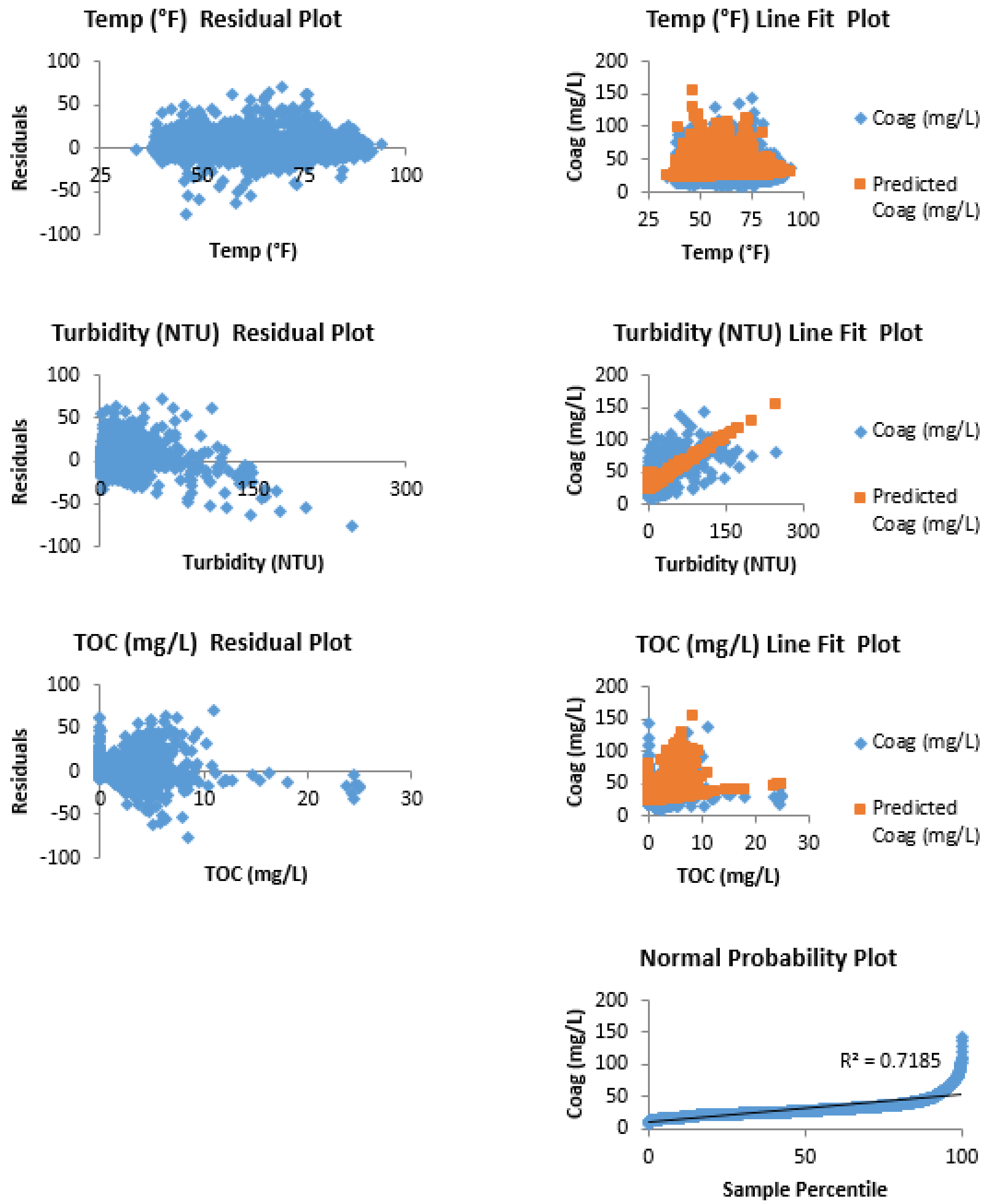


Figure 3.6 Residual plots, line fit plots, and normal probability plot for Fairfax Water's coagulant dose regression

A sensitivity analysis was conducted to determine the potential percent change in coagulant dose based on observed historic changes in each predictor variable. Using the developed regression equation, if the water quality-treatment dose relationship is solved twice using the average observed daily turbidity and TOC values – once with the observed maximum and once with the observed minimum daily temperature values – there is a resulting 19 percent change in predicted coagulant dose. Similarly, holding other predictor variables constant at average observed values results in a 398 percent change in predicted dose based on observed high and low turbidity values and a 72 percent change in predicted dose based on observed high and low TOC values. This is not an estimation of uncertainty or error, but rather an indication of how sensitive the regression is to each of the predictor variables

TREATMENT CHEMICAL DOSE BY UTILITY AND SCENARIO

Application of the water quality-treatment dose relationships resulted in predicted daily mean, minimum, and maximum treatment chemical doses at each utility. Table 3.2, Table 3.3, Table 3.4, and Table 3.5 provide the percent difference from Scenario 1 by treatment chemical and utility as a result of modeled application of Scenarios 2, 3, 4, and 5. The largest decrease in daily treatment chemical doses from the base 2030 scenario (Scenario 1) was 1.6 percent, found for the change in average daily maximum PACl dose at WSSC for Scenario 3. Similarly for the other utilities, the largest decrease in treatment chemical doses was for Scenario 3, which conserves approximately two percent of the total forest land in the study area. For reference, the Scenario 1 average daily doses for each utility and treatment chemical under consideration are provided in Table 3.6. As a reminder, a brief description of the five scenarios is provided in Figure 3.7.

Scenarios

1. Base 2030 scenario
2. Protect 50% of forests expected to be lost by 2030
3. Protect 100% of forests expected to be lost by 2030
4. Install forest buffers at minimum state and county requirements
5. Install forest buffers to 100 feet of Potomac River and major tributaries

Figure 3.7 Brief description of the five scenarios

Table 3.2
Percent difference from Scenario 1 in predicted Washington Aqueduct daily mean, minimum, and maximum chlorine doses

	Percent difference from Scenario 1, Chlorine (%)		
Scenario	Average mean	Average minimum	Average maximum
2	-0.35	-0.27	-0.36
3	-0.70	-0.54	-0.76
4	-0.19	-0.17	-0.16
5	-0.32	-0.32	-0.25

Table 3.3
Percent difference from Scenario 1 in predicted Washington Aqueduct daily mean, minimum, and maximum hydrated alum doses

	Percent difference from Scenario 1, Hydrated Alum (%)		
Scenario	Average mean	Average minimum	Average maximum
2	-0.62	-0.52	-0.62
3	-1.26	-1.02	-1.30
4	-0.34	-0.33	-0.28
5	-0.58	-0.61	-0.45

Table 3.4
Percent difference from Scenario 1 in predicted Fairfax Water daily mean, minimum, and maximum coagulant (PACl) doses

	Percent difference from Scenario 1, coagulant (%)		
Scenario	Average mean	Average minimum	Average maximum
2	-0.34	-0.22	-0.41
3	-0.69	-0.44	-0.84
4	-0.24	-0.17	-0.28
5	-0.49	-0.36	-0.56

Table 3.5
Percent difference from Scenario 1 in predicted WSSC daily mean, minimum, and maximum coagulant (PACl) doses

	Percent difference from Scenario 1, coagulant (%)		
Scenario	Average mean	Average minimum	Average maximum
2	-0.74	-0.56	-0.79
3	-1.50	-1.12	-1.63
4	-0.48	-0.41	-0.49
5	-0.94	-0.83	-0.93

Table 3.6
Scenario 1 average daily doses for each utility and treatment chemical*

Utility and treatment chemical	Scenario 1 average daily dose (mg/L)
Washington Aqueduct (Al_2O_3)	3.6
Washington Aqueduct (Chlorine)	6.7
Fairfax Water (Al_2O_3)	4.9
WSSC (Al_2O_3)	6.1

* Coagulants were converted to Al_2O_3 for direct comparison.

CHAPTER 4
DRINKING WATER UTILITY COSTS

The water quality modeling results presented in Chapter 2 and the water quality-treatment dose relationships developed in Chapter 3 were used to predict chemical costs under the five land use scenarios is this chapter. Recognizing that chemical costs are not the only or even the main cost driver for the utilities, two additional cost analyses are provided. One looks at capital costs and the other looks at solids handling. All costs reported in this chapter are in U.S. Dollars ($USD).

WATER TREATMENT CHEMICAL COST ESTIMATES BY UTILITY AND LAND USE SCENARIO

The portions of the overall method for estimating treatment chemical costs by utility described in this section are highlighted in red in Figure 4.1. The average costs of chemicals for which regression equations were developed were calculated for each utility. Historic costs were reviewed, cost metrics were calculated and evaluated, and sensitivity analyses were performed. The results of this analysis are presented below.

Three basic steps were employed to estimate the chemical costs:

Method for Estimating Treatment Chemical Costs by Utility

Water quality-treatment dose relationships

↓

Future withdrawals

↓

Chemical doses by scenario

↓

Current cost of each chemical

↓

Daily cost of each chemical by scenario

↓

Average annual costs of each chemical by scenario

↓

Total average annual treatment chemical cost by scenario

Figure 4.1. Method for estimating treatment chemical costs by utility

Step 1. Calculate Average Cost of Each Chemical at Each Utility by Summarizing Historic Cost Data

Testing was performed to see what type of average cost figure best matched observed costs by the utilities. Options included, but were not limited to, an average of prices over the last two to five years or percent increases per year from a baseline cost.

Step 2. Calculate Daily Cost of Each Chemical

The daily cost of each chemical is calculated using Equation 4.1.

$$Cost_{ChemxDaily} = quantity_{ChemxDaily} * average\ chemical\ cost_{utilityx} \qquad (4.1)$$

Quantity is in tons from Step 3b of the water quality-treatment dose relationship development. Average chemical costs are in cost/weight. For example, average WSSC chemical costs are in $USD/ton.

Step 3. Calculate Average Annual Costs of Each Chemical

This was done by summing daily costs for each chemical for each year and dividing by the number of days in the year. The average annual costs for the period of record was then calculated.

Step 4. Calculate the Total Average Annual Cost of Chemicals Used for Each Model Scenario

To do this the average annual cost for all chemicals identified in Step 1 of the water quality-treatment dose relationship development were summed. The temporal resolution of this calculation could be adjusted as necessary from annual to seasonal, monthly, daily, etc.

Historic Costs

The average annual cost of each chemical was plotted to evaluate trends over time for Fairfax Water and WSSC (Figure 4.2, Figure 4.3, Figure 4.4, and Figure 4.5). Only current costs were provided by Washington Aqueduct.

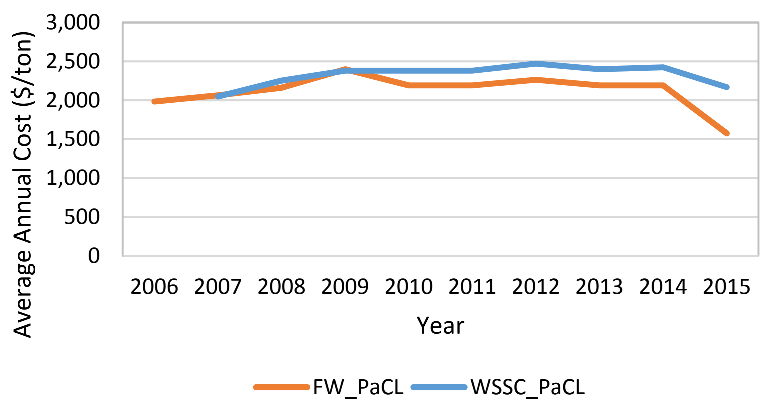


Figure 4.2 Historic average annual cost of coagulant (PACl) for Fairfax Water and WSSC ($USD/ton, 2006-2015)

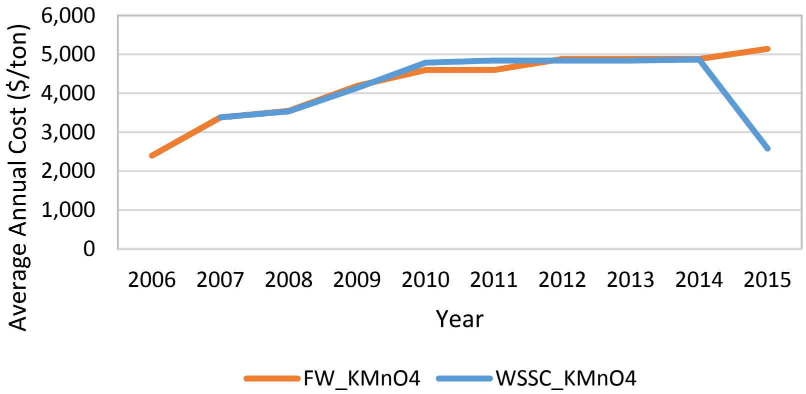


Figure 4.3 Historic average annual cost of potassium permanganate for Fairfax Water and WSSC ($USD/ton, 2006-2015)

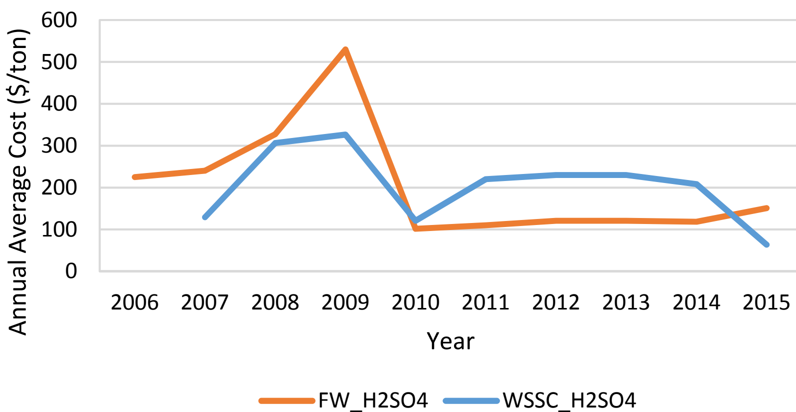


Figure 4.4 Historic average annual cost of sulfuric acid for Fairfax Water and WSSC ($USD/ton, 2006-2015)

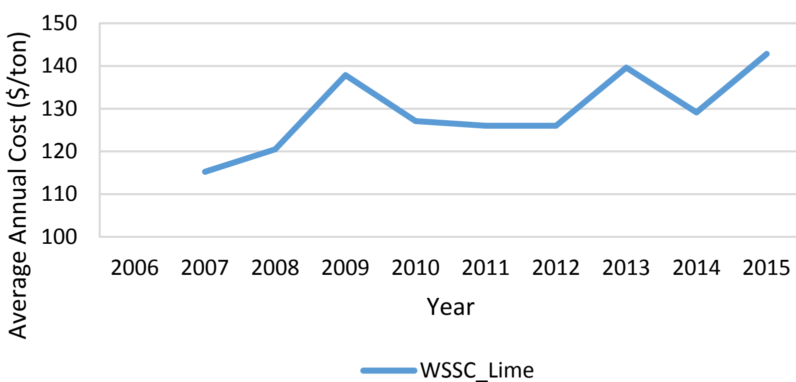


Figure 4.5 Historic average annual cost of lime for WSSC ($USD/ton, 2007-2015)

Using the historic chemical costs provided by Fairfax Water and WSSC, a summary of several cost metrics was developed (Table 4.1). The two- and five-year average costs were evaluated for their ability to predict historic annual costs. The average of the absolute percent difference between the two-year average and five-year average cost metrics and each year's observed cost were used as the indicators of the strength of the predictions. Given the uncertainty associated with predicting future costs and the variability in historic costs (see the average percent change per year for each chemical in Table 4.1), the current costs of chemicals were used. The differences in costs for treatment chemicals reported in Table 4.1 when comparing between utilities are due primarily to differences in the products used by each utility and the way in which those products are used in the treatment process.

Table 4.1
Cost metrics for each treatment chemical by utility ($USD/ton)*

	Current (2015) ($USD/ton)	2-year average (2014-2015) ($USD/ton)	5-year average (2011-2015) ($USD/ton)	Average change per year	Average diff, 2 year (%)	Average diff, 5 year (%)
Fairfax Water						
Coagulant (PACl)	1,574	1,883	2,082	-46	14	8
$KMnO_4$	5,140	5,010	4,876	305	25	22
Sulfuric acid	151	135	124	-8	32	30
WSSC						
Coagulant (PACl)	2,144	2,296	2,368	15	5	4
KMnO4	5,160	3,723	4,393	-100	21	20
Sulfuric acid	127	136	190	-8	44	49
Lime	143	136	133	3	8	7
Washington Aqueduct**	Current (2016) ($USD/ton)					
Coagulant (Hydrated Alum)	278					
Chlorine	1,380					

*The current, two-year average, and five-year average costs are provided followed by the average percent change per year for each treatment chemical. The last two columns are the absolute percent difference between the two-year average and five-year average cost metrics and each year's observed cost.
**Historic cost data were not obtained from Washington Aqueduct.

The total cost for each chemical for the three utilities over the past several years where data are readily available are shown in Table 4.2. Based on this information, coagulant comprises 76 percent of the chemical cost for the three chemicals under consideration during the period of analysis for Fairfax Water (2006-2015). Similarly, coagulant comprises 70 percent of the chemical cost for the four chemicals under consideration for the period of analysis for WSSC (2007-2015). Of Washington Aqueduct's two chemicals under consideration, hydrated alum (the coagulant) comprises 55 percent of the total chemical cost from 2011-2015. As with Table 4.1, the differences in costs for treatment chemicals reported in Table 4.2 when comparing between utilities are due primarily to differences in the products used by each utility and the way in which those products are used in the treatment process.

Table 4.2
Historic total cost ($USD/yr) by chemical, year, and utility

Fairfax Water	Cost ($USD/yr)		
Year	$KMnO_4$	Sulfuric acid	PACl
2006	6,518	119,085	1,292,948
2007	133,885	324,267	1,085,336
2008	45,290	367,719	1,050,294
2009	35,480	800,940	1,199,839
2010	31,343	231,965	1,081,078
2011	10,069	202,046	1,241,627
2012	114,289	186,531	911,927
2013	149,322	148,899	1,182,315
2014	106,119	139,874	1,215,322
2015	237,209	172,665	842,323

WSSC	Cost ($USD/yr)			
Year	$KMnO_4$	Sulfuric acid	PACl	Lime
2007	302,205	241,371	1,858,297	133,325
2008	0	913,227	2,023,791	193,003
2009	122,803	714,006	2,365,709	207,270
2010	441,478	293,496	2,456,811	175,682
2011	403,921	522,452	2,603,984	233,875
2012	274,915	439,365	2,124,636	163,181
2013	274,550	415,459	2,119,844	238,218
2014	467,663	373,015	2,253,231	239,938
2015	323,149	152,819	2,161,843	325,189

Washington Aqueduct	Cost ($USD/yr)	
Year	Coagulant	Chlorine
2011	2,714,953	1,984,594
2012	2,354,796	1,900,072
2013	2,267,281	1,832,319
2014	2,011,878	1,841,815
2015	2,093,286	1,844,156

Sensitivity Analysis

A sensitivity analysis using the high, low, and average daily doses that were predicted using the water quality-treatment dose relationships (Chapter 3) and current, two-year, and five-year average costs was conducted (Table 4.3). The purpose of this sensitivity analysis was to test the regressions with observed water quality data and cost information prior to applying the regressions to modeled data. This analysis demonstrates the range of costs that result from application of the water quality-treatment dose relationships. Evaluation of the results in Table 4.3 indicate that the predicted cost ranges are comparable to the range of participating utility observed costs (personal communication, participating utilities).

Table 4.3
Sensitivity analysis of high, low, and average doses predicted using the water quality-treatment dose relationships and three cost metrics (avg $USD/day)*

	Coagulant (PACl)			Sulfuric acid			Potassium permanganate			Lime		
WSSC	High dose	Low dose	Avg	High dose	Low dose	Avg	High dose	Low dose	Avg	High dose	Low dose	Avg
Current costs	19,315	2,464	10,681	3,693	0	1,330	7,582	0	3,289	2,104	0	1,157
2yr avg costs	20,681	2,638	11,437	3,943	0	1,420	5,471	0	2,374	2,001	0	1,100
5yr avg costs	21,334	2,721	11,798	5,525	0	1,990	6,456	0	2,801	1,953	0	1,074

	Coagulant (PACl)			Sulfuric acid			Potassium permanganate		
Fairfax Water	High dose	Low dose	Avg	High dose	Low dose	Avg	High dose	Low dose	Avg
Current costs	12,722	1,540	6,224	3,482	0	1,446	3,855	0	1,405
2yr avg costs	15,279	1,842	7,446	3,108	0	1,291	3,758	0	1,370
5yr avg costs	16,897	2,037	8,235	2,863	0	1,189	3,657	0	1,333

	Coagulant (hydrated alum)			Chlorine		
Washington Aqueduct	High dose	Low dose	Avg	High dose	Low dose	Avg
Current costs	19,122	7,837	10,868	13,876	5,230	9,293

*Average low dose costs of zero indicate that the treatment chemical is not used each day; therefore, the lowest predicted dose (and associated cost) is zero.

TREATMENT COST ESTIMATES

Treatment chemical costs were calculated for each of the five scenarios (Table 4.4) using current chemical costs provided above and predicted doses from the water quality-treatment dose relationships (Chapter 3). As expected, the base scenario (Scenario 1) is the most expensive in terms of treatment chemical costs. Scenario 3 is associated with the largest average annual cost savings ($94,831) followed by Scenario 5 ($49,457). These scenarios also have the largest amount of forest protection measures (either land conserved or BMPs installed). It should be noted that the uncertainties driven by the elements in the modeling framework, predicted river concentrations from the watershed model, and the regression relationships used to calculate concentrations at the intakes and the dosages of chemicals to treat them are at least comparable in size to the predicted reductions in treatment costs, if not larger.

Table 4.4
Average annual cost ($USD) for treatment chemicals by utility for the five scenarios

Scenario	Washington Aqueduct* ($USD)	WSSC ($USD)	Fairfax Water ($USD)	Total ($USD)
1	5,146,413	2,411,190	1,101,288	8,658,890
2	5,121,040	2,393,433	1,097,692	8,612,165
3	5,094,855	2,375,197	1,094,007	8,564,059
4	5,132,942	2,400,110	1,098,947	8,631,999
5	5,123,535	2,389,445	1,096,453	8,609,433

*Costs for Washington Aqueduct include coagulant and chlorine and are, therefore, higher than the WSSC and Fairfax Water costs that only include coagulant.

The ratio of percent change in annual treatment cost to the percent change in forest land is approximately 1:2 (ranging from 0.4 to 0.6). That is, for every two percent of forest land conserved or BMP installed, an approximately one percent reduction in annual treatment costs is expected. This ratio holds for all scenarios including land conservation and BMP implementation scenarios.

All scenarios result in approximately one dollar per acre per year of cost savings on selected treatment chemicals. This highest and lowest average annual cost savings were for the BMP scenarios (Scenario 4 and 5, respectively). This is due to the fact that, for the BMP scenarios, the effectiveness (or pollutant reducing capability) of the BMP depends on whether the BMPs are installed on agricultural or urban lands. Given the assumptions built into the Watershed Model, developed based on empirical studies (EPA 2010), forest buffers on agricultural lands remove more nutrients and sediments than those applied on urban lands (four times more nitrogen and two times more phosphorus and sediments) (EPA 2010 - Section 6). Scenario 4 has a larger proportion of agricultural forest buffers than Scenario 5 and, therefore, has the largest average annual cost savings per acre (Table 4.5).

Table 4.5
Predicted average annual cost savings ($USD) from Scenario 1

Scenario	Percent diff. in cost from Scenario 1 (%)	Predicted annual treatment cost savings ($USD)	Acres forest conserved	Acres BMPs installed	Percent of total forest land (%)	Average annual cost savings ($USD/acre)
2	-0.54	46,725	41,569	0	0.99	1.12
3	-1.10	94,831	86,733	0	2.06	1.09
4	-0.31	26,891	0	21,644	0.51	1.24
5	-0.57	49,457	0	59,597	1.41	0.83

THRESHOLD-BASED APPROACH FOR RELATING CAPITAL IMPROVEMENT COSTS TO WATERSHED DEVELOPMENT

There are examples of water systems avoiding capital or one-time costs through source water protection in addition to the chemical cost savings explored above (Gartner et al. 2013, Alcott et al. 2013); however, these examples typically compare green infrastructure with the costs of constructing filtration plants, dredging following wildfire sedimentation of reservoirs, or temperature TMDLs. The participating water utilities on this project all employ conventional treatment, including filtration. Wildfire risk is minimal in the watershed and there are no temperature TMDLs that apply to drinking water utilities in the Potomac basin.

Limited examples are provided in the literature for changing or avoiding treatment improvements as a result of source protection efforts. Worcester, Massachusetts, was granted 0.5 log *Giardia* removal requirements for the EPA's Long Term 2 Enhanced Surface Water Treatment Rule (LT2-ESWTR) (EPA 2006) based on the utility's progress towards source water protection (Alcott et al. 2013). This allowed the treatment plant to reduce chlorine concentrations in the winter. However, this is 1) an operational change rather than a capital improvement and 2) reduced existing treatment rather than avoiding future treatment upgrades.

Accordingly, there is a knowledge gap regarding the use of source water protection in lieu of treatment upgrades for conventional treatment systems other than the well-known examples of water systems with Filtration Avoidance Determinations. The following analysis uses the land use change projections presented earlier in this report to develop water quality degradation thresholds at which different treatment technologies could be implemented. Changes in additional water quality parameters which were not modeled, including pathogens, inorganic contaminants, and disinfection by-product precursors, were also evaluated for their potential to trigger capital improvements.

Analysis Methods and Data

Geospatial and Historical Basin Population Analysis

County boundary shapefiles were obtained from the U.S. Census Bureau (U.S. Census Bureau 2016). Population by county from the decennial census was obtained from the National Historical Geographic Information System database (Minnesota Population Center 2016). U.S.

Census tract shapefiles (U.S. Census Bureau 2012b) and tract gazetteer files (U.S. Census Bureau 2012c) were also used for analyses requiring finer spatial resolution.

Costs for Treatment Alternatives

Costs for implementing alternative treatment technologies at Washington Aqueduct were estimated during two studies: The Future Treatment Alternatives Study (Malcom Pirnie 2012) and the Advanced Treatment Study (CH2M 2016). The Future Treatment Alternatives Study derived cost estimates from greenfield construction and retrofits of comparably-sized facilities. The Advanced Treatment Study estimated site-specific costs for those retrofits which were considered most feasible and applicable to the water quality challenges encountered by Washington Aqueduct.

Effectiveness of Treatment Alternatives in Meeting Water Quality Objectives

Between 2009 and 2012, Washington Aqueduct performed a site-specific, risk-based prioritization of contaminants and evaluation of advanced treatment technologies with the help of an international expert panel (Spiesman and Speight 2014). A summary of treatment costs and effectiveness is provided in Table 4.6. Cost estimates are reported as the sum of treatment costs at both of Washington Aqueduct's treatment plants. UV AOP received a low score for pathogen inactivation because it would be implemented prior to filtration. PAC cost estimates assume feeding 20 mg/L of PAC year-round.

Table 4.6
Summary of cost for implementing advanced treatment technologies for Washington Aqueduct, effectiveness for priority source water contaminants, and land use changes which are expected to exacerbate priority issues*

Increased TOC							X									
Increased nutrients											X		X			
Agricultural activity				X	X	X					X	X	X	X	X	X
Population growth				X	X	X		X	X	X						
Treatment alternative	Capital costs† ($USD, millions)	O&M costs† ($USD, millions)	Life cycle costs ($USD, millions)	Cryptosporidium	Bacteria/protozoa	Viruses	TTHMs & HAA5	NDMA	Perchlorate	Hexavalent chromium	MIB & geosmin	Atrazine, sinazine	Cyanobacterial toxins	Metolachlor	2,4-D	Nitrate
UV disinfection	55	0.5	60.0	3‡	1	0	0	0	0	0	0	0	0	0	0	0
Increase PAC + separation	45	7.0	160.0	0	0	0	0	0	0	0	2	3	1	3	3	0
Ozone AOP + biofiltration	190	5.0	270.0	0	1	1	1	2	0	0	3	2	2	2	2	0
UV AOP + biofiltration	155	5.0	240.0	0	0	0	0	0	0	0	3	2	2	2	2	0
GAC filter adsorber caps	80	20.5	410.0	0	0	0	1	0	0	0	2	2	1	2	2	0
LP membranes	300	10.5	470.0	3	1	1	0	0	0	0	0	0	0	0	0	0
Post filter GAC contactors	200	20.0	520.0	0	0	0	1	1	0	0	3	3	2	3	3	0
Ion exchange	400	30.0	880.0	0	0	0	0	-1	3	2	0	0	0	0	0	3
LP membranes + RO	700	30.5	1,190.0	3	1	1	1	2	3	2	3	3	3	3	3	3

*Top rows indicate which land uses changes (or impacts from changes) are expected to exacerbate the priority issues.
†Capital and O&M costs are reported for Washington Aqueduct's Dalecarlia (225) MGD and McMillan (120 MGD) WTPs.
‡Treatment efficacy was determined by an international expert panel to be low (1), medium (2), or high (3).
UV – ultraviolet; AOP – advanced oxidation process; GAC – granular activated carbon; LP – low pressure; RO – reverse osmosis.

Nutrient and Temperature Data

Nutrient and temperature data used in the development of algal growth thresholds were obtained from 20-year simulations described in Chapter 2. The five scenarios tested showed negligible differences in water quality under the source water protection scenarios. For this reason, modeled water quality data from the most conservative 2030 development scenario (Scenario 1) were used.

Unregulated Contaminant Monitoring Rule (UCMR) Data

Publicly available data from the Second Unregulated Contaminant Monitoring Rule (UCMR 2) and the Third Unregulated Contaminant Monitoring Rule (UCMR 3) were used in assessing the occurrence of unregulated contaminants in the Potomac River.

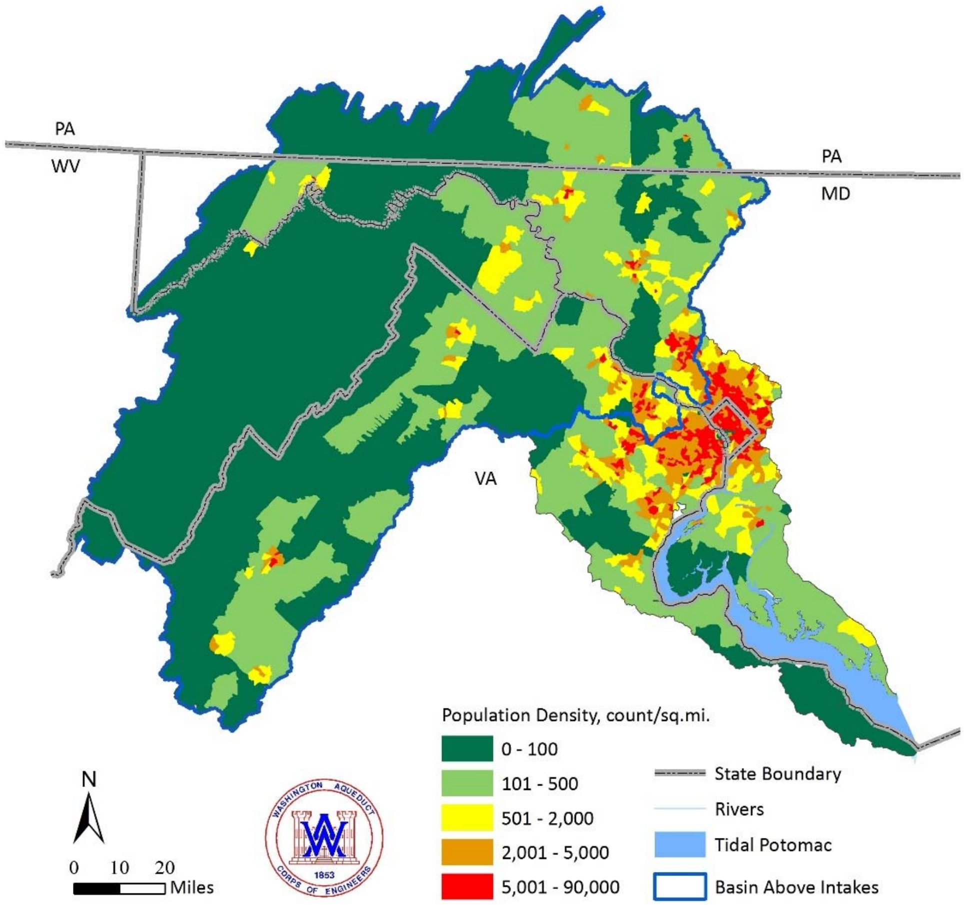
Chloride, Bromide, and Cryptosporidium Data

Washington Aqueduct routinely monitors for chloride, bromide, and *Cryptosporidium* at its Potomac River intake. Chloride and bromide were measured using EPA Method 300.0 (Pfaff 1993). *Cryptosporidium* was measured using EPA Method 1623.1 (EPA 2012).

Analysis, Results, and Discussion

Geospatial and Historical Basin Population Analysis

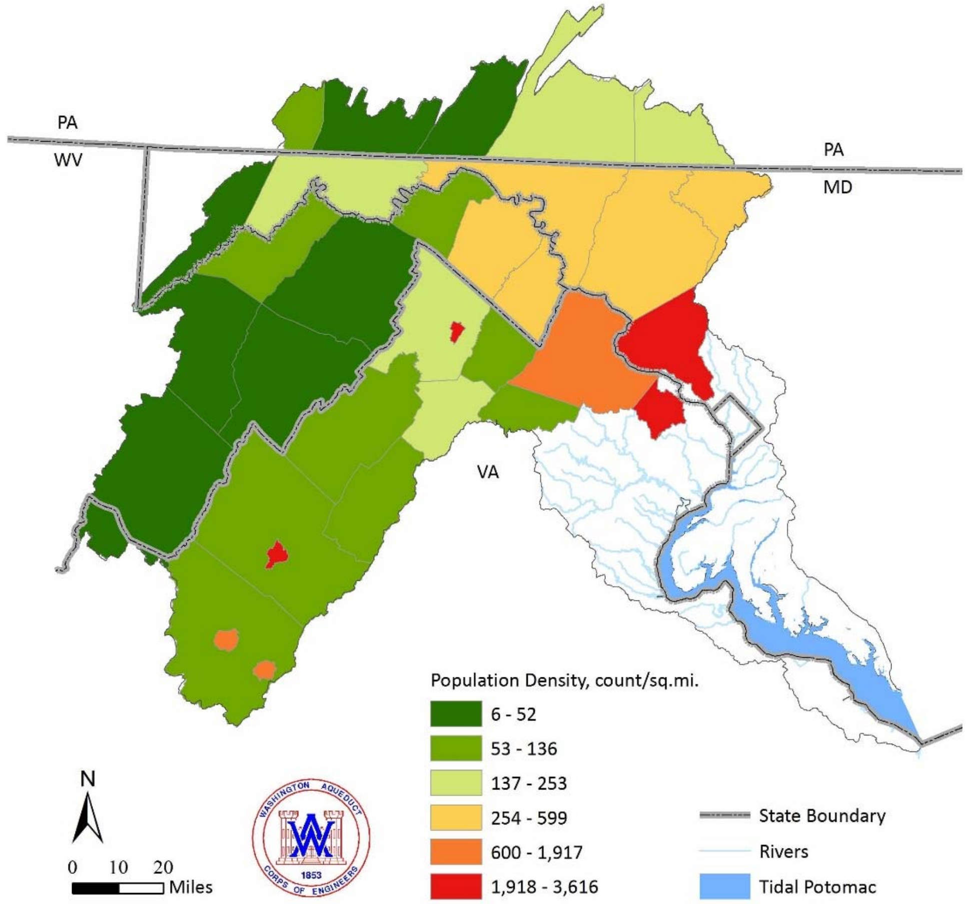
Although historical information on land use change is limited, census data provides detailed, spatially-referenced population information. To understand how population is distributed throughout the basin, and how basin population has changed over time, geospatial analyses were performed. Figure 4.6 shows population density in the Potomac River basin based on the 2010 census. Results are shown at high spatial resolution by using census-tract level data. From this figure, it can be concluded that a majority of the densely populated areas within the basin are downstream of water treatment plant intakes. This indicates that source water contamination from domestic and urban sources are more likely to affect the downstream Chesapeake Bay than drinking water intakes. However, there are portions of the Washington metropolitan area to the north and west which lay within the basin. Forested areas near these locations may be at greater risk for development than areas further upstream.



Source: Data from U.S. Census Bureau 2012b and 2012c.

Figure 4.6 2010 Census tract population density in the Potomac River basin

Population upstream of plant intakes over time was also estimated to provide historical context to growth within the basin. Census tracts change over time, preventing a historical analysis at the level of spatial resolution provided in Figure 4.6. However, county-level census data are available back to the year 1790 (Minnesota Population Center 2016). In order to make use of this historical information, it was assumed that population was equally spatially distributed at the county level. Based on the proportion of the overall county area within the basin, upstream population from each county could be calculated (see Figure 4.7).



Source: Data from U.S. Census Bureau 2016 and Minnesota Population Center 2016.

Figure 4.7 2010 county level population density in the Potomac River basin

The estimate of upstream population using county-level data is shown in Figure 4.8 along with key milestones in Washington Aqueduct's history. When the United States Congress named Washington, D.C., the capital in 1790, there were only approximately 150,000 people living upstream. There were 320,000 people upstream when Washington Aqueduct first delivered Potomac River water to the capital in 1863. Filtration and routine chlorination began with an upstream population of 530,000 and 780,000, respectively. By the time the Surface Water Treatment Rule (SWTR) and Interim Enhanced Surface Water Treatment Rule (IESWTR) regulated the performance of the filtration and disinfection as pathogen barriers, basin population had increased to roughly 2,000,000 people by 2000. Between 2010 and 2040, the upstream basin population is expected to increase by 35 percent (Ahmed et al. 2015), bringing the estimated upstream population to 3,500,000 by 2040. The growing population in the watershed provides pressure to install additional treatment barriers and/or protect source water to mitigate the impacts of population growth.

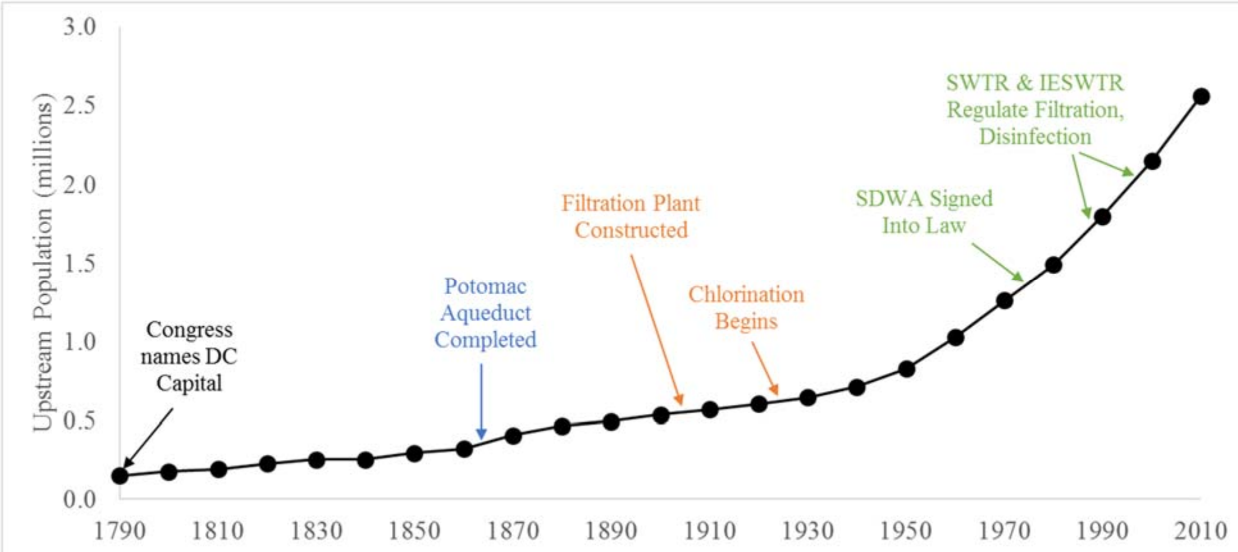


Figure 4.8 Estimated population upstream of plant intakes over time with major landmarks in treatment highlighted

Nutrient and Temperature Thresholds for Algal Treatment

Nutrient criteria were developed for Washington Aqueduct's intermediate reservoirs which are prone to algae growth. These intermediate reservoirs are located between sedimentation and filtration at Washington Aqueduct's McMillan WTP. The reservoirs were assumed to be phosphorous limited. The Carlson Trophic State Index (TSI) (Carlson 1977) is a numeric index describing the trophic status of lakes (Figure 4.9). TSI is scaled from 0 to 100 where each increase of 10 on the TSI scale (e.g., from 40 to 50) indicates a doubling of algal biomass (Carlson 1977).

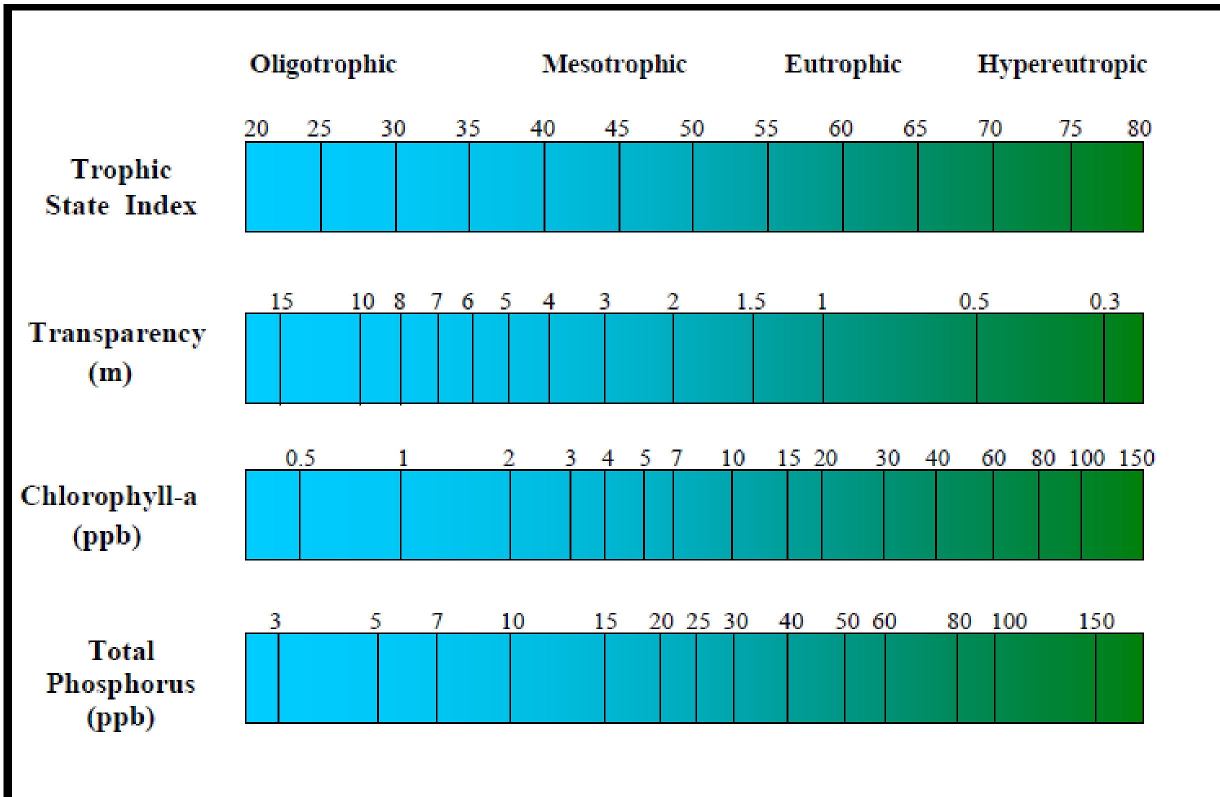
TSI can be calculated based on Secchi depth, chlorophyll *a* concentration, or total phosphorous concentration. TSI can be calculated from TP using the linearized version of Carlson's (1977) equation (Equation 4.2) as shown below (Heiskary and Wilson 2005).

$$\text{Total Phosphorous TSI (TSIP)} = 14.42 * \ln(\text{TP}) + 4.15 \tag{4.2}$$

Similar equations exist for Secchi depth and chlorophyll *a* concentrations; however, TP was chosen because it is output by the Watershed Model.

Increasing TSI can result in degraded water quality. Arruda and Fromm (1989) observed that TSI was strongly correlated with taste and odor, dissolved iron, and dissolved manganese, all of which can result in aesthetically undesirable water if not removed during treatment. Carlson and Simpson (1996) estimate that for a drinking water source with a TSI of 40-50, iron and manganese issues occur, raw water has a noticeable odor, and trihalomethane precursors exceed 100 µg/L. These problems worsen with increasing TSI (Carlson and Simpson 1996).

TSI < 30	Classic Oligotrophy: Clear water, oxygen throughout the year in the hypolimnion, salmonid fisheries in deep lakes.
TSI 30 - 40	Deeper lakes still exhibit classical oligotrophy, but some shallower lakes will become anoxic in the hypolimnion during the summer.
TSI 40 - 50	Water moderately clear, but increasing probability of anoxia in hypolimnion during summer.
TSI 50 - 60	Lower boundary of classical eutrophy: Decreased transparency, anoxic hypolimnia during the summer, macrophyte problems evident, warm-water fisheries only.
TSI 60 - 70	Dominance of blue-green algae, algal scums probable, extensive macrophyte problems.
TSI 70 - 80	Heavy algal blooms possible throughout the summer, dense macrophyte beds, but extent limited by light penetration. Often would be classified as hypereutrophic.
TSI > 80	Algal scums, summer fish kills, few macrophytes, dominance of rough fish.



After Moore, 1. And K. Thornton, [Ed.]1988. Lake and Reservoir Restoration Guidance Manual. USEPA>EPA 440/5-88-002.

Source: Heiskary and Wilson 2005 referencing EPA 1988.

Figure 4.9 Carlson's Trophic State Index (TSI)

Based on the relationship between TSIP and algal concentrations, low, medium, and high phosphorous thresholds were set at 25, 50, and 100 µg/L.

These thresholds were chosen based on their correspondence with TSI value and statewide phosphorous nutrient criteria (EPA 2017). As of July 2017, EPA reported that the only states with statewide phosphorous criteria for lakes and reservoirs were Florida, Minnesota, New Jersey, West Virginia, and Wisconsin (EPA 2017). The low (25 µg/L) threshold corresponds to TSI ≈ 50 and is similar to the 30 µg/L criterion set by Florida for clear lakes of comparable alkalinity, West Virginia for cool water lakes, and Wisconsin for stratified reservoirs. The medium (50 µg/L) threshold corresponds to TSI ≈ 60 and equals the 50 µg/L New Jersey criterion for lakes. The high (100 µg/L) threshold corresponds to TSI ≈ 70 and equals the 100 µg/L criterion set by Minnesota for numerous stream classifications, New Jersey for non-tidal streams, and Wisconsin for numerous river segments.

Temperature is also an important predictor of algal growth, with temperatures between 60°F and 80°F (15.6°C to 26.7°C) being typical conditions for growth (AWWA and WRF 2015). Cyanobacteria have been reported to rarely occur below 15°C with blooms occurring when temperatures exceeded 23-26°C (Silvey et al. 1974). Others have observed growth rates to be significantly higher at 25-27.5°C than at 20°C (Lurling et al. 2013). Based on this information, low, medium, and high thresholds for algae growth were set at 15, 20, and 25°C.

The triggers for temperature and total phosphorous are summarized in Table 4.7. This table also includes the proposed treatment if water quality exceeds a given threshold and the cost associated with that treatment at Washington Aqueduct's McMillan WTP (120 MGD). Powdered activated carbon was expected to be sufficient to address minor and infrequent taste and odor (T&O) concerns resulting from exceedance of the low threshold. Costs for powdered activated carbon in Table 4.7 represent a 20 mg/L dose, four months per year at the McMillan WTP, and thus are lower than the costs of feeding 20 mg/L year-round at both WTPs (Table 4.6). Most of the cost of implementing PAC at the facility is related to building contact and separation basins which do not currently exist. As temperatures and total phosphorous increase, more algae growth is expected, producing more taste and odor and increasing filter clogging. Ozone paired with biologically active filtration (BAF) provides a robust barrier to taste and odor, and microflocculation effects are expected to address minor filterability issues arising from increased algal loading if the medium threshold is exceeded. Costs for ozone and BAF in Table 4.7 are only for retrofitting the McMillan WTP, which is smaller and requires fewer retrofits than the Dalecarlia WTP, and thus costs are lower than reported in Table 4.6 for both WTPs. For the high threshold, it is anticipated that greater algal loadings will require dissolved air floatation (DAF) to achieve filter production targets.

Table 4.7
Low, medium, and high temperature and nutrient thresholds along with associated water quality concern, treatment improvement, and cost of treatment at one of Washington Aqueduct's treatment plants (120 MGD)

Threshold	Temp (°C)	Total P (µg/L)	Concern	Treatment	Net present worth ($USD)
Low	15	25	Minor T&O	PAC + separation	55M
Medium	20	50	Frequent T&O and minor filter issues	Ozone/BAF	80M
High	25	100	Severe T&O and significant filter issues	Ozone/BAF + DAF	210M

The trigger for constructing treatment improvements was set at ten percent simultaneous exceedance of the temperature and total phosphorous thresholds based on the 20-year model run under 2030 development scenarios. The frequency of exceeding these thresholds is shown in Table 4.8. The low threshold was exceeded for 41 percent of model outputs, triggering at minimum construction of PAC contact and separation facilities. The medium threshold was triggered as well with 15 percent exceedance; however, the high threshold was not. This analysis suggests that ozone/BAF would be the highest level of treatment to be triggered, carrying with it a lifecycle cost of $80 million.

Table 4.8
Frequency of exceeding the low, medium, and high nutrient and temperature thresholds

	Frequency of threshold exceedance (%)		
Threshold	Total P only	Temperature only	Total P & temperature
Low	91	49	41
Medium	53	36	15
High	20	21	3

Nutrient reduction had been considered as an opportunity for cost-effective source water protection, however none of the Potomac River protection scenarios studied had a significant impact on nutrient levels. For that reason, algal growth resulting from nutrient runoff may require constructing treatment improvements and cannot be effectively addressed through the source water protection scenarios considered. Significant investments in wastewater treatment plants have substantially reduced nutrient loading from these sources in the watershed (EPA 2016b). Further reductions in nutrients would likely have to target other sources (e.g., agriculture, EPA 2016b).

De Facto Reuse

Quantifying De Facto Reuse Trends in the Potomac Basin. The National Academies of Science define de facto reuse (DFR) as "a drinking water supply that contains a significant fraction of wastewater effluent, typically from upstream wastewater discharges, although the water supply has not been permitted as a water reuse project" (NRC 2012). Although there is no minimum threshold for percent effluent, DFR is considered to be a situation where "effluent accounts for more than a few percent of overall flow" (NRC 2012).

DFR in the Potomac basin can be estimated using upstream water use estimates generated as part of a detailed water supply study (Ahmed et al. 2015). Table 4.9 shows annual average withdrawals in the Potomac basin by use type. Assuming that effluent discharge occurs in the same proportion as withdrawals and that the vast majority of municipal and domestic water is returned to the basin on an annual average basis, upstream withdrawals also provides an estimate of the annual average re-use flows (Table 4.9). The total effluent flow excluding thermoelectric cooling was estimated at 331 MGD. Of this total, 174 MGD was for domestic use and 157 MGD was for other uses (aqua- and agriculture, mining, industrial, etc.).

Table 4.9
Water use upstream of Washington metropolitan area*

Water use category	Annual average withdrawals (MGD)
Aquaculture	33.2
Commercial self-supplied	2
Industrial self-supplied	60.6
Golf course irrigation	3.1
Mining	33.5
Mt. Storm thermoelectric	1,105.9
Other thermoelectric	409.5
Public water supply	123.3
Irrigation	7.9
Livestock	16.3
Self-supplied domestic use	50.8
Total water use	1,846
Total non-thermoelectric water use	331
Total public water supply and domestic	174
Total thermoelectric, public water supply, domestic	157

Source: Adapted from Ahmed et al. 2015
*Upstream water use is used as a surrogate effluent estimate.

Four estimates of upstream water use were compared to streamflow values obtained from the National Hydrography Dataset (USGS 2014). The four effluent discharge estimates are derived from a combination of Ahmed et al.'s (2015) work (Table 4.9) and an assumed 100 gal/capita per day for the 2010 upstream population (see Figure 4.8). Results of calculated DFR at different percentile streamflows are shown in Figure 4.10. Reuse at median flow was estimated to be between 4 and 10 percent depending on the effluent discharge estimate used. DFR was much higher at lower flows: between 22 and 53 percent at the 5th percentile flow and 40 to 95 percent at the 1st percentile flow. These results suggest that DFR exists in the Potomac River at median flow based on the National Research Council (NRC) definition (NRC 2012) and that DFR might be significant at lower flows.

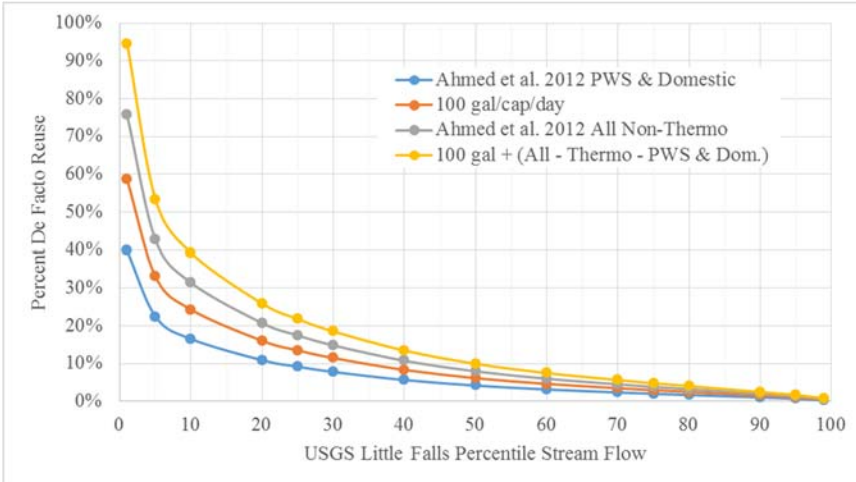


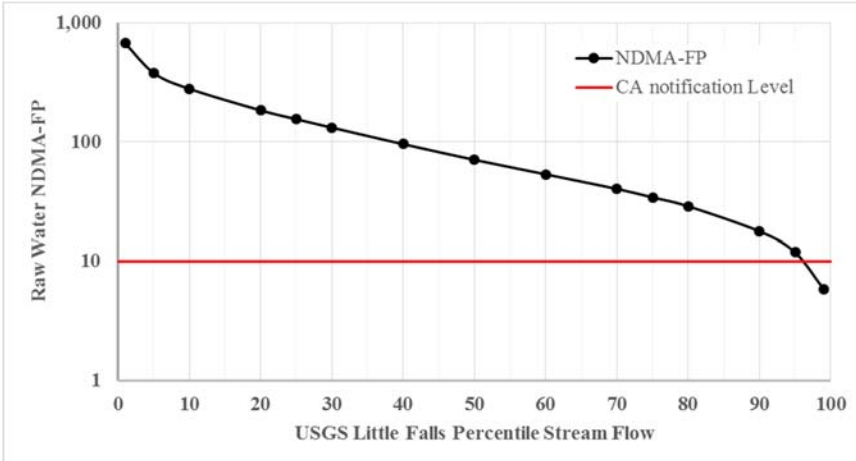
Figure 4.10 Estimated percent DFR versus USGS streamflow using four estimates of effluent discharge

Potential Threshold Indicators. Assessing whether additional water treatment technologies should be constructed to address DFR requires comparison to a DFR threshold. DFR thresholds could be based on predicted occurrence of contaminants which are either regulated or have established guideline concentrations. Rice et al. (2015) used a geospatial model to predict concentrations of steroid hormones, nitrosamines, and *Cryptosporidium* and compared them to relevant thresholds.

A similar analysis was conducted specific to the Potomac basin. Steroid hormones were considered a low risk as there were no regional detects during UCMR 3. Typical concentrations in secondary wastewater effluent (Rice et al. 2015) are also orders of magnitude below the associated UCMR 3 reference concentrations for most compounds. This is consistent with predictions by Rice et al. (2015) that UCMR 3 steroid hormones would only exceed minimum reporting limits under the highest DFR scenarios.

In contrast, *N*-Nitrosodimethylamine (NDMA) formation potential (NDMA-FP) is more likely to rise to a level of concern due to DFR. NDMA-FP has been predicted to exceed the ten ng/L California public notification level in raw water at many locations throughout the United States under average streamflow conditions (Rice et al. 2015); a recent study of nine treatment plants observed raw water NDMA-FP at concentrations of 12-98 ng/L (Uzun et al. 2017).

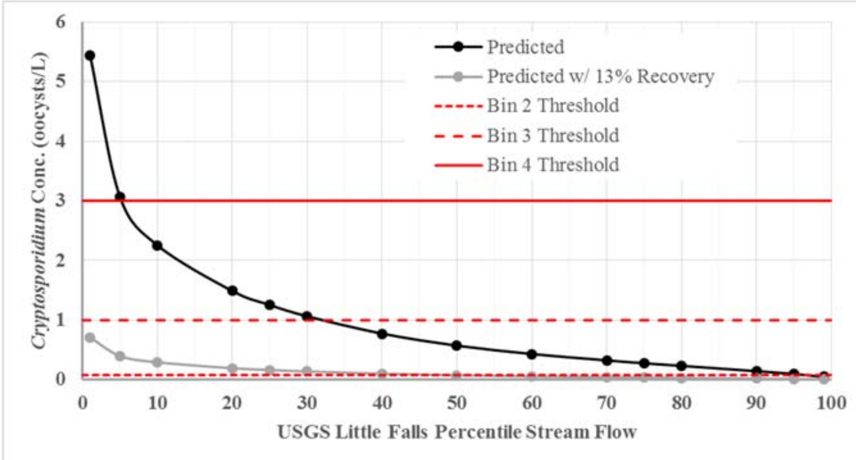
Predicted raw water NDMA-FP at different streamflows is shown in Figure 4.11. NDMA-FP in wastewater effluent was assumed to be equal to 1,000 ng/L (Rice et al. 2015, Hanigan et al. 2012), although formation potential has been observed over a wide range, often lower than 1,000 ng/L (Yoon et al. 2011). The quantity of wastewater flow was assumed to be the average of the four estimates in Figure 4.10. Results in Figure 4.11 suggest that raw water NDMA-FP could exceed 10 ng/L even at high flows. However, two utilities in this study that use chloramines and the Potomac River as a source (e.g., Fairfax Water and Washington Aqueduct) did not detect NDMA above the two ng/L minimum reporting level in UCMR 2. Potential explanations for the difference between Figure 4.11 and UCMR 2 data include that 1) NDMA-FP is lower than 1,000 ng/L in wastewater returned to the Potomac River, potentially due to advanced wastewater treatment in the region, 2) the quantity of wastewater flow returned to the Potomac river is lower than estimated by Figure 4.10, 3) in stream services reduce NDMA-FP before reaching plant intakes, or 4) regional plants achieve far better overall reduction in NDMA-FP than the 40-59 percent observed by others (Uzun et al. 2017).



NDMA-FP estimates are based on the average of the four wastewater effluent flows shown in Figure 4.10 and an assumed wastewater NDMA-FP concentration of 1,000 ng/L (Rice et al. 2015, Hanigan et al. 2012). These results are inconsistent with UCMR 2 data.

Figure 4.11 Predicted raw water NDMA-FP versus streamflow

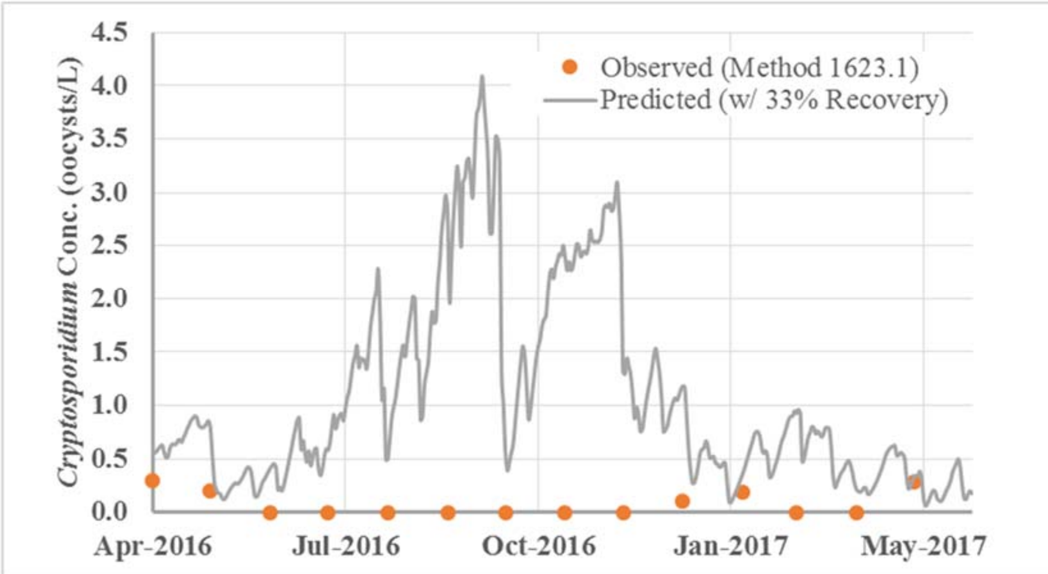
Similar to NDMA-FP, predicted *Cryptosporidium* loadings exceed observed concentrations. Figure 4.12 shows predicted concentrations at different flow rates. Prediction assumes 17 oocysts/L in secondary effluent (Rice et al. 2015, NRC 2012) and uses the sum of public water supply and livestock extraction for flow; it was assumed that other extractions did not lead to loadings of *Cryptosporidium* to the river. Based on these assumptions, it is anticipated that all systems in the Washington metropolitan area would fall within EPA's LT2-ESWTR Bins 2 or 3. An NRC (2012) case study assumed that a conventional treatment system with five percent DFR would end up in Bin 2, installing UV disinfection for 1-log *Cryptosporidium* credit. However, most Potomac River utilities are in Bin 1 and only a small number are in Bin 2. This could be explained in part by the low method recoveries as well as the relatively small sampling volumes and frequency used in LT2 monitoring that may not fully represent actual average concentrations; minimum allowable recoveries for matrix spikes are 13 and 33 percent in EPA Methods 1623 (EPA 2005) and 1623.1 (EPA 2012), respectively. Nationally, many water suppliers ended up in lower bins than EPA had originally predicted.



Assumes 17 oocysts/L in wastewater effluent (NRC 2012) and a total effluent flow of 140 MGD (sum of public water supply and livestock extraction from Table 4.9). Minimum allowable recovery on matrix spikes using EPA Method 1623 (EPA 2005) is 13 percent, presenting a lower bound for predicted observations during LT2 sampling.

Figure 4.12 Predicted *Cryptosporidium* concentrations versus streamflow as compared to LT2 bin thresholds

Even accounting for low recoveries, predictions overestimate the number of *Cryptosporidium* oocysts that would be detected in the river. Figure 4.13 shows predicted concentrations and concentrations observed by Washington Aqueduct using EPA Method 1623.1 (EPA 2012). Not only do predictions greatly exceed detected concentrations, they are also out of sync with flows. If loadings were constant, higher detections at lower flows would be expected. However, detections typically correspond to higher flows (i.e., lower predictions). This could be explained by non-steady oocyst loading to the river, as evidenced by previous work in the Potomac basin where detection of *Cryptosporidium* in DNA was observed in 82 percent of samples taking following storm events compared to 42 percent of base flow samples (Yang et al. 2008).



Assumes 17 oocysts/L in wastewater effluent (NRC 2012) and a total effluent flow of 140 MGD (sum of public water supply and livestock extraction from Table 4.9). Minimum allowable recovery on matrix spikes using EPA Method 1623.1 (EPA 2012) is 33 percent, presenting a lower bound for predicted observations during LT2 sampling.

Figure 4.13 Observed and predicted *Cryptosporidium* concentrations over time

In summary, DFR thresholds based on contaminants considered by others (i.e., steroid hormones, NDMA-FP, and *Cryptosporidium*) do not appear to be appropriate for triggering treatment improvements in the Potomac River basin.

Framework for Assessing Treatment Benefits and Setting Source Water Protection Priorities for De Factor Reuse Systems. As illustrated in the previous section, identifying DFR thresholds for treatment triggers on the basis of regulated, or unregulated, contaminants is fraught with situations where predictive models are either inconsistent with observed data or the constituents of concern are difficult to monitor. A risk-based framework for evaluating DFR risk (NRC 2012) can help prioritize contaminants associated with DFR similar to the process which was used to prioritize site-specific contaminants (Spiesman and Speight 2014).

A more general approach for prioritizing treatment upgrades and focusing source water protection efforts is shown in Figure 4.14. This process begins by acknowledging that municipal wastewater often receives a lesser degree of treatment in DFR than planned reuse projects (NRC 2012). For example, the Big Spring Regional Water Reclamation Project uses microfiltration/reverse osmosis/UV- H_2O_2 (MF/RO/UV-H_2O_2) prior to recycling not more than 20 percent wastewater (CRMWD 2007). By comparison, Figure 4.10 suggests that the Potomac River may equal 20 percent DFR under approximately one-fifth of flow scenarios. State regulations of planned reuse provide more public health protection than federal regulations, which are not tailored to DFR or planned reuse. California requires significant pathogen removal or inactivation (i.e., 12-log virus, 10-log *Cryptosporidium*, 10-log *Giardia*) for indirect potable reuse (CDPH 2014). Texas targets a 10^{-4} infection risk with baseline removal (i.e., 8-log virus, 5.5-log *Cryptosporidium*, 6-log *Giardia*) which can be increased depending on wastewater effluent quality (TWDB 2015).

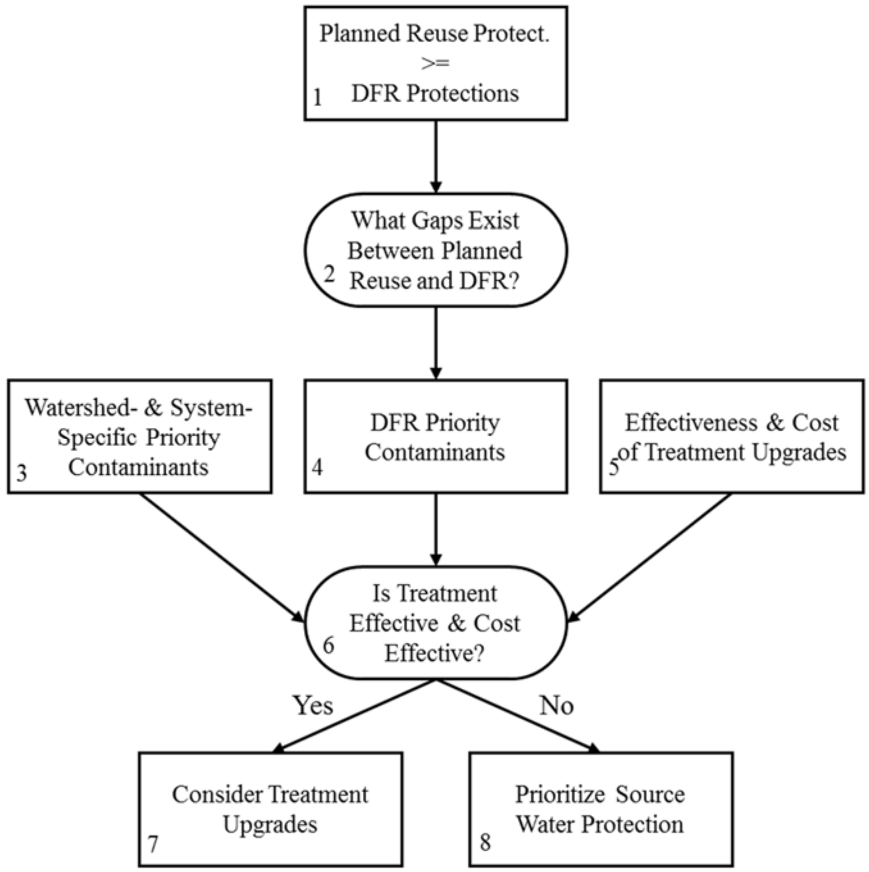


Figure 4.14 Approach to prioritizing treatment upgrades and source water protection efforts based on DFR protection gaps, watershed- and system-specific priority contaminants, and treatment benefits and costs

NRC (2012) concluded that a planned reuse system consisting of MF/RO/UV-H_2O_2 with groundwater injection would have greater margin of safety for constituents of concern than a system with five percent DFR (Figure 4.14 Box 2). Some constituents, such as pharmaceuticals, have margins of safety (risk-based action level divided by expected drinking water concentration) greater than 10^6, indicating that they are unlikely to be a concern to human health in DFR (NRC 2012). Those constituents where DFR was of greater risk and had lower factors of safety were pathogens, recalcitrant synthetic organics, disinfection by-products (DBP), and inorganics. A separate evaluation of treatment efficacy (TWDB 2015) found similar results when comparing conventional and reuse treatment trains.

Priority Contaminant Groups for Evaluation. A list of priority contaminant groups was developed based on a previous system-specific prioritization (see Table 4.6, Figure 4.14 Box 3) and the public health concerns stemming from DFR (Figure 4.14 Box 4). These groups consist of pathogens, DBPs, recalcitrant synthetic organic compounds (RSOC), and inorganics. Examples of contaminants within these classes are provided below:

- Pathogens: viruses, bacteria/protozoa, *Cryptosporidium*
- DBPs: NDMA, trihalomethanes (THM) and haloacetic acids (HAA), bromate

- RSOCs: perfluorooctanesulfonic acid/perfluorooctanoic acid (PFOS/PFOA), 1,4-Dioxane
- Inorganics: perchlorate, chloride, bromide, chlorate, nitrate, hexavalent chromium

Cost and Effectiveness of Treatment Technologies, Classification of Contaminants. Evaluation of the effectiveness of various treatment alternatives was based on a previous analysis (see Table 4.6) and data available from literature (TWDB 2015) (Figure 4.14 Boxes 3-5). The results of this analysis are shown in Table 4.10 (Figure 4.14 Box 6). These findings indicate that pathogens and DBPs can be reasonably addressed through combinations of ozone biofiltration, PAC, and UV disinfection. However, treatment costs increase significantly when RSOCs or inorganics must be treated, or when pathogen loadings require high treatment effectiveness.

Table 4.10
Cost of potential treatment improvements at Washington Aqueduct's two treatment plants and treatment efficacy for prioritized contaminant groups

Treatment technologies	Life cycle costs ($USD, millions)	Treatment effectiveness for contaminant groups			
		Pathogens	DBPs	RSOCs	Inorganics
PAC	160	None	Low	Low	None
UV + PAC	220	Medium	Low	Low	None
O_3-H_2O_2/BAF	270	Low	Low	Low	None
O_3-H_2O_2/BAF + UV	330	Medium	Medium	Low	None
IX	890	None	None	None	Medium
UV + PAC + IX	1,110	Medium	Low	Low	Medium
MF + RO	1,210	High	High	Medium	High

IX – ion exchange

Based on these findings, contaminants can be classified into those that could be addressed through treatment improvements (Figure 4.14 Box 7) and those where source water protection could help avoid significant treatment costs (Figure 4.14 Box 8). Pathogens and DBPs appear to be cost-effectively addressed through treatment. RSOCs and inorganics appear to be the highest value contaminants to focus on through source water protection, largely due to their relative difficulties and/or high costs for treatment.

Inorganic Halide Thresholds

Bromide. Bromide, while not toxic itself, is an important DBP precursor. Chlorination in the presence of organic matter and bromide can lead to the formation of brominated THMs and HAAs. Risk of non-compliance is more difficult for brominated DBPs due to the higher molecular weight of bromine relative to chlorine. The increased discharge of bromide into surface waters as a result of wet scrubbers on coal fired power plants has been linked to increased brominated THMs (McTigue et al. 2014). Bromide also reacts with ozone to form bromate, a regulated DBP.

Levels of bromide in the Potomac River have been rising over the last 15 years as shown in Figure 4.15. Increasing bromide likely explains an observed trend of increasing brominated THM and HAA speciations and may present a challenge for ozonating systems in the basin. Bromate control strategies include pH suppression, pre-ammonia, and pre-chloramination. These strategies would be more cost effective than removing bromide with RO. However, if the goal is prevention of other brominated DBPs, limiting bromide loadings to the Potomac River through source water protection is a preferable alternative to expensive (> $1 billion) RO treatment.

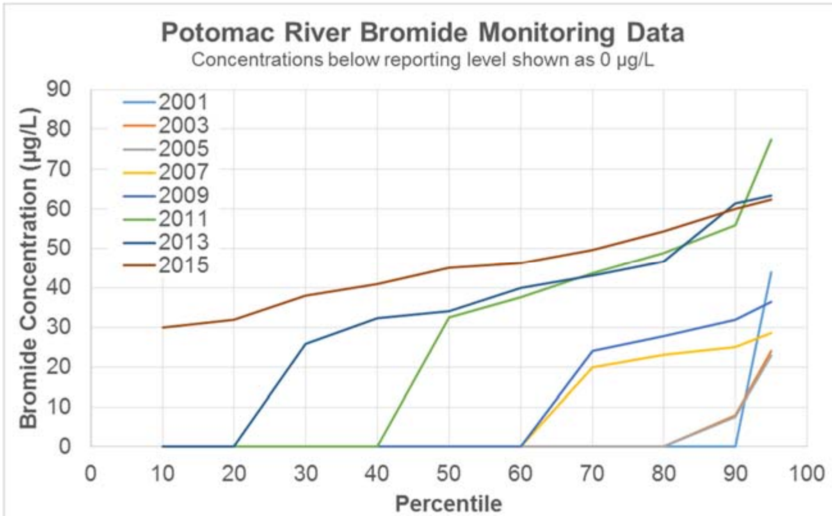


Figure 4.15 Percentile bromide concentrations over time in the Potomac River

Chloride. Chloride in drinking water contributes to the corrosion of iron and lead distribution system components. Chloride concentrations in the Potomac River spike above baseline levels following snowfall events as shown in Figure 4.16. Spikes in chloride concentration result from the application of roadway deicing salts. Corsi et al. (2015) analyzed longitudinal data for chloride in rivers across the northern United States, including the Potomac River and Patuxent River, a sub watershed of the Potomac. They observed that chloride concentrations in the two rivers increased by approximately 50 percent and 100 percent, respectively, between 1980 and 2010. Chloride concentrations were correlated with percent urban area, and the researchers also observed that chloride concentrations were increasing at a faster rate than urbanization. This indicates that chloride concentrations are increasing not only due to development, but also due to changing roadway management behaviors that lead to increased salt application.

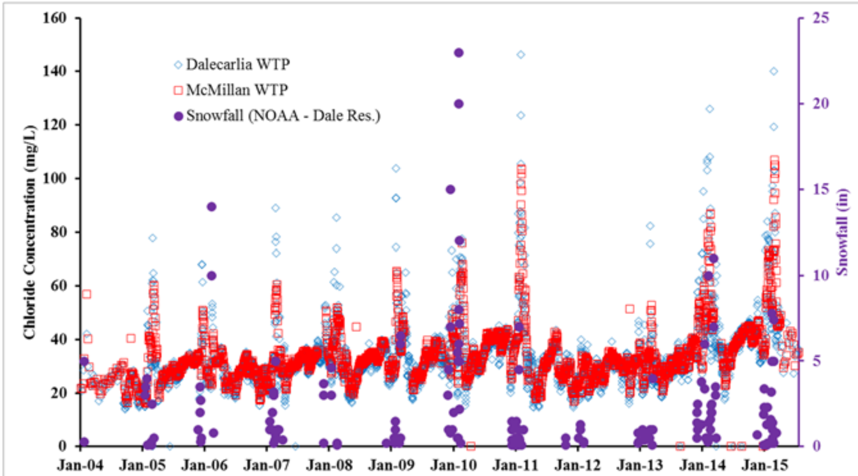


Figure 4.16 Chloride concentrations over time correlated with snowfall

Chloride has been linked to increasing red water complaints through the Larson Index (Clement et al. 2002) or similar indices using the ratio of chloride to alkalinity (Imran et al. 2005). One of Washington Aqueduct's wholesale customers has predominantly older, unlined cast iron mains which are particularly susceptible to chloride-induced corrosion. Targeting a 100-year replacement frequency (one percent per year) will cost that system $41 million dollars per year over the next decade; this cost would continue for over 50 years before the unlined cast iron mains are replaced. Considerable cost savings and aesthetic improvements could potentially be realized if reducing chloride could extend the service life of unlined cast iron mains. Unfortunately, much of the numerical guidance for chloride appears geared towards reclaimed water in cooling water applications (Thompson et al. 2006), making the comparison to thresholds difficult.

Increasing chloride also increases chloride-to-sulfate mass ratio (CSMR), an index used to identify waters which are aggressive to leaded components (Nguyen et al. 2010). Stets et al. (2017) concluded through empirical observation that the probability of exceeding a lead action level was <50 percent when systems had CSMR < 1.0, but increased to >90 percent when CSMR exceeded 3.0. CSMR has been observed to more than triple during recent chloride runoff events that follow winter storms. Washington Aqueduct adds orthophosphate as a corrosion inhibitor; orthophosphate was shown to reduce lead leaching related to increases in CSMR in some cases, however results were mixed and varied between different waters (Nguyen et al. 2010). The effect of these short duration chloride spikes on lead scales is uncertain and warrants further study.

RO is the only treatment technology that can remove chloride. Given the high cost of RO, water quality concerns related to chloride are likely best managed through source water protection rather than treatment.

Perchlorate. Washington Aqueduct collected and analyzed over 1,800 samples for perchlorate between January 2011 and March 2017. Of these samples, only ten (0.56 percent) exceeded the 2.0 µg/L Maximum Contaminant Limit (MCL) set by the state of Massachusetts and four (0.22 percent) exceeded the California 6.0 µg/L MCL with a maximum detection of 9.3 µg/L. The highest concentrations were observed under low flow conditions (i.e., when DFR is highest and dilution flow is lowest).

Depending on the concentration at which perchlorate is regulated in the future, and to what extent averaging is incorporated, will determine the risk posed by perchlorate in the Potomac

River. The options available for treating perchlorate have high costs. Life cycle costs for ion exchange and reverse osmosis were estimated for Washington Aqueduct at $880 million and $1,190 million, respectively (Table 4.6). This demonstrates the importance of protecting the source water from perchlorate given the high cost of treatment.

Chlorate. Similar to perchlorate, chlorate is believed to be a thyroid toxicant (USD-HHS 2005). Chlorate was detected above a health reference concentration more frequently than any other UCMR 3 contaminant and may present a significant compliance risk to utilities depending on if, and how, it is regulated in the future (Gorzalski and Spiesman 2015). Although most chlorate is introduced to drinking water through disinfection using hypochlorite or chlorine dioxide, there is some evidence that chlorate may be present in source waters, particularly at low flows; this includes the Potomac River specifically (Figure 4.17). Higher chlorate concentrations were associated with lower flows (i.e., higher DFR).

Chlorate may be introduced to surface water through its use in paper and pulp bleaching, as well as the use of hypochlorites for laundry bleaching or the disinfection of pool water, drinking water, or wastewater (Gorzalski and Spiesman 2015). Increasing DFR with upstream development would be expected to increase source water chlorate concentrations.

Whether source water chlorate concentration rise to a level of concern for drinking water utilities depends on a number of variables. Variables include 1) future regulatory or health-based determination of a concentration of concern, 2) chlorate added at water treatment plants (a function of chlorine dose, storage time, storage temperature, etc.), and 3) chlorate introduced through upstream DFR. By making assumptions about regulatory concentrations and modeling chlorate added through disinfection, the source water concentration of chlorate that would exceed a concentration threshold can be estimated.

If chlorate will be regulated, and at what concentration, remains uncertain. Two possible concentrations are either the UCMR 3 health reference level of 210 µg/L, or 840 µg/L if different assumptions are made regarding chlorate exposure from water relative to food (Gorzalski and Spiesman 2015). Chlorate introduced to drinking water was estimated assuming 30 days of storage using American Water Works Association's (AWWA) Hypochlorite Assessment Model (AWWA 2018) (Table 4.11). Based on these assumptions, allowable source water chlorate can be calculated, the results of which are shown in Table 4.12. If chlorate were regulated at 840 µg/L, systems could be in compliance even with considerable source water contribution (344-765 µg/L). However, even systems that dilute hypochlorite upon delivery would likely have concentrations above 210 µg/L if DFR is significant (Figure 4.17); a system feeding eight mg/L of total chlorine would exceed 210 µg/L if source water chlorate exceeded 10 µg/L.

Table 4.11
Chlorate concentrations* introduced to drinking water from hypochlorite disinfection

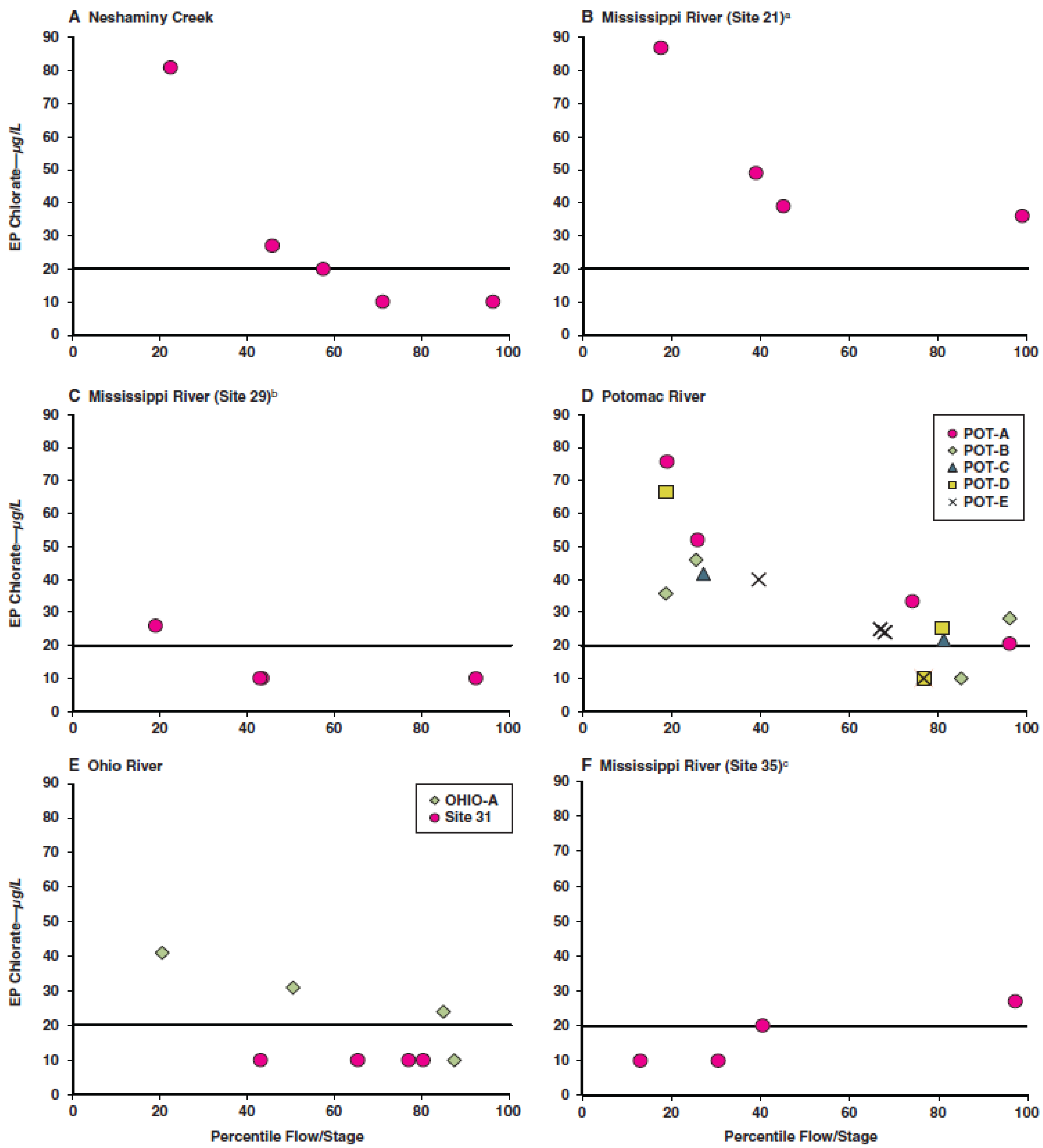
	Bulk hypochlorite	Dilute hypochlorite
Trade strength (%)	12.5	6.0
Storage temperature (°F)	75	75
Initial chlorate (g/L)	1.5	0.75
µg Chlorate / mg FAC @ 30 days	62	25
µg/L Chlorate @ 3 mg/L FAC dose	186	75
µg/L Chlorate @ 8 mg/L FAC dose	496	200

*Calculated using default assumptions in the AWWA Hypochlorite Assessment Model.
FAC – free available chlorine

Table 4.12
Allowable source water chlorate concentration under different regulatory and operational scenarios

	Total chlorine dose			
	Non-dilute hypochlorite		Dilute hypochlorite	
Allowable concentration	3 mg/L	8 mg/L	3 mg/L	8 mg/L
210 µg/L	24	0	135	10
840 µg/L	654	344	765	640

There is no standard treatment for removal chlorate once it has formed (Alfredo et al. 2014). Water systems will be pressed to implement low-chlorate hypochlorite solutions if chlorate is found to be a human health concern at 210 µg/L. Data in Figure 4.17 indicates that pressure will be even greater under high DFR scenarios where chlorate introduced from source waters may be significant. This suggests that further study is needed on the possible contributions of DFR to source water chlorate, and whether chlorate should be prioritized in source water protection efforts.



EP—entry point, MRL—minimum reporting level

[a]Above confluence with the Missouri River
[b]Near the Gulf of Mexico
[c]Downstream of the confluence with the Missouri River

Source waters with data for multiple stream intakes (i.e., Potomac River and Ohio River) are listed from upstream to downstream intake location. Samples below the reporting limit are shown as one-half of the 20 µg/L MRL.

Source: Reprinted with permission from Gorzalski and Spiesman 2015. *Journal AWWA*, 175:11:E623. Copyright © AWWA 2017. All rights reserved.

Disinfection with gaseous chlorine is not known to produce chlorate unlike hypochlorite or chlorine dioxide disinfection.

Figure 4.17 Chlorate concentrations in gaseous chlorine systems versus percentile streamflow in systems using source waters previously identified as containing DFR

Conclusions

Nutrient reduction was unaffected by the modest forest protection scenarios considered. As a result, treatment challenges presented by excessive algal growth may be most effectively addressed through constructed treatment improvements. Given significant regional investment in nutrient reduction and wastewater treatment plants, further nutrient reductions would likely need to target other sources.

DFR may be significant in the Potomac River at low flows and is expected to increase with further development in the basin. Constructing additional drinking water treatment barriers at moderate cost or implementing advanced treatment at certain upstream wastewater facilities may reduce potential health risks posed by DFR.

Certain water contaminants cannot be cost-effectively removed through treatment, including perchlorate, chloride, bromide, and chlorate. Source water protection efforts focused on sources of these types of contaminants may have a greater impact and provide better value than efforts focused on bulk water quality parameters, such as TSS or TOC, particularly in a large watershed like the Potomac.

CHANGING SOLIDS HANDLING COSTS DUE TO INCREASED CHEMICAL DOSES AND SOURCE WATER LOADINGS

The following section estimates current solids handling costs and how those costs might change with increased chemical doses and source water solids loadings.

Solids handling costs were investigated for two water utilities of varying size with differing solids management practices. The City of Hagerstown's R.C. Willson WTP treats an annual average of 11 MGD and stores solids in lagoons prior to land application. The Washington Aqueduct collects settled solids from its two treatment plants and mechanically dewaters them prior to hauling dried cake off site. Washington Aqueduct also has a reservoir between its Potomac River intakes and WTPs. Solids accumulate in this reservoir and must be dredged periodically.

Washington Aqueduct

The Washington Aqueduct operates two treatment plants that produce an annual average of 140 MGD. Solids handling costs are primarily attributable to two activities: dredging of a presedimentation reservoir and the dewatering and disposal of settled coagulation solids.

As discussed in Chapter 2, the Dalecarlia Reservoir produces substantial turbidity reductions prior to entering the treatment plant. Although an average turbidity reduction of 75 percent was estimated based on data in Figure 2.5, that estimate was based on a regression which is heavily influenced by higher turbidity storms. For the purposes of dredging calculations, TSS removal was estimated to be 50 percent in the Dalecarlia Reservoir.

Solids deposition in the Dalecarlia Reservoir can be estimated using TSS removal along with average flow and influent TSS. Assuming 50 percent TSS removal along with annual average flows and TSS loadings of 140 MGD and 25 mg/L, respectively, annual deposition was estimated to be 2,665 tons/year (Table 4.13). These solids must be periodically dredged, dewatered, and hauled offsite. Recent commercial dredging costs for these activities were $203,000 for equipment mobilization and $120.31/wet ton for dewatering, weighing, hauling, and disposal. These solids were more readily dewatered than coagulation solids, and thus it was possible to achieve a very dry cake (60 percent solids), bringing the estimated cost on a dry basis to $200.52/dry ton.

Assuming dredging is conducted every ten years, the cost of dredging the Dalecarlia Reservoir would be approximately $5.5 million every ten years. On a cost-per-volume basis, this comes out to approximately $4,000/year/MGD of flow. Increasing sediment loading due to changes in land use would likely to have an impact on solids handling costs in the Dalecarlia Reservoir. A 1 mg/L (four percent) increase in TSS would be expected to increase solids handling costs by $21,400/year.

Table 4.13
Costs for dredging solids in a presedimentation reservoir

Parameter	Value	Units
Reservoir deposition estimate		
Deposition in Dalecarlia Reservoir	50	percent
Annual average flow	140	MGD
Average reservoir influent TSS	25	mg/L
Solids deposition (dry weight)	2,665	ton/yr
Reservoir dredging costs		
Equipment mobilization/demobilization	203,000	$USD
Dewatered percent solids	60	percent
Dewatering, weighing, hauling, and disposal (dry)	120	$USD/wet ton
	200	$USD/dry ton
Dredge frequency	10	years
Accumulated solids (dry weight)	26,655	ton
Cost every 10 years	5,547,731	
Annual average cost	3,963	$USD/year/MGD
Cost per one mg/L TSS increase	21,379	$USD/year

The cost of handling coagulation residuals was also calculated as shown in Table 4.14. Cost estimates were limited to the cost of dewatering polymer and residuals disposal. The costs of energy, equipment maintenance, and personnel were excluded from this analysis. Generation of coagulation residuals was calculated assuming a plant influent TSS of 10 mg/L, a 30 mg/L alum dose (as hydrated alum), 0.33 mg of solids generated per mg of hydrated alum added, and 140 MGD average flow. These assumptions yield a daily residuals production of 23,235 lb/day.

Settled coagulation solids are collected, thickened by gravity, and dewatered via centrifugation. The price for dewatering polymer at the time of calculation was $0.82 per pound (neat), and contained 41 percent active polymer. Polymer was typically applied at ten active lb/dry ton, resulting in a polymer cost of $230/day or $85,000 per year.

Centrifugation typically produces a cake that is 28 percent solids by weight. Given the high cost of disposal ($58.83/wet ton) in the Washington area, the average cost of solids disposal was estimated to be $2,400/day or $890,000/year. The cost of disposal was approximately ten times greater than the cost of dewatering polymer.

The total cost of solids dewatering at the facility can be estimated at nearly $1 million per year, or approximately $7,000/year/MGD of production. Source water changes that might increase plant influent TSS by 0.5 mg/L and alum dose by 2 mg/L would result in an additional cost of $63,000/year in solids handling costs.

Table 4.14
Estimated coagulation solids dewatering costs

Parameter	Value	Units
Solids generation		
Annual average flow	140	MGD
Plant influent turbidity, TSS	10	NTU, mg/L
Alum dose	30	mg/L
Alum solids production factor	0.33	mg solids / mg alum
Residuals production	23,235	lb/day
Dewatering polymer usage		
Polymer cost	0.82	$USD/lb Neat
Polymer percent active	41	percent
Polymer dose	10	lb/dry ton (active)
Polymer cost	232	$USD/day
	84,809	$USD/year
Disposal cost		
Disposal unit cost	58.83	$USD/wet ton
Percent solids	28	percent
Disposal cost	2,441	$USD/day
	890,945	$USD/year
Total cost		
Total cost	975,754	$USD/yr
	6,970	$USD/yr/MGD
Cost of 0.5 mg/L TSS & 2 mg/L alum dose increase	63,110	$USD/yr

City of Hagerstown

The City of Hargerstown operates the R.C. Willson WTP. It is a conventional water treatment plant producing an annual average of 11.2 MGD. Vacuum sludge collectors pump solids into holding lagoons, from which solids are collected by a contractor and land applied on a semiannual basis.

The previous eight years of solids disposal information were used to estimate solids handling costs (Table 4.15). Over that period, solids production was estimated to be 7,400 gal/day based on hauling records. The most recent cost for land application was $0.04/gal, or an average cost of $296 per day or $108,040 per year.

Disposal cost per MGD of production (at the average annual rate of 11.2 MGD) were calculated to be approximately $9,600/year/MGD. For every one percent increase in solids production, either due to increasing influent TSS or increasing coagulant dose, solids disposal cost would increase by $1,100 per year.

Table 4.15
Estimated solids disposal costs for the City of Hagerstown

Parameter	Value	Units
Annual production	11.2	MGD
Solids production	7,400	gal/day
Solids disposal cost	<1	$USD/gal
Disposal cost	296	$USD/day
	108,040	$USD/year
	9,646	$USD/year/MGD
Cost per one percent increase in solids production	1,080	$USD/year

Comparison of Utility Case Studies

Solids handling costs are expected to vary considerably by location depending on the availability of solids disposal options, to potentially include surface water or sanitary sewer discharge. However, costs are provided here to estimate changes in operational costs due to watershed land use change, as well as to serve as a benchmark for other water systems.

The City of Hagerstown and Washington Aqueduct had similar solids handling costs on a cost per MGD of flow basis despite differences in scale and handling processes. Cost for the City of Hagerstown was estimated to be $9,600/year/MGD and $10,900/year/MGD for the Washington Aqueduct. It should be noted that these estimates exclude capital costs, as well as energy, maintenance, and personnel costs, which may be significant.

Increase in solids production, either due to increased source water solids loading or increased coagulant dose, would present additional costs for each utility. Every one percent increase in solids production at the R.C. Willson WTP would cost the City of Hagerstown approximately $1,100/year. A one mg/L (four percent) increase in Dalecarlia Reservoir TSS, which might correspond to an 0.5 mg/L TSS and two mg/L alum increase in plant influent, would increase cost to Washington Aqueduct by $84,000/year.

CHAPTER 5
USING RESULTS TO PRIORITIZE SOURCE WATER PROTECTION

Building on the results of the modeling effort in Chapter 2, the water quality-treatment dose relationships in Chapter 3, and the associated costs to drinking water utilities described in Chapter 4, this chapter provides land-based information to inform source water protection activities. Specifically, current land cover conditions are assessed, Potomac-specific forest protection opportunities are identified, and existing forest protection prioritization methods are reviewed.

CURRENT LAND COVER CONDITIONS

This section presents a summary of land cover in the non-tidal portion of the Potomac River basin. Land cover is evaluated first followed by a summary of forest land ownership including a preliminary characterization of forest land management activities in the basin. Finally, an overview of forest preservation programs is provided at the federal, state, and local levels, including a review of local zoning ordinances.

Land Cover Characteristics

This section summarizes the land cover characteristics of the non-tidal Potomac basin, including evaluating the latest land cover data and identifying riparian and upland forests.

Land Cover

The most recent land cover dataset available for the study area is the 2011 National Land Cover Database (NLCD) produced by the Multi-Resolution Land Characteristics Consortium, a partnership between multiple federal agencies and led by the U.S. Geological Survey (USGS) (Homer et al. 2015). The 2011 NLCD is based on Landsat 30-meter resolution satellite imagery. The NLCD contains 20 land cover classifications. Fifteen of these classes are observed in the Potomac River basin. For the purposes of this analysis, the 15 land cover classes were aggregated into seven broad classes: water, developed, barren land, forest, shrub/scrub, agriculture, and wetlands (Table 5.1).

Table 5.1
Original NLCD classifications aggregated into seven broad categories for this analysis

NLCD land cover code	NLCD land cover class	Aggregated land cover class
11	Open water	Water
21	Developed, open space	
22	Developed, low intensity	
23	Developed, medium intensity	
24	Developed, high intensity	Developed
31	Barren land (rock/sand/clay)	Barren land
41	Deciduous forest	
42	Evergreen forest	
43	Mixed forest	Forest
52	Shrub/scrub	Shrub/scrub
71	Grassland/herbaceous	
81	Pasture/hay	
82	Cultivated crops	Agriculture
90	Woody wetlands	
95	Emergent herbaceous wetlands	Wetland

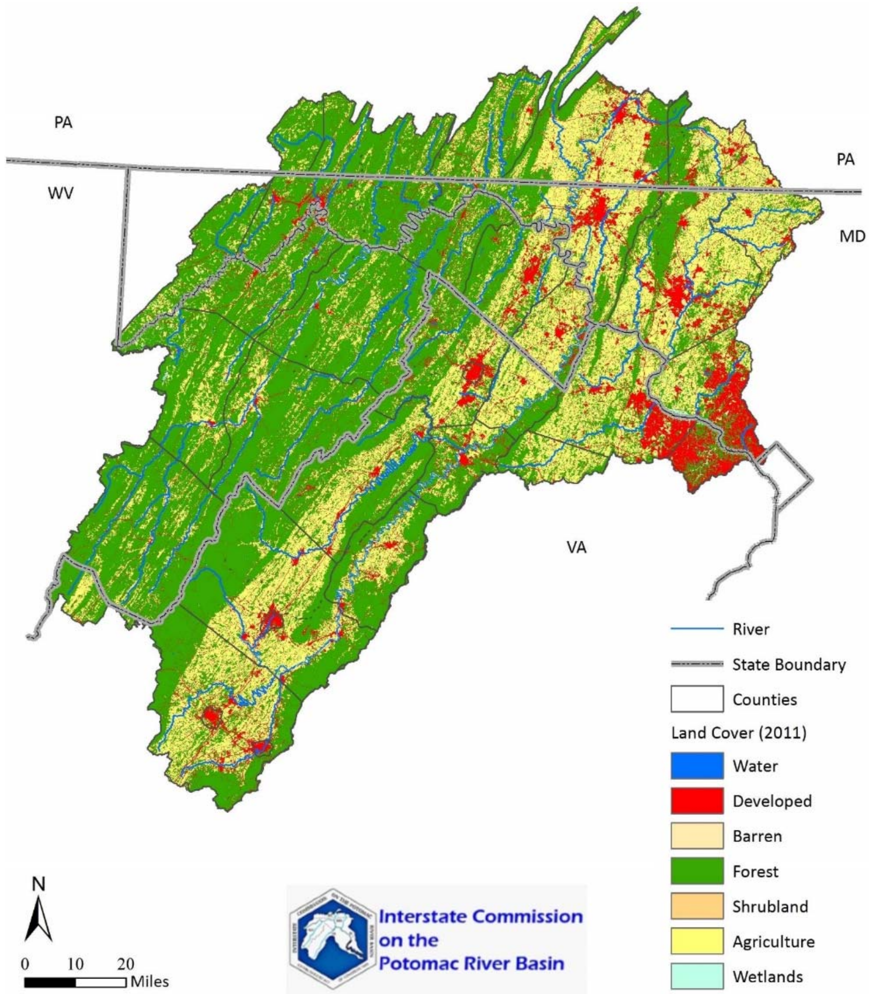
Land cover in the non-tidal Potomac River basin is predominantly forest (58 percent) and agriculture (29 percent). Developed lands account for 11 percent of the drainage area while wetlands, barren land, shrub/scrub, and water account for the remaining two percent of the land area.

Table 5.2 provides a breakdown of land cover. Figure 5.1 shows the spatial distribution of land cover in the watershed.

Table 5.2
Summary of land cover in the non-tidal Potomac basin

Aggregated NLCD land cover class	Acres	Percent
Water	53,660	0.72
Developed	783,658	10.58
Barren land	21,062	0.28
Forest	4,307,850	58.13
Shrub/scrub	21,580	0.29
Agriculture	2,183,847	29.47
Wetland	38,707	0.52
Total	7,410,364	100

Source: Data from NLCD 2011



Source: Data from NLCD 2011.

Figure 5.1 Aggregated land cover

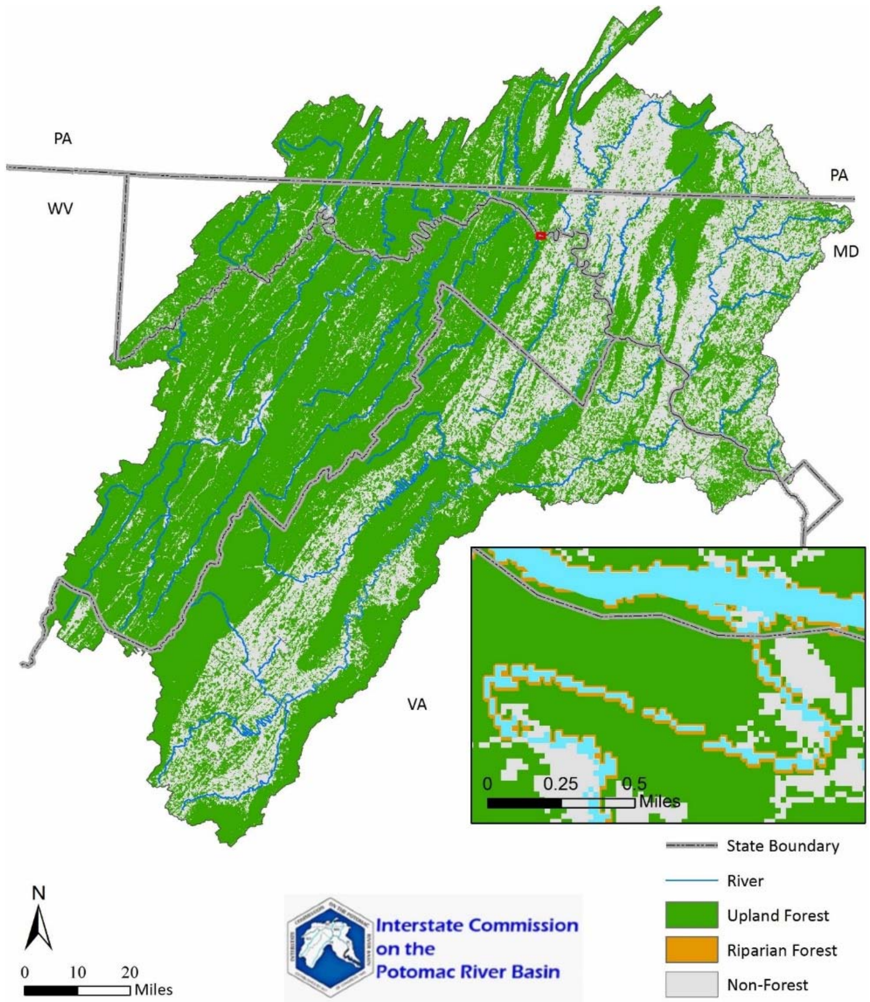
Upland and Riparian Forest

The remainder of this section further explores the forested lands, starting with differentiating between upland and riparian forest lands in this section. Identifying riparian forests is important because forested stream buffers are potential opportunities for protection with water quality benefits.

To be consistent with the definition of forested buffers in the Watershed Model (EPA 2010), land cover within riparian lands was evaluated using two definitions of "riparian" as provided in Section 6 of EPA (2010), namely, 35 ft and 100 ft. Buffers at least 35 ft wide receive credit in the Watershed Model and are considered to reduce the impact of upstream land uses. The average riparian forest buffer in the Chesapeake Bay watershed is 101'. These width designations are based on the U.S. Department of Agriculture's (USDA) standard practice definition, as documented in EPA (2010).

Using the NLCD, the water classification was extracted and converted to a waterbody polygon for Watershed Model simulated reaches. From this, two new polygons were created using ArcGIS's buffer tool that extend a user-defined distance (35 ft and 100 ft) from the edge of the river in both directions. These polygons represent riparian areas. Land cover was then characterized within the riparian and non-riparian (upland) areas.

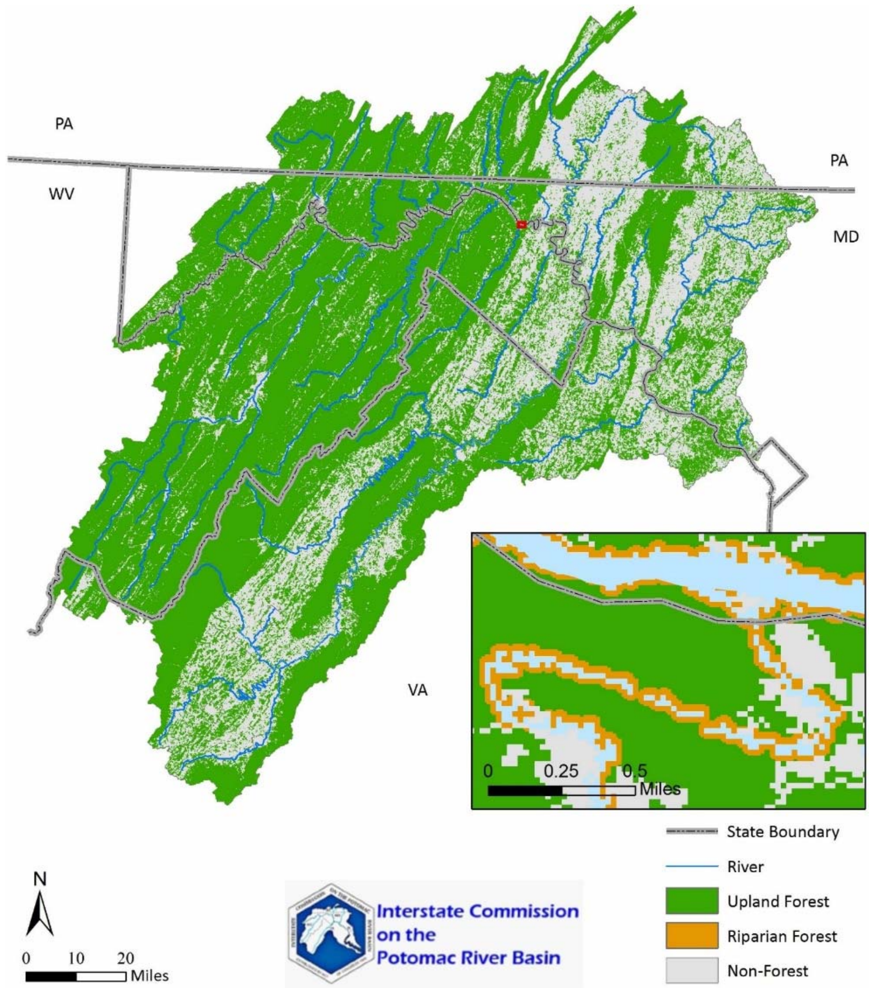
Figure 5.2 and Figure 5.3 show the location of upland and riparian forests in the 35 ft and 100 ft buffer polygons in the basin. Using the 35 ft buffer, there are 14,629 acres of riparian forest in the basin and using the 100 ft buffer there are 35,535 acres. Overall riparian forest accounts for less than one percent of total forest land in the basin. It is difficult to distinguish upland from riparian forests on a basin scale map. Figure 5.4 provides a closer look at a selected reach along the Potomac River to illustrate the resulting 35 ft and 100 ft riparian forest designations. Forested land accounts for approximately half of the riparian area under both width definitions. Table 5.3 summarizes the land cover in the riparian buffer for both the 35 ft and 100 ft widths.



Source: Data from NLCD 2011.

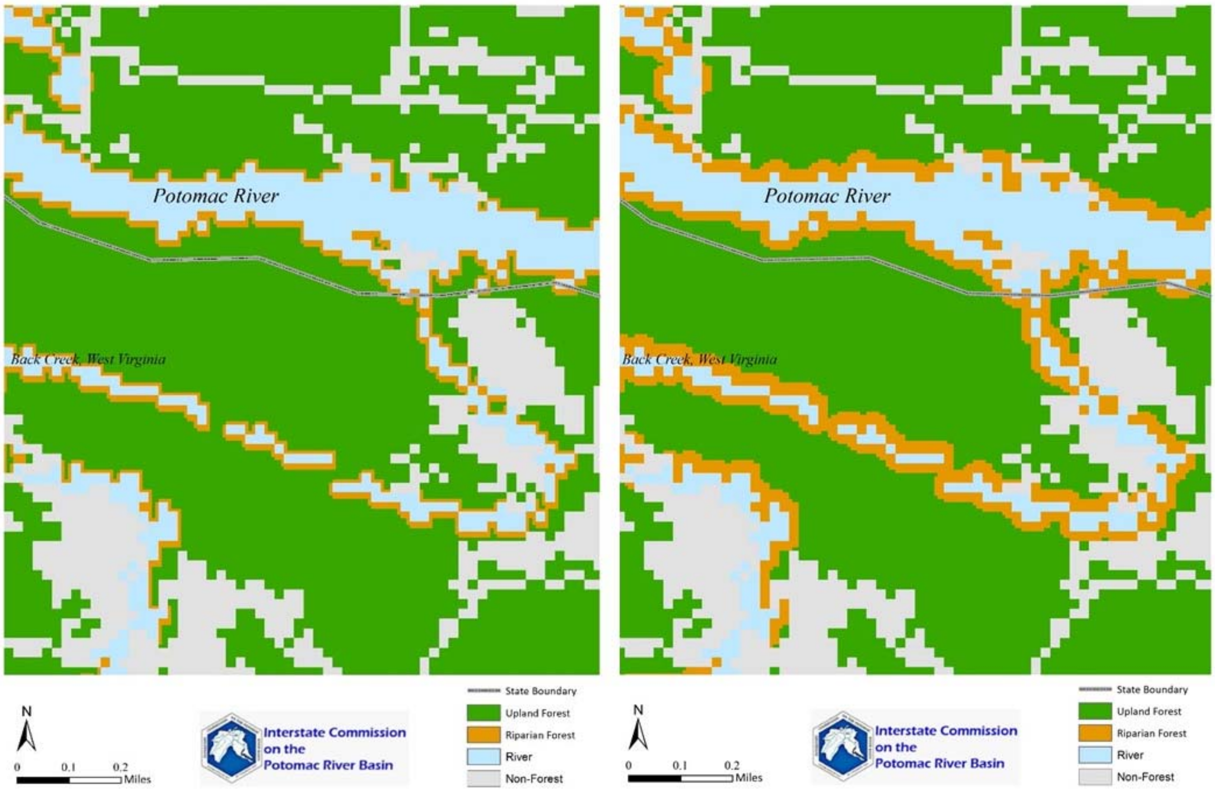
The inset map displays riparian (brown) and upland (green) forests along a randomly selected portion of the mainstem Potomac (shown with a red box on the larger map).

Figure 5.2 Upland and riparian forest cover - 35 ft buffer



Source: Data from NLCD 2011.
The inset map displays riparian (brown) and upland (green) forests along a randomly selected portion of the mainstem Potomac (shown with a red box on the larger map).

Figure 5.3 Upland and riparian forest cover - 100 ft buffer



Source: Data from NLCD 2011.

Figure 5.4 Riparian forest (brown) identified in 35 ft (left) and 100 ft (right) riparian buffer along a portion of the Potomac River

Table 5.3
Summary of riparian land cover within 35 ft and 100 ft buffers around open water

	35 ft buffer		100 ft buffer	
NLCD land cover class	Acres	Percent	Acres	Percent
Open water	0	0	0	0
Developed	2,412	9.43	6,596	10.23
Barren land	100	0.39	237	0.37
Forest	14,629	57.23	35,535	55
Shrub/scrub	31	0.12	88	0.14
Agriculture	6,865	26.85	18,458	28.62
Wetlands	1,528	5.98	3,578	5.55
Total	25,563	100	64,490	100

Source: Data from NLCD 2011

Forest Ownership and Easements

This section summarizes forest ownership and conservation easements in the Potomac basin. Ownership and easements are classified as federal, state, local, and private (family, corporate, and non-governmental organizations - NGOs).

Ownership

Unlike forest lands in the western and southwestern United States, the majority of forests east of the Mississippi River are privately owned. According to a 2013 USDA Forest Service (USFS) inventory of forest lands (USDA 2013a), 70 percent of forests in the Potomac basin are privately owned and 57 percent are family owned. Private forest ownership includes family-owned, corporate-owned, and other (e.g., NGOs).

Aside from the aforementioned USFS forest inventory, information about forest activities and management practices occurring on privately held forest lands is difficult to obtain. This was confirmed in discussions with The Nature Conservancy (personal communications, TNC, 12/7/16). Databases such as the Protected Areas Database and GAP Analysis provide detailed information about forest lands but are limited to publicly owned forest tracts (USGS 2016). Information about stewardship plans on privately owned lands is generally tracked at the county and local levels is not readily available. This type of data collection is beyond the scope of this project.

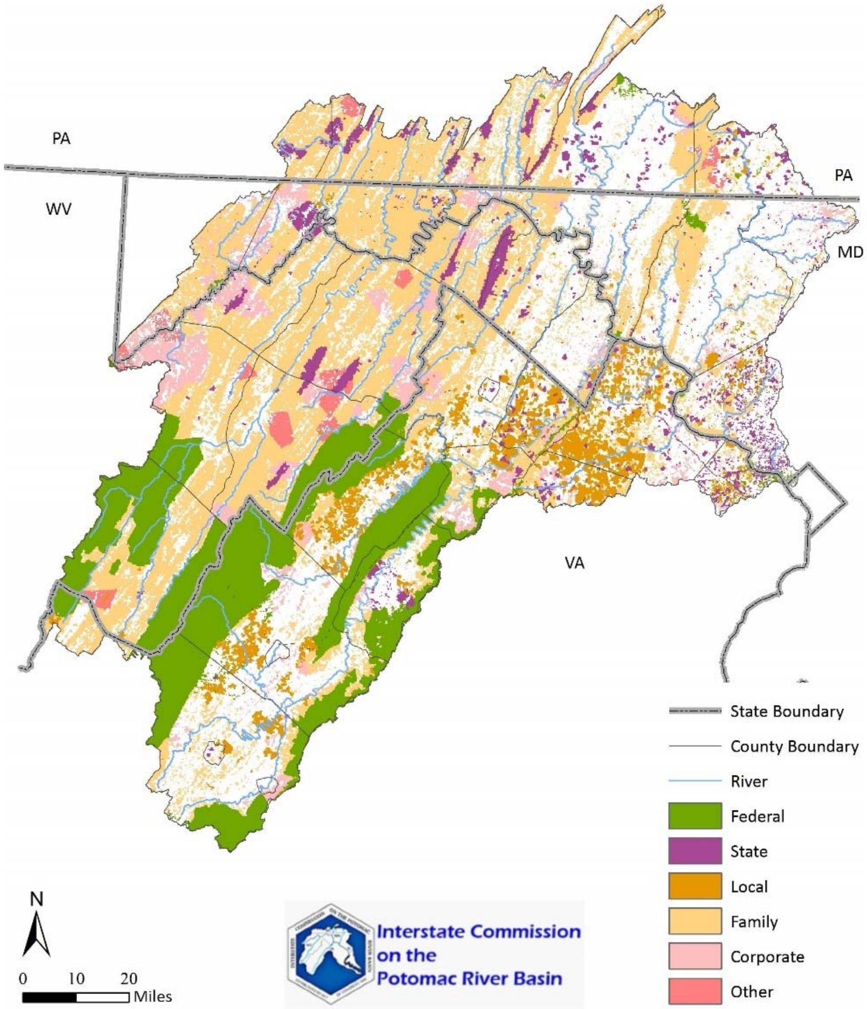
Road density may be used as a proxy to identify active forest management on privately owned forests. There is evidence that poorly constructed and maintained forest roads may be an important factor in water quality (Brion 2011).

Table 5.4 summarizes forest ownership and Figure 5.5 shows the distribution across the basin. There are three major federal holdings of forest land in the basin. Shenandoah National Park, George Washington National Forest, and Monongahela National Forest are completely or partially located within the basin. These forests only account for 19 percent of all forested land in the basin.

Table 5.4
Summary of forest ownership in the Potomac River basin

Ownership	Acres	Percent
Federal	804,574	19.2
State	390,271	9.3
Local	43,907	1.1
Family	2,386,046	56.9
Corporate	458,117	10.9
Other	109,637	2.6
Total	4,192,553*	100

Source: Data from USDA 2013a
*The data set produced from this national survey is approximately 250-meter resolution. Compared to the higher resolution (30 meter) NLCD, total acreage of forest will vary between data sets.



Source: Data from USDA 2013a.

Figure 5.5 Forest ownership in the Potomac basin

Easements

An easement is a vehicle for a private landowner to give up some rights to their land but still retain full ownership. Under conservation easements, landowners give up the right to develop or subdivide their land but retain the ability to farm or manage the resources. The easement is donated or sold to a third party - usually a government agency or land trust. There are many benefits for landowners to put their land under easement including tax incentives and ensuring the land stays in productive use or conservation in perpetuity. Before easements become legally binding, the landowner and easement holder will lay out the terms of the easement including the specific conservation objectives. The easement holder is responsible for ensuring the terms of the easement are upheld.

Easement shapefiles were downloaded from Virginia Department of Forestry (VDOF 2016), Virginia Department of Conservation and Recreation (VA DCR 2016), and the National Conservation Easement Database (NCED 2016). Easements are divided into four categories for this analysis: federal, state, local, and private. The category is determined by the easement holder which is not the same as the landowner. For example, the USFS may own a forest parcel but the easement is held by The Nature Conservancy (private) or a private landowner owns the land but the conservation easement is held by a state agency (state). Easements are not necessarily limited to protecting forested lands. Overall, 1.6 million acres in the Potomac basin are under some type of conservation easement protecting 1.3 million acres (30 percent) of forest.

Table 5.5 summarizes the land cover within conservation easements for each category (federal, state, local, and private). The percent column is a percentage of the land use area under easement in that category. Private conservation easements overwhelmingly favor agriculture, accounting for 61 percent of total land cover while forests account for 33 percent. Local conservation easements favor agriculture slightly less than private easements and represent 52 percent of the total. The total area of local forest conservation easements is almost identical to the area of private easements at 33 percent (but is almost 67,000 acres less).

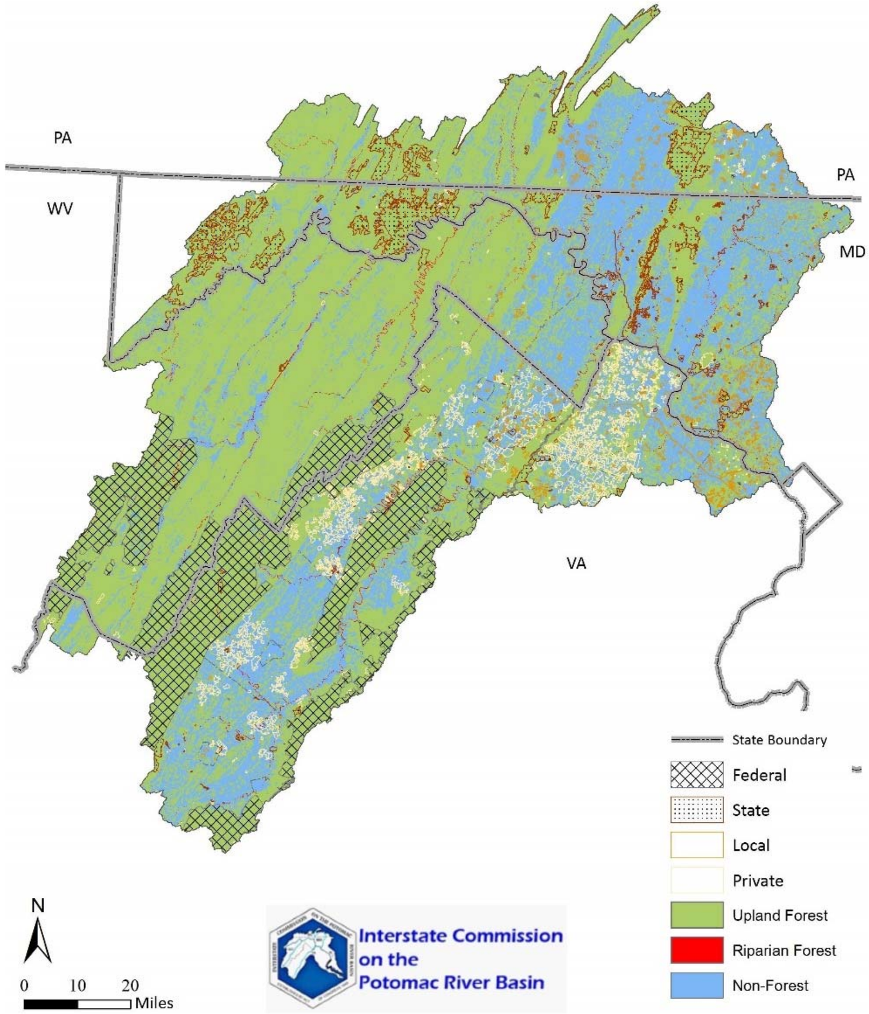
There appears to be more emphasis on forest conservation easements over agricultural easements at the state and federal levels. State conservation easements are 88 percent forested lands while under federal easements it is 92 percent. Of the 1.3 million acres of forest currently under easement, 1.2 million acres are protected by federal- and state-held conservation easements. This includes Shenandoah National Park, George Washington National Forest, and Monongahela National Forest in Virginia and West Virginia.

Figure 5.6 shows the spatial distribution of forest ownership within the Potomac watershed.

Table 5.5
Summary of land cover under conservation easement by category

Land cover class	Private		Local		State		Federal	
	Acres	Percent	Acres	Percent	Acres	Percent	Acres	Percent
Open water	981	0.36	277	0.42	1,655	0.55	2,547	0.25
Developed	13,085	4.87	6,635	10.02	9,732	3.26	27,997	2.77
Barren land	82	0.03	85	0.13	269	0.09	726	0.07
Forest	88,638	32.96	21,750	32.86	262,479	87.95	933,848	92.40
Shrub/scrub	685	0.25	492	0.74	830	0.28	377	0.04
Agriculture	164,491	61.16	34,279	51.79	20,490	6.87	45,047	4.46
Wetlands	975	0.36	2,670	4.03	3,002	1.01	131	0.01
Total	268,935	100	66,188	100	298,457	100	1,010,672	100

Source: Data from VDOF 2016, VA DCR 2016, and NCED 2016



Source: Data from VDOF 2016, VA DCR 2016, and NCED 2016.

Figure 5.6 Easements by category

Some of these easements are located in the 35 ft and 100 ft riparian areas described above. Specifically, there are 1,661 acres of easements within 35 ft riparian area and 4,744 acres of easements within the 100 ft riparian area.

Existing Protection Efforts

This section summarizes existing forest protection efforts at the federal, state, and local level. There are a variety of programs which seek to protect and restore forests throughout the basin and range from voluntary conservation easements to mandatory riparian buffer ordinances.

Federal Programs

The goal of federal forest conservation programs is to encourage the protection of forest resources and provide funding to state and local governments for the purchase of conservation easements or to run education and outreach campaigns to inform landowners how to sustainably manage forest resources on their property. These programs also provide technical support for developing resource management plans and conduct scientific research to inform management and policy decisions at all levels of government. The following programs are described below and summarized in Table 5.6:

- Forest Legacy Program
- Community Forest Program
- Forest Stewardship Program
- National Flood Insurance Program

The Forest Legacy Program is a partnership between federal and state governments to support the protection of environmentally sensitive forest lands. The program is designed to encourage the protection of privately owned forests by providing financial support to help states purchase conservation easements or other legally binding actions to ensure conservation and proper management of these resources. As of 2015 the program has helped protect 26,600 acres of forest across the four basin states (USFS 2016a).

The Community Forest Program was established by Congress in 2008. It provides assistance to local governments and qualified nonprofits to establish community forests providing continuing and accessible benefits to local communities. The program will fund 50 percent of project costs with a 50 percent match and requires public access to the land. The land must be owned by a local government or qualified nonprofit organization to be eligible. Conservation easements are not eligible under this program (USFS 2008).

The objective of the Forest Stewardship Program is to help "private forest landowners develop plans for the sustainable management of their forest" (USFS 2016b). The program provides assistance to owners of forest land where good stewardship will enhance the long-term productivity of forest resources. Owners of forest lands identified in State Forest Action Plans are prioritized in receiving technical assistance. This program is available to non-industrial private forest landowners (USFS 2016b). According to the database, Maryland has 336,000 acres covered by approved forest stewardship plans, Pennsylvania has 535,000 acres, Virginia has 452,000 acres, and West Virginia has 14,500 acres, respectively.

The Federal Emergency Management Agency produce Flood Insurance Rate Maps (FIRM) which guide the National Flood Insurance Program. The FIRM data identifies floodplains and the government regulates development within these flood zones. However, the federal government does not prevent development from occurring in flood zones or other riparian buffers. The regulations require actions to reduce disturbances or impede flood waters in the event of a flood but do not protect riparian buffers per se. Local governments have the ability to require additional regulations to prevent floodplain disturbances through stronger riparian buffer ordinances but few local governments do.

In 2000, the Potomac Watershed Partnership was created through a USFS initiative to fund 15 large-scale projects across the country with a focus on watershed restoration. The Cacapon Institute coordinates the partnership. Eight member agencies and organizations work on issues ranging from septic systems to riparian buffers to forest stewardship (PWP 2016). Since its formation, the partnership has created 2,500 acres of riparian forest buffers, initiated a backyard program to encourage forest buffers in suburban neighborhoods, and rehabilitated 10 miles of forest service roads in the State of Maryland (MD DNR 2016a).

Table 5.6
Summary of federal conservation programs

Program	Acres affected	Dollars spent ($USD)	Notes
Forest Legacy Program	26,600	N/A	Supports private land owners with land management and conservation easements.
Community Forest Program	N/A	N/A	50 percent cost share and requires public access to land.
Forest Stewardship Program	1,337,500	N/A	The program supports nonindustrial private forest owners to certify forest stewardship plan. Acres affected is a statewide figure for Maryland, Pennsylvania, Virginia, and West Virginia.
National Flood Insurance Program	N/A	N/A	Sets minimum development regulations in flood zones.
Potomac Watershed Partnership	2,500	N/A	Program started in 2000.

State Programs

At the state level, the most common forest conservation efforts are programs which encourage conservation easements and technical extension services to provide resources to landowners for sustainable land management practices. The following sections highlight the programs in Maryland, Pennsylvania, Virginia, and West Virginia which encourage the conservation of forest resources on private property. Table 5.7 summarizes state conservation programs.

Table 5.7
Summary of state conservation programs

State	Program	Acres affected	Dollars spent ($USD)	Notes
Maryland	Maryland Environmental Trust	132,000	N/A	Statewide program
	Rural Legacy Program	83,100	300,000,000	Statewide program to protect critical natural resources identified across 920,000 acres throughout the state.
	Forest Service	99,000	N/A	Acres affected are estimated figures for the Potomac basin.
Pennsylvania	Forest Legacy Program	N/A	N/A	A federal-state partnership to assist in identification of critical natural resources.
Virginia	Ag-Forestal Districts	N/A	N/A	Administered at the local level.
	Department of Forestry	n/a	n/a	
West Virginia	Department of Forestry	n/a	n/a	Works with private landowners to place property in conservation easements.
	Regional Conservation Partnership Program	n/a	1,000,000	Administered through USDA and targets conservation easements and riparian forest buffers.

Maryland. The State of Maryland has three primary programs for forest conservation, each administered through the Department of Natural Resources: Maryland Environmental Trust, Rural Legacy Program, and Maryland Forest Service.

The Maryland Environmental Trust is a state-run program to assist landowners in placing property under conservation easements and often becomes the holder of these easements. The program provides resources to eligible landowners including a Conservation Easement Planner to assist in navigating the application and approval process. The Conservation Easement Planner also assists landowners in creating a suitable land management strategy. The trust has protected 132,000 acres on 1,065 properties across the state (MD DNR 2016b).

The Rural Legacy Program provides funding to support the preservation of large, contiguous tracts of forest or agricultural land for sustaining natural resource-based industries. The program encourages local governments and land trusts to work together to protect critical natural resources. Each county in the state has a Rural Legacy Area amounting to 920,694 acres. Over $300 million has been allocated to protect 83,100 acres since 1997. More than $17.5 million in funding is available for fiscal year 2017 (MD DNR 2016c).

The Maryland Forest Service manages approximately 99,000 acres of forest in the Potomac basin for a variety of uses including timber production. The primary goals of Forest Service programs are to restore, manage, and protect ecosystems and sustain natural resources, and connect people to the land (MD DNR 2016d).

Pennsylvania. The Pennsylvania Department of Conservation and Natural Resources administers multiple programs to provide landowners assistance in protecting and properly managing forest resources throughout the state. The Forest Legacy Program, described in more detail above, is a federal-state partnership established to assist states in inventorying forest resources and provides a framework for designating critical areas for protection and sustainable management (PA DCNR 2003).

The state also provides forestland and estate planning resources through the Pennsylvania State University extension service. Landowners can receive assistance in developing forest management plans and access other technical resources for sustainable forest management (PSU 2016).

Virginia. The Commonwealth of Virginia has programs available to forest landowners to assist in conservation and sustainable management. The Virginia Department of Forestry (VDOF) encourages landowners to consider placing their forests in conservation easements. To facilitate and encourage conservation easements, the Commonwealth enacted the Local Agricultural and Forestal Districts Act to allow counties to designate agriculture and forestry conservation districts. The law provides the framework for county governments to protect and enhance agriculture and forest resources from future development by providing tax incentives to property owners. The program is administered at the local level and is commonly referred to as Ag-Forestal Districts (Code of Virginia 2016).

VDOF owns and manages forests across the Commonwealth and in the Potomac basin. The department manages forests to meet a variety of objectives including maintaining a steady supply of timber, providing resources for clean air and clean water, protecting water quality, protecting or improving habitat, and providing residents with recreation opportunities (VDOF 2013).

West Virginia. The West Virginia Department of Forestry encourages landowners to put their property in conservation easements and has funding available through the federal Forest Legacy Program, described in more detail above, to purchase easements from willing landowners (WV DOF 2016).

In 2016, the Regional Conservation Partnership Program, administered by USDA, awarded $1 million to the WV Chesapeake Headwaters Conservation Partnership. The project will target the creation of conservation easements on lands critical to water quality in the Chesapeake Bay and the Potomac basin (USDA 2016a).

Local Ordinances and Programs

Local conservation programs vary across the Potomac basin. In Virginia, counties use ag-forestal districts as a popular approach to protecting forest and agriculture resources. In Montgomery County, Maryland, the Maryland National Capital Parks and Planning Commission owns 34,000 acres for parks, recreation, and conservation (Maryland National Capital Parks and Planning Commission 2016). Some counties have more resources available to acquire conservation easements and others encourage landowners to put land into easements through local soil and water conservation districts or private land trusts.

Comprehensive plans can identify and prioritize forest conservation policies which can be supported by local land use laws or ordinances. Incorporating resource conservation policy statements in land use planning documents also signals to residents the value and importance of sustainable management of local forest resources. Comprehensive plans also provide a legal framework to support resource management decisions. Of the 55 comprehensive plans (and similar policy documents) reviewed from jurisdictions across the basin, 34 (62 percent) included statements related to protecting stream buffers and nine (16 percent) had statements relate to protecting, promoting, and monitoring forestry activities.

Riparian Buffers. Stream protection ordinances are one approach to protecting riparian habitat from development or other land uses. Generally, state departments of environment provide recommendations for appropriate buffer widths based on width of stream channel, slope of stream bank, type of soils, etc. States may offer incentives to private landowners to voluntarily protect stream buffers but individual counties may choose to adopt local land use regulations to ensure riparian buffers are protected under land use laws. The four states in the study area have not adopted mandatory minimum stream protection standards.

There are two common types of stream protection ordinances: stream setbacks and riparian buffers. Stream setback ordinances are typically more narrow in scope and generally only apply to new development. Stream setback ordinances require new structures to be built a specified distance from the stream as defined by each ordinance. Setbacks can be measured from top of bank, middle of stream, edge of primary floodplain and can be scaled to reflect other physical conditions of the site (e.g., slope of streambank). Stream setbacks protect streams from encroaching development but they may not protect riparian habitat from disturbance.

Riparian buffer ordinances can be broadly characterized as regulations which prohibit specific land uses within a riparian zone with the goal of leaving riparian corridors or riparian habitat undisturbed. Riparian buffers are similarly defined as stream setbacks and can vary in width. Similar to stream setbacks, new development may not occur within the buffer but unlike most stream setback ordinances, native vegetation must remain undisturbed within the riparian zone which may prohibit agriculture or other similar activities.

Of the 49 counties and cities in the project study area, 12 have either a stream setback or riparian buffer ordinance. Figure 5.7 identifies which counties have ordinances. When applied spatially, these ordinances combine to protect 33,000 acres of riparian buffers. This is likely a conservative estimate, however. The specific language in the ordinance, the year it was adopted, and stream characteristics, make it difficult to accurately assess total riparian buffers under protection at the basin scale. Some of these ordinances are more restrictive than others and the presence of an ordinance does not guarantee protection of riparian buffers or even enforcement of the ordinance. Higher resolution analysis at the county scale would produce a more accurate assessment of riparian buffers.

Table 5.8 provides a summary of land cover in existing county stream setback or riparian buffer ordinances.

Table 5.8
Summary of land cover in existing county stream setback or riparian buffer ordinances

NLCD land cover class	Acres	Percent
Open water	15,457	47.33
Developed	2,024	6.20
Barren land	889	2.72
Forest	8,934	27.36
Shrub/scrub	53	0.16
Agriculture	4,028	12.33
Wetlands	1,273	3.90
Total	32,658	

Source: Data from NLCD 2011

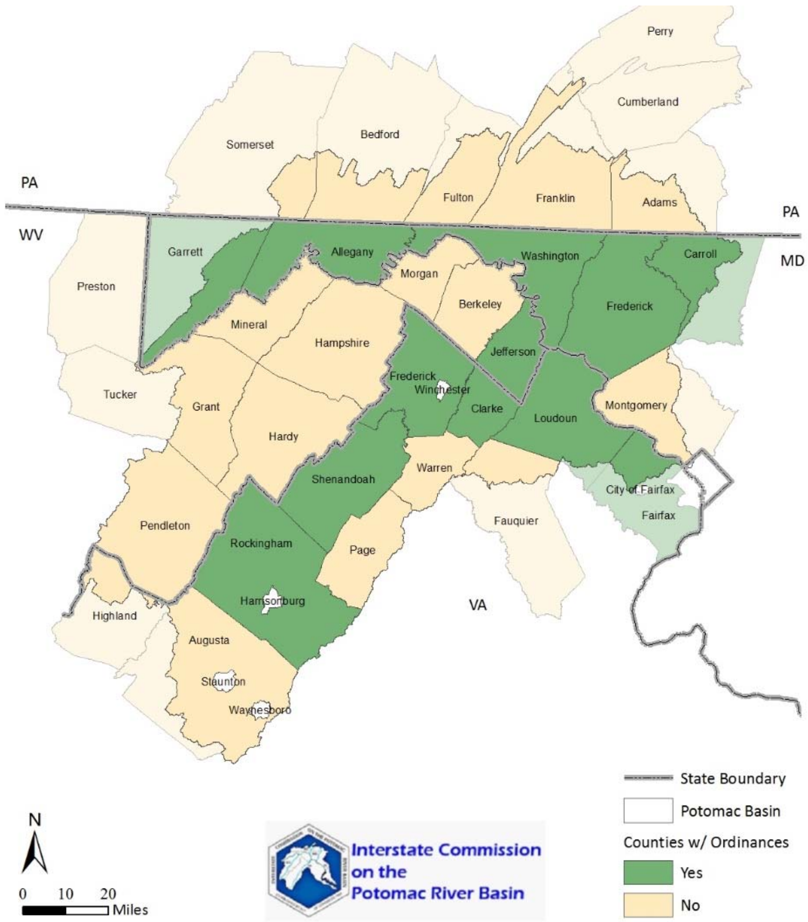


Figure 5.7 Counties with stream setback or riparian buffer ordinances

Summary

There are 4.3 million acres of forest in the non-tidal portion of the Potomac River basin, accounting for 58 percent of total land cover. The majority of these forest lands are in private ownership (70 percent), of which, 57 percent are family owned and, according to the U.S. Forest Service, less than 25 percent of private forest owners have land management plans (USDA 2013a). Furthermore, 1.3 million acres of forests are protected by conservation easements and less than half of the counties in the basin protect riparian forest buffers from development through land use regulations.

The next step of this project, described below, builds on the results of this analysis to identify and prioritize opportunities for forest protection in the Potomac basin.

FOREST PROTECTION OPPORTUNITIES

The previous section indicates that the majority of the Potomac watershed is forested and a portion of these lands are already protected. This section characterizes the remaining unprotected forested lands as opportunities for forest protection within the watershed. These opportunities can be prioritized using a set of criteria that account for factors that improve water quality and reduce utility treatment costs. These could include protection status, ownership, connectivity, health, and distance to stream, among others. A GIS was used to implement the criteria and identify specific opportunities.

Method

The purpose of this risk-based geospatial analysis is to identify and prioritize forest protection opportunities at the pixel level for the 2011 NLCD land use raster used to assess current land cover conditions, described in the previous sections. Conducting the analysis at the pixel scale allows for aggregation of results at multiple levels (e.g., land parcel, Watershed Model land-river segments) in the future. The land use grid, or derivatives of it, were used as the active computational layer throughout the analysis; therefore, avoiding inconsistencies in raster boundaries during aggregation of metric values.

The following steps were completed to identify and prioritize forest protection opportunities in the study area:

Step 1. Identify Protected Forest Lands Based on The Results of the Current Land Cover Assessment

Since they are already protected, they are not considered protection opportunities. Protected lands include:

- riparian areas (as defined by local ordinance) in counties with riparian buffer ordinances;
- land under easement; and
- public (federal, state, or local) forests.

Step 2. Identify Potential Opportunities for Forest Protection

This is the inverse of forest lands identified in Step 1 above. Unprotected forest lands define the universe of potential protection opportunities.

Step 3. Create 30m Raster Grids

For potential protection opportunity forest lands, create 30m raster grids for the non-tidal Potomac basin for the following metrics:

Local Roads. Rationale: Local (low use) roads have been associated with deterioration in forest habitats and may be a significant source of sediment pollution from forested areas (Boomer 2014; Brion 2011; and personal communication, TNC, 12/7/16).

- Using Euclidean Distance tool in ArcGIS 10, calculate straight line distance from forest to the closest local road using TIGER feature class code S1400. Normalize values on a 0-100 scale using the Geomorphometry and Gradient Metrics Toolbox (Evans et al. 2014),[7] where higher values equal higher priority. Forests in close proximity are expected to have more degraded water quality; therefore, higher scores are given to forests farther from unpaved roads.

Forest Morphology. Rationale: Forest fragmentation has negative effects on water quality (Stein et al. 2012). In addition, the size of the forest has water quality implications – larger forests are associated with better water quality (Stein et al. 2012). Protecting large patches of core (un-fragmented) forests; therefore, may assist in achieving desired water quality benefits.

- Morphology Metric 1: Using Morphological Spatial Pattern Analysis (MSPA) tool (Soille and Vogt 2008), identify forest type based on user-specified input criteria (i.e., distance threshold that defines forest edges[8]). Forest type categories were scored as discrete values between 0-100 based on the rationale that core areas are forests that meet the minimum size requirement and are expected to achieve full forest-related benefits. This scoring scheme prioritizes core areas, edges of core areas, extensions of core areas, and connection between core areas. Specifically:
    - Core = 100
    - Edge = 80
    - Branch = 60
    - Bridge = 40
    - Loops = 20
    - Islets = 0
- Morphology Metric 2: Create a forest patch polygon from the opportunity raster grid. Calculate the area of each patch and add it to the attribute table. Assign the patch area value to each opportunity forest raster pixel that falls within it. Normalize the values on a 0-100 scale using the Geomorphometry and Gradient Metrics Toolbox, where higher values equal higher priority. In this case, larger patch size is higher priority.

[7] This tool was selected based on its ability to normalize raster grids while retaining the original distribution of values.
[8] A 100-meter threshold was used to define the width of edges in the MSPA tool based on the scientific literature on edge effects (e.g., Laurance et al. 2007; Penariol and Madi-Ravazzi 2013).

Distance from Stream. Using Euclidean Distance tool in ArcGIS 10, calculate straight line distance to nearest stream from each opportunity forest cell. Normalize values on a 0-100 scale using the Geomorphometry and Gradient Metrics Toolbox, where higher values equal higher priority. In this case, forests closer to streams are higher priority because disturbances close to the stream have a greater potential to impact water quality conditions than disturbances farther from streams.

Slope.

- Calculate slope using a 30m Digital Elevation Model and ArcGIS's Spatial Analyst.
- Assign slope values to each opportunity forest land use pixel. Normalize the values on a 0-100 scale using the Geomorphometry and Gradient Metrics Toolbox, where higher values equal higher priority. In this case, higher slope values are higher priority because disturbance of high slope forests have the potential for greater impact to water quality conditions.

Distance from Census Urban Areas. Using Euclidean Distance tool in ArcGIS 10, calculate straight line distance from each opportunity forest pixel to the nearest census urban area. Normalize values on a 0-100 scale using the Geomorphometry and Gradient Metrics Toolbox, where higher values equal higher priority. In this case, forests closer to urban areas are higher priority because they are likely under more intense development pressure.

Distance from Protected Forests. Using Euclidean Distance tool in ArcGIS 10, calculate straight line distance from each opportunity forest pixel to the nearest protected forest (as identified in Step 1). Normalize values on a 0-100 scale using the Geomorphometry and Gradient Metrics Toolbox, where higher values equal higher priority. In this case, opportunity forests closer to protected forests are higher priority because they would add to existing protected forest patches.

Distance from Nearest Downstream Surface Water Intake. Created a multi-ring buffer around surface water intakes at 0.1, 0.5, 1, 5, 10, and 20 miles for opportunity forests within each intake's watershed. Assign discrete values for each buffer ring on a 0-100 scale, where forests closer to surface water intakes are considered higher priority.

Step 4. Evaluate Correlations between Metrics

Once all metric rasters were calculated, correlations between metrics were evaluated using Band Collection Statistics tool with compute covariance and correlation matrices enabled in ArcGIS' Spatial Analyst to select final set of non-correlated metrics.

Step 5. Sum Normalized Values for Non-Correlated Metrics

Each metric was given equal weight when summed. The combined raster represents the prioritized opportunities for forest protection opportunities where higher numbers are higher priority.

Results

Opportunities for forest protection were identified based on Step 2 of the process, described above. A map of the resulting opportunity forests is provided in Figure 5.8.

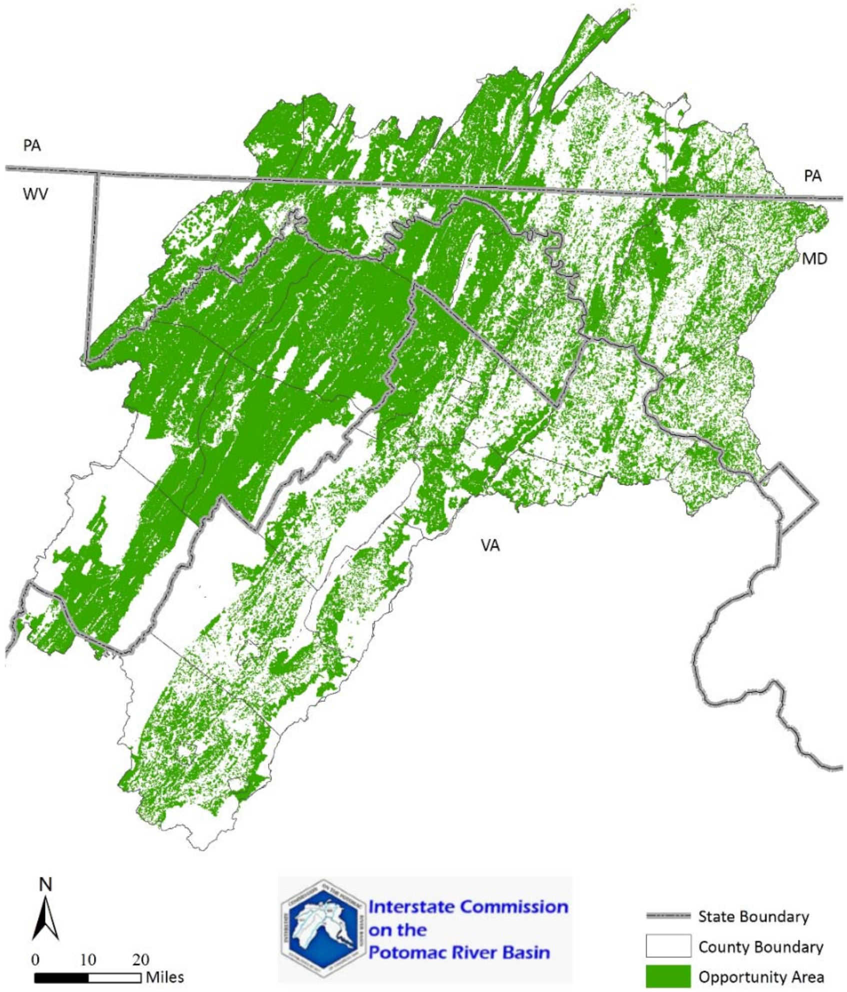


Figure 5.8 Opportunities for forest protection

Maps of individual metrics are presented in Figure 5.9 through Figure 5.15. The cumulative prioritization is presented in Figure 5.16. Please note that an individual map is not presented for the distance to downstream surface water intake to maintain the security of intake locations; it is included in the cumulative prioritization scheme (Figure 5.16).

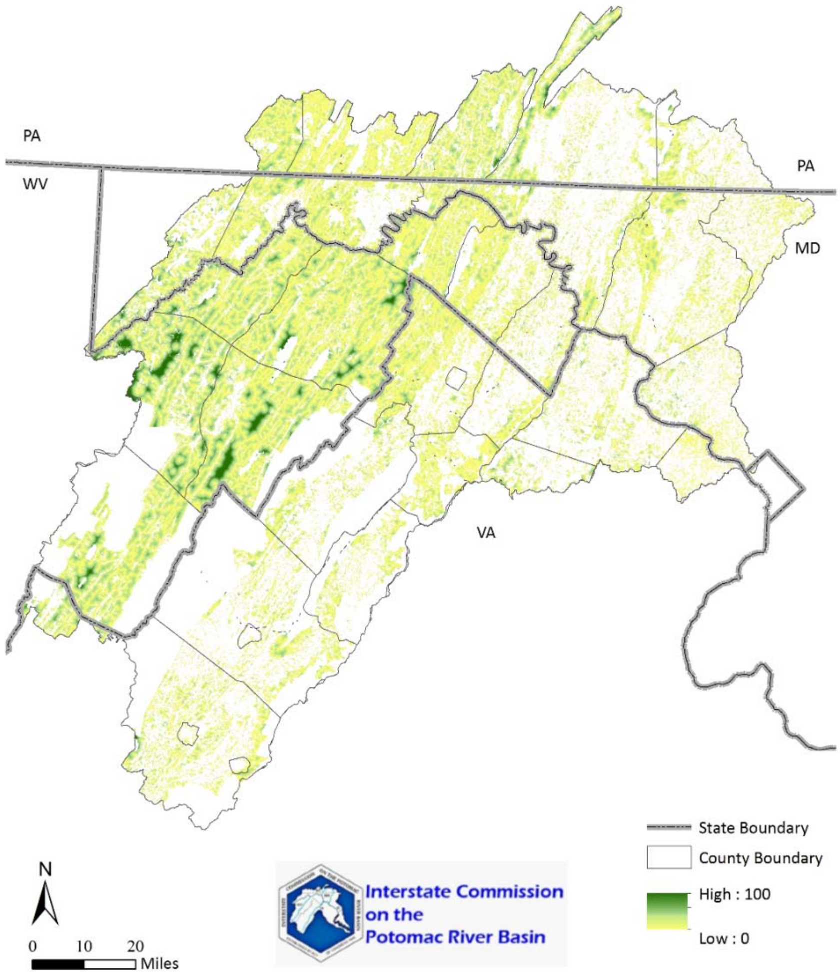


Figure 5.9 Normalized distance to local road metric; higher values are higher priority

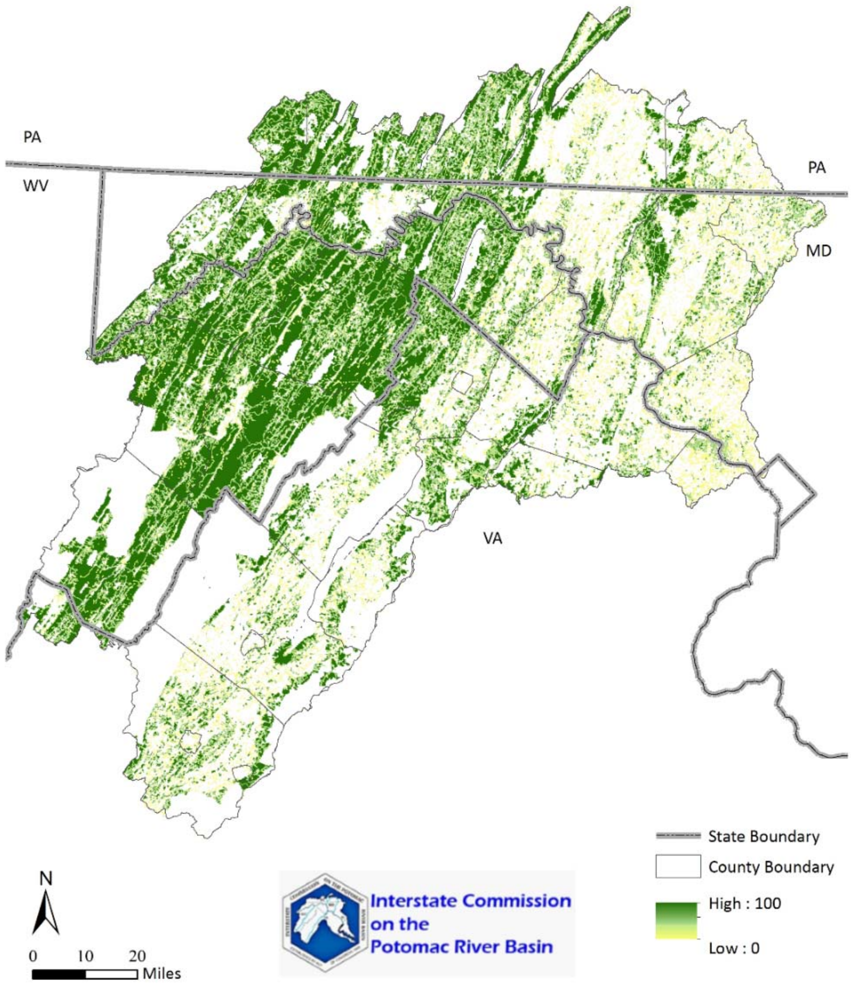


Figure 5.10 Forest type metric; higher values are higher priority

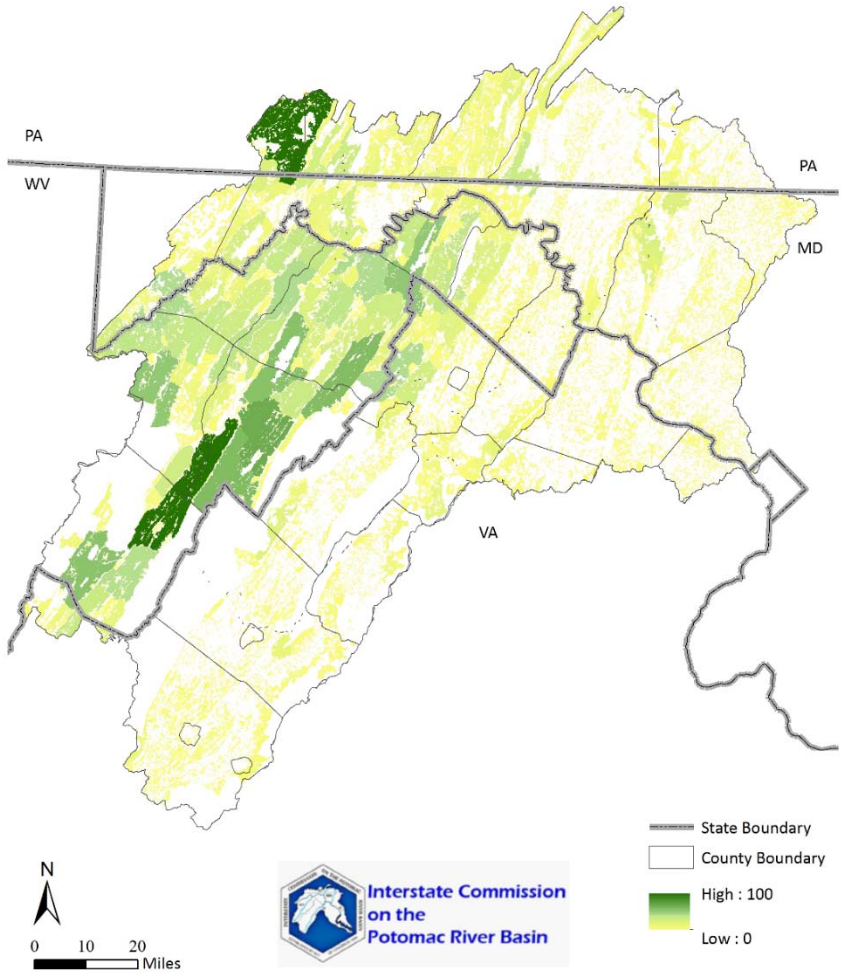


Figure 5.11 Normalized forest patch metric; higher values are higher priority

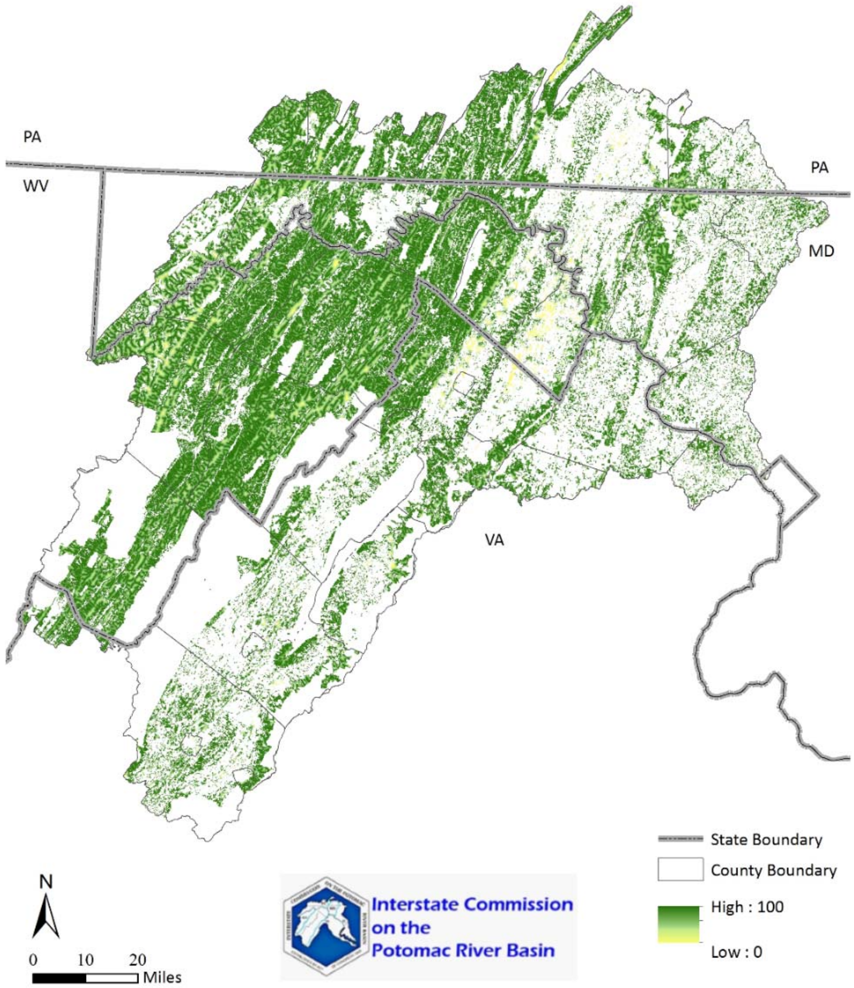


Figure 5.12 Normalized distance from stream metric; higher values are higher priority

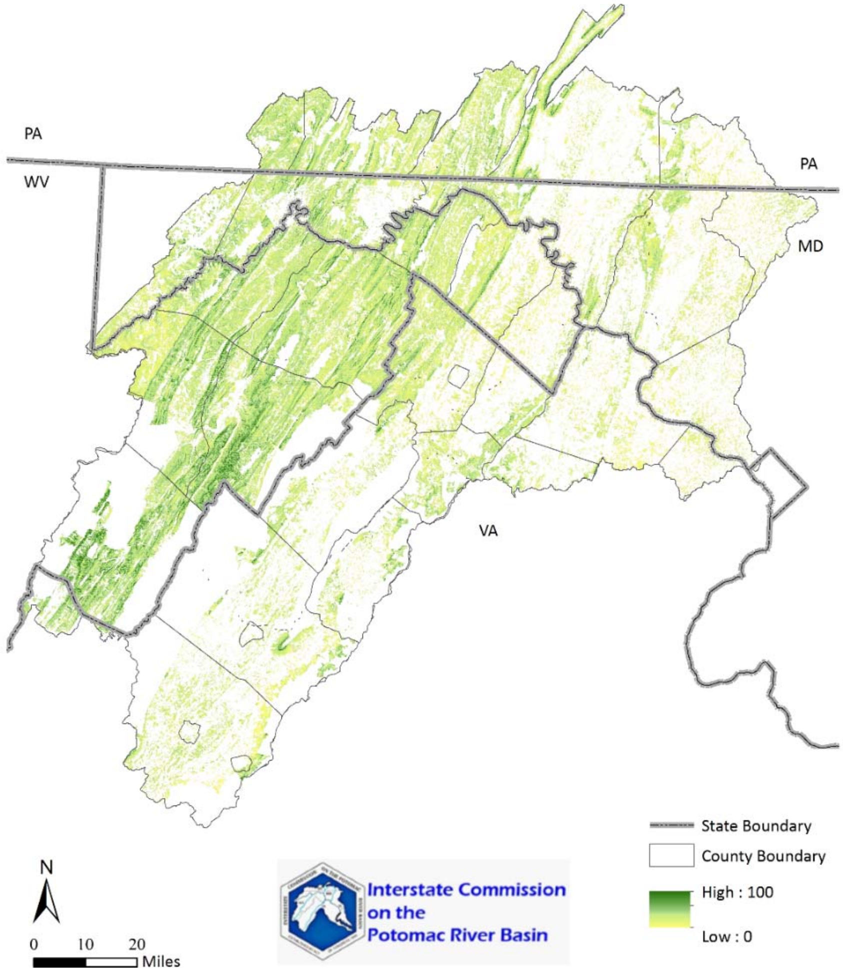


Figure 5.13 Normalized slope metric; higher values are higher priority

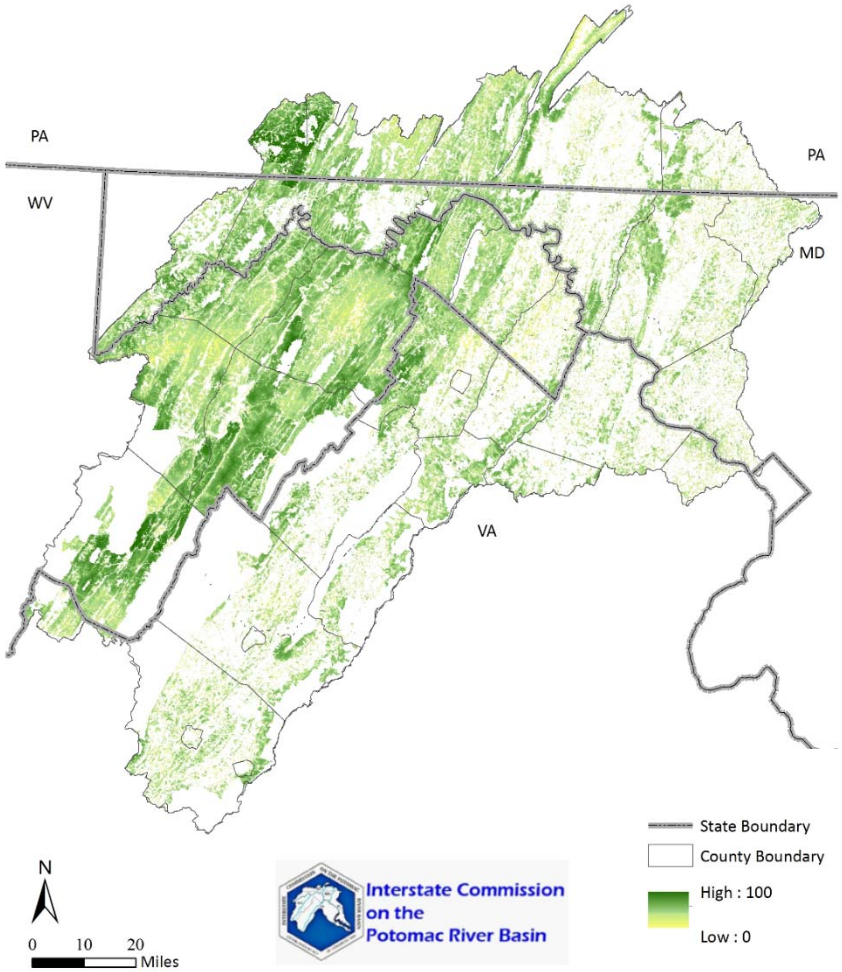


Figure 5.14 Normalized distance from census urbanized area; higher values are higher priority

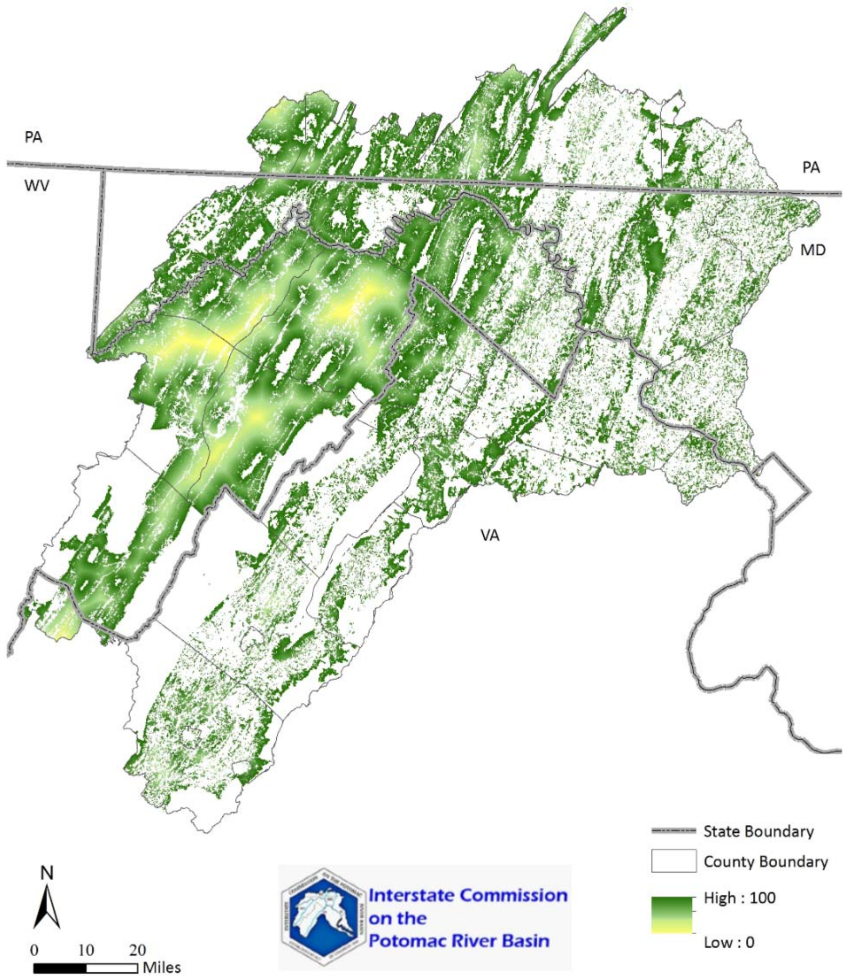


Figure 5.15 Normalized distance from protected forests; higher values are higher priority

Table 5.9 displays the correlation between metrics. The eight metrics are not strongly correlated and are, therefore, all included in the normalized cumulative prioritization (Figure 5.16).

Table 5.9
Metric correlation table

Metric	Forest type	Opportunity forest size	Distance from roads	Percent slope	Distance from intake	Dist. from protected forest	Distance from stream	Distance from urban places
Forest type	1	0.28	0.32	0.28	-0.07	-0.16	-0.07	-0.20
Opportunity forest size		1	0.24	0.30	-0.14	-0.37	-0.01	-0.35
Distance from roads			1	0.22	-0.06	-0.21	-0.09	-0.24
Percent slope				1	-0.04	-0.11	-0.01	-0.22
Distance from intake					1	0.11	-0.03	0.28
Distance from protected forest						1	0.02	0.27
Distance from stream							1	-0.01
Distance from urban places								1

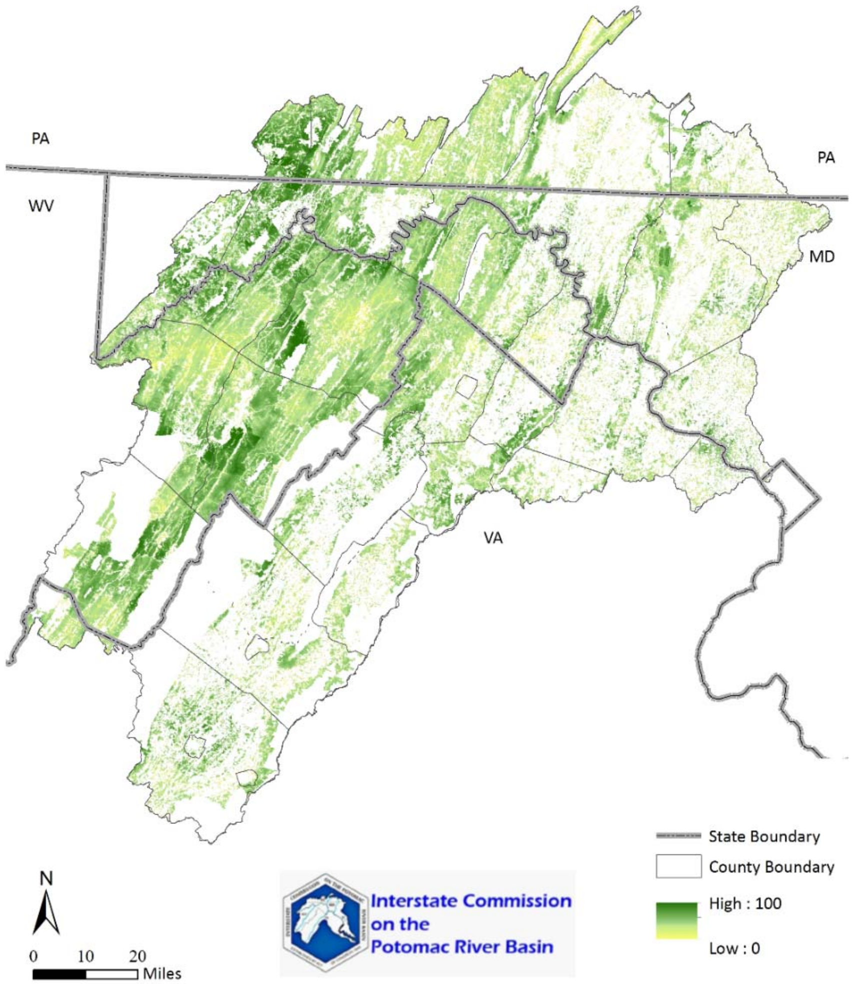


Figure 5.16 Normalized cumulative prioritization; higher value equals higher priority

The number of acres of forests and opportunity forests with normalized cumulative score greater than 80 are provided by state in Table 5.10.

Table 5.10
Number of acres of opportunity forests and opportunity forests with cumulative prioritization score greater than 80 by state

State	Total opportunity forest area (acres)	Normalized cumulative score >=80 (acres)
Maryland	456,751	3,873
Pennsylvania	413,752	7,981
Virginia	576,755	52
West Virginia	1,269,490	18,123
Total	2,716,748	30,029

FOREST PROTECTION PRIORITIZATION

There are numerous existing tools and literature resources that aim to geospatially identify and prioritize critical areas for protection. Although not all of them were developed specifically for forest protection, they all employ identification and prioritization techniques that may be applicable to forest protection efforts in the Potomac basin by incorporating forest-specific risk criteria (e.g., the Watershed Forest Management Information System, Zhang and Barten 2009 as described in Gartner et al. 2013).

Several available tools and resources pertinent to the Potomac basin and/or of specific applicability to this project are described in the sections below including the work of the Chesapeake Bay Program, the USDA Forest Service Forests to Faucets program, the Natural Capital Project, the Massachusetts Department of Conservation and Recreation (MA DCR) land acquisition program, and Global Forest Watch (GFW) Water. Forest protection work in the Potomac basin should build on and learn from these previous efforts, incorporating and adapting their strengths where possible.

Chesapeake Bay Program

The Chesapeake Bay Program, created in 1983, is a partnership of federal and state agencies, local governments, non-profit organizations, and academic institutions charged with leading efforts to reduce pollution and restore the Bay's ecosystem. Two CBP and partner projects may help illuminate opportunities for forest prioritization and protection in the Potomac basin; namely, the Healthy Watersheds Forest Retention Project and the CBP Resource Lands Assessment (RLA).

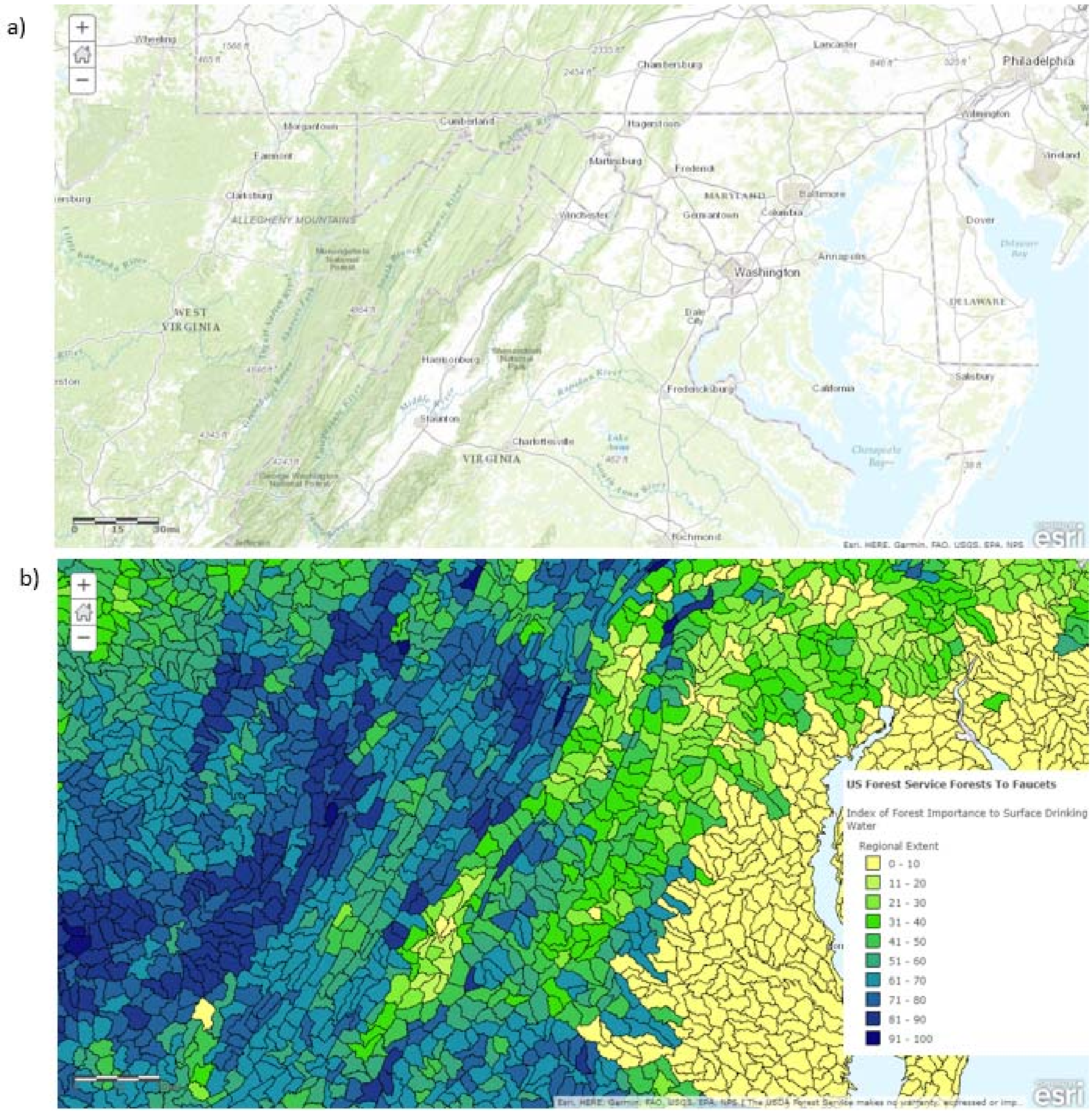
The Healthy Watersheds Forest Retention Project, whose project team consisted of staff from the Virginia Department of Forestry, the Rappahannock River Basin Commission, and the Pennsylvania Department of Conservation and Natural Resources, aimed to answer two questions. "Can we quantify the contribution of forestland in economic terms toward achieving Chesapeake Bay cleanup goals; and if the value is significant, what needs to be done to incentivize forestland retention so that contribution is maximized?" Through the research, it was determined that incentives could be found through forest conservation TMDL credits; stormwater management planning, regulations, and the Chesapeake Bay Program; use of dynamic TMDL models; tax programs; and nutrient trading/nutrient credit programs to name a few (Evans et al. 2017).

According to CBP (2018), the CBP RLA includes a watershed model that identifies those "forests and wetlands that, if lost, would have the greatest potential to compromise or degrade watershed and water quality." The approach used is similar to the one employed in this project. Parameters of interest were identified (e.g., erodible soils, proximity to water, slope) and assembled, scores were assigned to specific values within each data set, weights were given to each data set, and a composite score was calculated. The methodology resulted in a geospatial layer of prioritized areas. Users implement the results in combination with the results of other models in the RLA (i.e., ecological network hubs and corridors, forest economics, cultural assets, prime farmland, and vulnerability) as part of multi-state, state, regional, and local planning efforts.

USDA Forest Service Forests to Faucets

"The USDA Forest Service Forests to Faucets project uses GIS to model and map the continental United States land areas most important to surface drinking water, the role forests play in protecting these areas, and the extent to which these forests are threatened by development, insects and disease, and wildland fire" (USDA 2016b). One of the ultimate objectives of the work was to identify, or begin the process of identifying, watersheds where payment for watershed services may be a viable option for making conservation and management of forested lands economically possible. The methodology for the Forests to Faucets program is documented in Weidner and Todd (2011).

This effort resulted in a mapping tool and corresponding static maps based on a surface drinking water importance index and a forest importance to surface drinking water index for the United States. The mapping tool is available online (USDA 2018). The index of forest importance to surface drinking water for the Potomac region from the mapping tool is provided in Figure 5.17. Comprehensive research findings from the project are summarized in Mockrin et al. (2014).



Source: USDA n.d.

Figure 5.17 Geographic extent (a) of the index of forest importance to surface drinking water in the Potomac region (b)

An effort is underway to revise the initial products of the Forests to Faucets project. The original analyses will be enhanced in a number of ways including updating data layers, incorporating scenario-based interactive mapping, and improving development projections to name a few.

Natural Capital Project

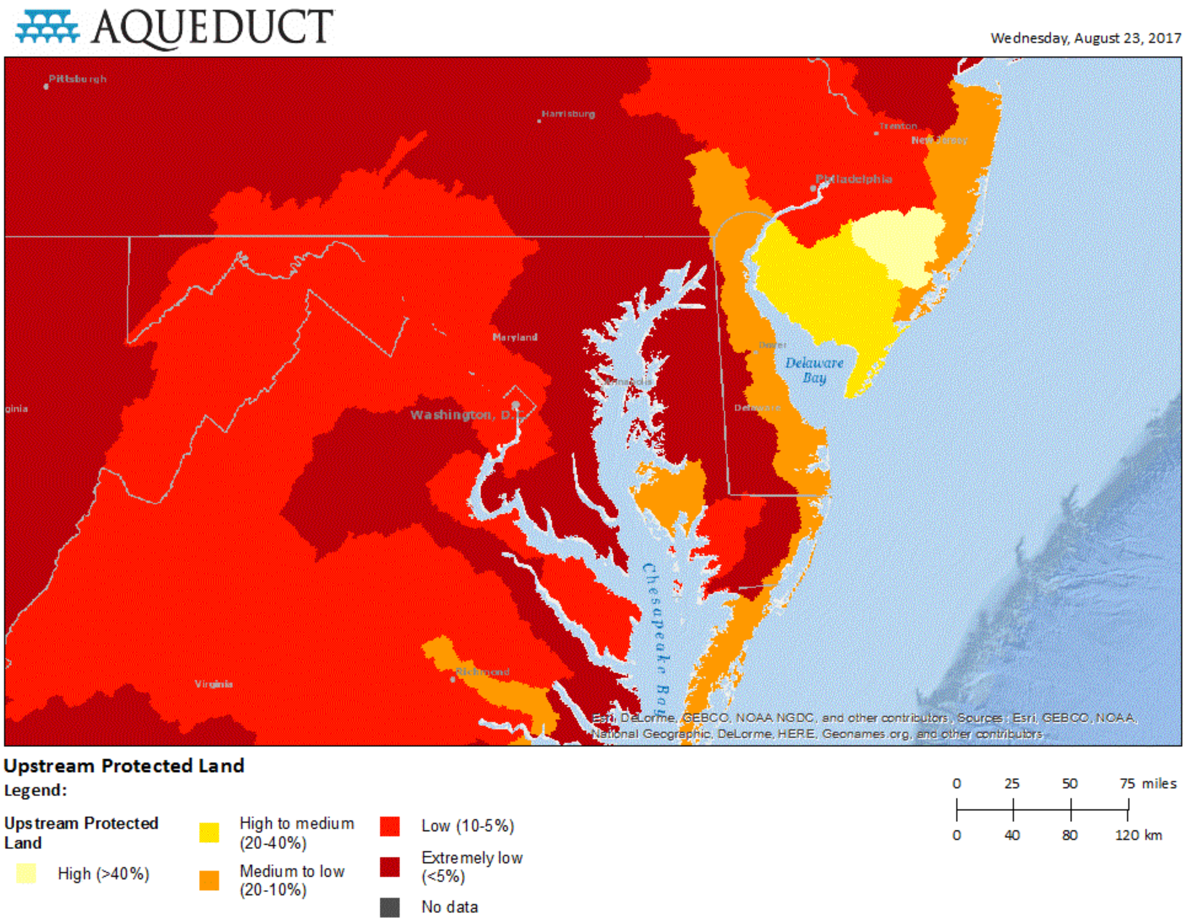
The Natural Capital Project, while not focused specifically on forest prioritization, utilizes an approach that may be helpful for forest prioritization in the Potomac basin. The Natural Capital Project has developed open-source software tools such as InVEST for use around the globe. They aim to bring natural capital into decision-making. InVEST, for example, "is a suite of free, open-source software models used to map and value the goods and services from nature that sustain and fulfill human life" (Sharp et al. 2016). According to its developers, "the multi-service, modular design of InVEST provides an effective tool for balancing the environmental and economic goals of these diverse entities."

Massachusetts DCR

The Massachusetts DCR acquires land as part of the water supply protection efforts. The land acquisition program utilizes a GIS-based prioritization model coupled with an interdisciplinary review team to identify and prioritize land parcels. Geospatial prioritization is conducted using metrics such as slope, zoning, aquifers, habitat protection, and threat from development. Between 1985 and 2013, nearly 100,000 acres were acquired through the program (MA DCR 2016; Zimmerman and French 2014).

Global Forest Watch Water

The GFW is marketed as "forest monitoring designed for action." Initiated by the World Resources Institute, the GFW brings together technology and diverse stakeholders to enhance forest-related information for decision-making and action (GFW 2018). The products of the GFW include a series of interactive maps. For example, as part of the AQUEDUCT Water Risk Atlas (WRI 2018), the Potomac basin is scored medium to high risk overall. One of the drivers for assignment of this risk category is the low to extremely low amount of upstream protected land (Figure 5.18). The metric used in the map below is a measure of "the percentage of total water supply that originates from protected ecosystems."



Source: WRI 2018.

Figure 5.18 AQUEDUCT Water Risk Atlas map of upstream protected land, screenshot of the Potomac basin region

IMPLEMENTATION COSTS

A utility's source water protection decisions are not made absent of information on implementation costs. Prices for purchasing land varies considerably based on specific locations and characteristics (Lynch and Palm 2007). Based on the research by Lynch and Palm (2007), the average statewide per-acre price for Maryland agricultural and forested lands was $4,512. In the absence of state-specific research for other states in the study area, this average cost was applied to forests with a normalized cumulative score greater than 80 (Table 5.11). The total estimated cost of purchasing these lands would be approximately $135.5 million.

Table 5.11
Cost of conserving forest lands with a normalized cumulative score greater than 80

State	Normalized Cumulative Score >=80 (Acres)	Cost ($USD)
Maryland	3,873	17,474,525
Pennsylvania	7,981	36,009,821
Virginia	52	234,624
West Virginia	18,123	81,770,074
Total	30,029	135,489,043

Establishing easements or encouraging other types of conservation activities can be much more cost effective than purchasing forested lands, but it is difficult to estimate actual cost savings (Lynch and Palm 2007), especially across a large and diverse study area such as this. One existing tool that could help with estimating BMP costs is the Chesapeake Assessment Scenario Tool. Table 5.12 shows the default costs for the Watershed Model BMPs (Devereux and Rigelman 2016).

Table 5.12
Cost of installing, operating, and maintaining agricultural and urban forest buffers

BMP	Lifespan (Years)	Capital Cost ($USD/acre)	O&M ($USD/acre/year)
Agricultural forest buffers	75	1738.2	156
Urban forest buffers	75	1790.67	0

Source: Data from Devereux and Rigelman 2016

CHAPTER 6
RISK MITIGATION

In addition to implementation costs utilities may consider factors that are more difficult to evaluate economically. These could include reducing the risk (and costs) associated with impacts from fire, climate change, pests, population growth (urbanization), and land use and drinking water regulations. Each of these is discussed in the sections below.

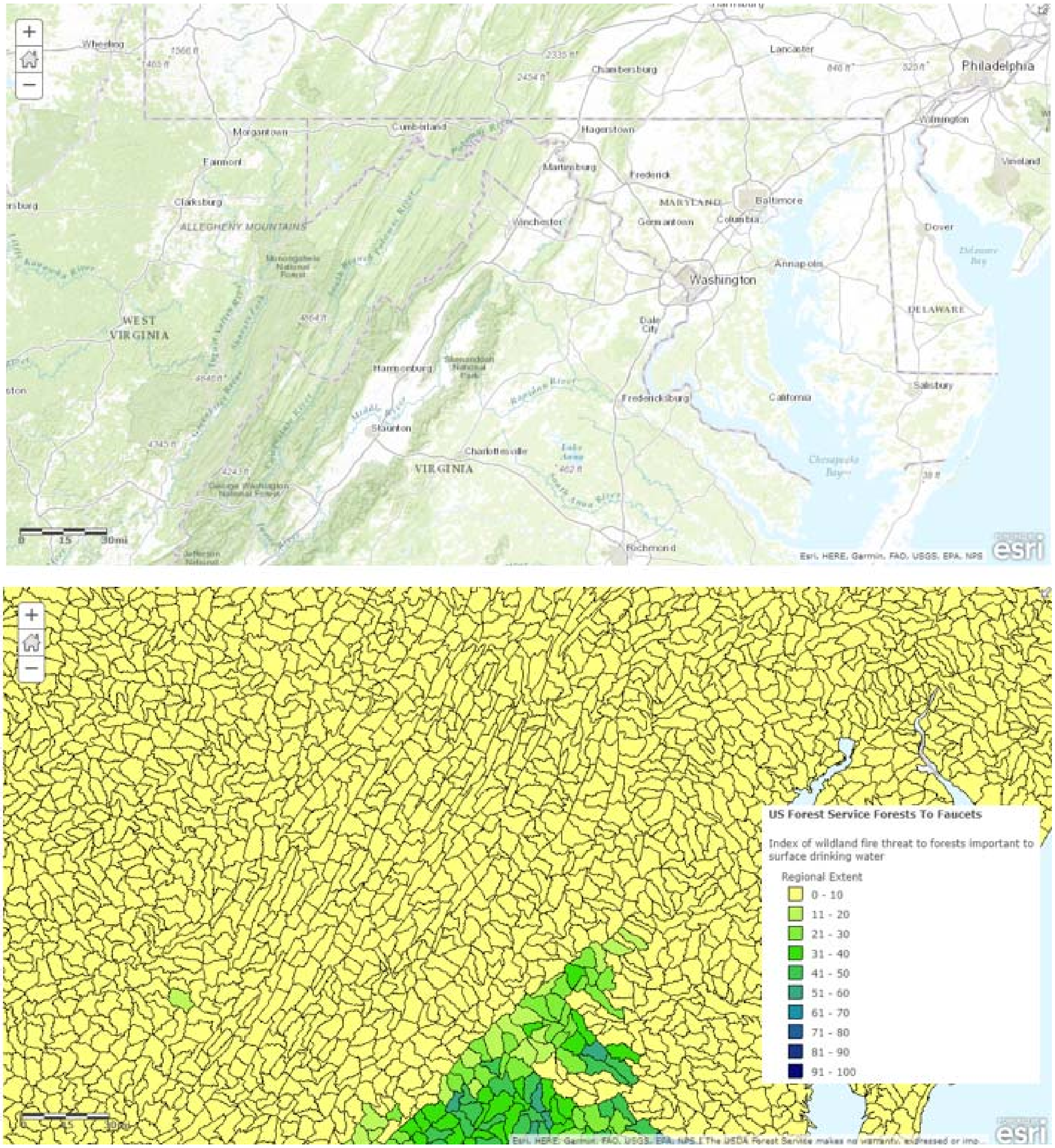
Risks to the forests in the Potomac basin, especially in the face of population growth, are described in each state's Forest Action Plan (National Association of State Foresters 2018a). Common risks to all states include pests, disease, and wildfires. In addition, Virginia and Maryland plans also prioritize threats from climate change. A holistic approach to proactive manage forests in the face of these risks is recommended as part of a number of forest-climate change reports (e.g., FAO 2010).

FIRE

Figure 6.1 shows the index of wildland fire threat to forests important to surface drinking water from the Forests to Faucets online mapping tool, discussed in Chapter 5. Although the overall risk may be low in the Potomac basin, forest fires and associated negative impacts do occur. A historic and a more recent event illustrate the point. The West Virginia Division of Forestry was established as a result of the 1908 fire season that burned more than 1.7 million acres. The agency now responds to hundreds of wildfires each year that burn 20,000 to 30,000 acres of forest (National Association of State Foresters 2018b). More recently, the Potomac basin was in the midst of a considerable drought in the year 2002. The effects of the drought included serious threats of wildfire (ICPRB 2002).

When wildfires occur, they can affect water quality and quantity to downstream drinking water supplies (e.g., increased sediment, increased peak flows – Gartner et al. 2013). Forest protection and management have been identified as the most economic methods of surface drinking water protection in some watersheds, to reduce the likelihood of fires and associated negative impacts to water supplies (Schmidt and Batker 2012).

a)
b)



Source: USDA n.d.

Figure 6.1 Geographic extent (a) of the index of wildland fire threat to forests important to surface drinking water in the Potomac region (b)

CLIMATE CHANGE

The uncertainty associated with the potential effects of climate change on forests necessitates adaptive, flexible approaches to forest management (Millar et al. 2007). In recognition of the importance of proactive forest management as related to climate change, Potomac basin states have developed numerous forest-related climate change plans. Some of these plans are discussed in the paragraphs below.

Maryland developed a climate change strategy that includes expanding and retaining forests (MD DNR 2008). The state Commission on Climate change highlights increased risks to forests (e.g., forest fires) as well as positive impacts of proactive forest as a result of climate change (ARWG 2016).

The 2015 Pennsylvania climate impacts assessment update includes a discussion of forest management opportunities related to climate change (Shortle et al. 2015). Specifically, they expect increased tree growth rates, longer growing seasons, and increased precipitation. They also expect that forest composition may change, especially for tree species whose southern extent is found in Pennsylvania. Pennsylvania Department of Conservation and Natural Resources identified impacts of climate change to forests and developed a strategic approach to climate change related to forests (PA DCNR 2015).

Virginia Department of Forestry identifies four ways to enhance the positive role of forests in climate change: conserving forest land, afforestation and reforestation, forest management, and as biofuels (VDOF 2017).

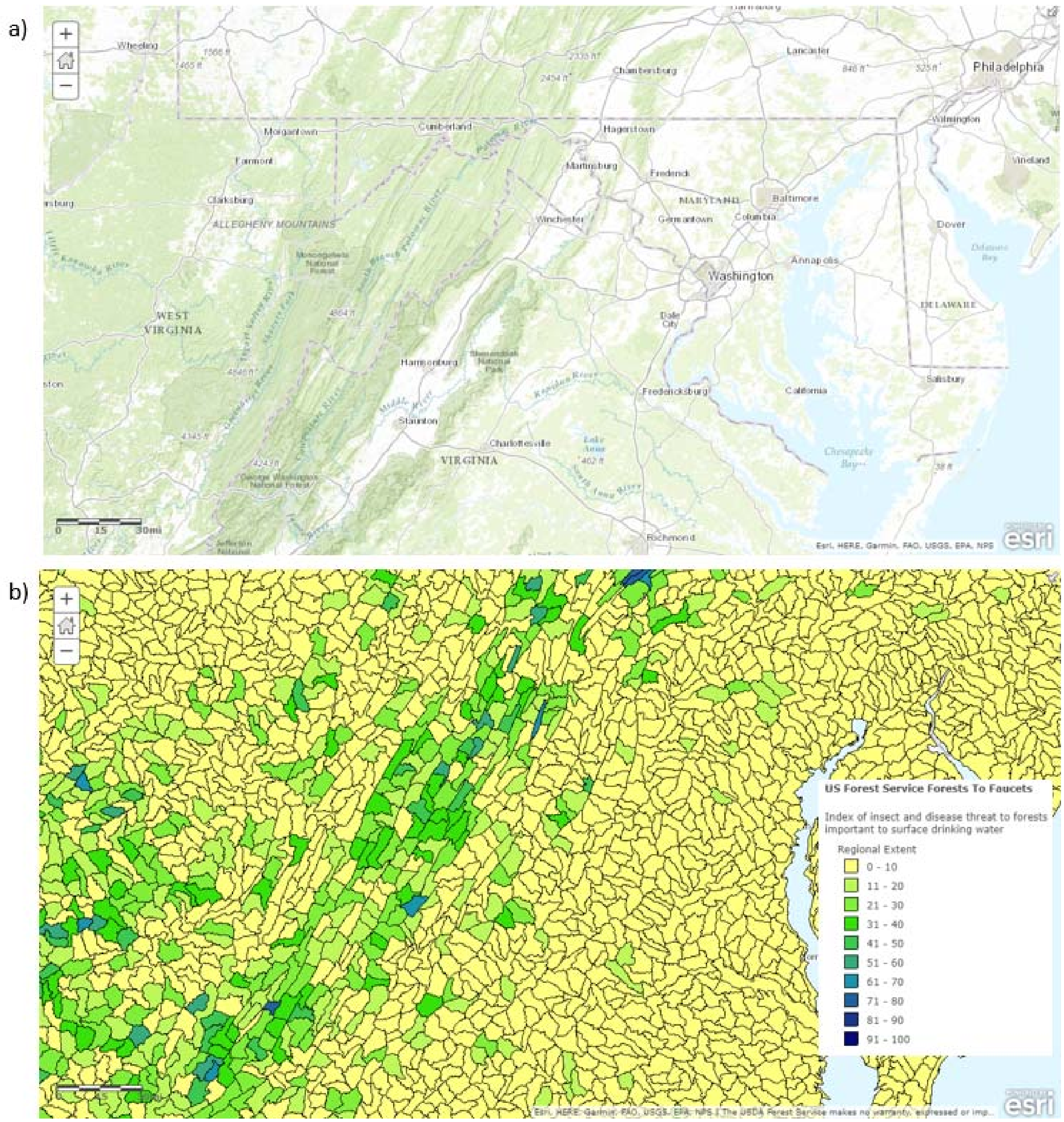
In West Virginia, a heavily forested state, change in forest composition is a primary concern related to changing precipitation and temperature regimes (EPA 2016a); however, if the climate becomes drier, forests could transition to grasslands and pasture (EPA 1998).

> "Climate change and forests are intrinsically linked: climate change is a threat to forests, and protecting forests from conversion and degradation helps mitigate the impacts of climate change."
>
> Van Bodegom et al. 2009

> "The ability of forests to reduce peak storm flows, maintain snowpack, and filter sediment, nutrients, and other pollutants is an essential 'first line of defense' against the extreme events expected to increase in frequency and intensity as the climate changes."
>
> James Mulligan, Green Community Ventures from Gartner et al. 2013

PESTS

Pests, like wildfires, can increase in-stream sediments that downstream drinking water utilities subsequently need to treat (Gartner et al. 2013). Figure 6.2 shows the index of insect and disease threat to forests important to surface drinking water from the Forests to Faucets online mapping tool, Chapter 5. Pests found in the region include the Southern Pine Beetle and the Emerald Ash Borer (National Association of State Foresters 2018c).



Source: USDA n.d.

Figure 6.2 Geographic extent (a) of the index of insect and disease threat to forests important to surface drinking water in the Potomac region (b)

POPULATION GROWTH/URBANIZATION

Maintaining and increasing forest cover has an added benefit of minimizing increases in anthropogenic sources of other pollutants like chloride and bromide (CASE 2015 and McTigue et al. 2014). These pollutants are difficult and expensive to remove from drinking water supplies and are more effectively and economically addressed through source water protection activities.

Further exploration of the economic benefits of source water protection for reduction of these pollutants is of considerable interest, given the costly infrastructure requirements (and associated capital costs) needed to treat them.

LAND USE AND DRINKING WATER REGULATIONS

Water utilities may be interested in source water protection activities to avoid regulation and/or additional regulatory compliance requirements (Gartner et al. 2013). This raises the question, is there a need for source water protection in the Potomac basin that is driven by regulation?

CHAPTER 7
CONCLUSIONS FOR SOURCE WATER PROTECTION

This study endeavored to enhance the understanding of the implications of forest protection and forest buffer for drinking water treatment costs at three treatment plants in the Potomac River basin. The study also examined whether these activities would prevent concentrations of algae, bromides, THM, and other contaminants from exceeding thresholds that might trigger significant capital costs. The analysis was undertaken utilizing a readily available modeling tool[9] in conjunction with observed water quality and treatment-dose data from three utilities in the Washington, D.C., metro region. Although the specific relationships found may not hold true in other watersheds with hydro-geographic, land use, or treatment characteristics different from the Potomac River basin, the research methods used in this study can provide a blueprint for others looking to understand potential economic incentives for source water protection by water utilities.

DISCUSSION OF FINDINGS

The major methodological elements of this study were (1) a model of projected land-use change in the Potomac River basin through 2030; (2) a watershed model capable of predicting daily concentrations of nutrients, TOC, and sediment in Potomac River and other major rivers in the basin; (3) regression models relating simulated concentrations in the Potomac River to concentrations at the water utilities' intakes; and (4) regression models relating dosages of treatment chemicals to intake water quality. Using this modeling framework, savings in treatment costs were estimated in comparison to 2030 baseline conditions for two scenarios for forest preservation and two scenarios for forest buffer implementation. The largest reductions in estimated average concentrations under the forest preservation and forest buffer scenarios were only 2.4 percent for turbidity and 3.1 percent for TOC. Water quality changes of this magnitude are not expected to change drinking water utility treatment operations. In fact, the largest reductions in treatment chemical doses across all chemicals and utilities under the forest preservation and forest buffer scenarios were estimated to be only 1.6 percent. Uncertainties driven by the elements in the modeling framework, predicted river concentrations from the watershed model, and the regression relationships used to calculate concentrations at the intakes and the dosages of chemicals to treat them are at least comparable in size to the predicted reductions in treatment costs, if not larger.

The magnitude of the effects of forest preservation or buffer implementation on treatment costs can be put in context by the following highly idealized examples. Assume, for the sake of argument, that forests make a negligible contribution to contaminant loads and that forests are converted to a relatively constant mixture of other land uses (i.e., 10 percent crops, 30 percent pasture, and 60 percent developed land). In a watershed that was 99 percent forest, the loss of one percent of forested land could result in double the contaminants and the treatment cost, while in a watershed that was ten percent forest, conserving ten percent of the forest (one percent of the overall land) would result in only about one percent savings in treatment costs. These simplified examples illustrate that the marginal benefits of forest preservation may depend on the amount of

[9] This study utilized the Chesapeake Bay Program's HSPF Watershed Model (EPA 2010). HSPF is a readily available model that can be applied in other watersheds through software such as EPA's BASINS (Better Assessment Science Integrating point and Non-point Sources).

forest cover in the watershed. The watershed above the intakes for this study is approximately 50 percent forest and the maximum percent change in forest acreage in the scenarios is approximately two percent. Using the same simplifying assumptions, the maximum estimated reduction in treatment chemical costs is about 5 percent. The findings of this study indicate that the ratio of percent change in treatment cost to the percent change in forest land for this water system is approximately 1:2. That is, for every two percent of forest land conserved or forest buffer acres installed, an approximately one percent reduction in annual treatment chemical costs is predicted. This ratio holds for both forest preservation scenarios and buffer implementation scenarios. The effect of substantial amounts of existing forest cover in this study may be further demonstrated in the finding that all scenarios result in approximately one dollar per acre per year of cost savings on selected treatment chemicals. The expected cost to protect the land exceeds this potential cost savings.

Further, the relatively low magnitude of changes in nutrients and sediments in the scenarios are unlikely to trigger capital improvements. Constituents that cannot readily be treated with existing systems (e.g., chloride, bromide, perchlorate, pharmaceuticals and personal care products [PPCPs]) may provide financial drivers for source water protection activities, but were outside of the scope of this existing study. Further exploration of the capital costs associated with increases in these constituents when forests are lost may bolster the economic case for utility-driven forest protection efforts.

It is important, therefore, not to draw the general conclusion from this study that it is not cost-effective for water utilities to fund forest conservation or the installation of forest buffers. As indicated above, the effectiveness of forest preservation may be a function of how much forest there is to preserve: the more forested the watershed, the more cost-effective it is to preserve forests. The value of forest preservation, restoration, or forest buffers to a water utility should be determined on the basis of the specific characteristics of the watershed and the specific features of the treatment processes and their tolerance for risk.

Other limitations of this study should also be taken into account before drawing general conclusions about the benefits of source water protection. Watersheds in the vicinity of intakes may make have a greater impact on water quality at the intakes than more distant watersheds, and correspondingly, forest conservation or forest buffers may be more cost-effective in nearby watersheds. The watershed model used in this study simulates the Potomac River in the vicinity of the intakes as well-mixed laterally, longitudinally, and vertically. It is unable to determine, therefore, whether a nearby watershed is having a disproportionate effect on intake water quality, and therefore cannot capture the additional benefits from localized forest conservation and buffer installations.

The economic component of this project focused narrowly on specific treatment chemicals. The actual costs and benefits to utilities are much broader. These may include cost and benefits that are difficult to quantify such as reduction in the risks from spills, public confidence, ecological protections, or goodwill from recreational users of forests or rivers and streams with forest buffers. There may also be effects on treatment costs not considered here including power consumption, filter life and operations, and other operation and maintenance costs.

In this study, the most aggressive forest protection scenario addressed only two percent of the forest land. In large basins such as the Potomac, opportunities for forest protection may be small due to existing protection efforts, land ownership, urbanization, or other factors. The 2030 planning horizon also limited the amount of forest land available for protection. Extending the planning horizon may provide additional conservation opportunities.

Finally, source water protection is a much broader effort than forest conservation or the installation of forest buffers alone. BMPs on agricultural and developed land also can reduce treatment costs and in watersheds already heavily impacted by these land uses, may be as cost-effective, if not more, than forest conservation and forest buffers. This is an important consideration in the Potomac basin. The Potomac River, as a major tributary to the Chesapeake Bay, is subject to the Chesapeake Bay Total Maximum Daily Loads (TMDLs) for nitrogen, phosphorus, and sediment, and there is a major ongoing effort to reduce nutrients and sediment in the basin, which has the possibility of improving water quality at the water utilities' intakes. Conversely, source protection efforts undertaken by water utilities can have water quality benefits not captured by treatment costs or other costs borne by the utilities, such as aesthetic qualities that go beyond regulatory requirements. These benefits indirectly accrue to utility customers through improvements in water quality and could also be considered in source water protection efforts.

RECOMMENDATIONS

The results of this study indicate that reducing water treatment chemical costs by themselves may not be a sufficient driver for forest protection or installation of forest buffers. This conclusion would seem to be true for the NCR water utilities, at least over the scale and time frame examined in this study. It would be wrong, however, to conclude it is never true for any water utility: one recommendation from this study is to resist generalizations.

There are multiple reasons for conserving forests or installing forest buffers, some of which may stem from other interests of the utilities, such as conserving forests in sensitive areas where development would make the likelihood of runoff from a transportation corridor or industrial activity more likely and thus increase the risk of spills threatening the water supply. There are also reasons which do not directly concern water supply. Forest conservation may be required to preserve local water quality. Forest buffers may result from nutrient trading to reduce the amount of retrofitting in ultra-urban areas necessary to restore water quality in Chesapeake Bay. Therefore, even if reduction of treatment costs or source water protection is not by itself sufficient to justify forest preservation, it may be one element among others to provide adequate justification.

In a river basin as large as the Potomac with multiple uses and multiple interests, subject to nutrient and sediment management for the restoration of Chesapeake Bay, yet still expected to grow in population, source water protection is by necessity a collaborative process. The approach to source water protection in the Potomac basin includes the need for continued dialogue with the numerous stakeholders and upstream and downstream interests. By working together, common ground can be identified and strategies for moving forward can be developed. One such collaborative effort in the basin is the Potomac Drinking Water Source Protection Partnership (DWSPP). As an open forum for continued dialogue between utilities, state agencies, and other partners, participation in this effort will continue to encourage identification of opportunities for mutual benefit. Future research opportunities, discussed below, may provide additional information to the recommended collaborative effort.

Future Research

Several questions were raised during the course of this project that could be addressed through future research efforts. The pursuit of any particular option depends on utility interest and the availability of funding. Suggested research topics are listed below in no particular order.

- The Source Water Assessment for WSSC's Potomac Water Filtration Plant has results from several studies on the influence of the Watts Branch, a small tributary to the Potomac, on water quality at the intake. These results could be used to determine whether there are additional benefits from targeting forest preservation or forest buffer installation in watersheds near intakes.
- The Chesapeake Bay Program (CBP) is currently finalizing a new version of its Watershed Model (Phase 6), which will be used to revise implementation plans for meeting the goal of full implementation of the Chesapeake Bay TMDLs by 2025, and planning is already underway to develop the next generation of models for use after 2025. A revised land-change model is also part of these efforts, which will extend the planning horizon beyond 2030. The revised models and the resulting implementation plans could be used to quantify benefits to the utilities from the whole spectrum of forest, agricultural, and urban BMPs which are planned to be implemented in the Potomac River basin. The cost-effectiveness of BMPs for source water protection could also be analyzed.
- The revised CBP Watershed Model could be adapted to simulate other contaminants, such as pathogens. (This was done at a coarse scale for the District of Columbia Source Water Assessment using the Phase 4 version of the CBP Watershed Model.) Sources of pathogens, like cattle, also tend to be sources or nutrients, and nutrient and sediment BMPs also act as pathogen controls, so there is a lot of overlap in the simulation of nutrients and pathogens. Other possible contaminants which could be simulated include the different types and sources of organic material which serve as precursors to DBPs.
- The utilities have already expressed an interest in simulating chloride. There is significant interest in looking at the impact of road salts on the capital improvement program for water main replacement. Since treatment is not feasible, source water protection may be the best way to control the problem. ICPRB has developed a chloride model for a small watershed. The major difficulties to developing a chloride model for the entire Potomac River basin are (1) the lack of credible data on the application rates of chloride to roads, parking lots, and sidewalks; and (2) the lack of sufficient instream chloride and conductivity monitoring to calibrate the model on the basin scale. Addressing these two data needs could be the first steps in a long-term research project to develop a predictive model for chloride at the water utilities' intakes. It is quite possible the major sources of chloride are all within the Washington metropolitan area, so that simulating the entire basin would not be necessary, if monitoring provided a sufficient representation of the chloride inputs above, Point of Rocks, for example.

FINAL THOUGHTS

Considerable research has been conducted to evaluate the economic benefits of source water protection for drinking water utilities. This project built on the existing foundation to understand the economic implications of forest protection for three large utilities whose intakes are located on the Potomac River, a large basin in the Mid-Atlantic region of the United States. The analyses benefited from the existence of a widely accepted, community developed hydrologic model and large amounts of observed data from each utility. The methodology used in this study may serve as a template for others seeking to evaluate economic implications of source water protection activities. The results of this project will also inform Potomac-specific decision-making and will enhance local source water protection collaborations.

APPENDIX A
CALIBRATION OF THE SIMULATION OF TOTAL ORGANIC CARBON IN THE PHASE 5 WATERSHED MODEL REPRESENTATION OF THE POTOMAC RIVER BASIN

The Chesapeake Bay Program (CBP) Phase 5 (P5) Watershed Model (referred to as P5 or Watershed Model in this appendix) was used to model Total Organic Carbon (TOC), sediment, nitrogen, and phosphorus loads for each land cover scenario at a location on the mainstem Potomac just upstream of the utilities' intakes. As is, the P5 Watershed Model simulates TOC, although the simulation had not previously been calibrated. In order for P5 to generate TOC loads and concentrations under alternative land use scenarios, the P5 simulation of TOC had to be calibrated for the Potomac River basin.

This appendix describes the steps taken to calibrate the TOC simulation for the Potomac River basin. It begins with a brief description of the feature of P5 necessary to understand the tasks required to calibrate the model, and the state of the TOC simulation prior to undertaking those tasks. The tasks performed under this project to calibrate the TOC simulation are then reviewed. Four tasks are described in detail: (1) the incorporation of wetlands into P5; (2) the use of the U.S. Geological Survey (USGS) statistical regression software, LOADEST, to calibrate TOC regional factors; (3) modifications made to the P5 code to calibrate the TOC using P5's automated calibration procedures; (4) the calibration of the TOC simulation in the Potomac River basin.

The appendix ends with a brief discussion of the results of the TOC calibration. The simulated concentrations from P5 were subsequently used to develop estimates of required chemical doses under the scenarios as part of the water quality-treatment dose relationships described in Chapter 3.

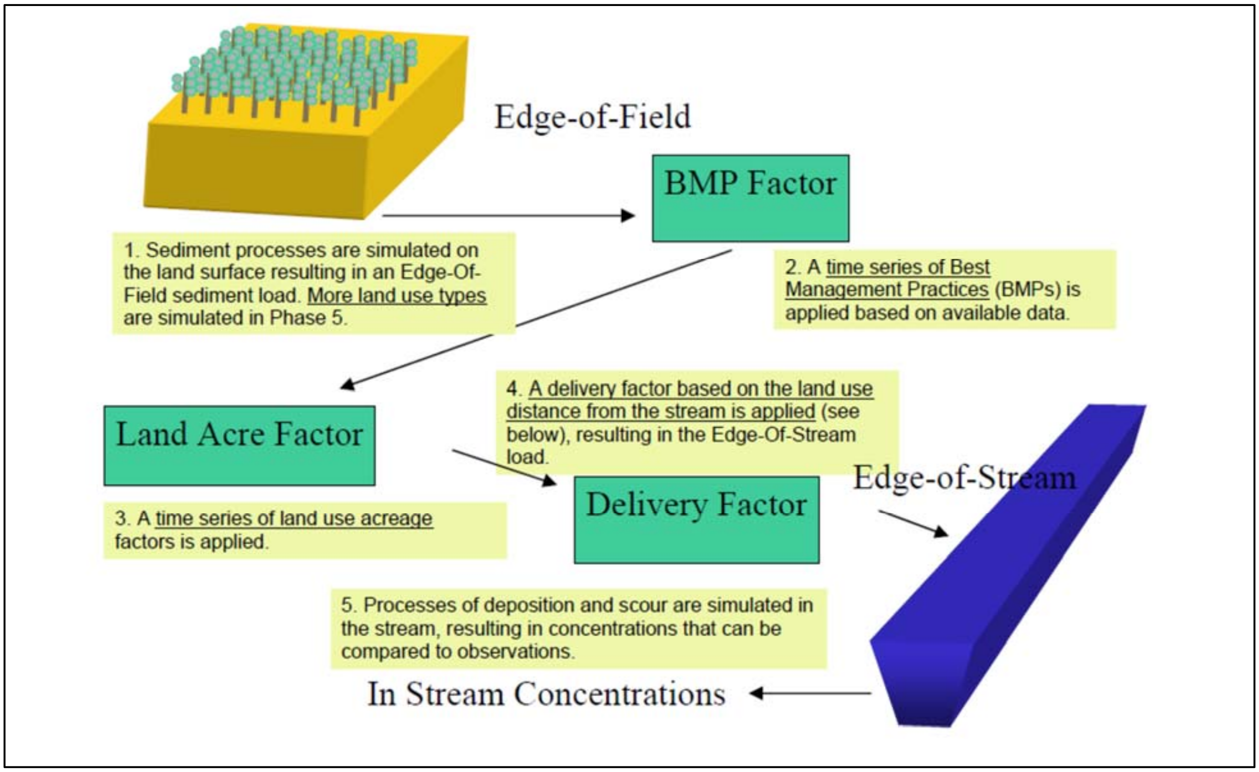
P5 BACKGROUND AND TERMINOLOGY

Chapter 2 of the main report discussed how in P5 land processes like runoff, infiltration, groundwater discharge, or erosion from the land surface, are simulated by land use on per acre basis, while river processes, such as river routing, scour and deposition, and eutrophication, are simulated in river reaches. Within a given land segment, all the acreage of a land use is simulated the same way. Land-river segments (LRS) define which areas of a land segment drain to a river segment.

This section discusses the relationship between land simulation and the river simulation in more detail. Figure A.1 is an illustration of the sediment processes simulated in P5. (1) For each land use in a land segment, P5 simulates the sediment transported in runoff from erosion. This simulation is calibrated to an edge-of-field export target. For sediment, the export targets are primarily derived from information collected by the Natural Resources Inventory (Nusser and Goebel 1997). (2) Best Management Practices (BMPs) may be applied to reduce erosion or to trap erosion leaving field. BMPs are represented in P5 either as a reduction rate applied to loads or as a fixed amount of load reduced. (3) The per acre load for each land use in a land segment is multiplied by its land use acreage in the LRS. (4) Not all of the sediment lost from a field is transported to the river; some of it is deposited on hillslopes or in streams at scales smaller than P5 river reaches. P5 used a formula to calculate the delivery factor, also called the sediment delivery ratio (SDR), based on the area of the average subwatershed in the LRS:

$$SDR = 0.417762 * A^{-0.134958} - 0.127097$$

where A is the drainage area in square miles (USDA, 1983).



Source: EPA 2010.

Figure A.1 Schematic of sediment simulation in the Phase 5 Watershed Model

The edge-of-stream (EOS) load is the load that is estimated to actually enter the simulated P5 river reach. The EOS load for a particular land use is the land simulation load multiplied by the number of acres of the land use in the watershed; the reductions from BMPs; and delivery factor.[10] Finally, in the river simulation (5), the EOS load is added to any loads from upstream river reaches or point sources discharging directly into the reach, and is subject to deposition and scour, or transport to reaches downstream.

The simulation of nitrogen and phosphorus is similar to the simulation of sediment. Of course different processes are at work, both on land and in the river, but schematically, there are two major differences between the simulation of nutrients and sediment. First, the starting points for land simulation targets for nutrient export are the median values reported in the scientific literature. These generally represent export rates determined for small homogeneous watersheds.

[10] The main way P5 differs from ordinary HSFP models is that each land use in a land segment and each river segment is simulated individually. The P5 modeling framework takes the output from the land simulations, together with information on land use acreage, BMPs, delivery factors, point sources, and upstream river simulations, and prepares the inputs for each individual river simulation. This enables P5 to more easily simulate changes in land use or BMP implementation over time.

Table A.1 gives the median literature values of nutrient export used in P5. The export rate target specific to a land use in a particular land segment is modified by the relative rate at which nutrients are applied on the land use in that land segment. The nitrogen export rate target for forest in a particular land segment, for example, is based on adjusting the median forest export by the rate of nitrogen applied to forest in that land segment, relative to the forest application rate in other land segments.

Table A.1
Median total phosphorus and total nitrogen export rates (lbs/ac/yr) from P5 literature survey

Land use	Phosphorus export rate	Nitrogen export rate
Alfalfa	0.7	5.5
High till crop without manure	2.5	23
High till crop with manure	2	23
Hay without nutrients	0.4	4
Hay with nutrients	0.8	6
Low till crop with manure	2	23
Pasture	0.7	4.5

Second, nutrient export from land segments is modified by delivery factors called "regional factors." The calculation of regional factors for nitrogen and phosphorus are generally based on improving agreement between average annual P5 loads and empirical estimates of nutrient loads calculated with the USGS regression software ESTIMATOR at the River Input Monitoring (RIM) stations at head of tide and at other major calibration points. If, for example, average annual P5 total nitrogen loads on the North Fork of the Shenandoah at Strasburg, Virginia, are smaller than the average annual loads calculated with ESTIMATOR, regional factors in the watersheds upstream of Strasburg are increased, increasing the EOS nitrogen loads to try to obtain between agreement between loads from the P5 river simulation and the ESTIMATOR nitrogen loads. In calculating regional factors, more weight is given to RIM stations, such as Chain Bridge on the Potomac River, than stations upstream.

The U.S. Environmental Protection Agency (EPA) (2010) provides documentation of P5. Nutrient inputs are discussed in Section 5, estimates of BMP effectiveness are discussed in Section 6, and regional factors are discussed in Sections 10 and 11 of the documentation. Brosch (2010) has a detailed discussion of nutrient inputs and BMP effectiveness used in P5.

STATE OF THE TOC SIMULATION IN P5

Early in P5 development, it was intended that TOC should be fully simulated and calibrated. The TOC simulation is fully functional in P5. Observed in-stream TOC concentration data was collected for the calibration of the river simulation. Somewhere in the development process, however, the calibration of TOC P5 was dropped, so TOC is not a calibrated parameter, though the statistics comparing observed and simulated TOC are calculated and reported.

In the river simulation, TOC is calculated as the sum of refractory organic carbon (ROC) and the carbon component of biochemical oxygen demand (BOD). Both ROC and BOD are state variables in the river simulation. ROC and BOD are not state variables in the land simulation, however. Land-based ROC loads are based on the load of refractory organic nitrogen (RON). Globally (for all land uses in all land segments) the mass ratio of ROC to RON is set to 17. BOD loads are based on labile organic nitrogen (LON) loads, with a conversion factor of 22.95 (in oxygen units). BOD loads are explicitly represented for point sources, which are simulated as direct discharges to river reaches. The point source BOD loads are based on monthly discharge monitoring data reported by the dischargers. Point source ROC loads are again based on RON loads, using the mass ratio of about 5.7:1.

Currently, the average of the nitrogen and phosphorus regional factors is used in calculating TOC EOS loads. In the Potomac River basin, TOC regional factors range from approximately 1.5 to 2. A similar approach (averaging total nitrogen and total phosphorus reductions) is used to estimate BMP reductions for BOD and ROC.

TOC export rates are a function of the simulated RON and LOC loads. The average EOS loading rate for forest in the Potomac River basin is about 40 lbs/ac/yr. EOS TOC loading rates (pound per acre) for forest in P5 are low, but not the lowest among land uses. Hay without nutrients and alfalfa have slightly lower EOS loads on a per acre basis, because about 50% of the nitrogen export from forest is organic (LON or ORN) while only 15% of the nitrogen exported from hay or alfalfa is organic. TOC EOS loading from pasture and hay with nutrients are comparable to forest loading rates, while loading rates from crops, pervious developed land, and impervious land are roughly eight times, three times, and five times, respectively, the forest rate. These relative rates include the impact of BMPs.

TASKS REQUIRED TO CALIBRATE THE TOC SIMULATION IN P5

The following tasks were considered to be required to calibrate the TOC simulation in P5 in the same manner as sediment and nutrients:

1. Assemble any additional existing in-stream monitoring data
2. Solicit and analyze TOC monitoring data from point sources and MS4s
3. Literature survey of estimates of land use export coefficients
4. Use LOADEST to calculate average annual TOC loads and set TOC-specific regional factors
5. Revise P5 code to calibrate TOC
6. Calibrate TOC simulation

When this project began, it was unclear whether CBP had stopped collecting the monitoring data and point source data necessary to simulate TOC when they stopped attempting to calibrate the TOC simulation. Upon investigation, it turned out that all the available monitoring data and point source information for the 1985-2005 calibration period had been used in P5. No monitoring data with TOC observations were collected by MS4s in the Potomac River watershed. The only additional data used in this project was provided by the water utilities and used in Chapters 2, 3, and 4.

As discussed above, literature surveys of land use nitrogen and phosphorus export rates were used to set the export targets for land simulations in P5. The organic carbon simulation piggybacked on the simulation of organic nitrogen. Appendix B documents a literature survey undertaken for this project to analyze the scientific literature on categorizing TOC export rates by land use and to determine whether the nitrogen-based TOC export rates used in P5 should be modified. The literature review did not find a strong consistent relation between land use and TOC export rates with the following exception: wetlands were generally credited with the largest TOC export rates among land use categories. Wetlands are not represented explicitly in P5, but are included in the forest land use. The representation of forests in P5 was modified to account for the contribution of wetlands to TOC loads, as described below.

In addition to describing the incorporation of the effects of wetlands, the next sections describe the calculation of TOC-specific regional factors using LOADEST, the revision of code for the P5 automated calibration to accommodate TOC, and the TOC calibration.

Wetlands

Wetlands are not represented explicitly in P5, but are included in the forest land use. To incorporate the impact of wetlands on TOC loads, the acres of wetlands in each land and river segment in the Potomac River portion of P5 was determined from the 2011 National Land Cover Database. The presence of wetland in a segment was taken into account by adjusting the regional factor for forest in that segment. The wetland export rate was set at ten times the forest export rate, so that the regional factor was increased by

$$10 \times \%wetlands + (1 - \%wetlands) \qquad (A.1)$$

A numerical example may help explain how this formula works. The watershed of Big Pipe Creek in Carroll County, Maryland, has 1,303 acres of wetlands. This is 6.08 percent of the forest land in that watershed. According to the formula, the presence of the wetlands increases the load from forest by about 55 percent. The regional factor for Big Pipe Creek originally had a value of two. This means that edge-of-stream loads are multiplied by two before they are input into the river. The effects of wetland were incorporated into the regional factor by increasing it to 3.1 for forest.

The factor of ten was taken from the ratio of wetland to mixed forest loading rates determined in the USGS SPARROW TOC model (Shih et al. 2010). Figure A.2 shows the acres of wetland by land and river segment. As Figure A.2 shows, wetlands are concentrated in the Piedmont physiographic province.

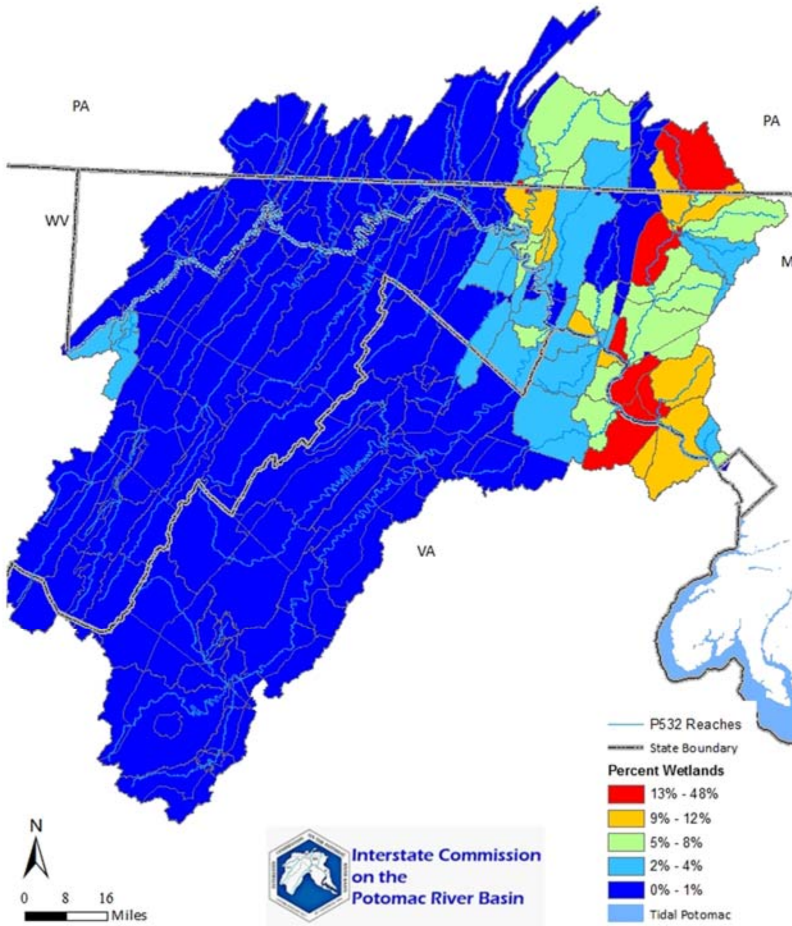


Figure A.2 Acreage of wetlands in the Potomac River basin by P5 land-river segment

ESTIMATOR/LOADEST Loads and Regional Factors

ESTIMATOR is U.S. Geological Survey (USGS) software which calculates daily, monthly, or annual constituent loads based on observed daily average flows and grab-sample monitoring data. ESTIMATOR has been used to calculate nutrient and sediment loads for the RIM (River Input Monitoring) program for the Chesapeake Bay Program, as well as to estimate sediment and nutrient trends in the region. Cohn et al. (1989) and Cohn et al. (1992) give the theory behind ESTIMATOR. Langland et al. (2001, 2005) demonstrate the application of ESTIMATOR in the Chesapeake Bay watershed.

ESTIMATOR contains three elements. The heart of ESTIMATOR is a multiple regression equation that relates the log of constituent concentrations to flow, time, and season. The equation for C, the constituent concentration in mg/l, takes the following form:

$$\ln[C] = \beta 0 + \beta 1 \ln[Q] + \beta 2 \ln[Q]^2 + \beta 3\ T + \beta 4\ T^2 + \beta 5 \operatorname{Sin}[2\pi T] + \beta 6 \operatorname{Cos}[2\pi T] + \varepsilon \tag{A.2}$$

where Q is flow (cfs); T is time (yrs); β_1, β_2, β_3, β_4, β_5, and β_6 are the coefficients estimated in the regression; and ε is the error term, which is assumed to have a normal distribution with mean zero.

The flow and time variables are centered so that terms are orthogonal. Regression relation is essentially a multivariate rating curve, which takes into account temporal trends and seasonal trends as well as trends in flow.

The second element is the use of a minimum variance unbiased (MVUE) procedure to obtain estimates of concentrations and loads from the log of constituent concentrations determined from the regression. Cohn et al. (1989) describe the motivations for using the MVUE procedure, as opposed to simpler methods.

The transformed constituent concentrations are combined with daily flows to estimate daily, monthly, and annual loads. Standard errors, confidence intervals, and standard errors of prediction can also be calculated.

A more recent USGS implementation of the ESTIMATOR methodology, LOADEST (Runkel et al., 2004), was used to calculate annual and monthly TOC loads at the stations in the Potomac River basin where nitrogen and phosphorus loads are calculated to determine P5 regional factors. Figure A.3 shows the location of these stations. Table A.2 summarizes the average annual TOC load and TOC yield estimated using LOADEST at these stations.

A TOC regional factor was calculated for each station shown in Figure A.2 and applied to all land and river segments upstream of the station, until another station in Table A.2 was reached. The regional factor was set equal to the average annual TOC load, calculated by LOADEST, divided by the average annual TOC load from the original P5 simulation.

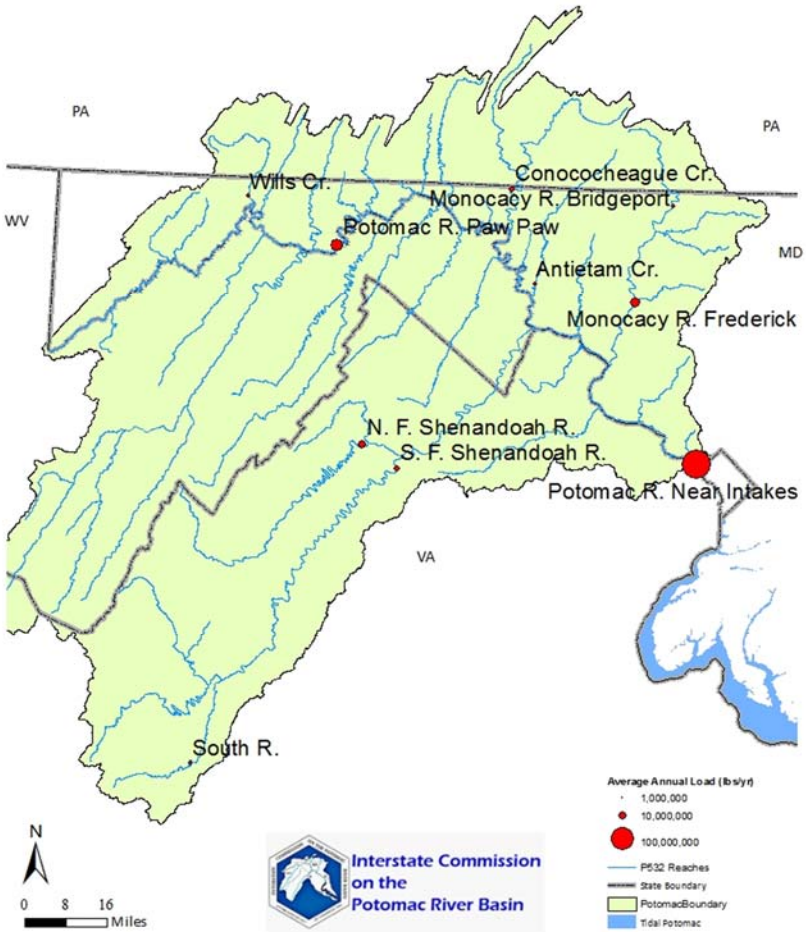


Figure A.3 Location of USGS gages where LOADEST total organic carbon loads were calibrated in the Potomac River basin

Table A.2
Average annual TOC loads and yields estimated with LOADEST at key Potomac River basin stations, 1985-2006

River Segment	USGS gage	Watershed area (acres)	Average annual load (lbs/yr)	Yield (lbs/ac/yr)
Monocacy River at Bridgeport, MD	01639000	110,720	3.97E+06	35.85
Monocacy River near Frederick, MD	01643000	522,880	1.48E+07	28.38
Potomac River near Washington, DC (Chain Bridge)[11]	01646500	7,398,400	1.50E+08	20.22
South River near Waynesboro, VA	01626000	81,280	3.74E+06	45.97
N F Shenandoah River near Strasburg, VA	01634000	492,800	1.43E+07	29.05
S F Shenandoah River at Front Royal, VA	01631000	1,045,760	7.32E+06	7.00
Antietam Creek near Sharpsburg, MD	01619500	179,840	1.96E+06	10.89
Conococheague Creek near Fairview, MD	01614500	316,160	4.79E+06	15.14
Wills Creek near Cumberland, MD	01601500	158,080	1.42E+06	8.95
Potomac River at Paw Paw, WV	01610000	2,002,560	2.34E+07	11.70

P5 Code Modifications

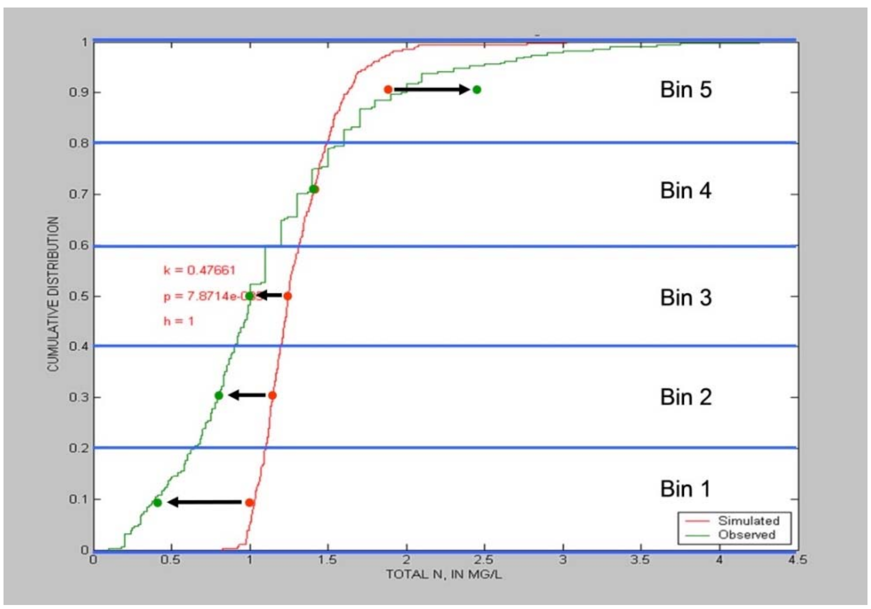
In preparation for calibrating the TOC simulation, several changes were made to the P5 code. P5 reads a file with nitrogen and phosphorus regional factors for every land use, land segment, and river segment in the P5 model. To incorporate TOC regional factors based on the LOADEST average annual loads, the code was adjusted to read factors for TOC that could be added to the file. Since there is a factor for each land use, these factors could also be used to adjust the TOC export rate by land use. This adjustment was made to incorporate wetlands, as described later in this appendix.

P5 uses an automated calibration routine to set river simulation parameters. In the automated calibration of river reaches, parameters are adjusted to reduce the biases between observed and simulated concentrations in the previous simulation iteration. Each parameter is associated with a specific bias. The biases are defined in terms of the quintiles on the observed and simulated cumulative frequency distribution (CFD) curves. For each observed quintile, the average of the log of the concentrations in that quintile are calculated; the same procedure is used for simulated constituents corresponding to the observed data—in other words, only simulated data

[11] Simulated flow for this river segment is calibrated against observed flow at the Little Falls Pump Station; water quality is calibrated against monitoring data collected about a mile downstream at Chain Bridge, which is approximately the Potomac River Fall Line.

paired with observations are used in the simulated CFD. The bias is the ratio of the simulated to the observed quintile averages. Parameters are adjusted based on the bias of a particular quintile or an average of the bias of quintiles. Figure A.4 illustrates the role of the quintiles in the calculation of biases. EPA (2010) contains a fuller discussion of the automated river calibration in Section 11.

The main parameter which controls TOC concentrations in the river is the organic matter settling rate. Although refractory organic nitrogen, refractory organic phosphorus, and refractory organic carbon are distinct state variables, a single settling rate is applied to all three refractory constituents. In the final CBP versions of P5, the settling parameter is adjusted based on the average bias in total nitrogen and total phosphorus concentrations in the top three quintiles of the observed and simulated distributions. In the initial versions of P5, however, the bias in TOC was also included in the calculation of bias used to set the refractory matter settling rate. In the version of P5 for this project, TOC bias was again included in the calibration of the settling rate. The automated calibration tended to undersimulate TOC concentrations at Chain Bridge, so a second version of the calibration routine was prepared which determined the settling rate based on the bias in the TOC concentrations alone.



Source: EPA 2010.

Figure A.4 CFD quintiles and calculation of biases

TOC Calibration Results

Using the TOC regional factors and the code changes discussed in the previous sections, the automated calibration of the TOC simulation resulted in good agreement between average annual TOC loads simulated by P5 and estimated using LOADEST. Figure A.5 compares the average annual loads. The simulated average annual TOC load at Chain Bridge is within one percent of the load calculated using LOADEST.

The one station at which there is little agreement between LOADEST and P5 loads is the South Fork of the Shenandoah River. Compared to LOADEST, P5 oversimulates TOC loads by an order of magnitude. As discussed below, however, there is relatively good agreement in the distribution of observed and simulated TOC concentrations at this location. It is likely that the LOADEST average annual loads underestimate TOC loads in the South Fork because there are not enough samples taken under storm flow conditions. Ideally, high flow loads should be estimated with targeted storm sampling. Figure A.6 compares the distribution of flows in the South Fork of the Shenandoah River when samples were taken and overall distribution of flows, regardless of whether a sample was taken or not. The distribution of flows when samples are taken should be shifted upward compared to the overall distribution, indicating that there is a higher percentage of storm flow samples than would be achieved by random sampling. This is not the case for the South Fork, indicating that LOADEST is likely to be estimating storm flow loads with too few samples.

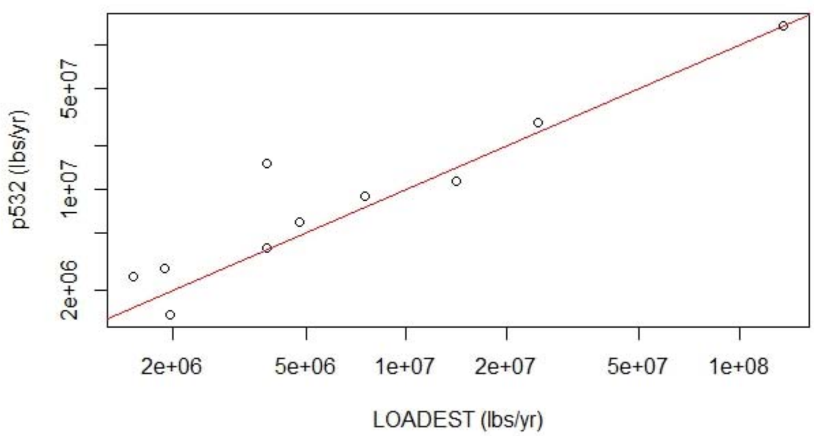


Figure A.5 Average annual TOC loads, 1985-2005, recalibrated P5 Watershed Model and LOADEST

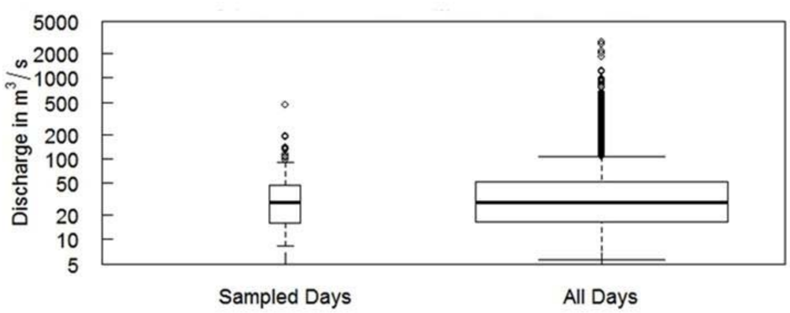


Figure A.6 Comparison of distribution of flows on days where sampling occurred compared to overall distribution of flows, South Fork of the Shenandoah River

There is a high degree of agreement in the CFDs between observed (monitored) and simulated concentrations at the monitoring stations on large rivers upstream of Chain Bridge. The Chesapeake Bay Program measures agreement in the CFDs of observed and simulated concentrations using the Kolmogorov-Smirnoff test (K-S test). For nutrients, it is rare that the test does not detect a difference in distribution between observed and simulated concentrations. For the P5 TOC simulation, however, the K-S test cannot detect a difference in distribution at three of the four stations on large rivers above Chain Bridge. Figures A.7, A.8, A.9, and A.10 compare the CFDs of observed and simulated TOC concentrations for the Monocacy River at Bridgeport, the South Fork of the Shenandoah River at Front Royal, the North Fork of the Shenandoah River at Strasburg, and the Potomac River at Point of Rocks, respectively. The K-S test rejects equality of distributions only for the North Fork, where TOC concentrations are clearly over simulated.

There was room for improvement in the agreement between observed and simulated TOC concentrations at Chain Bridge, so the river parameters were adjusted in the main Potomac River segments between Point of Rocks and Chain Bridge outside of the automated calibration. In addition to the organic matter settling rate, several parameters governing the behavior of biochemical oxygen demand (BOD) were adjusted to increase simulated BOD concentrations in the Potomac River downstream of Point of Rocks. Parameters adjusted include 1) BOD settling rate; 2) BOD decay rate; and 3) BOD benthic release. Figure A.11 shows a comparison of the cumulative frequency distributions of observed and simulated TOC concentrations. The presence of organic material may at Chain Bridge. There is good agreement in the distribution of observed and simulated concentrations, though not as good as the agreement at some of the upstream stations.

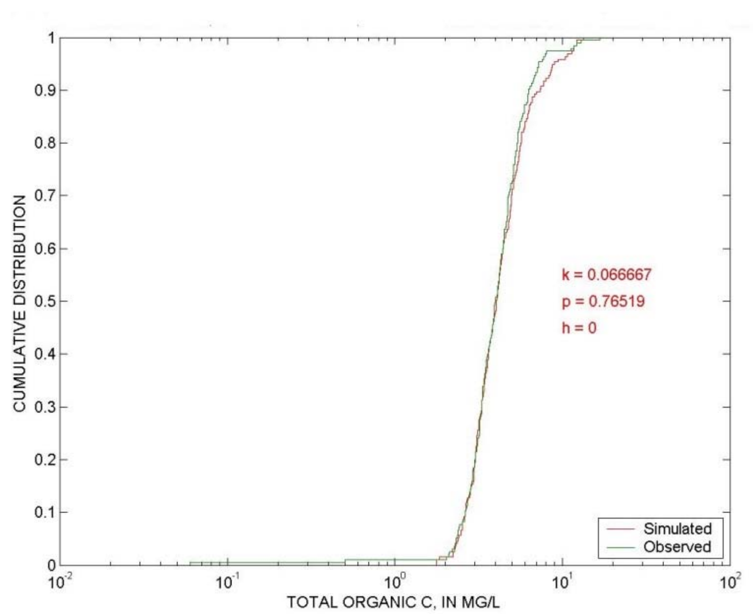


Figure A.7 Observed and simulated cumulative frequency distributions of TOC concentrations, Monocacy River at Bridgeport, 1985-2005

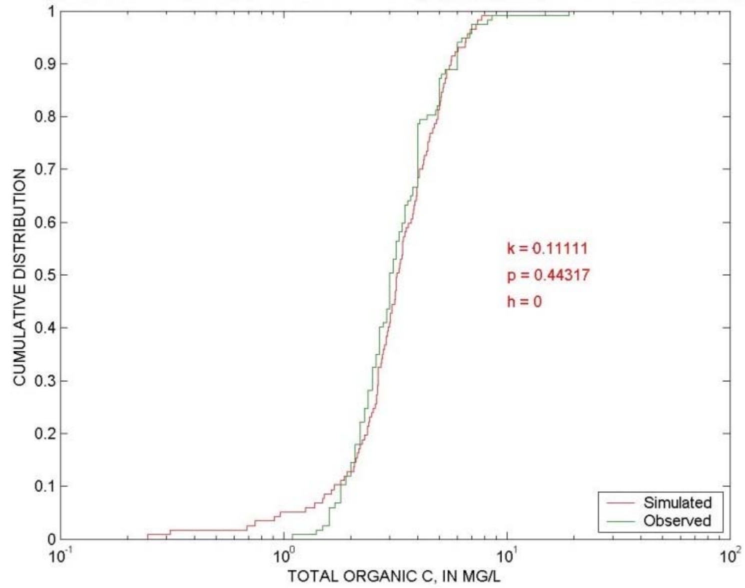


Figure A.8 Observed and simulated cumulative frequency distributions of TOC concentrations, South Fork of the Shenandoah River at Front Royal, 1985-2005

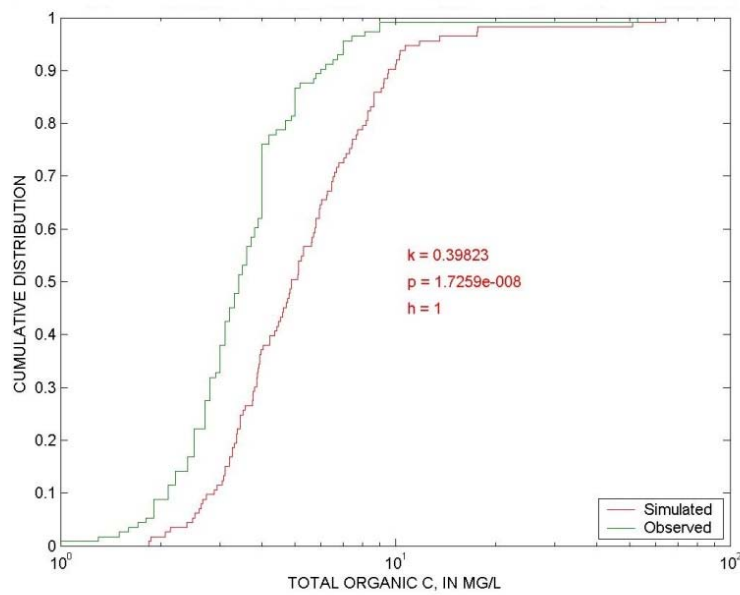


Figure A.9 Observed and simulated cumulative frequency distributions of TOC concentrations, North Fork of the Shenandoah River at Strasburg, 1985-2005

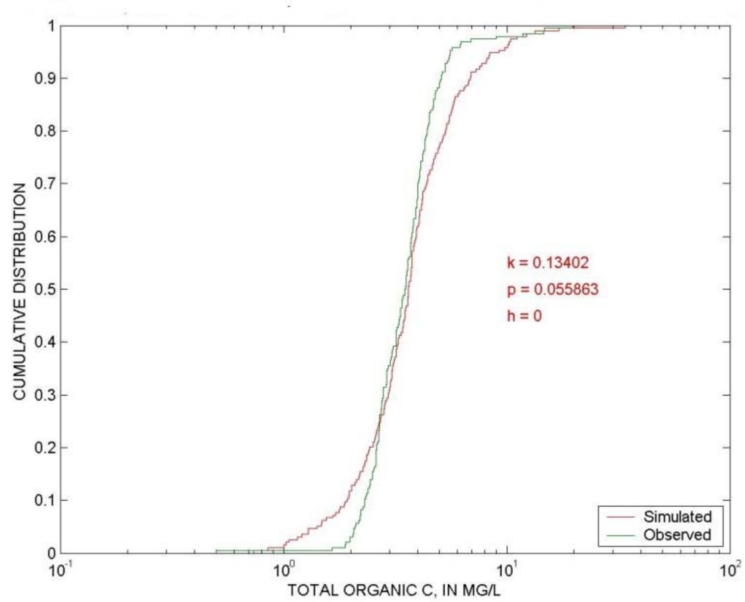


Figure A.10 Observed and simulated cumulative frequency distributions of TOC concentrations, Potomac River at Point of Rocks, 1985-2005

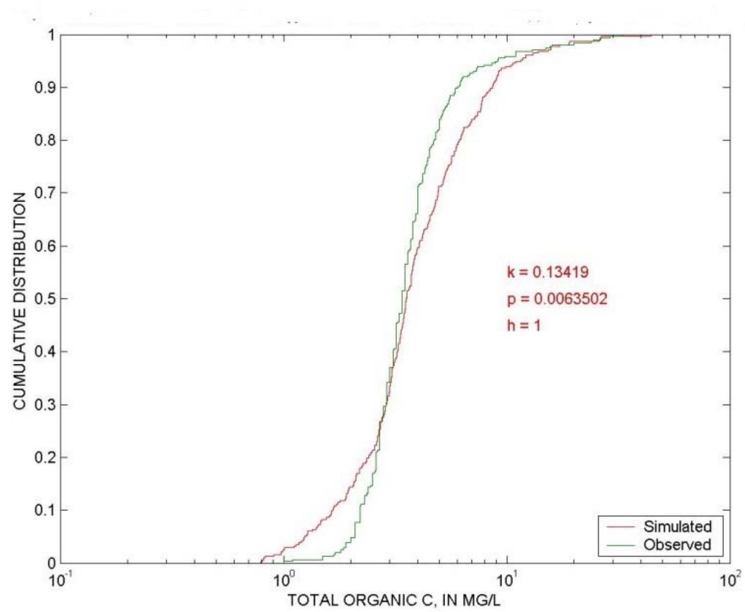


Figure A.11 Observed and simulated cumulative frequency distributions of TOC concentrations, Potomac River at Chain Bridge, 1985-2005

TOC CALIBRATION DISCUSSION

P5 has been calibrated to simulate TOC in the Potomac River basin. TOC loads have been calibrated to average annual loads calculated using LOADEST at key water quality monitoring stations throughout the basin. Simulated TOC concentrations match the empirical distribution of observed concentrations at stations on the large rivers upstream of the metropolitan Washington water supply intakes.

Figures A.12, A.13, and A.14 show the observed and simulated CFDs of concentrations of total nitrogen, total phosphorus, and total suspended solids, respectively, comparable to Figure A.11. The nitrogen, phosphorus, and sediment simulations generally capture the distribution of concentrations observed in the Potomac River at Chain Bridge. The TOC simulation captures the distribution of TOC concentrations observed at Chain Bridge to a similar degree. The TOC simulation is thus suitable for running scenarios which represent alternative land uses upstream of intakes and therefore provide a basis for estimating treatment chemical doses associated with alternative land use scenarios.

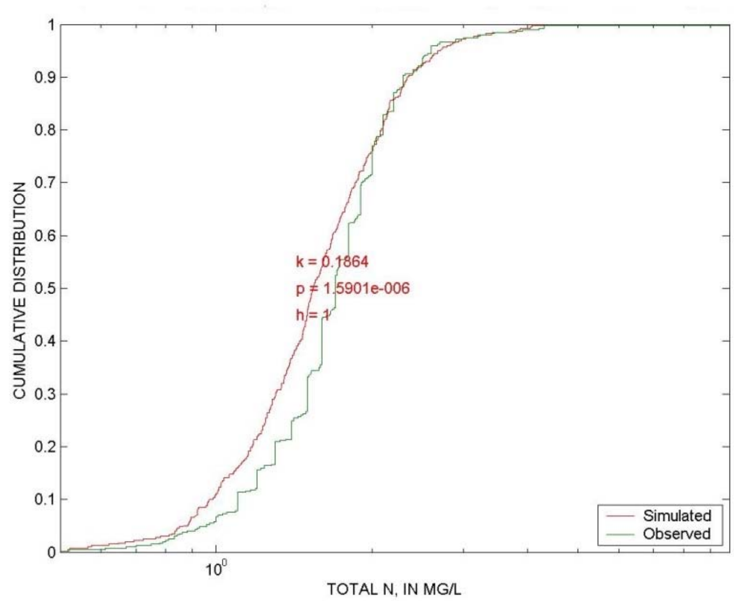


Figure A.12 Observed and simulated cumulative frequency distributions of TN concentrations, Potomac River at Chain Bridge, 1985-2005

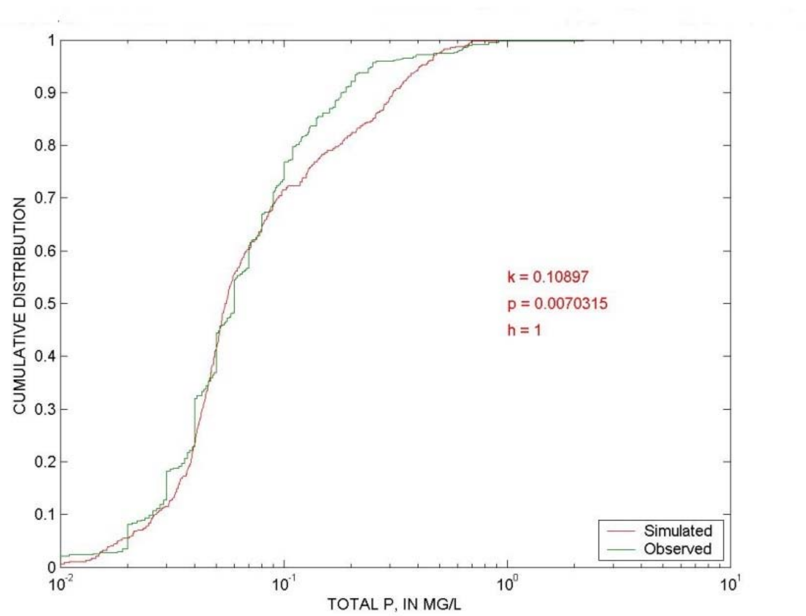


Figure A.13 Observed and simulated cumulative frequency distributions of TP concentrations, Potomac River at Chain Bridge, 1985-2005

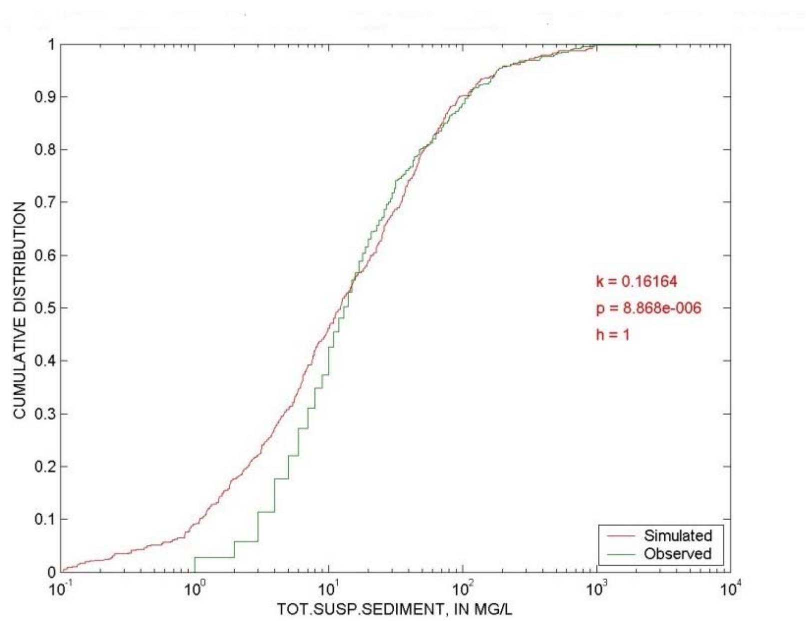


Figure A.14 Observed and simulated cumulative frequency distributions of TSS concentrations, Potomac River at Chain Bridge, 1985-2005

APPENDIX B
LITERATURE REVIEW OF TOTAL ORGANIC CARBON EXPORT RATES BY LAND USE

The Chesapeake Bay Program's Watershed Model (EPA 2010) was originally designed to simulate Total Organic Carbon (TOC), but the TOC simulation was never calibrated.

The most frequently used method of simulating land use loads in a watershed model is to start by calibrating the land simulation to target export coefficients for each land use. Export coefficients are simply the average annual load lost per acre from a given land use. The literature on this topic was reviewed to determine any estimates of TOC export coefficients to be used in the calibration. As in other modeling efforts, this was the approach used to calibrate the Watershed Model for nitrogen and phosphorus; although, there was a rich literature base from which to determine appropriate export coefficients.

This appendix describes the methodology and results of the effort to evaluate available literature-based TOC export rates by land use and determine their applicability for this project. Literature describing dissolved organic carbon (DOC) export rates by land use were also reviewed and translated to TOC export rate estimates when necessary using the methodology described in Xenopoulos et al. 2003 (increasing DOC by 10 percent). Included in this appendix are sections on the methodology, a brief description of the most applicable literature, a discussion of the main findings of the literature review, and a comprehensive list of references reviewed as part of the literature review. Note that not all references listed are discussed in the text below.

METHODOLOGY

A three-step process was utilized to identify applicable literature.

1) Previously identified sources of information were evaluated and authors were contacted directly as necessary.
2) Using two references that outlined an online literature search process for finding nutrient and sediment loading rates from agriculture, forest, and urban land uses for the Chesapeake Bay Program (Sievers 2014; Tetra Tech 2014), a search for similar TOC literature was conducted. Five online sources were searched: Chesapeake Bay Program documents, Web of Science, National Agricultural Library (AGRICOLA), Elton B. Stephens Co. (EBSCO), and Google Scholar. A variety of key words were used as search terms (Appendix B).
3) The cited literature in each identified source was reviewed as appropriate.

SUMMARY OF APPLICABLE LITERATURE

Over 100 articles were identified using the methodology described above. The sections below provide summary information from relevant papers. International papers were reviewed and incorporated as appropriate; however, it is expected that the cited export rates will differ from actual export rates in Potomac basin due to different physical conditions. Even within the United States, the reported values are likely to be less appropriate for use in the Watershed Model the farther the study area is from the Potomac basin. Literature-reported export rates from key sources are provided in a summary table at the end of this document appendix. The literature summary is divided into two sections based on the type of information reported – export rates and carbon-to-nitrogen ratios.

Literature Export Rates

Methods and discussion of TOC export rates by land use are described in this section for each applicable literature source.

Shih et al. 2010

This U.S. Geological Survey (USGS) report includes a summary table of TOC yields by land use type resulting from the reported Spatially Referenced Regression on Watershed Attributes (SPARROW) modeling effort and an associated literature review (reprinted as Table B.1 below). In general, the study found that the following land uses contributed to stream organic carbon load (listed from highest contribution to lowest contribution): wetlands, urban lands, mixed forests, agricultural lands, evergreen forests, and deciduous forests. Shih et al. (2010) states that mixed forests have higher export rates than agricultural lands due to particular conditions of the selected mixed forest watersheds.

Table B.1
Comparison of SPARROW and literature estimates of TOC yields for major land use types in the United States

Watershed land-cover type	Percentiles of total organic carbon yield exported from SPARROW watersheds[1] (kg ha^{-1} yr^{-1})						Literature yields[2] (kg ha^{-1} yr^{-1})
	No. of watersheds	10th	25th	50th	75th	90th	Range of values
Agriculture	1,841	15.1	19.1	24.5	34.7	59.9	14.1–19.52
Forest Deciduous	70	12.1	14.0	16.2	21.4	34.0	4–80[3]
Forest Evergreen	248	13.6	16.1	20.3	28.6	56.0	14–500[3]
Range	3,203	0.1	0.3	0.8	2.3	8.2	4–13[3]
Urban	143	36.3	48.3	73.3	108.6	329.3	19–146[3]
Wetlands	191	160.3	276.4	476.3	801.6	2180.0	50–220[4]

[1]The land-cover types represent the following percentages of the land area in SPARROW watersheds: agricultural land (>90 percent), forest (>95%), urban (>90%), wetlands (>95%), and range (95%).

[2]Dalzell and others, 2007.

[3]Hope and others, 1994; North America, New Zealand, and Russia (total organic carbon).

[4]Mulholland, 2003 (dissolved organic carbon).

Source: Shih et al. 2010

The studies cited in Table B.1 were reviewed. Estimates of TOC yield from agriculture were obtained from Dalzell et al. (2007), based on values from one 850 square kilometer Midwestern watershed. The forest, range, and urban estimates of TOC yield were obtained from Hope et al. (1994) which assessed catchments in North America, Europe, and New Zealand. TOC yield estimates for wetlands were obtained from Mulholland (2003) based on watersheds in Scotland, Nova Scotia, Quebec, Wisconsin, and North America. The source of information for the North American region, developed in Mulholland and Hill (1997), was a study of small streams in eastern Tennessee that found a significant relationship between average channel slope and DOC concentration.

Correll et al. 2001

Correll et al. (2001) evaluated organic carbon fluxes for eight watersheds along the Rhode River on the Atlantic Coastal Plain of Maryland. The Coastal Plain is hydrologically different than the study area; however, it is relevant due to the close proximity. The annual and seasonal TOC fluxes reported in Correll et al. (2001) are reprinted in Table B.2.

Table B.2
Annual and seasonal TOC fluxes from the entire Rhode River Watershed and from a crop sub-watershed and a forest sub-watershed

Watershed	N (# of yrs. of data)	Flux (kg C ha^{-1})
A. Annual		
Crop	20	35.30±34.2
Forest	20	26.60±19.5
Rhode River	21	21.60±12.5
B. Winter		
Crops	22	9.92±9.38
Forest	22	5.52±5.92
Rhode River	24	5.47±2.78
C. Spring		
Crops	23	13.90±22.5
Forest	22	12.30±9.69
Rhode River	24	8.71±7.18
D. Summer		
Crops	21	9.92±21.8
Forest	21	5.47±9.37
Rhode River	22	4.62±4.94
E. Fall		
Crops	21	1.83±2.25
Forest	22	3.58±8.67
Rhode River	23	3.76±6.49

Source: Adapted with permission from Copyright Clearance Center: Springer Nature; *Water, Air, and Soil Pollution;* Effects of Precipitation, Air Temperature, and Land Use on Organic Carbon Discharges from Rhode River Watersheds; David L. Correll, Thomas E. Jordan, Donald E. Weller; 2001.
Note: Values are ± 1 SD. N is the number of years of data.

Correll et al. (2001) also developed regressions for average annual and seasonal total organic carbon fluxes as a function of precipitation for crop and forest land use types. On an average annual basis, the regression equations are provided in Equation B.1 and B.2.

$$Crop\ TOC\ flux\ =\ 0.0000000241(P)^{4.42} \quad (B.1)$$
$$Forest\ TOC\ flux\ =\ 0.0000000122(P)^{4.48} \quad (B.2)$$

where TOC flux = kg C ha $^{-1}$ time period
P = precipitation in cm time period^{-1}

Further, Correll et al. (2001) conducted a literature review of TOC concentrations, fluxes, and percent DOC by watershed type (forested, cropland, large complex, and arctic). The reports cited in the forests, croplands, and select large complex watersheds sections were reviewed for applicable information. Three of the forested watersheds and seven of the cropland watersheds were located in Maryland. Although variation associated with land uses was not explicitly discussed in many of the articles, some insights were gained into the assumptions and conclusions:

- McDowell and Asbury (1994) evaluated organic carbon exports for three tropical rain forest watersheds in Puerto Rico.
- Naiman (1982) values are based on measured values from 1979 to 1981 in five pristine Quebec streams.
- Jordan et al. (1997a) found the highest in-stream TOC concentrations in the forested watershed of the outer Coastal Plain; however, TOC concentrations did not significantly correlate with land use.
- Howarth et al. (1991) used a Generalized Watershed Loading Function watershed model to evaluate carbon and sediment inflows to the Hudson River estuary by land use (forest, agriculture, and pasture) and transport path (surface and groundwater). The study found that "urban and suburban areas and agricultural fields are the dominant sources of both organic carbon and total sediment, and increases or decreases in the area of either would be expected to alter fluxes of materials to the estuary. In addition, more intensive land use within urban and suburban regions would be expected to increase fluxes of both organic carbon and sediments. That is, fluxes are quite sensitive to changes in suburban areas from a low or moderate density of housing to high-density housing or commercial uses."

Sickman et al. 2007

This study looked at point and non-point source TOC loads in the Sacramento River watershed. It provides yields for three sub-watersheds with different land use covers (mixed, urban, and undisturbed) for normal precipitation years. Literature values for select land use categories were provided (see Appendix B for summary information).

USDA Natural Resources Conservation Service 2013

This report evaluated the impact of agricultural conservation practices in the Chesapeake Bay watershed based on changes following a benchmark study that utilized observed data and modeling efforts. The modeling demonstrated that soil carbon management has either remained the same or improved over time. Average crop soil loss is reported as up to 189 lbs/acre/yr; however, this value represents loss at the field scale rather than a delivered amount to downstream waterways.

Canham et al. 2004

Canham et al. (2004) described a geospatial DOC modeling effort in lakes of New York's Adirondack Park as a function of land use. Export rates from major land use types were estimated. Wetlands had the highest DOC export rates, followed by forests; however, wetlands occupy much less of the overall watershed area resulting in a lower total yield.

Elias 2010

This doctoral dissertation evaluated the effects of urbanization on drinking water treatment costs and included both qualitative and quantitative discussions of TOC export rates by land use. Reported literature values indicate that the lowest TOC export rates correspond with forested land uses and the highest export rates are associated with urban land uses. Accumulation rates by land use were also developed for the Alabama watershed in the study area.

Summary

Substantial qualitative and quantitative literature information is available on TOC export rates, as evidenced by the extensive list of reviewed references. A table of the most pertinent information was summarized by land use in Appendix B.

The TOC export rates described in this literature review come from studies that did find relationships between land use and TOC export rates. It should be noted that a number of studies found no such relationship at the watershed scale (e.g., Aitkenhead-Peterson et al. 2009; Chow et al. 2007; Jordan et al. 1997a).

Literature Carbon-to-Nitrogen Ratios

In addition to setting target TOC rates for model calibration, the ratio of carbon to nitrogen is another option for calibration in the TOC component of the Watershed Model. Carbon exports are larger than nitrogen exports from all reported land uses. The TOC:TN and DOC:DON (dissolved organic nitrogen) ratios reported in the literature are provided in Table B.3 and B.4, respectively.

Table B.3
TOC:TN ratios by land use for Southeastern Australia

Land use	TOC:TN ratio
Pasture	9.6
Forest	7
Livestock	6.5

Source: Adapted from Vink et al. 2007

Table B.4
DOC:DON ratios from a literature review conducted by Stedmon et al. (2006)

Land use	DOC:DON ratio
Agriculture	10+/-2
Urban	18+/-12
Forest	53+/-36

Source: Adapted from Stedmon et al. 2006

DISCUSSION

Despite the limited applicability of the quantitative data, some general themes from the literature may provide insight for model calibration purposes.

Firstly, there is general agreement in the literature that wetlands have the highest TOC export rate of any land use found in the Potomac basin. Wetlands are classified as forests in P5, and it is anticipated that future versions of the model will try to take into account the proportion of wetlands in forest by land and river segment by assigning TOC export rates to forest land uses. Urban land uses are associated with the second highest TOC export rates.

In at least one study (Shih et al. 2010), the quantitative data suggests that mixed forests have higher TOC export rates than agricultural lands. This is generally supported by the findings of Sliva and Williams (2001). However, it is hypothesized that this was a function of the few watersheds used in that study and not a widely applicable conclusion. It is generally agreed that although croplands have lower soil TOC content than forests, higher erosion rates lead to higher TOC exports (e.g., Saha et al. 2014; Graeber et al. 2012; Vink et al. 2007; Swaney et al. 1996).

The next sections of this appendix include the online literature search key words and a summary table of the literature-reported export rates from key sources.

ONLINE LITERATURE SEARCH KEY WORDS

- Land Uses
  - Forest* TOC, Agricultur* TOC, Crop* TOC, Urban* TOC, and Pastur* TOC
  - Forest runoff TOC
  - Agricultur* runoff TOC
  - Crop* runoff TOC
  - Urban* runoff TOC
  - Pastur* runoff TOC
  - Urban*, Agricultur*, Pasture*, and Crop*
  - Cattle feedlot TOC
  - Manure storages TOC
  - "Contrasting land use*" TOC
- Geographic Locations
  - + Maryland
  - + Virginia
  - + West Virginia
  - + Pennsylvania
  - + Potomac
  - + Chesapeake
  - + Appalachia
  - + North America
- Export Dynamics
  - Landscape drainage
  - Watershed scale
  - Terrestrial OC
  - OC export
  - OC annual load
  - Agriculturally derived OC
  - Landscape-scale carbon dynamics
  - Annual carbon discharges
  - Modeling carbon loading
  - Carbon mobility
  - Carbon budget
  - Sources and transformations of dissolved organic matter
  - Terrestrial organic matter export
  - Sources and flowpaths of dissolved organic carbon
  - Sources of dissolved organic carbon
  - Large scale patterns in DOC
  - Sources of dissolved organic carbon
  - Land-derived organic material
  - Soil carbon storage
  - Carbon movement from agricultural watersheds
  - Soil carbon in agroecosystems
  - Losses from agronomy plots
  - Terrestrial organic matter export

- Organic matter sources to the water column
- Compositions and fluxes of particulate organic material
- Exports of organic carbon in rivers
- Carbon transport
- Organic matter in organic forest floor layer
- Organic carbon storage dynamics in croplands
- Transport of organic carbon
- Sources of particulate organic matter in rivers
- Agricultural drainage—Water quality impacts and subsurface drainage studies
- Flux
- TOC export coefficients
- Run-off losses
- Carbon losses in surface runoff
- Carbon discharge
- Edge-of-field
- Delivered load
- Water extractable organic carbon content

Google Scholar Search

- toc "land use"
- toc "annual load" "land use"
- toc load "edge-of-field"
- toc "annual load" "edge-of-field"
- carbon "annual load" "edge-of-field"
- carbon "edge-of-field"
- Landscape-scale carbon water* -dioxide
- carbon "annual load" "watershed contribution"
- toc "land use" contribution
- watershed-scale carbon export
- terrestrial TOC export coefficients
- terrestrial TOC load
- terrestrial carbon transport
- "total organic carbon" load*
- "total organic carbon" load* forest -ocean*
- "total organic carbon" load* urban -ocean*
- "total organic carbon" load* "developed land" -ocean*
- "total organic carbon" load* impervious -ocean*
- "total organic carbon" load* agriculture -ocean*
- "total organic carbon" load* pasture -ocean*
- "total organic carbon" load* crop -ocean*
- "total organic carbon" load* "golf course" -ocean*
- "total organic carbon" load* "roof top"
- "total organic carbon" load* "rural roads"
    - "total organic carbon" load* "urban roads"

LITERATURE DERIVED TOC EXPORT RATES

Table B.5
TOC export rates from the literature (lbs/acre/yr)

		TOC export rates (lbs/acre/yr) except where otherwise noted										
Reference	Study location	Wetland	Urban	Mixed forest	Evergreen forest	Deciduous forest	Forest	Range	Crop	Ag	Cool grassland	Large complex watersheds
Correll et al. 2001*	Maryland						14.9		22.2			
Correll et al. 2001**	Literature review						2.2-13.2		3.9-11.8			3.1-45.1
Sickman et al. 2007***	California		108.0	>66.9	13.4-66.9						<8.9	
Shih et al. 2010**	Literature review	44.6-196.3	17.0-130.3		12.5-446.1	3.6-71.4		3.6-11.6		12.6-17.4		
Shih et al. 2010[€]	Conterminous United States	424.9	65.4		18.1	14.5		0.7		21.9		
USDA 2013b‡	Chesapeake Bay								95-189			
Canham et al. 2004†	New York	184.9-222.8					37.0-46.1					
Elias 2010**	Literature review		108.0				8.0					

*Values calculated for the Potomac basin using Equation B.1 and Equation B.2. The study area is located in the Coastal Plain of Maryland, a hydrologically different system from the non-tidal Potomac basin.
**Literature review values.
***California urban watershed, other land uses based on literature values reported in study.
[€]Median modeled values.
†DOC export rates transformed to TOC using method described in Xenopoulos et al. 2003 (increasing DOC by 10 percent).
‡These values are average soil carbon change at edge of field, not delivered quantities and are, therefore, not directly comparable with other values in the table.

APPENDIX C
UTILITY TREATMENT PROCESS OVERVIEW AND AVAILABLE DATA

TREATMENT PROCESSES

Meetings were held with each utility to gain a better understanding of their specific treatment process and any special considerations that need to be accounted for when trying to link water quality to the treatment process. The sections below cover the factors that needed to be considered when developing the relationships.

Fairfax Water

Fairfax Water has two raw water intake structures on the mainstem Potomac that feed into the same plant: one offshore (approximately 750 feet from shore, not quite half-way across the river) and one onshore. Both are at the same location along the length of the river. Operators switch between the two depending on which is seeing higher quality water.

Starting in 2010, the offshore intake started to be used more consistently. It is more often used because it has lower TOC and turbidity levels. The switch to the onshore intake typically occurs when flows are greater than 20,000 cubic feet per second at the USGS Point of Rocks gage. This avoids catching debris at the offshore intake associated with high flows, even though TOC and turbidity will still be higher. A record of which intake is used at which time is available.

Water quality measurements are made at both the onshore and offshore intakes when they are in use. Chemical dose application occurs at the raw water control chamber, approximately five miles from the intake sample location. The travel time from the intake to the raw water pumping station typically takes between two to five hours. The longer times are experienced during colder weather due to lower flow rates. This distance and the associated travel time mean that water quality readings at the intake will not necessarily match the water quality of what is being treated at the pump station at any given time. For example, water entering the intake at 10 a.m. may not have chemicals applied at the pump station until noon. Thus, the water quality intake record for 10 a.m. should not be compared to the chemical dose record at 10 a.m., but should instead be compared to the noon dose. Daily averages of both water quality at the intake and chemical dose at the pump station can be used to avoid this issue.

Fairfax Water uses a conventional treatment process that includes ozonation as listed below. Only the chemicals that are considered in the TOC and turbidity relationships are noted.

Fairfax Water treatment process:

- Intake
  - Potassium permanganate
- Mixing
  - Sulfuric acid
- Coagulation
  - Polyaluminum chloride (PACl)
- Flocculation
- Sedimentation
- Ozonation

- Filtration
- Disinfection

Coagulant is the highest cost driver, covering 25 percent of their chemical budget. Sulfuric acid also has a high cost. There may be a quantifiable relationship between sulfuric acid and pH and alkalinity. Since the Watershed Model does not model either pH or alkalinity, any relationships could not be used to estimate future chemical doses based on the modeled land use scenarios. There may also be a relationship between potassium permanganate and alkalinity and/or chlorophyll in the summer, but this also cannot be used due to the same modeling limitation.

As chemical prices fluctuate, Fairfax Water suggested a sensitivity analysis on high, medium, and low prices.

Washington Aqueduct

Washington Aqueduct has the last two intakes on the Potomac River, Great Falls and Little Falls. Great Falls is the preferred and most often used of the two because it relies on gravity to carry the water to the treatment plant instead of the pumping required when Little Falls is used. The Aqueduct also has two treatment plants: Dalecarlia and McMillan.

There are a series of intermediate reservoirs between the Potomac River and the McMillan plant. Residence time in these reservoirs can exceed one week, complicating relationships between water quality and treatment chemical doses. For this reason, only the treatment process at Dalecarlia was considered in this study since it is closest to the raw water intake point.

Conventional treatment is used at Dalecarlia, and follows general path outlined below.

Washington Aqueduct treatment process:

- Intake
- Screening
- Pre-sedimentation in Dalecarlia Reservoir
- Coagulation
    - Aluminum sulfate (alum) is used as a coagulant aid to remove both particulates and organics
- Flocculation
- Sedimentation
- Filtration, using large gravity filters
    - Sodium hypochlorite is added prior to filtration to prevent biological growth and control iron and manganese
- Disinfection
    - Sodium hypochlorite and ammonia are used to form chloramine
    - Caustic soda and lime are added to adjust the pH

Alum and sodium hypochlorite are the two chemicals whose use is driven by source water quality changes that also have significant cost implications. Alum is the largest cost of the two. Caustic soda and lime are also significant costs but their use relates more to changes in river flow.

The raw water travels over ten miles from the river to the Dalecarlia Reservoir which feeds the treatment plant. Periodic dredging is required and is an additional cost consideration. This settling means that the water quality in the reservoir and entering the plant is not the same as it is in the river. The most frequent, highest quality turbidity readings are taken at the entrance to the reservoir as described in more detail below.

One potential challenge to determining relationships between turbidity and treatment costs is that the raw water is only measured with online monitors. The utility views these measurements as less accurate than the results from bench methods and the data are not as readily accessible. An online monitor records water quality at Great Falls and leaving the reservoir (entering the plant). Additionally, bench tests are conducted for water entering and leaving the reservoir, though less frequently. While not as frequent as the online results, staff has more confidence in these tests. Utility staff suggested two ideas for dealing with this issue. First, the obvious erroneous data from online measurements could be corrected, and secondly, that the water quality in the reservoir could be used to estimate river water quality based on an estimated relationship. Ultimately, a method to translate the modeled water quality to river water quality was developed. This is discussed in detail in Chapter 2.

Utility staff raised the issue of considering capital costs that may be incurred due to water quality changes. Interests include the potential for more road salts to be used following a change to a more urbanized watershed. This issue is considered in Chapter 4.

Regarding the relationship between dose changes and chemical costs, utility staff said there is a linear relationship between the two since they pay on a per unit basis. They recommended using their internal assumption of a two percent annual increase in cost.

Washington Suburban Sanitary Commission

WSSC's intake is along the shoreline of the river. There is very little travel time between the river and the plant, therefore no settling occurs before the water begins the treatment process. The plant uses conventional treatment with additional UV disinfection.

WSSC treatment process:

- Intake
- Raw water pump station
  - Potassium permanganate added intermittently prior to entering the pump station
- Rapid Mix
  - Sulfuric acid to adjust pH for enhanced coagulation, typically seasonal use only
  - PACl and/or ferric chloride are added for coagulation
- Flocculation
- Sedimentation
- Filtration
- UV disinfection
- Chlorine Disinfection
- Post-chemical addition (lime, fluoride, orthophosphate)

To gauge raw water quality, grab samples from the river are taken at the intake location for TOC. An online meter measures turbidity after the addition of permanganate. These samples may not capture the flashiness of raw water quality (e.g., during a storm), but for most days should provide a reasonable daily representation. During certain, localized storm events, water quality at the intake is heavily influenced by the water entering the river from Watts Branch, just 0.25 miles upstream. Water quality at the intake is more comparable to mid-river water quality when receiving runoff from storms occurring further upstream affecting more of the river basin. Excessive solids received over a short amount of time during a storm occasionally prompt the plant to shut down if treatment adjustments cannot keep up with the water quality changes.

AVAILABLE DATA

Fairfax Water

Water quality and treatment cost data received:

- **Raw water TOC:** 2006-2015, daily average and maximum, ppm
- **Raw water turbidity:** 2006-2015, daily average and maximum, NTU
- **Raw water temperature:** 2006-2015, daily average
- Onshore or offshore intake: April 2003-February 2016
- **Withdrawal:** 2006-2015, daily average, daily maximum and minimum starting in 2007, MGD
- **Doses of the chemicals used to treat TOC and turbidity:** 2006-2015; coagulant PACl (daily average, daily maximum – not all days, mg/L), sulfuric acid (daily average – not all days, daily maximum – not all days, mg/L), and potassium permanganate (daily average – not all days, daily maximum – not all days, mg/L)
- **Price of the chemicals used to treat TOC and turbidity:** 2006-2015, annual rates for coagulant PACl ($/wet ton; $/dry ton), sulfuric acid ($/gallon), and potassium permanganate ($/dry ton)

Model calibration data received:

- **Raw water TOC:** 1981-2005, periodic samples, mg/L
- **Raw water turbidity:** 1981-2005, periodic samples, NTU

Washington Aqueduct

Water quality and treatment cost data received:

- Raw water TOC:
  - Online monitor: January 2001-October 2015; approximately weekly data from Great Falls intake, Little Falls intake, and leaving Dalecarlia Reservoir (entering plant); mg/L
  - Bench test: 2011-2015, daily leaving Dalecarlia Reservoir as UV 254, 1/cm
- Raw water turbidity:
  - Online monitor: 1999-2015, daily averages and maximums (starting in 2003) leaving Dalecarlia Reservoir, NTU
- Bench test: 2011-2015, daily leaving Dalecarlia Reservoir, NTU
- **Withdrawal:** 1999-2015, daily from Great Falls and Little Falls, MGD
- **Doses of the chemicals used to treat TOC and turbidity:** 2011-2015; coagulant (hydrated alum), daily, mg/L; chlorine, daily, mg/L

- **Price of the chemicals used to treat TOC and turbidity:** Current chemical costs for alum and sodium hypochlorite are $278.19/dry ton and $1,380/dry ton

Model calibration data received:

- **Raw water TOC:** same as above
- **Raw water chlorophyll *a***: may be available

Washington Suburban Sanitary Commission

Water quality and treatment cost data received:

- **Raw water TOC:** grab samples at river intake
- 1982-June 2009, weekly, grab, mg/L
- July 2009-mid 2014, daily, grab, mg/L
- Mid-2014 to present, weekly, grab, mg/L
- **Raw water turbidity:** 1988-present, daily average, NTU; daily max could be retrieved through minute data if needed; some data are available for 1982-1987 if needed
- Note: The turbidity meter may be after acid and permanganate chemical addition, but WSSC has not observed a significant difference compared to raw river intake turbidity
- **Raw water temperature:** 2007-May 2016, daily average
- **Withdrawal:** 1982-present, daily average, MGD
- **Doses of the chemicals used to treat TOC and turbidity:** 1984-present, daily average, no daily maximum available
  - Coagulant (Ferric chloride and PACl) – mg/L
  - Sulfuric acid – mg/L
  - Potassium Permanganate – mg/L
  - Coagulant aid – mg/L
  - Lime – mg/L
- **Price of the chemicals used to treat TOC and turbidity:** February 2007- January 2016; monthly; $/ton; for coagulant (polyaluminum hydroxychlorosulfate, ferric chloride), sulfuric acid, potassium permanganate, coagulant aid, and lime (lime, hydrated lime); no adjustments should be needed to account for concentration of coagulants or sulfuric acid

Model calibration data received:

- **Raw water TOC:** same as above

APPENDIX D
EXCLUDED WATER QUALITY-TREATMENT DOSE RELATIONSHIPS

Water quality-treatment dose relationships were initially explored for all treatment chemicals at each utility thought to be affected by upstream land use activities. Relationships for some of the treatment chemicals did not have sufficient explanatory power to include in subsequent analysis. Further, the treatment chemicals with the weakest relationships were also responsible for the smallest portion of the treatment chemical costs (although it should be noted that in practice these treatment chemicals are used in combination to achieve the desired effect). Additional information on the elimination of some treatment chemicals from further consideration is provided in the Additional Analyses section of Appendix E. This appendix documents the water quality-treatment dose relationships that were developed and subsequently not used to estimate treatment costs.

WASHINGTON SUBURBAN SANITARY COMMISSION

Potassium Permanganate ($KMnO_4$)

The following relationship (Equation D.1) was identified between potassium permanganate, water temperature, turbidity, and TOC where R^2=0.43. All predictor variables, the intercept, and the overall F test statistic have $p<0.0001$ and are significant at a 95 percent confidence level.

$$mg/L\ KMnO_4 = -0.80 + 0.015(°F\ Temp) - 0.0023(NTU\ Turbidity) + 0.073(mg/L\ TOC) \quad (\mathrm{D.1})$$

Figure D.1 is provided for visual inspection of the residual plots, line fit plots, and normal probability plot associated with this regression. Negative predicted dose values were forced to zero in the line fit plots. Note that the normal probability plot was developed for all non-zero values since this chemical is not applied during part of the year.

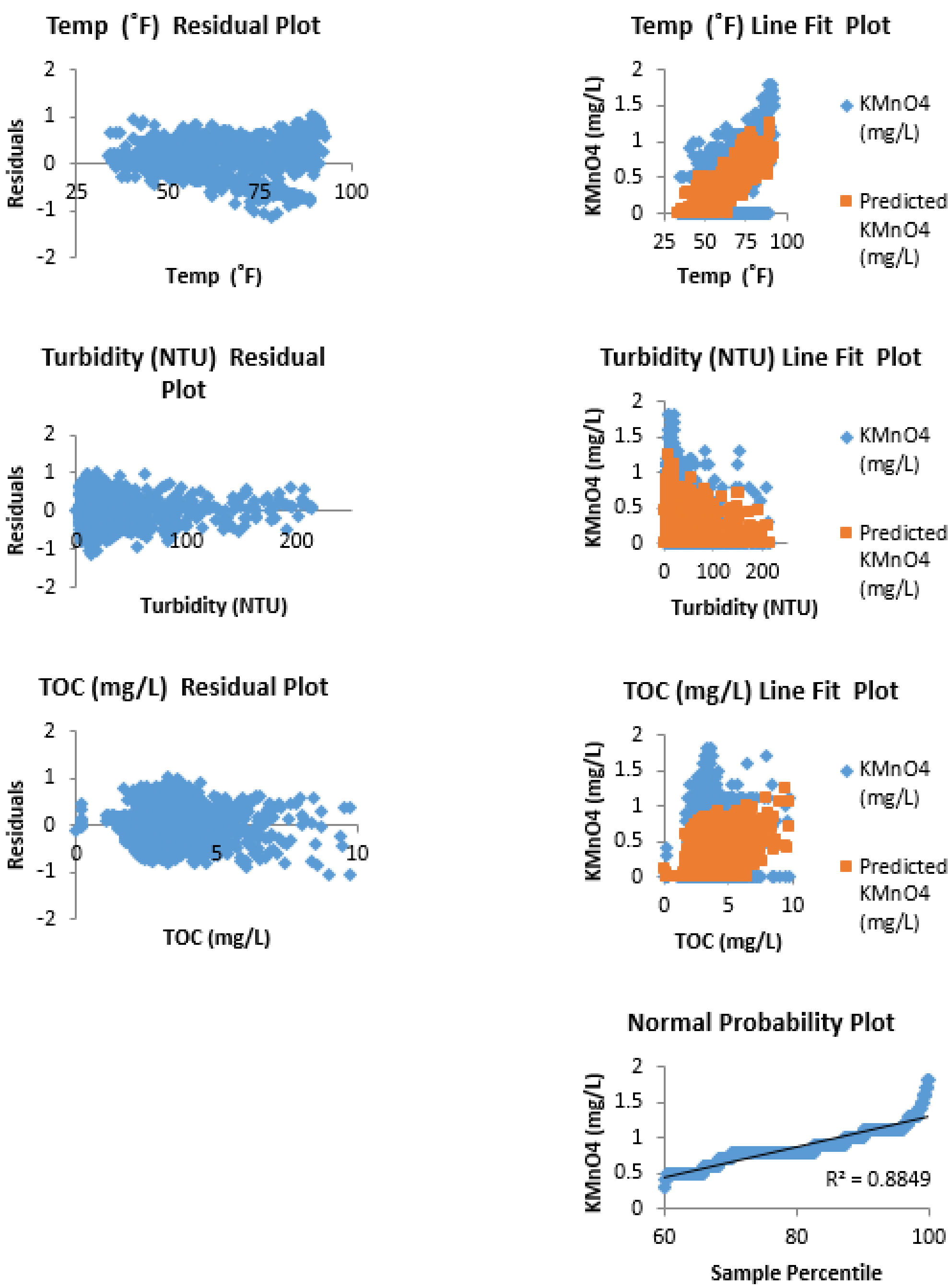


Figure D.1 Residual plots, line fit plots, and normal probability plot for WSSC's potassium permanganate dose regression

Conceptually, it is expected that the water quality-treatment dose relationship for potassium permanganate is not as strong as coagulant because it is not fed based on treatability needs (personal communication, WSSC, 7/26/16).

A sensitivity analysis was conducted to determine the potential percent change in potassium permanganate dose based on observed historic changes in each predictor variable. Using the developed regression equation, if the water quality-treatment dose relationship is solved twice using the average observed daily turbidity and TOC values – once with the observed maximum and once with the observed minimum daily temperature values – there is a resulting 342 percent change in predicted potassium permanganate dose. Similarly, holding other predictor variables constant at average observed values results in a 67 percent change in predicted dose based on observed high and low turbidity values and a 113 percent change in predicted dose based on observed high and low TOC values.

Sulfuric Acid

The following relationship (Equation D.2) was identified between sulfuric acid, water temperature, turbidity, and TOC where R^2=0.46. All predictor variables, the intercept, and the overall F test statistic have p<0.0001 and are significant at a 95 percent confidence level.

$$mg/L\ Sulfuric\ Acid = -19 + 0.46(°F\ Temp) - 0.10(NTU\ Turbidity) + 0.77(mg/L\ TOC) \quad (D.2)$$

Figure D.2 provided for visual inspection of the residual plots, line fit plots, and normal probability plot associated with this regression. Negative predicted dose values were forced to zero in the line fit plots. Note that the normal probability plot was developed for all non-zero values since this chemical is not applied during part of the year.

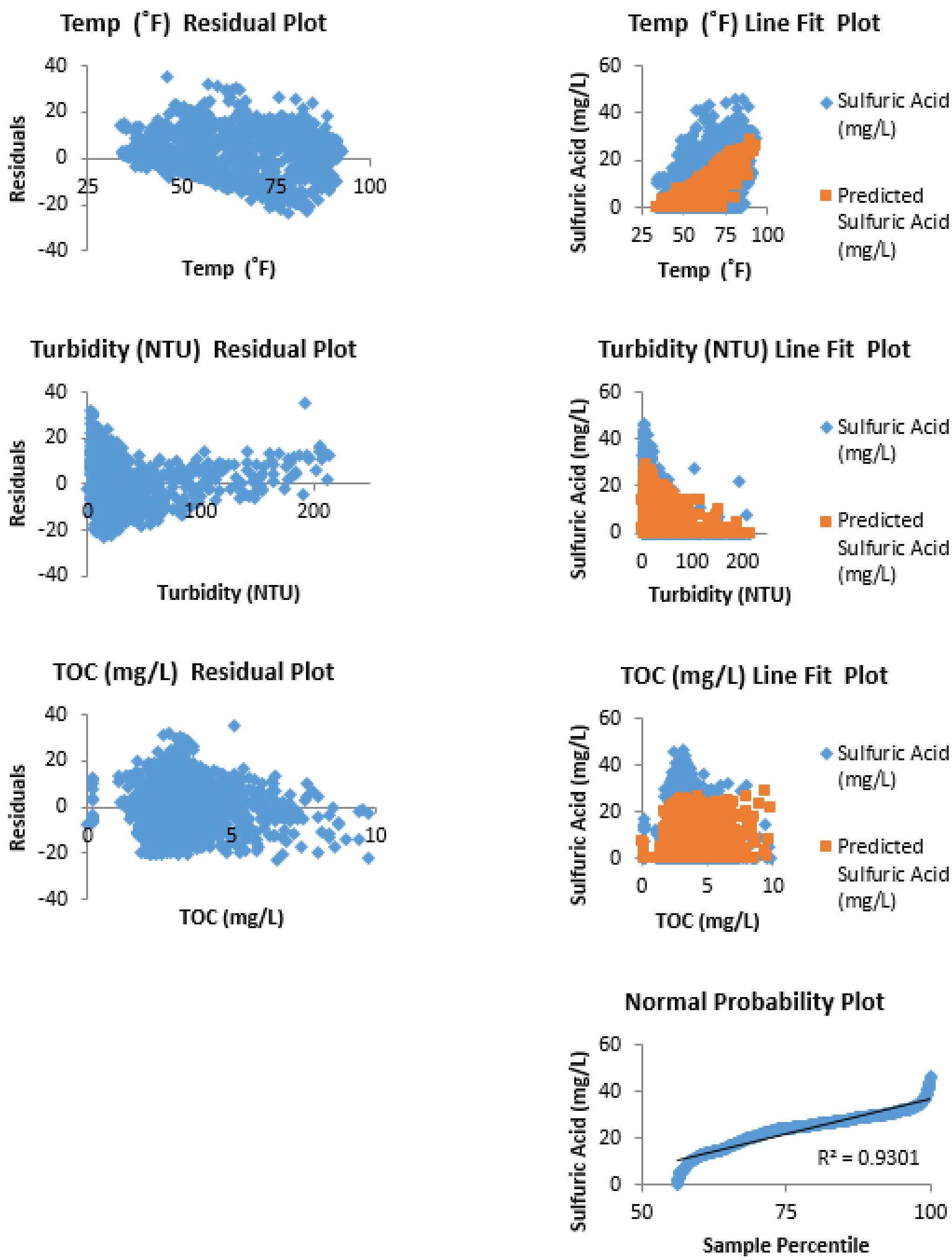


Figure D.2 Residual plots, line fit plots, and normal probability plot for WSSC's sulfuric acid dose regression

Conceptually, it is expected that the water quality-treatment dose relationship for sulfuric acid (and potassium permanganate) is not as strong as coagulant because it is not fed inflexibly based on month, but flexibly based on treatability needs (personal communication, WSSC, 7/26/16). A treatability example: In winter, it may be fine to remove less TOC and in summer it may be necessary to remove more TOC to avoid disinfection by-products. These types of treatability considerations drive the use of sulfuric acid. Not only is the magnitude of TOC important, but also the desired removal extent. Because of this, higher temperatures are associated with greater desired TOC removal. To this end, temperature is expected to be an important variable in the WSSC sulfuric acid water quality-treatment dose relationship.

A sensitivity analysis was conducted to determine the potential percent change in sulfuric acid dose based on observed historic changes in each predictor variable. Using the developed regression equation, if the water quality-treatment dose relationship is solved twice using the average observed daily turbidity and TOC values – once with the observed maximum and once with the observed minimum daily temperature values – there is a resulting 479 percent change in predicted sulfuric acid dose. Similarly, holding other predictor variables constant at average observed values results in a 205 percent change in predicted dose based on observed high and low turbidity values and a 76 percent change in predicted dose based on observed high and low TOC values.

Lime

Using the 1/2/2007 to 2/29/2016 time period, the following relationship (Equation D.3) was identified between lime, water temperature, turbidity, and TOC where R^2=0.35. The intercept, temperature, turbidity, and the overall F test statistic have $p<0.0001$ and are significant at a 95 percent confidence level. TOC has $p=0.05$ for this relationship.

$$mg/L\,Lime = -5.3 + 0.18(°F\,Temp) - 0.0071(NTU\,Turbidity) + 0.72(mg/L\,TOC) \quad (\mathrm{D.3})$$

Figure D.3 is provided for visual inspection of the residual plots, line fit plots, and normal probability plot associated with this regression.

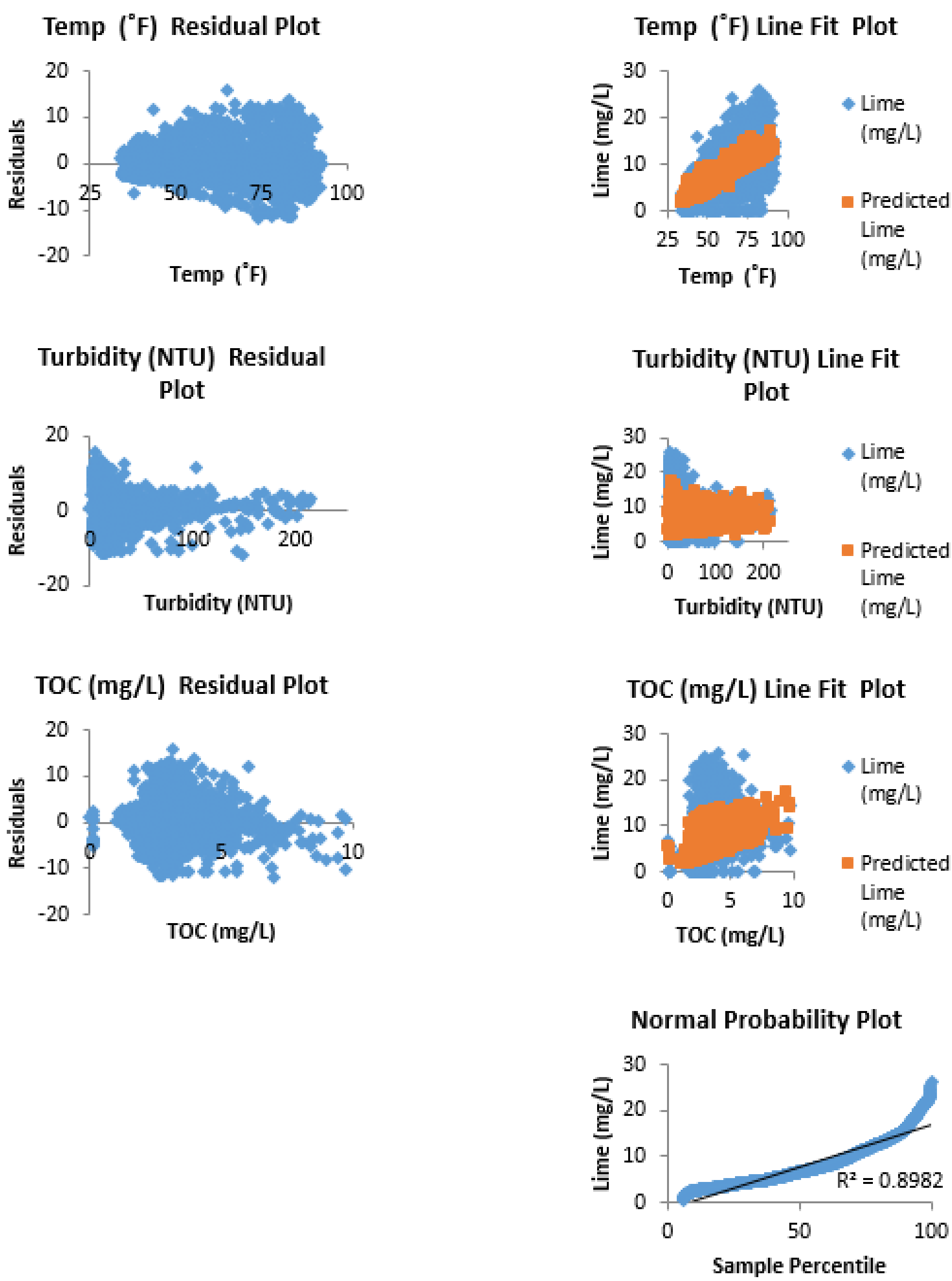


Figure D.3 Residual plots, line fit plots, and normal probability plot for WSSC's lime dose regression

A sensitivity analysis was conducted to determine the potential percent change in lime dose based on observed historic changes in each predictor variable. Using the developed regression equation, if the water quality-treatment dose relationship is solved twice using the average observed daily turbidity and TOC values – once with the observed maximum and once with the observed minimum daily temperature values – there is a resulting 242 percent change in predicted lime dose. Similarly, holding other predictor variables constant at average observed values results in a 26 percent change in predicted dose based on observed high and low turbidity values and a 92 percent change in predicted dose based on observed high and low TOC values.

FAIRFAX WATER

Potassium Permanganate (KMnO4)

Using the last ten years of data, the following relationship (Equation D.4) was identified between potassium permanganate dose, water temperature, and turbidity where R^2=0.22. All predictor variables, the intercept, and the overall F test statistic have p<0.0001 and are significant at a 95 percent confidence level.

$$mg/L\ KMnO_4 = -0.36 + 0.0078(°F\ Temp) - 0.00068(NTU\ Turbidity) \qquad (D.4)$$

Figure D.4 is provided for visual inspection of the residual plots, line fit plots, and normal probability plot associated with this regression. Negative predicted dose values were forced to zero in the line fit plots. Note that the normal probability plot was developed for all non-zero values since this chemical is not applied during part of the year.

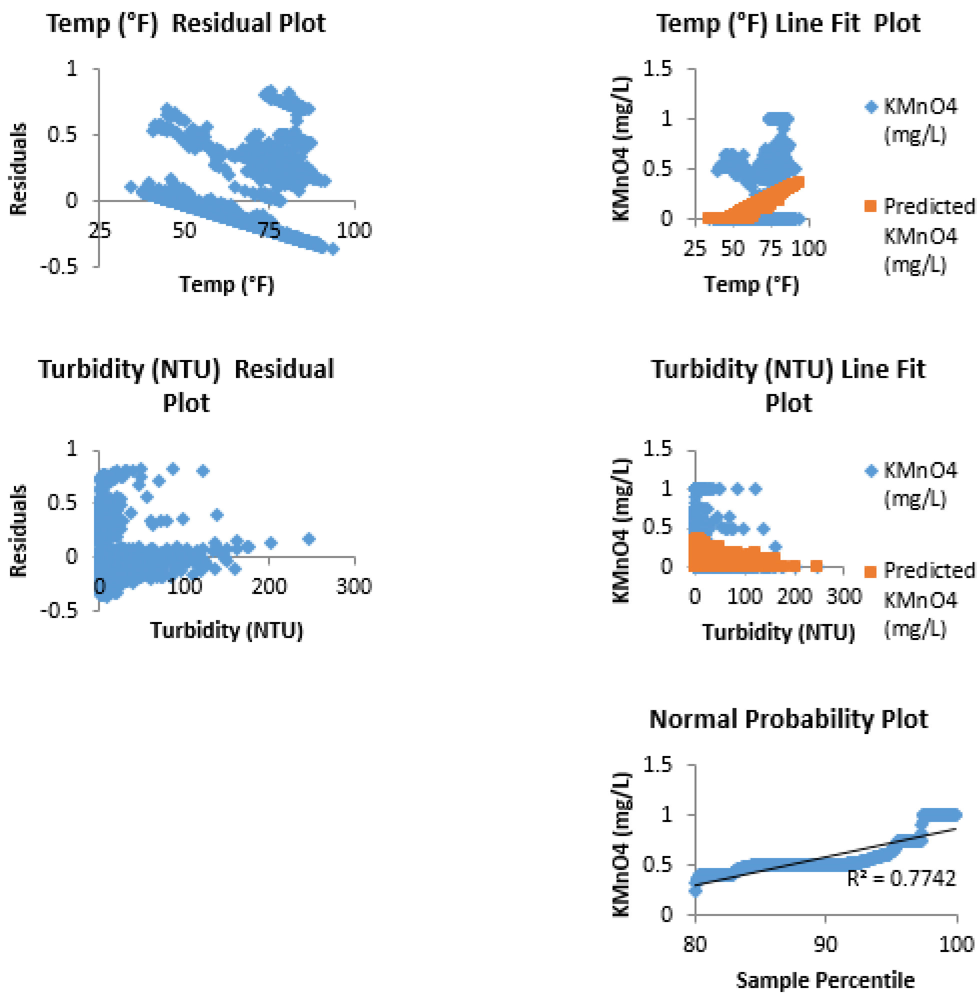


Figure D.4 Residual plots, line fit plots, and normal probability plot for Fairfax Water's potassium permanganate dose regression

A sensitivity analysis was conducted to determine the potential percent change in potassium permanganate based on observed historic changes in both predictor variables. Using the developed regression equation, if the water quality-treatment dose relationship is solved twice using the average observed daily turbidity – once with the observed maximum and once with the observed minimum daily temperature values – there is a resulting 219 percent change in predicted potassium permanganate dose. Similarly, holding temperature constant at average observed values results in a 63 percent change in predicted dose based on observed high and low turbidity values.

Sulfuric Acid

Using the last ten years of data, the following relationship (Equation D.5) was identified between sulfuric acid dose, water temperature, turbidity, and TOC where R^2=0.2. All predictor variables, the intercept, and the overall F test statistic have p<0.0001 and are significant at a 95 percent confidence level.

$$mg/L\, Sulfuric\ Acid = 3.0 + 0.11(°F\ Temp) - 0.13(NTU\ Turbidity) + 0.39\left(\frac{mg}{L}TOC\right)\ (D.5)$$

Figure D.5 is provided for visual inspection of the residual plots, line fit plots, and normal probability plot associated with this regression. Negative predicted dose values were forced to zero in the line fit plots.

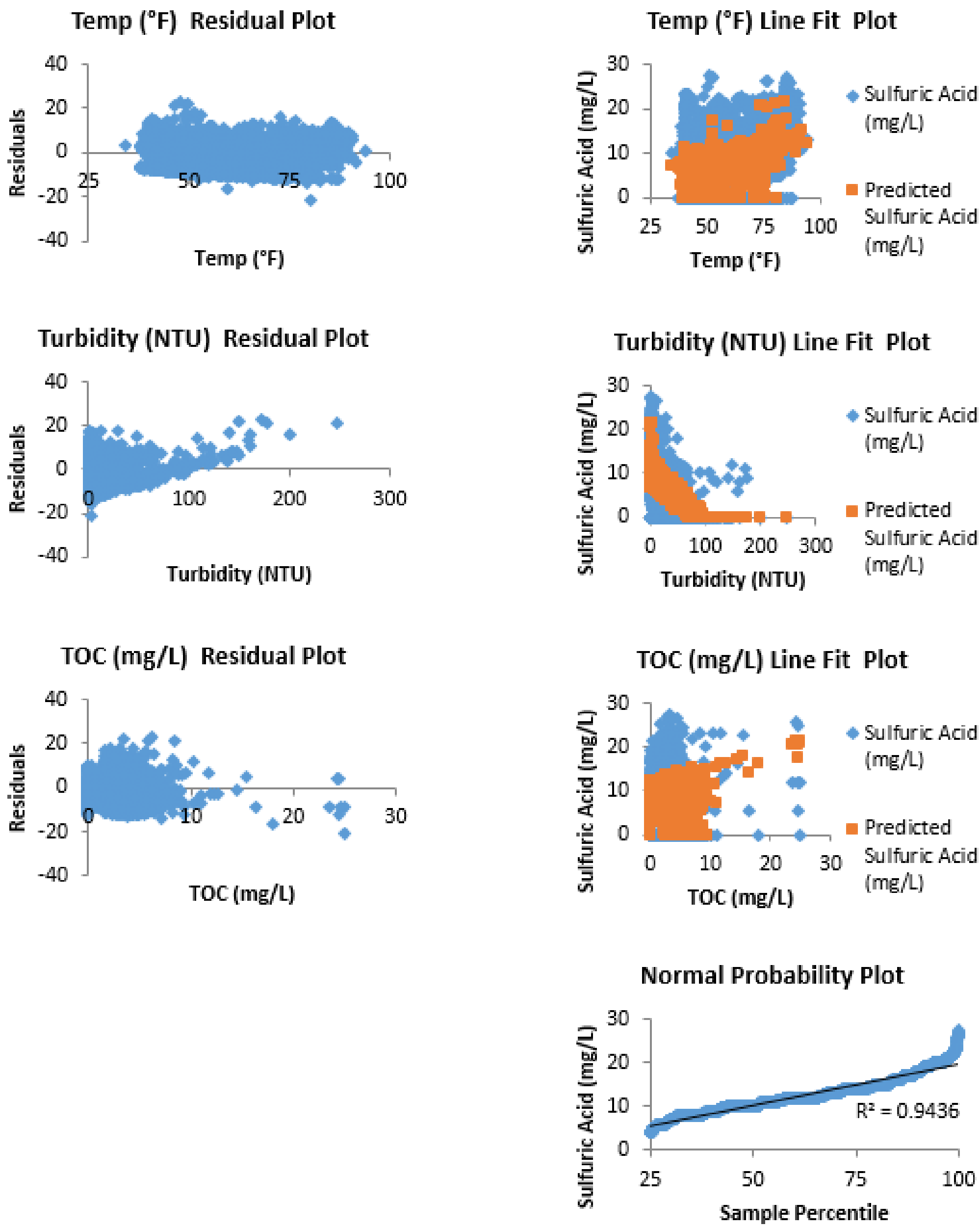


Figure D.5 Residual plots, line fit plots, and normal probability plot for Fairfax Water's sulfuric acid dose regression

A sensitivity analysis was conducted to determine the potential percent change in sulfuric acid based on observed historic changes in each predictor variable. Using the developed regression equation, if the water quality-treatment dose relationship is solved twice using the average observed daily turbidity and TOC values – once with the observed maximum and once with the observed minimum daily temperature values – there is a resulting 69 percent change in predicted sulfuric acid dose. Similarly, holding other predictor variables constant at average observed values results in a 336 percent change in predicted dose based on observed high and low turbidity values and a 102 percent change in predicted dose based on observed high and low TOC values.

APPENDIX E
REGRESSION RESULTS

WASHINGTON AQUEDUCT

Table E.1 provides the regression results for each combination of response and independent variables that were used to test relationships for Washington Aqueduct's data. Shading indicates relationships that were selected for discussion in the main body of this document. Int=intercept; Sig=significance; TOC=Total Organic Carbon; Temp=water temperature. The number of the coefficient and p value correspond to the number of the independent variable. So, for any particular regression, independent variable 1 has the p value shown in column "pvalue 1" and the coefficient shown in column "Coefficient 1."

Four decimal places are provided for the significance of the test statistic and the p value columns to allow comparison with a 0.0001 threshold. Coefficients are provided to two decimal places in this table for formatting reasons. Two significant digits are provided for each coefficient in Chapter 3.

Table E.1
Regression statistics for Washington Aqueduct

Response variable	Independent variables 1	2	3	R^2	Sig. of test statistic	Coefficient Int	1	2	3	pvalue Int	1	2	3	N
Coagulant dose	Month	Turbidity	UV 254	0.500	0.0000	2.30	0.02	0.004	9.50	0.0000	0.0000	0.0001	0.0000	1786
Coagulant dose	Month	UV254		0.496	0.0000	2.29	0.02	10.43		0.0000	0.0000	0.0000		1786
Coagulant dose	Month	Turbidity		0.310	0.0000	2.67	0.06	0.02		0.0000	0.0000	0.0000		1786
Coagulant dose	Turbidity	UV 254		0.482	0.0000	2.39	0.001	10.80		0.0000	0.3047	0.0000		1786
Coagulant dose	Turbidity			0.181	0.0000	3.07	0.02			0.0000	0.0000			1786
Coagulant dose	UV 254			0.482	0.0000	2.38	11.00			0.0000	0.0000			1786

(continued)

Response variable	Independent variables 1	2	3	R^2	Sig. of test statistic	Coefficient Int	1	2	3	pvalue Int	1	2	3	N
Coagulant dose	Season	Turbidity	UV 254	0.519	0.0000	2.22	0.10	0.01	9.19	0.0000	0.0000	0.0000	0.0000	1786
Coagulant dose	Season	UV254		0.512	0.0000	2.21	0.09	10.34		0.0000	0.0000	0.0000		1786
Coagulant dose	Season	Turbidity		0.332	0.0000	2.56	0.20	0.02		0.0000	0.0000	0.0000		1786
Coagulant dose	Temp	Turbidity	UV 254	0.569	0.0000	2.11	0.02	0.01	9.33	0.0000	0.0000	0.0000	0.0000	1786
Coagulant dose	Temp	UV254		0.560	0.0000	2.10	0.02	10.51		0.0000	0.0000	0.0000		1786
Coagulant dose	Temp	Turbidity		0.355	0.0000	2.55	0.03	0.02		0.0000	0.0000	0.0000		1786
Coagulant dose	Month	Turbidity	TOC	0.535	0.0000	2.01	0.02	0.01	0.35	0.0000	0.0016	0.0002	0.0000	256
Coagulant dose	Month	TOC		0.509	0.0000	1.96	0.01	0.43		0.0000	0.0658	0.0000		256
Coagulant dose	Turbidity	TOC		0.517	0.0000	2.07	0.01	0.40		0.0000	0.0059	0.0000		256
Coagulant dose	TOC			0.502	0.0000	2.01	0.44			0.0000	0.0000			256
Coagulant dose	Season	Turbidity	TOC	0.543	0.0000	1.97	0.09	0.01	0.35	0.0000	0.0002	0.0001	0.0000	256
Coagulant dose	Season	TOC		0.514	0.0000	1.93	0.06	0.42		0.0000	0.0135	0.0000		256
Coagulant dose	Temp	Turbidity	TOC	0.581	0.0000	1.88	0.02	0.01	0.34	20.7175	0.1478	0.0899	3.4035	256
Coagulant dose	Temp	TOC		0.546	0.0000	1.83	0.01	0.42		0.0000	0.0000	0.0000		256
Coagulant dose	Month	Turbidity	TOC+	0.513	0.0000	1.97	0.02	0.005	0.39	0.0000	0.0000	0.0000	0.0000	2042
Coagulant dose	Month	TOC+*		0.508	0.0000	1.93	0.02	0.43		0.0000	0.0000	0.0000		2042

(continued)

Response variable	Independent variables			R^2	Sig. of test statistic	Coefficient				pvalue				N
	1	2	3			Int	1	2	3	Int	1	2	3	
Coagulant dose	Month	Turbidity		0.312	0.0000	2.67	0.06	0.02		0.0000	0.0000	0.0000		2042
Coagulant dose	Turbidity	TOC+		0.498	0.0000	2.01	0.002	0.44		0.0000	0.1112	0.0000		2042
Coagulant dose	Turbidity			0.180	0.0000	3.07	0.02			0.0000	0.0000			2042
Coagulant dose	TOC+			0.497	0.0000	1.99	0.45			0.0000	0.0000			2042
Coagulant dose	Season	Turbidity	TOC+	0.530	0.0000	1.90	0.10	0.01	0.38	0.0000	0.0000	0.0000	0.0000	2042
Coagulant dose	Season	TOC+		0.522	0.0000	1.86	0.08	0.43		0.0000	0.0000	0.0000		2042
Coagulant dose	Season	Turbidity		0.335	0.0000	2.55	0.20	0.02		0.0000	0.0000	0.0000		2042
Coagulant dose	Temp	Turbidity	TOC+	0.576	0.0000	1.46	0.01	0.01	0.38	0.0000	0.0000	0.0000	0.0000	2042
Coagulant dose	Temp	TOC+		0.565	0.0000	1.44	0.01	0.43		0.0000	0.0000	0.0000		2042
Coagulant dose	Temp	Turbidity		0.357	0.0000	2.05	0.02	0.02		0.0000	0.0000	0.0000		2042
Chlorine dose	Month	Turbidity	UV 254	0.230	0.0000	5.18	0.07	-0.02	11.76	0.0000	0.0000	0.0000	0.0000	1786
Chlorine dose	Month	UV254		0.213	0.0000	5.21	0.09	8.21		0.0000	0.0000	0.0000		1786
Chlorine dose	Month	Turbidity		0.149	0.0000	5.63	0.12	0.01		0.0000	0.0000	0.0013		1786
Chlorine dose	Turbidity	UV 254		0.182	0.0000	5.43	-0.03	15.75		0.0000	0.0000	0.0000		1786
Chlorine dose	Turbidity			0.001	0.2668	6.43	0.00			0.0000	0.2668			1786
Chlorine dose	UV 254			0.130	0.0000	5.61	10.79			0.0000	0.0000			1786

(continued)

Response variable	Independent variables 1	2	3	R^2	Sig. of test statistic	Coefficient Int	1	2	3	pvalue Int	1	2	3	N
Chlorine dose	Season	Turbidity	UV 254	0.334	0.0000	4.77	0.40	-0.01	9.55	0.0000	0.0000	0.0001	0.0000	1786
Chlorine dose	Season	UV254		0.328	0.0000	4.78	0.43	7.60		0.0000	0.0000	0.0000		1786
Chlorine dose	Season	Turbidity		0.278	0.0000	5.13	0.50	0.01		0.0000	0.0000	0.0000		1786
Chlorine dose	Temp	Turbidity	UV 254	0.591	0.0000	4.28	0.08	-0.01	9.69	0.0000	0.0000	0.0010	0.0000	1786
Chlorine dose	Temp	UV254		0.589	0.0000	4.30	0.08	8.52		0.0000	0.0000	0.0000		1786
Chlorine dose	Temp	Turbidity		0.527	0.0000	4.75	0.09	0.01		0.0000	0.0000	0.0000		1786
Chlorine dose	Month	Turbidity	TOC	0.278	0.0000	4.69	0.07	-0.02	0.52	0.0000	0.0002	0.0172	0.0000	256
Chlorine dose	Month	TOC		0.261	0.0000	4.75	0.08	0.41		0.0000	0.0000	0.0000		256
Chlorine dose	NTU	TOC		0.237	0.0000	4.85	-0.03	0.64		0.0000	0.0001	0.0000		256
Chlorine dose	TOC			0.189	0.0000	5.05	0.50			0.0000	0.0000			256
Chlorine dose	Season	NTU	TOC	0.349	0.0000	4.46	0.34	-0.01	0.43	0.0000	0.0000	0.0880	0.0000	256
Chlorine dose	Season	TOC		0.342	0.0000	4.50	0.37	0.36		0.0000	0.0000	0.0000		256
Chlorine dose	Temp	NTU	TOC	0.570	0.0000	4.05	0.08	-0.01	0.40	0.0000	0.0000	0.2554	0.0000	256
Chlorine dose	Temp	TOC		0.568	0.0000	4.07	0.08	0.36		0.0000	0.0000	0.0000		256
Chlorine dose	Month	Turbidity	TOC+	0.245	0.0000	4.72	0.07	-0.02	0.51	0.0000	0.0000	0.0000	0.0000	2042
Chlorine dose	Month	TOC+		0.224	0.0000	4.88	0.09	0.36		0.0000	0.0000	0.0000		2042

(continued)

Response variable	Independent variables 1	2	3	R^2	Sig. of test statistic	Coefficient Int	1	2	3	pvalue Int	1	2	3	N
Chlorine dose	Month	Turbidity		0.149	0.0000	5.62	0.12	0.01		0.0000	0.0000	0.0004		2042
Chlorine dose	Turbidity	TOC+		0.203	0.0000	4.83	-0.03	0.66		0.0000	0.0000	0.0000		2042
Chlorine dose	Turbidity			0.001	0.2392	6.42	0.00			0.0000	0.2392			2042
Chlorine dose	TOC+			0.147	0.0000	5.16	0.46			0.0000	0.0000			2042
Chlorine dose	Season	Turbidity	TOC+	0.343	0.0000	4.41	0.38	-0.01	0.42	0.0000	0.0000	0.0000	0.0000	2042
Chlorine dose	Season	TOC+		0.335	0.0000	4.49	0.42	0.33		0.0000	0.0000	0.0000		2042
Chlorine dose	Season	Turbidity		0.276	0.0000	5.13	0.49	0.01		0.0000	0.0000	0.0000		2042
Chlorine dose	Temp	Turbidity	TOC+	0.592	0.0000	2.50	0.05	-0.01	0.41	0.0000	0.0000	0.0001	0.0000	2042
Chlorine dose	Temp	TOC+		0.589	0.0000	2.52	0.05	0.36		0.0000	0.0000	0.0000		2042
Chlorine dose	Temp	Turbidity		0.522	0.0000	3.14	0.05	0.01		0.0000	0.0000	0.0000		2042

*TOC+ indicates used of a combined TOC and UV254 data set where UV254 values were converted to TOC using an empirically developed relationship and combined with observed TOC values.

WASHINGTON SUBURBAN SANITARY COMMISSION

Table E.2 provides the regression results for each combination of response and independent variables that were used to test relationships for WSSC's data. Shading indicates relationships that were selected for discussion in the main body of this document. Int=intercept; Sig=significance; TOC=Total Organic Carbon; Temp=water temperature. The number of the coefficient and p value correspond to the number of the independent variable. So, for any particular regression, independent variable 1 has the p value shown in column "pvalue 1" and the coefficient shown in column "Coefficient 1."

Four decimal places are provided for the significance of the test statistic and the p value columns to allow comparison with a 0.0001 threshold. Coefficients are provided to two decimal places in this table for formatting reasons. Two significant digits are provided for each coefficient in Chapter 3.

Table E.2
Regression statistics for WSSC

Response	Independent variables				Sig. of test	Coefficient				pvalue				
variable	1	2	3	R^2	statistic	Int	1	2	3	Int	1	2	3	N
Coagulant dose	Month	Turbidity	TOC	0.741	0.0000	2.20	-0.01	0.04	0.62	0.0000	0.1588	0.0000	0.0000	1996
Coagulant dose	Month	TOC		0.431	0.0000	2.14	-0.10	1.13		0.0000	0.0000	0.0000		1996
Coagulant dose	Month	Turbidity		0.639	0.0000	3.33	0.08	0.05		0.0000	0.0000	0.0000		1996
Coagulant dose	Turbidity	TOC		0.740	0.0000	2.17	0.04	0.61		0.0000	0.0000	0.0000		1996
Coagulant dose	Turbidity			0.623	0.0000	3.85	0.05			0.0000	0.0000			1996
Coagulant dose	TOC			0.406	0.0000	1.78	1.03			0.0000	0.0000			1996
Coagulant dose	Season	Turbidity	TOC	0.740	0.0000	2.17	0.00	0.04	0.61	0.0000	0.9603	0.0000	0.0000	1996
Coagulant dose	Season	TOC		0.445	0.0000	2.40	-0.39	1.15		0.0000	0.0000	0.0000		1996
Coagulant dose	Season	Turbidity		0.645	0.0000	3.10	0.28	0.05		0.0000	0.0000	0.0000		1996

(continued)

Response variable	Independent variables 1	2	3	R^2	Sig. of test statistic	Coefficient Int	1	2	3	pvalue Int	1	2	3	N
Coagulant dose	Temp	Turbidity	TOC	0.740	0.0000	2.16	0.00	0.04	0.61	0.0000	0.9092	0.0000	0.0000	1996
Coagulant dose	Temp	TOC		0.431	0.0000	2.89	-0.02	1.10		0.0000	0.0000	0.0000		1996
Coagulant dose	Temp	Turbidity		0.637	0.0000	2.86	0.02	0.05		0.0000	0.0000	0.0000		1996
Sulfuric acid dose	Month	Turbidity	TOC	0.260	0.0000	0.76	1.28	-0.14	1.39	0.2806	0.0000	0.0000	0.0000	1996
Sulfuric acid dose	Month	TOC		0.173	0.0000	0.96	1.58	-0.27		0.1977	0.0000	0.2232		1996
Sulfuric acid dose	Month	Turbidity		0.247	0.0000	3.29	1.47	-0.11		0.0000	0.0000	0.0000		1996
Sulfuric acid dose	Turbidity	TOC		0.162	0.0000	5.02	-0.17	2.95		0.0000	0.0000	0.0000		1996
Sulfuric acid dose	Turbidity			0.090	0.0000	13.15	-0.12			0.0000	0.0000			1996
Sulfuric acid dose	TOC			0.015	0.0000	6.61	1.22			0.0000	0.0000			1996
Sulfuric acid dose	Season	Turbidity	TOC	0.447	0.0000	-5.21	6.91	-0.08	0.08	0.0000	0.0000	0.0000	0.6991	1996
Sulfuric acid dose	Season	TOC		0.415	0.0000	-5.68	7.69	-1.01		0.0000	0.0000	0.0000		1996
Sulfuric acid dose	Season	Turbidity		0.447	0.0000	-5.09	6.94	-0.08		0.0000	0.0000	0.0000		1996
Sulfuric acid dose	Temp	Turbidity	TOC	0.458	0.0000	-18.76	0.46	-0.10	0.77	0.0000	0.0000	0.0000	0.0001	1996
Sulfuric acid dose	Temp	TOC		0.411	0.0000	-20.54	0.51	-0.42		0.0000	0.0000	0.0181		1996
Sulfuric acid dose	Temp	Turbidity		0.454	0.0000	-17.88	0.48	-0.09		0.0000	0.0000	0.0000		1996
KMnO4 dose	Month	Turbidity	TOC	0.211	0.0000	-0.11	0.03	0.00	0.11	0.0000	0.0000	0.0000	0.0000	1996

(continued)

Response variable	Independent variables			R^2	Sig. of test statistic	Coefficient				pvalue				N
	1	2	3			Int	1	2	3	Int	1	2	3	
KMnO4 dose	Month	TOC		0.155	0.0000	-0.10	0.04	0.06		0.0001	0.0000	0.0000		1996
KMnO4 dose	Month	Turbidity		0.146	0.0000	0.09	0.05	0.00		0.0000	0.0000	0.0000		1996
KMnO4 dose	Turbidity	TOC		0.167	0.0000	-0.01	0.00	0.15		0.8011	0.0000	0.0000		1996
KMnO4 dose	Turbidity			0.025	0.0000	0.40	0.00			0.0000	0.0000			1996
KMnO4 dose	TOC			0.078	0.0000	0.04	0.10			0.1476	0.0000			1996
KMnO4 dose	Season	Turbidity	TOC	0.303	0.0000	-0.26	0.17	0.00	0.08	0.0000	0.0000	0.0000	0.0000	1996
KMnO4 dose	Season	TOC		0.280	0.0000	-0.27	0.19	0.04		0.0000	0.0000	0.0000		1996
KMnO4 dose	Season	Turbidity		0.272	0.0000	-0.14	0.20	0.00		0.0000	0.0000	0.0001		1996
KMnO4 dose	Temp	Turbidity	TOC	0.434	0.0000	-0.80	0.02	-0.002	0.07	0.0000	0.0000	0.0000	0.0000	1996
KMnO4 dose	Temp	TOC		0.413	0.0000	-0.84	0.02	0.05		0.0000	0.0000	0.0000		1996
KMnO4 dose	Temp	Turbidity		0.402	0.0000	-0.72	0.02	0.00		0.0000	0.0000	0.0001		1996
Lime dose	Month	Turbidity	TOC	0.170	0.0000	2.47	0.42	-0.02	1.04	0.0000	0.0000	0.0000	0.0000	1996
Lime dose	Month	TOC		0.157	0.0000	2.50	0.47	0.77		0.0000	0.0000	0.0000		1996
Lime dose	Month	Turbidity		0.129	0.0000	4.36	0.57	0.00		0.0000	0.0000	0.2527		1996
Lime dose	Turbidity	TOC		0.112	0.0000	3.87	-0.03	1.56		0.0000	0.0000	0.0000		1996

(continued)

Response variable	Independent variables 1	2	3	R^2	Sig. of test statistic	Coefficient Int	1	2	3	pvalue Int	1	2	3	N
Lime dose	Turbidity			0.002	0.0343	8.17	-0.01			0.0000	0.0343			1996
Lime dose	TOC			0.080	0.0000	4.19	1.21			0.0000	0.0000			1996
Lime dose	Season	Turbidity	TOC	0.313	0.0000	0.20	2.48	0.00	0.53	0.5295	0.0000	0.3859	0.0000	1996
Lime dose	Season	TOC		0.312	0.0000	0.18	2.51	0.48		0.5676	0.0000	0.0000		1996
Lime dose	Season	Turbidity		0.303	0.0000	1.00	2.73	0.01		0.0003	0.0000	0.0371		1996
Lime dose	Temp	Turbidity	TOC	0.353	0.0000	-5.31	0.18	-0.01	0.72	0.0000	0.0000	0.0462	0.0000	1996
Lime dose	Temp	TOC		0.352	0.0000	-5.44	0.18	0.63		0.0000	0.0000	0.0000		1996
Lime dose	Temp	Turbidity		0.333	0.0000	-4.49	0.20	0.01		0.0000	0.0000	0.0584		1996

FAIRFAX WATER

Table E.3 provides the regression results for each combination of response and independent variables that were used to test relationships for Fairfax Water's data. Shading indicates relationships that were selected for discussion in the main body of this document. Int=intercept; Sig=significance; TOC=Total Organic Carbon; Temp=water temperature. The number of the coefficient and p value correspond to the number of the independent variable. So, for any particular regression, independent variable 1 has the p value shown in column "pvalue 1" and the coefficient shown in column "Coefficient 1."

Four decimal places are provided for the significance of the test statistic and the p value columns to allow comparison with a 0.0001 threshold. Coefficients are provided to two decimal places in this table for formatting reasons. Two significant digits are provided for each coefficient in Chapter 3.

Table E.3
Regression statistics for Fairfax Water

Response variable	Independent variables 1	2	3	R^2	Sig. of test statistic	Coefficient Int	1	2	3	pvalue Int	1	2	3	N
Coagulant dose	Month	Turbidity	TOC	0.477	0.0000	2.74	0.04	0.06	0.11	0.0000	0.0000	0.0000	0.0000	3627
Coagulant dose	Month	TOC		0.113	0.0000	3.16	-0.02	0.35		0.0000	0.0054	0.0000		3627
Coagulant dose	Month	Turbidity		0.467	0.0000	2.94	0.05	0.07		0.0000	0.0000	0.0000		3627
Coagulant dose	Turbidity	TOC		0.472	0.0000	2.96	0.06	0.12		0.0000	0.0000	0.0000		3627
Coagulant dose	Turbidity			0.459	0.0000	3.25	0.07			0.0000	0.0000			3627
Coagulant dose	TOC			0.111	0.0000	3.03	0.34			0.0000	0.0000			3627
Coagulant dose	Season	Turbidity	TOC	0.477	0.0000	2.68	0.12	0.06	0.11	0.0000	0.0000	0.0000	0.0000	3627
Coagulant dose	Season	TOC		0.113	0.0000	3.20	-0.07	0.35		0.0000	0.0045	0.0000		3627
Coagulant dose	Season	Turbidity		0.467	0.0000	2.86	0.15	0.07		0.0000	0.0000	0.0000		3627

(continued)

Response variable	Independent variables 1	2	3	R^2	Sig. of test statistic	Coefficient Int	1	2	3	pvalue Int	1	2	3	N
Coagulant dose	Temp	Turbidity	TOC	0.482	0.0000	2.20	0.01	0.06	0.11	0.0000	0.0000	0.0000	0.0000	3627
Coagulant dose	Temp	TOC		0.111	0.0000	2.88	0.00	0.34		0.0000	0.1958	0.0000		3627
Coagulant dose	Temp	Turbidity		0.471	0.0000	2.39	0.01	0.07		0.0000	0.0000	0.0000		3627
Sulfuric acid dose	Month	Turbidity	TOC	0.165	0.0000	8.03	0.28	-0.13	0.38	0.0000	0.0000	0.0000	0.0000	3622
Sulfuric acid dose	Month	TOC		0.045	0.0000	7.15	0.40	-0.11		0.0000	0.0000	0.0795		3622
Sulfuric acid dose	Month	Turbidity		0.156	0.0000	8.71	0.31	-0.12		0.0000	0.0000	0.0000		3622
Sulfuric acid dose	Turbidity	TOC		0.144	0.0000	9.68	-0.14	0.48		0.0000	0.0000	0.0000		3622
Sulfuric acid dose	Turbidity			0.129	0.0000	10.81	-0.13			0.0000	0.0000			3622
Sulfuric acid dose	TOC			0.000	0.7986	9.53	-0.02			0.0000	0.7986			3622
Sulfuric acid dose	Season	Turbidity	TOC	0.181	0.0000	7.04	1.15	-0.13	0.34	0.0000	0.0000	0.0000	0.0000	3622
Sulfuric acid dose	Season	TOC		0.068	0.0000	6.01	1.54	-0.14		0.0000	0.0000	0.0181		3622
Sulfuric acid dose	Season	Turbidity		0.174	0.0000	7.58	1.25	-0.12		0.0000	0.0000	0.0000		3622
Sulfuric acid dose	Temp	Turbidity	TOC	0.203	0.0000	3.00	0.11	-0.13	0.39	0.0000	0.0000	0.0000	0.0000	3622
Sulfuric acid dose	Temp	TOC		0.085	0.0000	1.62	0.13	-0.07		0.0006	0.0000	0.2073		3622
Sulfuric acid dose	Temp	Turbidity		0.194	0.0000	3.64	0.11	-0.12		0.0000	0.0000	0.0000		3622
KMnO4 dose	Month	Turbidity	TOC	0.040	0.0000	0.04	0.01	0.00	0.01	0.0002	0.0000	0.0000	0.0053	3627

(continued)

Response variable	Independent variables 1	2	3	R^2	Sig. of test statistic	Coefficient Int	1	2	3	pvalue Int	1	2	3	N
KMnO4 dose	Month	TOC		0.032	0.0000	0.03	0.01	0.00		0.0030	0.0000	0.3451		3627
KMnO4 dose	Month	Turbidity		0.038	0.0000	0.05	0.01	0.00		0.0000	0.0000	0.0000		3627
KMnO4 dose	Turbidity	TOC		0.015	0.0000	0.11	0.00	0.01		0.0000	0.0000	0.0000		3627
KMnO4 dose	Turbidity			0.010	0.0000	0.13	0.00			0.0000	0.0000			3627
KMnO4 dose	TOC			0.001	0.0312	0.11	0.01			0.0000	0.0312			3627
KMnO4 dose	Season	Turbidity	TOC	0.088	0.0000	-0.03	0.06	0.00	0.00	0.0015	0.0000	0.0001	0.1772	3627
KMnO4 dose	Season	TOC		0.084	0.0000	-0.04	0.06	0.00		0.0001	0.0000	0.9150		3627
KMnO4 dose	Season	Turbidity		0.088	0.0000	-0.03	0.06	0.00		0.0039	0.0000	0.0001		3627
KMnO4 dose	Temp	Turbidity	TOC	0.223	0.0000	-0.37	0.01	0.00	0.00	0.0000	0.0000	0.0001	0.0387	3627
KMnO4 dose	Temp	TOC		0.220	0.0000	-0.38	0.01	0.00		0.0000	0.0000	0.4424		3627
KMnO4 dose	Temp	Turbidity		0.222	0.0000	-0.36	0.01	0.00		0.0000	0.0000	0.0006		3627

ADDITIONAL ANALYSES

Two analyses were performed to further evaluate the water quality-treatment dose relationships. Specifically, the relationships were explored with one year of data and, for select treatment chemicals, temperature-only relationships were developed for comparison purposes.

One Year Relationships

The water quality-treatment dose relationships were evaluated using one year of data. Additional testing with one year of data (instead of the full selected period that represents current utility operations) removes statistical significance derived only from lengthy input data sets and removes potentially repeating trends found in the temperature data set. The year 2015 was selected, being the most recent common year of data for the utilities.

For Fairfax Water, the independent variables for the selected relationships remain significant with only one year of data (n=365) (Table E.4). The R^2 increases for relationships with one year of data for all three response variables. For WSSC, the turbidity and TOC variables become insignificant ($p>0.05$) in the relationships for sulfuric acid, potassium permanganate, and lime (Table E.5). The R^2 increases for relationships with one year of data for both response variables for Washington Aqueduct (Table E.6); however, the turbidity variable becomes insignificant in the chlorine dose relationship.

The purpose of this exercise was to evaluate the significance of the variables using a shorter period of record. Despite lower R^2 values, the longer period of record was preferred for use in subsequent steps of the project in an effort not to over-fit the data. Developing relationships with more complete data sets that are physically understood to coincide with current treatment practices is expected to make more robust water quality-treatment dose relationships.

Table E.4
Regressions for Fairfax Water for the year 2015 (n=365)

Response Variable	Independent variables			R^2	Sig of test stat	Coef Int	Coef 1	Coef 2	Coef 3	pvalue Int	pvalue 1	pvalue 2	pvalue 3	N	Years
Coagulant Dose	Temp	Turbidity	TOC	0.705	0.0000	6.80	0.09	0.43	5.83	0.0006	0.0003	0.0000	0.0000	365	2015
Coagulant Dose*	Temp	Turbidity	TOC	0.482	0.0000	17.62	0.10	0.51	0.91	0.0000	0.0000	0.0000	0.0000	3627	1/1/2006 to 12/31/15**
Sulfuric Acid Dose	Temp	Turbidity	TOC	0.241	0.0000	7.17	0.08	-0.09	-1.25	0.0000	0.0000	0.0000	0.0002	365	2015
Sulfuric Acid Dose	Temp	Turbidity	TOC	0.203	0.0000	3.00	0.11	-0.13	0.39	0.0000	0.0000	0.0000	0.0000	3622	1/1/2006 to 12/31/15**
KMnO4 Dose	Temp	Turbidity		0.662	0.0000	-1.09	0.02	0.00		0.0000	0.0000	0.0942		365	2015
KMnO4 Dose	Temp	Turbidity		0.222	0.0000	-0.36	0.01	0.00		0.0000	0.0000	0.0006		3627	1/1/2006 to 12/31/15**

*The regressions for the full period of analysis are shown using shading for comparison.
**The time period for analysis that represents current operating conditions as determined through utility discussions. These time periods were used in development of the draft water quality-treatment dose relationships.

Table E.5
Regressions for WSSC for the January 2015 to February 2016 time period

Response variable	Independent variables			R^2	Sig of test stat	Coef Int	Coef 1	Coef 2	Coef 3	pvalue Int	pvalue 1	pvalue 2	pvalue 3	N	Year
Coagulant Dose	Turbidity	TOC		0.759	0.0000	2.44	0.07	0.32		0.0000	0.0000	0.0048		61	Jan 2015 to Feb 2016
Coagulant Dose*	Turbidity	TOC		0.740	0.0000	2.17	0.04	0.61		0.0000	0.0000	0.0000		1996	1/2/2007 to 2/29/2016**
Sulfuric Acid Dose	Temp	Turbidity	TOC	0.742	0.0000	-24.73	0.66	-0.07	-0.91	0.0000	0.0000	0.0910	0.2074	61	Jan 2015 to Feb 2016
Sulfuric Acid Dose	Temp	Turbidity	TOC	0.458	0.0000	-18.76	0.46	-0.10	0.77	0.0000	0.0000	0.0000	0.0001	1996	1/2/2007 to 2/29/2016**
KMnO4 Dose	Temp	Turbidity	TOC	0.608	0.0000	-0.45	0.02	0.00	0.03	0.0003	0.0000	0.8524	0.2236	61	Jan 2015 to Feb 2016
KMnO4 Dose	Temp	Turbidity	TOC	0.434	0.0000	-0.80	0.02	0.00	0.07	0.0000	0.0000	0.0000	0.0000	1996	1/2/2007 to 2/29/2016**
Lime Dose	Temp	Turbidity	TOC	0.763	0.0000	-13.59	0.41	0.01	-0.31	0.0000	0.0000	0.6091	0.4681	61	Jan 2015 to Feb 2016
Lime Dose	Temp	Turbidity	TOC	0.353	0.0000	-5.31	0.18	-0.01	0.72	0.0000	0.0000	0.0462	0.0000	1996	1/2/2007 to 2/29/2016**

*The regressions for the full period of analysis are shown using shading for comparison.
**The time period for analysis that represents current operating conditions as determined through utility discussions. These time periods were used in development of the draft water quality-treatment dose relationships.

Table E.6
Regressions for Washington Aqueduct for the year 2015 (n=398)

Response variable	Independent variables**			R^2	Sig of test stat	Coef Int	Coef 1	Coef 2	Coef 3	pvalue Int	pvalue 1	pvalue 2	pvalue 3	N	Year
Coagulant Dose	Temp	Turbidity	TOC+	0.731	0.0000	19.83	0.05	0.08	4.40	0.0000	0.0000	0.0007	0.0000	398	2015
Coagulant Dose*	Temp	Turbidity	TOC+	0.576	0.0000	17.54	0.13	0.08	4.57	0.0000	0.0000	0.0000	0.0000	2042	1/1/2011 to 12/31/2015†
Chlorine Dose	Temp	Turbidity	TOC+	0.597	0.0000	2.36	0.04	0.00	0.49	0.0000	0.0000	0.9272	0.0000	398	2015
Chlorine Dose	Temp	Turbidity	TOC+	0.592	0.0000	2.50	0.05	-0.01	0.41	0.0000	0.0000	0.0001	0.0000	2042	1/1/2011 to 12/31/2015†

*The regressions for the full period of analysis are shown using shading for comparison.
**"TOC+" is a compiled variable data set derived from both UV 254 and TOC monitoring data. See the Task 6 memo for a full description of the meaning of "TOC+."
†The time period for analysis that represents current operating conditions as determined through utility discussions. These time periods were used in development of the draft water quality-treatment dose relationships (Task 6 memo).

Temperature-Only Relationships

Per the utilities, sulfuric acid and lime may be most correlated with only temperature. It was suggested that regressions between those treatment chemicals and a lone temperature variable be explored. To this end, relationships with only temperature as an independent variable for sulfuric acid, potassium permanganate, and lime for WSSC and Fairfax Water were developed (Table E.7 and Table E.8).

Two regressions were developed for each treatment chemical under consideration at each utility (shown in white); namely, a temperature-only relationship for one year of historic observed data and a temperature-only relationship for the full time period under consideration. While the coefficients for the temperature variables are significant in all cases, the R^2 values for the full periods decrease slightly from original relationships (shown in gray). WSSC relationships for sulfuric acid, potassium permanganate, and lime as well as Fairfax Water relationship for potassium permanganate, the R^2 values are much higher for 2015 data alone (n=61).

Table E.7
WSSC relationships exploring temperature as the only independent variable using one year of data and the full time period

Response variable	Independent variables			R^2	Sig of test stat	Coef Int	Coef 1	Coef 2	Coef 3	pvalue Int	pvalue 1	pvalue 2	pvalue 3	N	Year
Sulfuric Acid Dose	Temp			0.695	0.0000	-27.60	0.63			0.0000	0.0000			61	Jan 2015 to Feb 2016
Sulfuric Acid Dose	Temp			0.411	0.0000	-21.54	0.51			0.0000	0.0000			1996	1/2/2007 to 2/29/2016*
Sulfuric Acid Dose*	Temp	Turbidity	TOC	0.458	0.0000	-18.76	0.46	-0.10	0.77	0.0000	0.0000	0.0000	0.0001	1996	1/2/2007 to 2/29/2016**
KMnO4 Dose	Temp			0.589	0.0000	-0.40	0.02			0.0008	0.0000			61	Jan 2015 to Feb 2016
KMnO4 Dose	Temp			0.400	0.0000	-0.77	0.02			0.0000	0.0000			1996	1/2/2007 to 2/29/2016*
KMnO4 Dose	Temp	Turbidity	TOC	0.434	0.0000	-0.80	0.02	0.00	0.07	0.0000	0.0000	0.0000	0.0000	1996	1/2/2007 to 2/29/2016**
Lime Dose	Temp			0.761	0.0000	-13.69	0.40			0.0000	0.0000			61	Jan 2015 to Feb 2016
Lime Dose	Temp			0.330	0.0000	-4.29	0.19			0.0000	0.0000			1996	1/2/2007 to 2/29/2016**
Lime Dose	Temp	Turbidity	TOC	0.353	0.0000	-5.31	0.18	-0.01	0.72	0.0000	0.0000	0.0462	0.0000	1996	1/2/2007 to 2/29/2016**

*The original relationships are shown using shading for comparison.
**The time period for analysis that represents current operating conditions as determined through utility discussions. These time periods were used in development of the draft water quality-treatment dose relationships.

Table E.8
Fairfax Water relationships exploring temperature as the only independent variable using one year of data and the full time period

Response variable	Independent variables			R^2	Sig of test stat	Coef Int	Coef 1	Coef 2	Coef 3	pvalue Int	pvalue 1	pvalue 2	pvalue 3	N	Year
Sulfuric Acid Dose	Temp			0.042	0.0001	3.80	0.07			0.0005	0.0001			365	2015
Sulfuric Acid Dose	Temp			0.084	0.0000	1.45	0.13			0.0014	0.0000			3622	1/1/2006 to 12/31/15**
Sulfuric Acid Dose*	Temp	Turbidity	TOC	0.203	0.0000	3.00	0.11	-0.13	0.39	0.0000	0.0000	0.0000	0.0000	3622	1/1/2006 to 12/31/15**
KMnO4 Dose	Temp			0.659	0.0000	-1.09	0.02			0.0000	0.0000			365	2015
KMnO4 Dose	Temp			0.221	0.0000	-0.38	0.01			0.0000	0.0000			3627	1/1/2006 to 12/31/15**
KMnO4 Dose	Temp	Turbidity		0.222	0.0000	-0.36	0.01	0.00		0.0000	0.0000	0.0006		3627	1/1/2006 to 12/31/15**

*The original relationships are shown using shading for comparison.
**The time period for analysis that represents current operating conditions as determined through utility discussions. These time periods were used in development of the draft water quality-treatment dose relationships.

Results

Based on the results of these and previous analyses, it was recommended that the following treatment chemicals were dropped from further consideration:

- WSSC: sulfuric acid, potassium permanganate, and lime; Fairfax Water: sulfuric acid and potassium permanganate. This decision and discussion can be informed by the following conclusions from previous analyses:
  - The predictive power of these water quality-treatment dose relationships is relatively statistically weak (R^2 values range from 0.203 to 0.458). When evaluating these relationships using only one year of data, the turbidity and TOC values become insignificant for WSSC ($p>0.05$); however, development of temperature-only relationships does not increase the predictive power of the relationships for the full period. Turbidity becomes insignificant ($p>0.05$) for the potassium permanganate relationship at Fairfax Water.
  - Further comments from WSSC suggested that sulfuric acid and lime may not be expected to vary with turbidity and TOC. A PAC member also communicated during a previous review that these chemicals are likely to not be correlated with changes in land use.
  - These treatment chemicals work together to achieve the desired effects (e.g., enhanced coagulation) and, while their use (and therefore costs) do not occur independently, coagulant accounts for the largest portion of the cost of the chemicals under consideration at Fairfax Water and WSSC. Specifically, sulfuric acid and potassium permanganate represent only 24 percent of the chemical cost for the three chemicals under consideration during the period of analysis for Fairfax Water (2006-2015). Sulfuric acid, potassium permanganate, and lime account for only 30 percent of the chemical cost for the four chemicals under consideration for the period of analysis for WSSC (2007-2015).

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ABBREVIATIONS

AGRICOLA	National Agricultural Library
AOP	Advanced oxidation process
AWWA	American Water Works Association
BAF	Biologically active filtration
BMP	Best management practice
BOD	Biochemical oxygen demand
°C	Degrees Celsius
CAST	Chesapeake Assessment Scenario Tool
CBP	Chesapeake Bay Program
CFD	Cumulative frequency distribution
cfs	Cubic feet per second
cm	Centimeter
CSMR	Chloride-to-sulfate mass ratio
DAF	Dissolved air floatation
DBP	Disinfection by-product
DC	District of Columbia
DFR	De facto reuse
DON	Dissolved organic nitrogen
DOC	Dissolved organic carbon
DWSPP	Potomac River Basin Drinking Water Source Protection Partnership
EBSCO	Elton B. Stephens Co. Information Services
EOS	Edge-of-stream
EPA	United States Environmental Protection Agency
°F	Degrees Fahrenheit
FAC	Free available chlorine
FIRM	Flood Insurance Rate Maps
g/L	Grams per liter
GAC	Granular activated carbon
GIS	Geographic information system
ha	Hectares
HAA	Haloacetic acids
HSPF	Hydrological Simulation Program—Fortran
ICPRB	Interstate Commission on the Potomac River Basin
IESWTR	Interim Enhanced Surface Water Treatment Rule
IX	Ion exchange

kg C ha^{-1}	Kilograms carbon per hectare
lb	Pound
lbs/acre/yr	Pounds per acre per year
LON	Labile organic nitrogen
LP	Low pressure
LRS	Land-river segments
LT2-ESWTR	EPA's Long Term 2 Enhanced Surface Water Treatment Rule
µg/L	Micrograms per liter
MA DCR	Massachusetts Department of Conservation and Recreation
MCL	Maximum Contaminant Limit
MD DNR	Maryland Department of Natural Resources
MF	Microfiltration
mg	Milligrams
mg/L	Milligrams per liter
MGD	Million gallons per day
MVUE	Minimum variance unbiased
NCR	National Capital Region
NDMA	*N*-Nitrosodimethylamine
NDMA-FP	*N*-Nitrosodimethylamine formation potential
ng/L	Nanograms per liter
NLCD	National Land Cover Database
NRC	National Research Council
NTU	Nephelometric Turbidity Unit
P5	Phase 5 Watershed Model
PAC	Powdered activated carbon
PACl	Polyaluminum chloride
R^2	Coefficient of determination
RLA	Resource Lands Assessment
RO	Reverse osmosis
ROC	Refractory organic carbon
RON	Refractory organic nitrogen
RSOC	Recalcitrant synthetic organic compounds
SDR	Sediment delivery ratio
SPARROW	Spatially Referenced Regression on Watershed Attributes
sq. mi.	Square mile
SWTR	Surface Water Treatment Rule
T&O	Taste and odor
THM	Trihalomethanes
TMDL	Total Maximum Daily Load

TN	Total nitrogen
TOC	Total organic carbon
TP	Total phosphorus
TSI	Carlson Trophic State Index
TSIP	Total phosphorus trophic state index
TSS	Total suspended solids
UCMR	Unregulated Contaminant Monitoring Rule
$USD	United States dollar
U.S.	United States
USDA	United States Department of Agriculture
USFS	United States Forest Service
USGS	United States Geological Survey
UV	Ultraviolet
VDOF	Virginia Department of Forestry
WRI	World Resources Institute
WRF	Water Research Foundation
WTP	Water treatment plant
WSSC	Washington Suburban Sanitary Commission

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