Appendix 6. Cost Evaluation for Phosphorus Removal at Wastewater Treatment Facilities

This appendix contains the cost analysis report prepared by Tetra Tech for Ohio EPA.

Cost Evaluation for Phosphorus Removal at Wastewater Treatment Facilities

EPA01-0000010173
December 21, 2022

PRESENTED TO

Ohio EPA - Division of Surface Water
50 West Town Street,
Suite 700
Columbus, Ohio 43215

PRESENTED BY

Tetra Tech
10306 Eaton Place,
Suite 340
Fairfax, VA 22030-2201

TETRA TECH

EXECUTIVE SUMMARY

The Ohio Environmental Protection Agency (Ohio EPA) is developing a total maximum daily load (TMDL) for the Maumee River watershed to address nutrient-loading that impairs the Western Basin of Lake Erie. To facilitate TMDL implementation, Ohio EPA is evaluating the potential costs associated with implementing new phosphorus removal technologies at new wastewater treatment facilities and at existing wastewater treatment facilities during planned upgrades or expansions.

The cost estimation approach used for the analysis considers the potential incremental cost of adding treatment process for total phosphorus (TP) removal to existing municipal wastewater treatment plants (WWTPs) either through retrofitting or replacement of existing treatment units over a range of design flow rates. A software tool, CapdetWorks, was used to estimate costs. CapdetWorks is designed for preliminary, planning-level cost estimation of WWTP construction project alternatives. Options are evaluated for three groups of WWTPs established in the Maumee Watershed Nutrient TMDL:

- **Group 1**: Major WWTP with an average daily design flow greater than 10 million gallons per day (mgd) and an existing average monthly TP limit of 1.0 milligrams per liter (mg/L).
- **Group 2**: Major WWTPs, 1.0 mgd and 10 mgd, and an existing monthly TP limit of 1.0 mg/L;
- **Group 3**: Minor WWTPs, 0.5 mgd and 1.0 mgd, and no existing monthly TP limits.

To estimate costs of implementing new phosphorus removal technologies, baseline system configurations are assumed. For **Group 1** and **Group 2**, two baseline systems are assumed:

- Conventional biological treatment with a plug-flow activated sludge unit and one-point chemical addition (alum) at the primary clarifier, activated sludge basins, or before the secondary clarifier
- Enhanced biological phosphorus removal (EBPR) using an anaerobic/oxic process (A/O) or using an anaerobic/anoxic/oxic process (A2O).

For **Group 3** facilities, the baseline system is assumed to be a conventional biological treatment system with a plug-flow activated sludge unit.

For each group and each baseline system, options are considered for additional phosphorus removal through retrofitting, replacing, or adding treatment units. For facilities in **Group 1** or **Group 2**, additional treatment options allow the facility to meet a lower target average monthly TP effluent concentration of 0.5 mg/L (or below). The specific options available depend on the configuration of the baseline system; options included a second point of chemical addition and cloth filtration (for systems with chemical addition) or fermentation, one-point chemical addition, and cloth filtration (for EBPR systems). For facilities in **Group 3**, the additional treatment options include both EBPR and chemical addition and allow the facility to attain an average monthly TP effluent concentration of 1.0 mg/L (or below).

CapdetWorks allows users to modify the default inputs for parameters related to the treatment system and to parameters that affect cost estimate calculations for both capital and O&M costs. The analysis modifies a limited number of default inputs related to the treatment system and modifies selected key cost calculation inputs to make them more specific to Ohio and to update costs as close as possible to 2022 dollars. However, CapdetWorks does not include all of the unit processes considered in the analysis (e.g., fermentation). In addition, as noted, an option for some facilities is to retrofit rather than replace an existing unit to achieve better phosphorus removal. Consequently, the analysis makes assumptions regarding the cost of these unit processes based on assumptions from prior U.S. EPA studies and best professional judgment. Capital cost calculations also depend on assumptions about how to assign other direct and indirect capital costs to a particular treatment unit and how the capital cost will be financed. The analysis recognizes that the uncertainties and assumptions inherent in CapdetWorks and in the analysis of CapdetWorks results may cause an underestimation or overestimate on of costs.

In general, for facilities in Group 1 and Group 2, a second point of chemical addition (for facilities with chemical treatment) or a fermentation unit or single point of chemical addition (for EBPR facilities) would be the most cost-effective options in terms of cost per gallon per day ($/gpd) of wastewater treated to achieve the required concentration of 0.5 mg/L. Based on the results from CapdetWorks, the capital cost of a second point of chemical addition are negligible. For EBPR facilities, the capital cost of adding fermentation or one-point chemical addition are similar at the lower range of design flows, but the capital cost of adding fermentation becomes relatively more expensive than chemical addition as design flow increases. On the other hand, chemical addition generally has the highest operation and maintenance (O&M) costs across all design flow rates. Because of these higher O&M costs, facilities with an existing EBPR system typically would find that adding fermentation would be the most cost-effective option for achieving required total phosphorus concentrations, if feasible. The incremental capital cost and cost in $/gpd of adding cloth filtration, if necessary, are significantly greater than the costs for chemical addition or fermentation.

For facilities in Group 3, which currently have no total phosphorus requirements, the most cost-effective option in terms of both incremental capital cost and incremental cost in $/gpd are retrofitting an existing activated sludge unit to convert it to an A/O unit. Slightly more expensive in terms of both capital cost and O&M cost is adding one-point chemical addition. Replacing the existing activated sludge unit with an A/O unit increases the incremental capital cost when compared to both A/O retrofit and one-point chemical addition, but O&M costs are lower than O&M costs for chemical addition. As a result, the overall cost in $/gpd treated is only slightly higher than the cost for one-point chemical addition. Group 3 facilities retrofitting or replacing an existing activated sludge unit with an A2O unit to achieve both total phosphorus and total nitrogen removal have notably higher incremental capital and O&M costs than facilities that are able to select one of the other options.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYMS/ABBREVIATIONS

Acronyms/Abbreviations	Definition
AACEI	Association for the Advancement of Cost Engineering International
A/O	anaerobic/oxic
A2O	anaerobic/anoxic/oxic
BLS	Bureau of Labor Statistics (U.S. Department of Labor)
EBPR	enhanced biological phosphorus removal
EIA	Energy Information Administration (U.S. Department of Energy)
gpd	gallons per day
mgd	million gallons per day
Ohio EPA	Ohio Environmental Protection Agency
O&M	operations and maintenance
TMDL	total maximum daily load
U.S. EPA	United States Environmental Protection Agency
WLA	wasteload allocation

1.0 INTRODUCTION

The Ohio Environmental Protection Agency (Ohio EPA) is developing a total maximum daily load (TMDL) for the Maumee River watershed to address nutrient-loading that impairs the Western Basin of Lake Erie. The TMDL analysis showed that 20 percent of NPDES-permitted treatment facilities account for more than 85 percent of the point source waste load allocation. These discharges are largely municipal wastewater treatment facilities with some industrial facilities that contribute phosphorus at similar magnitudes.

The total wasteload allocation (WLA) in the TMDL was set based on the level of control demonstrated in 2008 which, through optimization and other actions, has been maintained when evaluated collectively. However, if the total WLA were distributed equitably to individual facilities, not all facilities would meet its individual allocation every season. To implement the WLA, Ohio EPA is considering a general permit to facilitate flexibility for permitted facilities. A general permit gives the option to manage compliance as a seasonal load averaged across the community, which should allow facilities to continue to optimize and operate in a way that maintains the WLA without incurring additional costs.

Facilities that are proposed to be part of the grouped WLA in the TMDL are generally based on what are currently considered “major” point source dischargers. Major municipal wastewater treatment plants have an average design flow of 1.0 million gallons per day (mgd) or greater. In addition, “significant minors” with an average design flow of > 0.5 mgd are also included in the group. Finally, there are several industrial facilities that have been previously identified as contributing significant amounts of total phosphorus that are included as well.

Facility groupings for municipal wastewater treatment plants are as follows:

- **Group 1**: Four major municipal wastewater treatment plants with an average daily design flow > 10 mgd and an existing average monthly total phosphorus limit of 1.0 mg/L;
- **Group 2**: Nineteen major municipal wastewater treatment plants with average design flows between 1.0 mgd and 10 mgd and an existing monthly total phosphorus limit of 1.0 mg/L; (there are also three industrial facilities within this group);
- **Group 3**: Seven municipal wastewater treatment plants with an average daily design flow between 0.5 mgd and 1.0 mgd (i.e., significant minors) that currently do not have total phosphorus limitations in their individual permits.

The plan also includes a grouping (GPX) with nine industrial facilities. These facilities have demonstrated that they discharge effluent with total phosphorus loads that require additional considerations, and they are included in the grouped WLA.

The preliminary implementation plan proposes managing future growth of wastewater treatment facilities, in part by using new phosphorus removal technologies at new facilities or when existing facilities go through planned upgrades or expansions. The analysis in this report considers capital and operation and maintenance (O&M) cost information for potential treatment system upgrades needed to support TMDL implementation at facilities from each of the three municipal wastewater treatment plant groupings. Because the report focuses on upgrades to biological treatment systems to enhance total phosphorus removal, the phosphorus treatment technologies and cost estimations in the report would have relevance to industrial facilities considered in the TMDL that employ biological treatment in a manner similar to a municipal wastewater treatment plant.

2.0 COST ESTIMATION APPROACH

The cost estimation approach used for the analysis considers the potential incremental cost of adding treatment process for total phosphorus removal to existing municipal wastewater treatment plants either through retrofitting or replacement of existing treatment units over a range of design flow rates. The report does not provide facility-specific cost estimates for each facility considered by the TMDL.

As discussed in this section, the cost analysis presented in this report includes several steps: 1) identifying a cost estimation model with the appropriate accuracy; 2) identifying a baseline biological wastewater treatment system for each facility grouping and selected additions to the baseline system to achieve target levels of phosphorus removal, including both enhanced biological phosphorus removal (EBPR) and chemical phosphorus removal; 3) selecting inputs to the cost estimation model, including changes to default values in the model; 4) using the cost estimation program to model the baseline system and estimate the incremental cost of various treatment system designs across various flow rates.

Section 3 of the report presents the results of the cost estimation modeling. In addition, although the report does not provide facility-specific cost estimates, section 4 considers the potential impact of site-specific factors, such as existing equipment or available land, and other treatment plant process, such as biosolids treatment and management, on the cost estimates presented in section 3.

2.1 COST ESTIMATION MODEL

CapdetWorks is a software tool for preliminary design and cost estimation of wastewater treatment plant construction project alternatives. CapdetWorks is based on the CAPDET program originally developed by the U.S. Army Corps of Engineers (Corps) in 1974 and later upgraded based on an agreement between the Corps and U.S. EPA (1979). CapdetWorks designs unit processes based on the proposed layout and influent characteristics. It then provides cost estimates for the design. The program focuses on estimating the costs of treatment system components rather than on the details of the design or the expected effluent quality. CapdetWorks has been used by U.S. EPA to estimate treatment system costs for EPA publications such as *Life Cycle and Cost Assessments of Nutrient Removal Technologies in Wastewater Treatment Plants* (2021) and *Municipal Nutrient Removal Technologies Reference Document* (2008).

Using the algorithms in CapdetWorks along with user inputs that allow for consideration of changing costs over time (e.g., cost indices) and limited consideration of site-specific factors (e.g., labor rates) provides information sufficient to develop Class 4 cost estimates as described by the Association for the Advancement of Cost Engineering International (AACEI) (formerly known as the American Association of Cost Engineers). Class 4 cost estimates generally are prepared based on limited information and used for purposes such as detailed planning, project screening at more developed stages, alternative scheme analysis, confirmation of economic and/or technical feasibility, and preliminary budget approval. The accuracy of the Class 4 cost estimates is in the range of -30 percent to +50 percent (AACEI 2005). Section 2.3 of this document describes inputs to CapdetWorks that were used in this analysis to achieve the desired accuracy of cost estimates.

2.2 MODEL TREATMENT SYSTEMS

Estimating the incremental costs of different treatment options requires developing treatment system configurations to input to the CapdetWorks cost estimation model. The analysis assumes a baseline biological wastewater treatment system for each facility grouping and identifies possible additions to the baseline system to achieve target levels of phosphorus removal. Depending on the configuration of the baseline system, these options may include EBPR, chemical phosphorus removal, or both. All baseline systems include preliminary treatment, primary clarification, chlorination, dechlorination, and sludge treatment and disposal.

2.2.1 Baseline Systems

The analysis identifies three possible baseline treatment system configurations as a starting point for estimating the incremental costs of additional treatment for total phosphorus removal. The baseline system varies depends on the facility grouping as identified in Section 1 of this report.

- For facilities in **Group 1** (> 10.0 mgd; existing average monthly limit for total phosphorus of 1.0 mg/L) and **Group 2** (≥ 1.0 to 10.0 mgd; existing average monthly limit for total phosphorus of 1.0 mg/L), two baseline treatment systems were used for the analysis:
    - Conventional biological treatment with a plug-flow activated sludge unit and one-point chemical addition (alum) at the primary clarifier, activated sludge basins, or before the secondary clarifier
    - Enhanced biological phosphorus removal using:
        - Anaerobic/oxic (A/O) process, which consists of an anaerobic zone (for phosphorus release) upstream of an aerobic zone (for phosphorus uptake) or
        - Anaerobic/anoxic/oxic (A2O) process, which adds the anoxic zone to allow for nitrogen removal through denitrification.
- For **Group 3** facilities (> 0.5 to < 1.0 mgd design flow; no existing average monthly effluent limits for total phosphorus), the baseline treatment system configuration used in the analysis is a conventional biological treatment system with a plug-flow activated sludge unit.

These baseline systems are intended to represent the range of municipal wastewater treatment systems in the Maumee watershed that are being considered in this analysis. In addition, it should be noted that estimates of the attainable monthly average effluent concentration of total phosphorus are intended to be conservative. For example, the analysis assumes that a facility with a conventional plug-flow activated sludge unit and one-point chemical addition would achieve a target average monthly total phosphorus effluent concentration of 1.0 mg/L. Depending on specific conditions and operations, a specific facility with this treatment system configuration may be capable of achieving total phosphorus concentrations well below 1.0 mg/L.

2.2.2 Treatment Options for Additional Total Phosphorus Removal

For each baseline system, options were considered for additional phosphorus removal through retrofitting, replacing, or adding treatment units.

- For facilities in Group 1 or Group 2, additional treatment options allow the facility to meet a lower target average monthly total phosphorus effluent concentration of 0.5 mg/L (or below). The specific options available depend on the configuration of the baseline system.
    - For the baseline system that employs conventional activated sludge treatment and one-point chemical addition, options include a second point of chemical addition and cloth filtration.
    - For the baseline system that employs EBPR, options include adding fermentation of primary sludge to produce volatile fatty acids to enhance phosphorus removal, one-point chemical addition, and cloth filtration.
- For facilities in Group 3, the additional treatment options include both EBPR and chemical addition and allow the facility to attain an average monthly total phosphorus effluent concentration of 1.0 mg/L (or below).

The baseline systems, target total phosphorus concentrations, and additional treatment unit options considered for each facility grouping are summarized in Table 1.

Table 1. Baseline Systems and Total Phosphorus Treatment Options

Facility Group	Existing Average Monthly Effluent Total Phosphorus Target/Limit	Baseline System	Potential Average Monthly Effluent Total Phosphorus Target/Limit	Additional Treatment Unit Options Considered
Group 1: > 10.0 mgd **Group 2:** ≥ 1.0 to 10.0 mgd	1.0 mg/L	Conventional biological treatment—plug-flow activated sludge + one-point alum addition	0.5 mg/L	**Chemical Treatment** • Second point of chemical addition • Cloth media filtration
		EBPR—A/O process or A2O process	0.5 mg/L	**EPBR** • Fermentation • Cloth media filtration **Chemical Treatment** • One-point chemical addition • Cloth media filtration
Group 3: ≥ 0.5 to < 1.0 mgd	No limit/target	Conventional biological treatment—plug-flow activated sludge	1.0 mg/L	**EPBR** • A/O unit – retrofit • A/O unit –replacement • A2O unit – retrofit • A2O unit –replacement **Chemical Treatment** • One-point chemical addition

2.3 MODEL INPUT VALUES AND COST CALCULATION ASSUMPTIONS

CapdetWorks allows users to modify the default inputs for parameters related to the treatment system and to parameters that affect cost estimate calculations for both capital and O&M costs. The analysis presented in this report modifies a limited number of default inputs related to the treatment system and modified selected key cost calculation inputs to make them more specific to Ohio and to update costs as close as possible to 2022 dollars.[1] CapdetWorks does not include all of the unit processes considered in the analysis (e.g., fermentation). In addition, for some unit processes, an option is to retrofit, rather than replace, an existing unit to achieve better phosphorus removal. Consequently, the analysis makes assumptions regarding the cost of these unit processes based on assumptions from prior U.S. EPA studies and best professional judgment. Finally, cost calculations

[1] Dates for the most recent cost calculation input values vary by input value. Some, inputs, such as labor rates, were not available for 2022 at the time the analysis was completed.

depend on assumptions about the capital cost financing period and interest rate. Inputs to CapdetWorks for the treatment system and cost calculations are described below.

2.3.1 Treatment System Inputs

CapdetWorks considers both influent concentrations of parameters of concern and the treated effluent volume to produce estimated costs. The analysis for this report uses the same values for key influent parameters used in U.S. EPA in prior studies (U.S. EPA 2008, 2021). These inputs, which include some CapdetWorks default values and some user-defined values, are shown in Table 2.

Table 2. Key Cost Model Influent Parameter Values

Parameter	Units	Quantity
Flow	mgd	Varies
Total suspended solids (TSS)	mg/L	220
% volatile solids	%	75
Biochemical oxygen demand (BOD)	mg/L	220
Soluble BOD	mg/L	80
Chemical oxygen demand (COD)	mg/L	500
Soluble COD	mg/L	300
Total Kjeldahl nitrogen (TKN)	mg/L	40
Soluble TKN	mg/L	25
Ammonia nitrogen	mg/L	22
Total phosphorus (TP)	mg/L	5
pH	s.u.	7.6
Nitrite/Nitrate	mg/L	0
Temperature (summer)	°C	23
Temperature (winter)	°C	10

°C = degrees Celsius; mg/L = milligram per liter; s.u. = standard units.

As shown in Table 5, Table 4, and Table 3, the model was used to estimate the cost of treatment options over a range of design flows for each facility grouping. For purposes of this analysis, the design flow was entered as the maximum effluent flow in CapdetWorks for each model run. CapdetWorks also includes inputs for average and minimum effluent flow. The values used for the average and minimum flow were 80% and 40% of the maximum (design) effluent flow, respectively.

Table 3. Flow Range for Cost Model—Group 1 Facilities

Average Effluent Flow (mgd)	Minimum Effluent Flow (mgd)	Maximum (Design) Effluent Flow (mgd)
8	4	10
16	8	20
24	12	30
32	16	40
40	20	50

Table 4. Flow Range for Cost Model—Group 2 Facilities

Average Effluent Flow (mgd)	Minimum Effluent Flow (mgd)	Maximum (Design) Effluent Flow (mgd)
0.8	0.4	1
2	1	2.5
4	2	5
6	3	7.5
8	4	10

Table 5. Flow Range for Cost Model—Group 3 Facilities

Average Effluent Flow (mgd)	Minimum Effluent Flow (mgd)	Maximum (Design) Effluent Flow (mgd)
0.4	0.2	0.5
0.6	0.3	0.75
0.8	0.4	1

CapdetWorks also allows users to modify unit process parameters that may have an impact on treatment system performance and cost, for example, percent solids removal for a clarifier or oxygen transfer efficiency for an aeration basin. The analysis for this report used the CapdetWorks default process design parameters with the exception of the chemical dosage used for alum addition. Table 6 summarizes the chemical addition design parameters used in the analysis, which are consistent with assumptions used by U.S. EPA (2008).

Table 6. Chemical Addition Design User-Modified Inputs

Existing Treatment	Chemical Addition Option	Chemical Dosage
Conventional plug-flow activated sludge	One-point chemical addition (alum)	2.4 mg/L as Al
Conventional plug-flow activated sludge	Two-point chemical addition (alum)	2.6 mg/L as Al (first point) 2.4 mg/L as Al (second point)
EBPR (A/O or A2O)	One-point chemical addition	1.3 mg/L as Al

mg/L as Al = milligrams per liter as aluminum

2.3.2 Cost Estimation Inputs

CapdetWorks allows users to override model inputs that directly impact cost estimate calculations. Inputs include default costs or algorithms in the CapdetWorks database for standard equipment cost, replacement schedules, construction-related unit costs (e.g., excavation, concrete, land), and indirect construction costs (e.g., engineering design, contingency). The analysis presented in this report used the default values in CapdetWorks for these inputs. Overriding default values for some inputs would require a facility-specific analysis, which goes beyond the level of detail needed for the level of cost estimates provided in this analysis. For other inputs, such as land costs, the overall impact on the cost estimate is negligible because most options involve either a retrofit or replacement of an existing treatment unit or addition of a unit process with a small footprint.

There were several user-defined cost estimation inputs to CapdetWorks that were included in the analysis. These inputs, which affect both capital and O&M costs, are discussed below.

2.3.2.1 Capital Cost Components

When estimating the capital cost of a treatment system, CapdetWorks allows users to overwrite the default values used in the program for the equipment cost indices and construction labor rate. For this analysis, default values in CapdetWorks were adjusted to provide more accurate cost estimate for Ohio.

Equipment Cost Indices

CapdetWorks allows users to choose from multiple equipment costing databases. The analysis uses the Hydromantis 2014 USA Average database for cost estimates.[2] CapdetWorks accounts for changing costs over time in its costing algorithms by using several equipment-related cost indices to adjust costs to the target year. CapdetWorks begins with 2014 equipment costs from its Hydromantis 2014 USA Average cost database and updates these costs periodically using three indices: Hydromantis Equipment Cost Index (HECI), Hydromantis Construction Cost Index (HCCI), Hydromantis Pipe Cost

[2] CapdetWorks is a Hydromantis product.

Index (HPCI). CapdetWorks allows the user to update these indices within the program. For this analysis, the cost indices were updated to cost index values provided by Hydromantis for August 2022.

Construction Labor

Construction labor rates used in CapdetWorks for this analysis assume a fully loaded rate of 2.1 times reported hourly wages. Wage rates for Construction Laborers were taken from the most recent Bureau of Labor Statistics (BLS) Occupational Employment Statistics data. These data are for May 2021 and were released in March 2022. The fully loaded hourly labor rate of $46.66 reflects the median (50th percentile) rate in Ohio.

2.3.2.2 O&M Cost Components

Cost estimates for O&M components provided by CapdetWorks depend on several factors that are based on either default or user-supplied values. Like capital cost components, O&M costs can vary by location and over time, and the cost estimates in the analysis are adjusted to account for these differences.

O&M cost estimates in the analysis are made up of several components: operation, maintenance, material, chemicals, and energy. Operation costs are further divided by type of labor and include wastewater treatment plant operator, administrative, and laboratory labor costs. CapdetWorks allows the user to overwrite default values for labor rates, energy costs, and chemical costs. For this analysis, default values for labor rates and energy costs in CapdetWorks were adjusted to provide more accurate cost estimate for Ohio.

Operation Costs

The CapdetWorks estimate of operation costs comprises three components: wastewater treatment plant operator labor, administrative labor, and laboratory labor. Labor rates used in the CapdetWorks estimate of operation costs are based on median (50th percentile) hourly wages in Ohio from taken from the BLS Occupational Employment Statistics from data, which are from May 2021. These data were published in March 2022. BLS provides median hourly wages for Water and Wastewater Treatment Plant and System Operators and Chemical Technicians. These hourly wages are multiplied by a wage rate multiplier of 2.1 (accounting for benefits, overhead, etc.) to estimate hourly labor rates for wastewater treatment plant operator labor ($48.80) and laboratory labor ($49.18) respectively. The analysis retains the assumption used by CapdetWorks that wages for the range of Administrative staff (e.g., plant managers, clerical staff) are, when averaged, the same as wages for Water and Wastewater Treatment Plant and System Operators.

Maintenance Cost

Maintenance cost estimates in CapdetWorks consist solely of wastewater treatment plant operator labor. The wastewater treatment plant operator labor rate used in the CapdetWorks estimate of maintenance costs in the analysis is based on median hourly wages for Water and Wastewater Treatment Plant and System Operators in Ohio taken from the BLS Occupational Employment

Statistics for May 2021. As with other hourly wages, the wage rate is multiplied by a wage rate multiplier of 2.1 (accounting for benefits, overhead, etc.) to estimate an hourly labor rate ($48.80).

Material and Chemical Costs

Material and chemical cost estimates are provided in CapdetWorks. The program allows the user to modify chemical costs; however, this analysis uses the CapdetWorks default costs.

Energy Cost

Energy costs used in the analysis are from the average cost of electricity in Ohio for the Commercial Sector for May 2022. The data were taken from Table 5.6.A in the U.S. Energy Information Administration's (EIA) *Electric Power Monthly with Data for May 2022* (July 2022). The EIA report notes that the Commercial Sector includes sewage treatment facilities.

2.3.2.3 Unit Process Cost Assumptions

As noted, CapdetWorks does not include all of the unit processes for total phosphorus removal that are considered in the analysis. Table 7 summarizes assumptions used in the analysis regarding the cost of these unit processes as well as the source for each assumption.

Table 7. Unit Process Cost Assumptions and Sources

Unit Process	Assumption	Source
A/O retrofit (of existing activated sludge unit)	• Capital cost = 25% of the cost of a new unit	*Municipal Nutrient Removal Technologies Reference Document*, Volume 1, p. 4-9 (U.S. EPA 2008)
A2O retrofit	• Capital cost = 50% of the cost of a new unit (estimate based on CapdetWorks cost estimate for “Biological Nutrient Removal—3/5 Stage”) • Additional capital cost for secondary clarification and blower capacity = 50% of the cost of new secondary clarifier and blower units • Additional O&M costs = increase in material and energy costs over baseline of 50% of the material and energy costs for a new A2O unit	*Municipal Nutrient Removal Technologies Reference Document*, Volume 1, p. 4-16 (U.S. EPA 2008)
A2O replacement	• Additional capital cost for secondary clarification and blower capacity = 50% of the cost of new secondary clarifier and blower units • Additional O&M costs = increase in material and energy costs over baseline of 50% of the material and energy costs for a new A2O unit	*Municipal Nutrient Removal Technologies Reference Document*, Volume 1, p. 4-16 (U.S. EPA 2008)
Fermentation	• Capital cost = 150% of the cost of a gravity thickener • O&M cost = 150% of the cost of a gravity thickener	*Municipal Nutrient Removal Technologies Reference Document*, Volume 1, p. 4-9 (U.S. EPA 2008)
Cloth media filtration	• Capital cost = 80% of the cost of a dual media filter • O&M cost = 100% of the cost of a dual media filter	Best professional judgment: The lower capital cost estimate is based on the smaller footprint required for the cloth media filtration system and the lower likelihood of needing intermediate pumping between the secondary clarifier and disinfection system, which follows filtration. An estimate of equivalent O&M costs for the two systems is based on assumptions that media replacement costs for the cloth media filtration system are greater than for a dual/multi-media filtration system (largely due to lifespan), but that maintenance costs are less.

2.3.2.4 Interest Rates and Amortization Period

CapdetWorks estimates both capital and O&M costs for each treatment process included in the treatment system being modeled. The analysis converts estimated total capital cost to annual costs using standard engineering economics formulas and assuming an interest rate, *i*, of 3 percent and a term, *n*, of 20 years. Annualized capital costs are added to the annual O&M cost estimates to determine overall annual costs. A higher interest rate or shorter term would result in an increase in estimated annualized capital costs and, in turn, total annual costs.

2.4 COST ESTIMATION CALCULATIONS

After incorporating the inputs and assumptions described in Section 2.3, CapdetWorks was used to estimate incremental costs for various total phosphorus removal options for facilities in each of the three facility groups across the selected flow ranges. CapdetWorks was used to model the baseline treatment systems as well as complete treatment systems that included additional units for total phosphorus removal. Incremental cost estimates in the analysis are based on the difference in costs between these systems.

2.4.1 Incremental Capital Cost Assumptions

For each unit process addition for improved total phosphorus removal, the estimated incremental capital cost is based on the estimated cost of the treatment unit itself plus other direct and indirect capital costs that can be attributed to installation of that treatment unit. Table 8 shows the direct and indirect capital costs estimated by CapdetWorks that were and were not considered in the analysis.

Table 8. Other Direct and Indirect Capital Costs in the Analysis Estimated by CapdetWorks

	Considered in the Analysis	Not Considered in the Analysis
Other Direct Costs	• Mobilization • Site preparation • Site electrical • Instrumentation and control	• Yard piping • Lab and administration buildings
Other Indirect Costs	• Miscellaneous cost • Legal cost • Engineering design fee • Inspection cost • Contingency • Technical • Profit	• Cost of land • Interest during construction

CapdetWorks does not break out other direct and indirect capital costs by treatment unit, but provides the total for each cost element shown in Table 8 for the entire model system. At each design flow rate, the analysis attributes a fraction of the total estimated other direct and indirect capital costs for the entire system to an individual total phosphorus treatment unit. This ratio is based on the ratio of the estimated cost of the total phosphorus treatment unit itself to the sum of estimated costs for all treatment units in the treatment system:

$$\text{Fraction of Other Costs Attributed to Treatment Unit} = \frac{\text{Cost of Treatment Unit}}{\text{Sum of Costs for All Treatment Units in System Modeled}}$$

This ratio is calculated at each design flow rate within a facility group. For example, in Group 3, the ratio is calculate at the 0.1 mgd, 0.5 mgd, and 1.0 mgd design flows for each phosphorus treatment unit addition or retrofit considered. The ratios for each treatment unit are averaged to determine an average ratio for the treatment unit across all design flow rates in the facility group.

$$\text{Average Ratio for Facility Group} = \frac{\text{Sum of Ratios for All Design Flow Rates Modeled for the Facility Group}}{\text{Number of Design Flow Rates Modeled for the Facility Group}}$$

In order to normalize assumptions across a facility group, the average ratio for the treatment unit across the group is used to estimate incremental other direct and indirect capital costs for the treatment unit at each design flow rate within the facility group.

$$\text{Incremental Other Direct and Indirect Capital Costs for Treatment Unit} = \text{Average Ratio for Facility Group(s)} \times \text{Sum of Other Direct and Indirect Capital Costs for System Modeled}$$

There are two exceptions to this assumption. The first is for the 10 mgd design flow rate, which overlaps Group 1 and Group 2 with the same treatment options in each group. To maintain consistency in estimated costs, the same ratio was used for the 10 mgd design flow whether the estimate was for Group 1 or Group 2. The second exception is for the incremental cost of chemical addition to an EBPR system in Group 1 and Group 2. If the average ratio for each facility group was applied to that group, the result is a situation where overall incremental capital cost of the additional treatment unit would decrease as design flow rate increases. To avoid this situation, the overall average ratio for both groups can be applied to both facility groups, and the capital cost will steadily increase (rather than decrease) as design flow increases.

The total incremental capital cost for a specific total phosphorus treatment unit is then estimated as:

$$\text{Total Incremental Capital Cost for Treatment Unit} = \text{Cost of Treatment Unit} + \text{Incremental Other Direct and Indirect Capital Costs for Treatment Unit}$$

2.4.2 Incremental O&M Cost Assumptions

Incremental O&M costs are based on the sum of incremental operation, maintenance, material, chemical, and energy costs. For EBPR configurations that retrofit or replace a conventional plug-flow activated sludge system with A/O or A2O, with the exception of material and energy costs for an A2O unit, incremental O&M costs are estimated as the difference between costs attributed to the new unit process and costs of the baseline, plug-flow activated sludge unit. If CapdetWorks algorithms calculate a negative difference in these costs, the incremental O&M cost is estimated as $0 in the analysis. As summarized in Table 7, the analysis assumes that incremental material and energy costs for a retrofitted or replacement A2O unit are 50% of the costs estimated by CapdetWorks for a new A2O unit. When fermentation, chemical addition, or cloth filtration is added as a total phosphorus treatment unit, O&M costs in the analysis are the O&M costs for that unit estimated by CapdetWorks after accounting for the assumptions outlined in Section 2.3.2.3, including the assumption that the costs for fermentation (which is not a unit process available in CapdetWorks) are 150% of the costs for gravity thickening.

3.0 INCREMENTAL COST ESTIMATES

Sections 3.1-3.3 summarize the capital and O&M cost estimates for total phosphorus treatment options over a range of design flows for each facility grouping. Incremental cost estimates are presented separately for EBPR and for chemical treatment options. Cost estimates are calculated as close as possible to 2022 dollars; however, the latest data for some cost model inputs were from 2021. This and other considerations that could affect actual costs for a specific facility are discussed further in Section 3.4.

3.1 FACILITY GROUP 1 COST ESTIMATES

Facility Group 1 includes major wastewater treatment plants that discharge more than 10 mgd and currently have permit limits for total phosphorus. The current total phosphorus limits, baseline treatment configuration used in the analysis, total phosphorus effluent target, and additional treatment options considered are summarized in Table 9.

Table 9. Facility Group 1: Baseline Treatment Configurations and Total Phosphorus Treatment Options

Facility Group	Existing Average Monthly Effluent Total Phosphorus Target/Limit	Baseline System	Potential Average Monthly Effluent Total Phosphorus Target/Limit	Additional Treatment Unit Options Considered
Group 1: > 10.0 mgd	1.0 mg/L	Conventional biological treatment—plug-flow activated sludge + one-point alum addition	0.5 mg/L	**Chemical Treatment** • Second point of chemical addition • Cloth media filtration
		EBPR—A/O process or A2O process	0.5 mg/L	**EPBR** • Fermentation • Cloth media filtration **Chemical Treatment** • One-point chemical addition • Cloth media filtration

Estimated capital, O&M, and total annual incremental costs (in $thousands) for chemical treatment and EPBR options for facility Group 1 (design flows of 10 mgd, 20 mgd, 30 mgd, 40 mgd, and 50 mgd) are summarized in Table 10.

Table 10. Facility Group 1: Estimated Incremental Costs by Treatment Option *($Thousands)*

Design Flow Rate	Total Capital Cost	Annualized Capital Cost (i = 3%, n = 20 yrs.)	Annual O&M Cost	Total Annual Cost
Baseline: Conventional Plug-Flow Activated Sludge + One-point Chemical Addition				
Second point of chemical addition				
10 mgd	$0	--	$206	**$206**
20 mgd	$109	$7	$405	**$413**
30 mgd	$174	$12	$597	**$609**
40 mgd	$259	$17	$790	**$808**
50 mgd	$336	$23	$985	**$1,008**
Cloth media filtration				
10 mgd	$3,616	$243	$98	**$341**
20 mgd	$5,945	$400	$158	**$558**
30 mgd	$8,210	$552	$212	**$764**
40 mgd	$10,246	$689	$260	**$948**
50 mgd	$12,091	$813	$304	**$1,117**
Baseline: EBPR (A/O or A2O)				
Fermentation				
10 mgd	$1,033	$69	$60	**$129**
20 mgd	$1,331	$89	$83	**$173**
30 mgd	$1,749	$118	$109	**$226**
40 mgd	$2,100	$141	$134	**$275**
50 mgd	$2,406	$162	$157	**$319**
One-point chemical addition				
10 mgd	$704	$47	$135	**$182**
20 mgd	$722	$48	$236	**$284**
30 mgd	$1,253	$84	$340	**$424**
40 mgd	$1,492	$100	$443	**$543**
50 mgd	$1,693	$114	$545	**$659**
Cloth media filtration				
10 mgd	$4,007	$269	$98	**$368**
20 mgd	$6,201	$417	$158	**$575**
30 mgd	$8,573	$576	$212	**$788**
40 mgd	$10,581	$711	$260	**$971**
50 mgd	$12,390	$833	$304	**$1,137**

Note: Estimated costs are rounded to the nearest thousand dollars. The sum of annual costs may not equal the *Total Annual Cost* due to rounding.

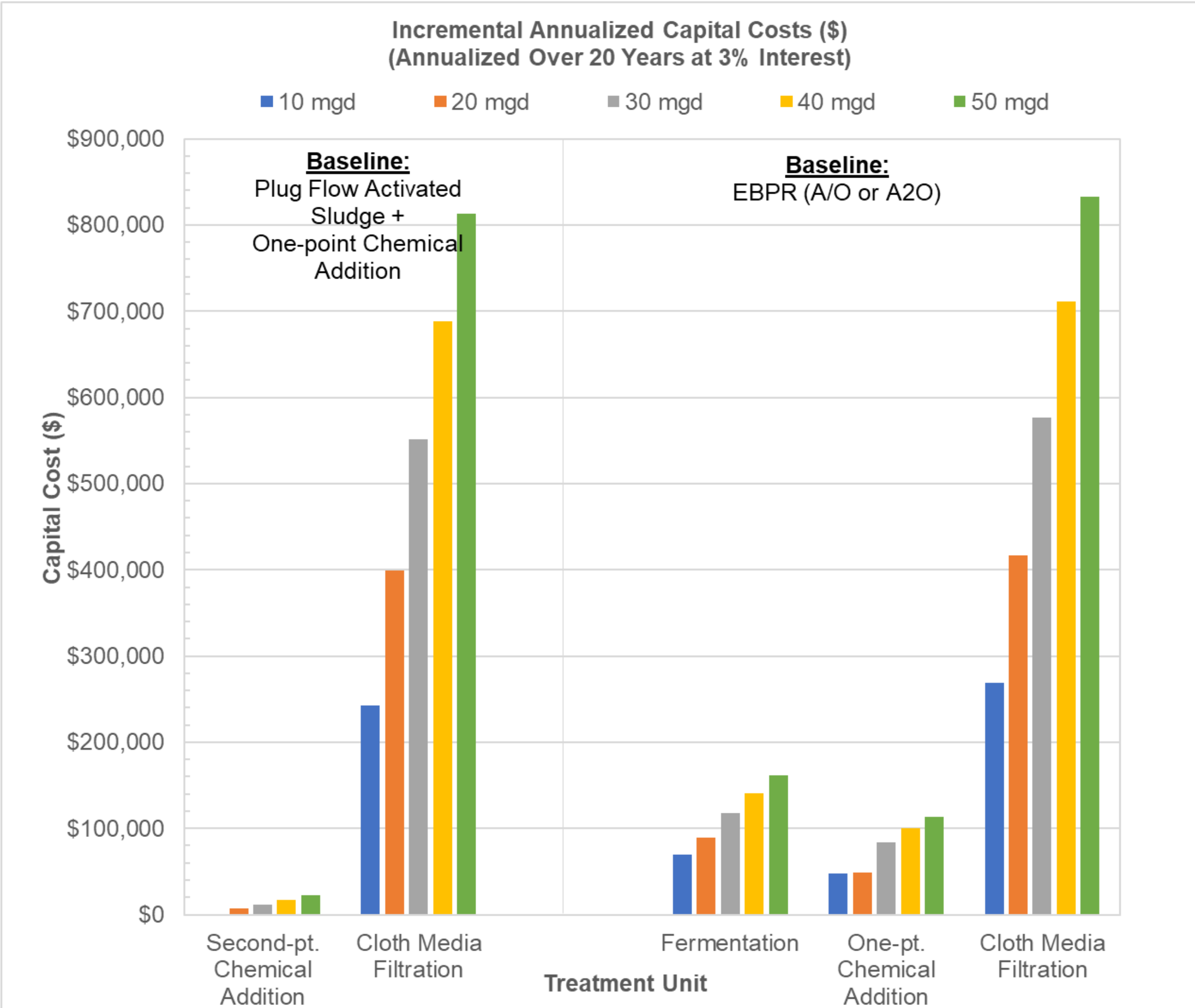

Figure 1. Facility Group 1: Estimated Incremental Annualized Capital Cost ($)

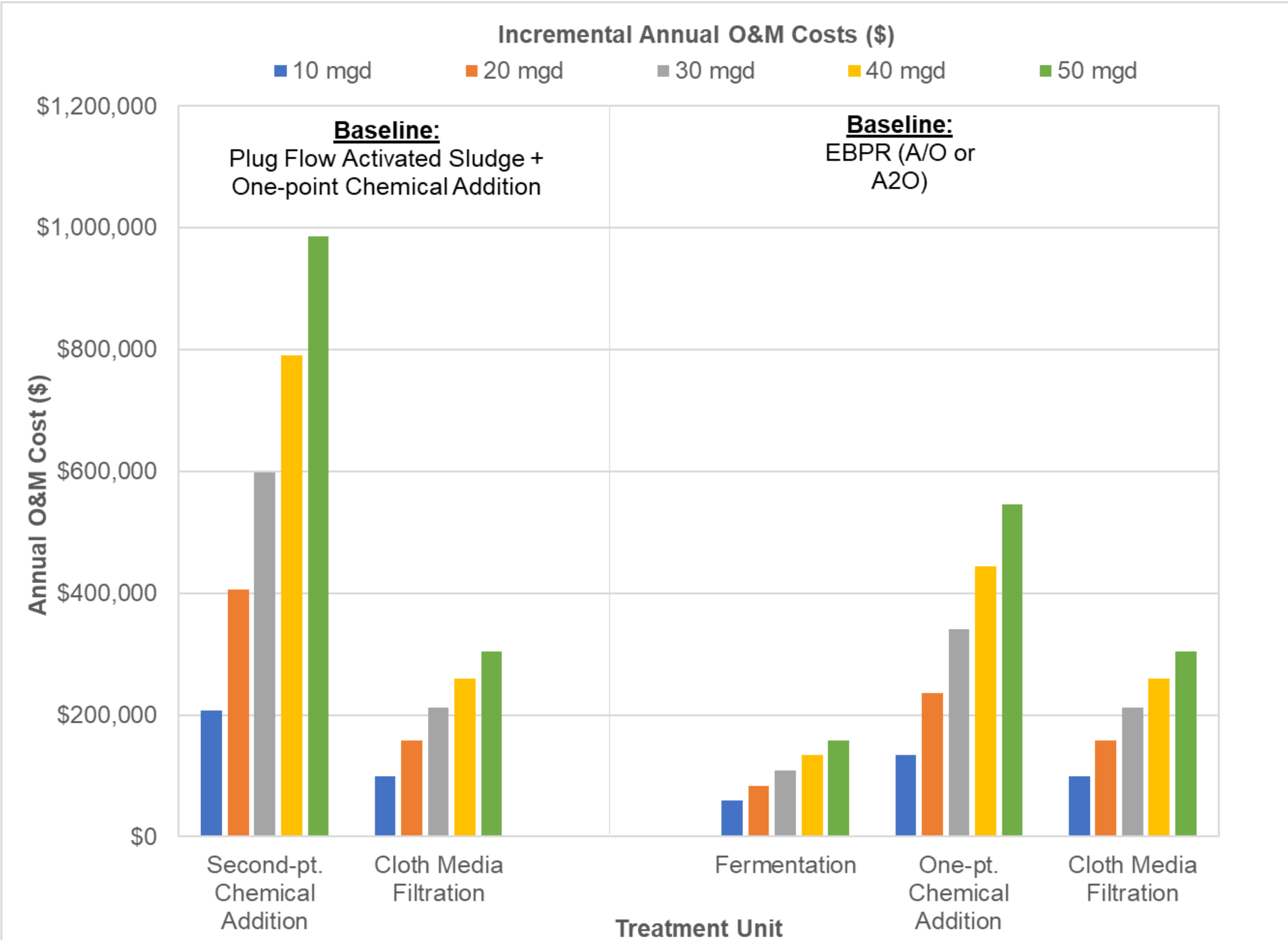

Figure 2. Facility Group 1: Estimated Incremental Annual O&M Cost ($)

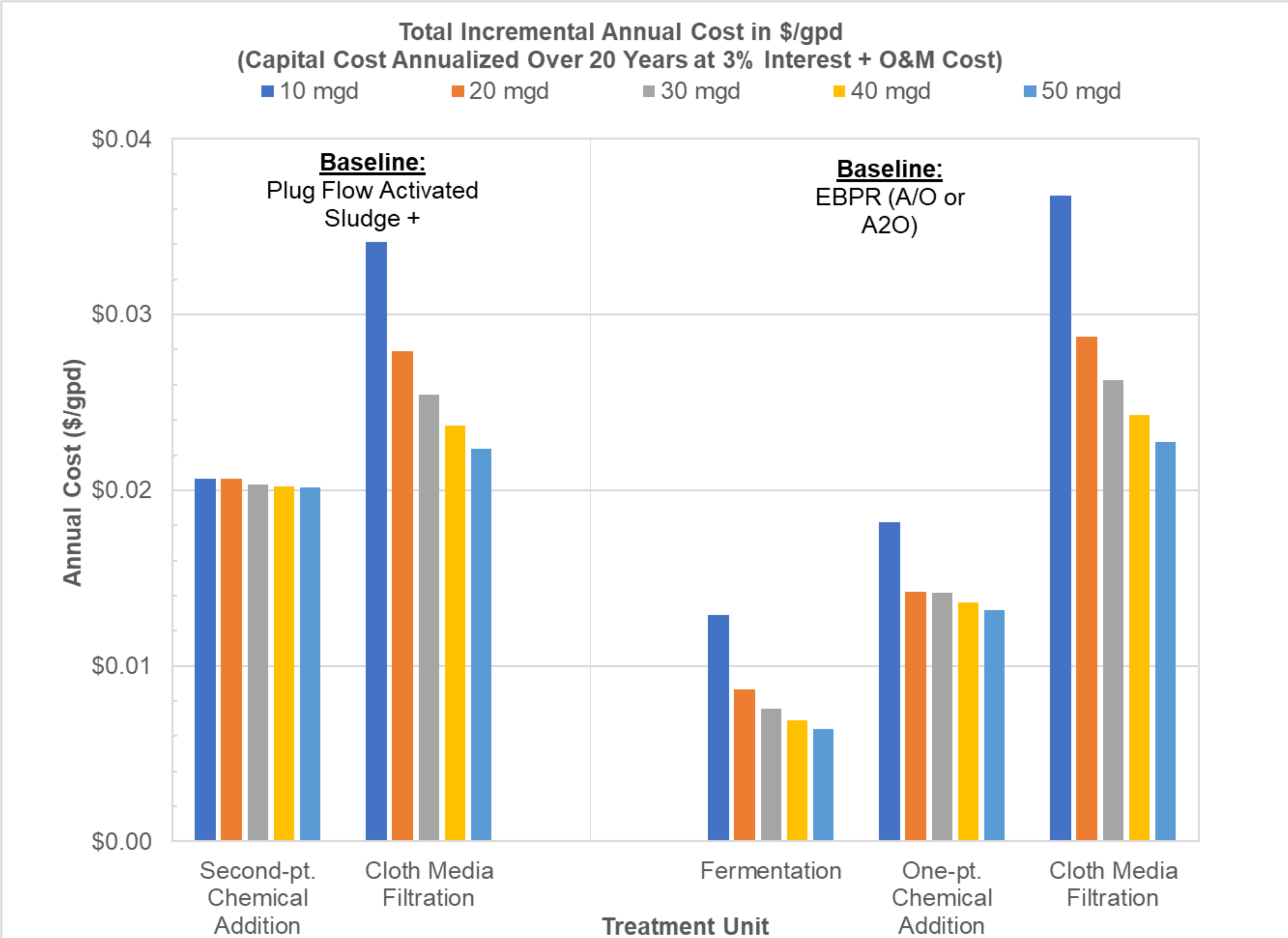

Figure 3. Facility Group 1: Incremental Annual Cost in $/gpd

3.2 FACILITY GROUP 2 COST ESTIMATES

Facility Group 2 includes major wastewater treatment plants that discharge between 1.0 and 10 mgd and currently have permit limits for total phosphorus. The current total phosphorus limits, baseline treatment configuration used in the analysis, total phosphorus effluent target, and additional treatment options considered are summarized in Table 11.

Table 11. Facility Group 2: Baseline Treatment Configurations and Total Phosphorus Treatment Options

Facility Group	Existing Average Monthly Effluent Total Phosphorus Target/Limit	Baseline System	Potential Average Monthly Effluent Total Phosphorus Target/Limit	Additional Treatment Unit Options Considered
Group 2: ≥ 1.0 to 10.0 mgd	1.0 mg/L	Conventional biological treatment—plug-flow activated sludge + one-point alum addition	0.5 mg/L	**Chemical Treatment** • Second point of chemical addition • Cloth media filtration
		EBPR—A/O process or A2O process	0.5 mg/L	**EPBR** • Fermentation • Cloth media filtration **Chemical Treatment** • One-point chemical addition • Cloth media filtration

Estimated capital, O&M, and total annual incremental costs (in $thousands) for chemical treatment and EPBR options for facility Group 2 (design flows of 1.0 mgd, 2.5 mgd, 5.0 mgd, 7.5 mgd, and 10 mgd) are summarized in Table 12.

Table 12. Facility Group 2: Estimated Incremental Costs by Treatment Option *($Thousands)*

Design Flow Rate	Total Capital Cost	Annualized Capital Cost (i = 3%, n = 20 yrs.)	Annual O&M Cost	Total Annual Cost
Baseline: Conventional Plug-Flow Activated Sludge + One-point Chemical Addition				
Second point of chemical addition				
1.0 mgd	$0	--	$19	**$19**
2.5 mgd	$0	--	$52	**$52**
5.0 mgd	$0	--	$101	**$101**
7.5 mgd	$0	--	$155	**$155**
10 mgd	$0	--	$206	**$206**
Cloth media filtration				
1.0 mgd	$1,464	$98	$49	**$148**
2.5 mgd	$1,762	$118	$43	**$161**
5.0 mgd	$2,597	$175	$61	**$236**
7.5 mgd	$3,417	$230	$81	**$310**
10 mgd	$4,153	$279	$98	**$377**
Baseline: EBPR (A/O or A2O)				
Fermentation				
1.0 mgd	$305	$20	$16	**$36**
2.5 mgd	$404	$27	$27	**$54**
5.0 mgd	$591	$40	$42	**$81**
7.5 mgd	$866	$58	$52	**$110**
10 mgd	$1,033	$69	$60	**$129**
One-point chemical addition				
1.0 mgd	$392	$26	$45	**$71**
2.5 mgd	$466	$31	$59	**$90**
5.0 mgd	$557	$37	$82	**$120**
7.5 mgd	$637	$43	$109	**$151**
10 mgd	$704	$47	$135	**$182**
Cloth media filtration				
1.0 mgd	$1,499	$101	$49	**$150**
2.5 mgd	$1,807	$121	$43	**$164**
5.0 mgd	$2,646	$178	$61	**$239**
7.5 mgd	$3,459	$233	$81	**$313**
10 mgd	$4,007	$269	$98	**$368**

Note: Estimated costs are rounded to the nearest thousand dollars. The sum of annual costs may not equal the *Total Annual Cost* due to rounding.

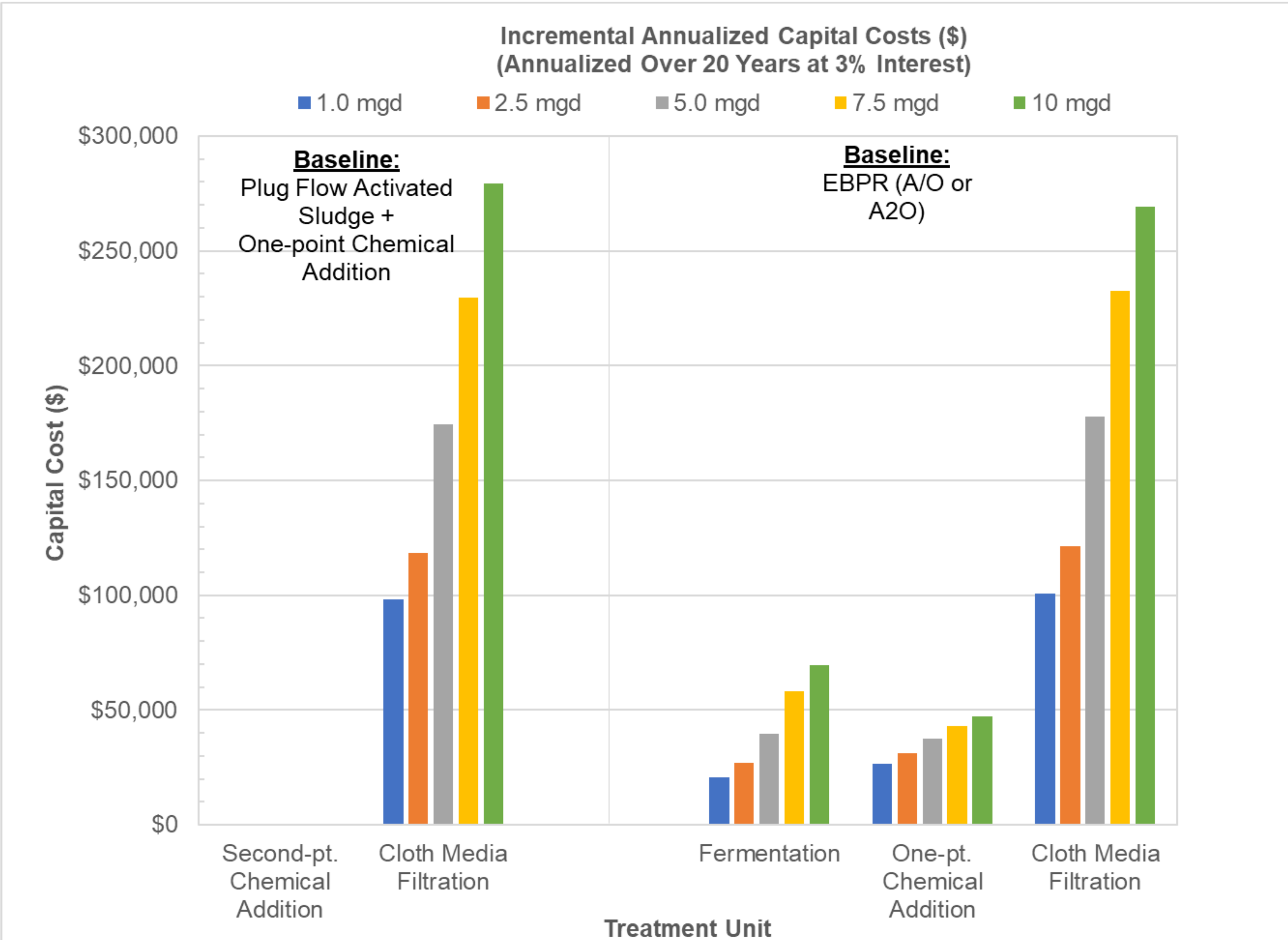

Figure 4. Facility Group 2: Estimated Incremental Annualized Capital Cost ($)

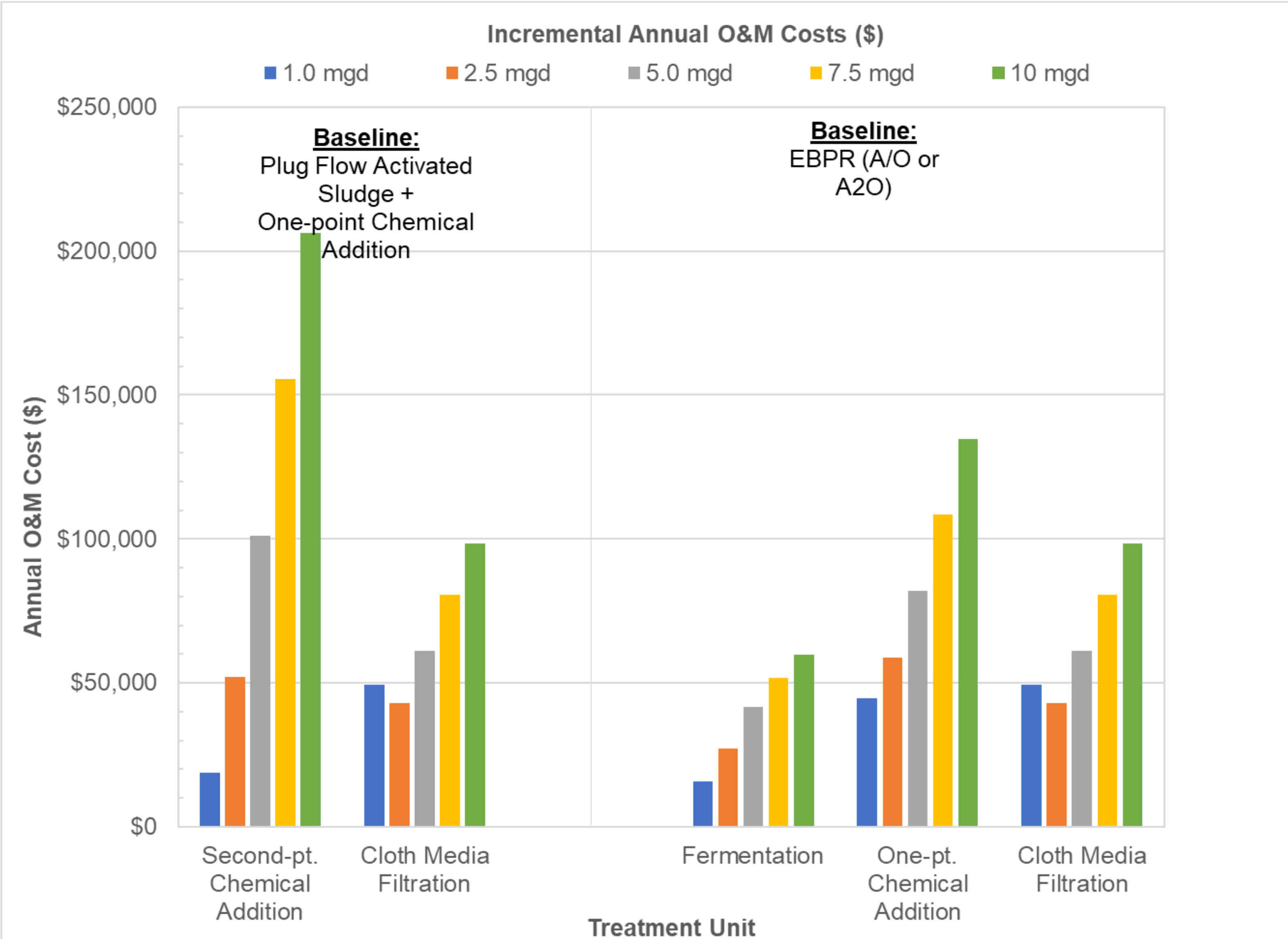

Figure 5. Facility Group 2: Estimated Incremental Annual O&M Cost ($)

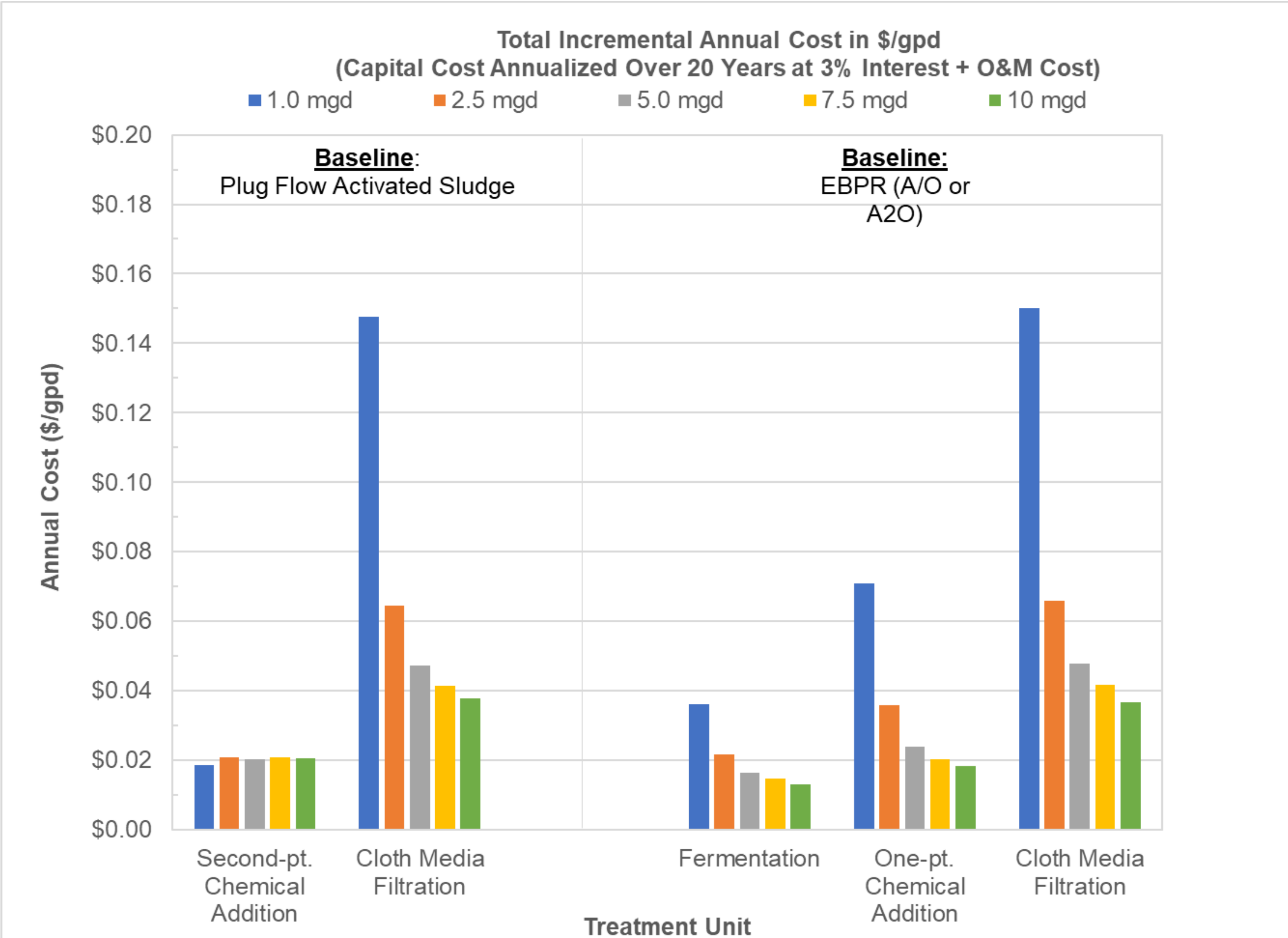

Figure 6. Facility Group 2: Incremental Annual Cost in $/gpd

3.3 FACILITY GROUP 3 COST ESTIMATES

Facility Group 3 includes significant minor wastewater treatment plants that currently have no permit limits for total phosphorus. The current total phosphorus limits, baseline treatment configuration used in the analysis, total phosphorus effluent target, and additional treatment options considered are summarized in Table 13.

Table 13. Facility Group 3: Baseline Treatment Configuration and Total Phosphorus Treatment Options

Facility Group	Existing Average Monthly Effluent Total Phosphorus Target/Limit	Baseline System	Potential Average Monthly Effluent Total Phosphorus Target/Limit	Additional Treatment Unit Options Considered
Group 3: ≥ 0.5 to < 1.0 mgd	No limit/target	Conventional biological treatment—plug-flow activated sludge	1.0 mg/L	**Chemical Treatment** • One-point chemical addition **EPBR** • A/O unit – retrofit • A/O unit –replacement • A2O unit – retrofit • A2O unit –replacement

Estimated capital, O&M, and total annual incremental costs (in $thousands) for chemical treatment and EPBR options for facility Group 3 (design flows of 0.5 mgd, 0.75 mgd, and 1.0 mgd) are summarized in Table 14.

Table 14. Facility Group 3: Estimated Incremental Costs by Treatment Option *($Thousands)*

Design Flow Rate	Total Capital Cost	Annualized Capital Cost (i = 3%, n = 20 yrs.)	Annual O&M Cost	Total Annual Cost
Chemical Treatment				
One-point chemical addition				
0.5 mgd	$527	$35	$44	**$79**
0.75 mgd	$578	$39	$48	**$87**
1.0 mgd	$629	$42	$53	**$95**
EBPR				
A/O – retrofit				
0.5 mgd	$218	$15	$30	**$45**
0.75 mgd	$285	$19	$32	**$51**
1.0 mgd	$359	$24	$37	**$61**
A/O – replacement				
0.5 mgd	$871	$56	$30	**$89**
0.75 mgd	$1,141	$77	$32	**$109**
1.0 mgd	$1,434	$96	$37	**$134**
A2O – retrofit				
0.5 mgd	$1,430	$96	$125	**$221**
0.75 mgd	$1,732	$116	$143	**$259**
1.0 mgd	$2,049	$138	$153	**$290**
A2O – replacement				
0.5 mgd	$2,429	$163	$125	**$288**
0.75 mgd	$2,947	$198	$143	**$341**
1.0 mgd	$3,488	$234	$153	**$387**

Table 14 and Figure 2 show the estimated incremental annualized capital cost and incremental annual O&M cost for each option. Figure 3 shows the estimated total incremental annual cost of each unit process per gallon per day (gpd) of wastewater treated for each design flow rate modeled.

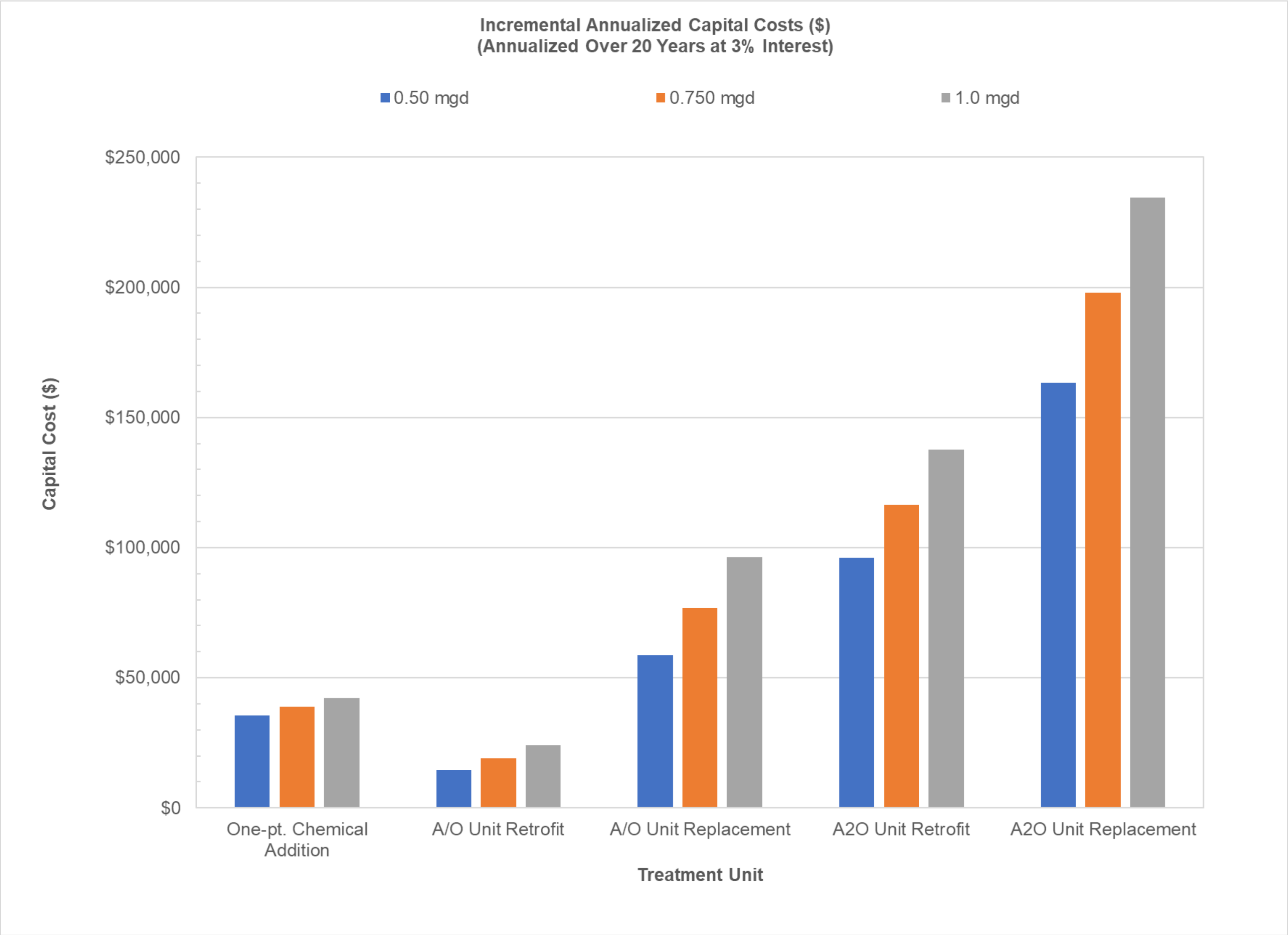

Figure 7. Facility Group 3: Estimated Incremental Annualized Capital Cost ($)

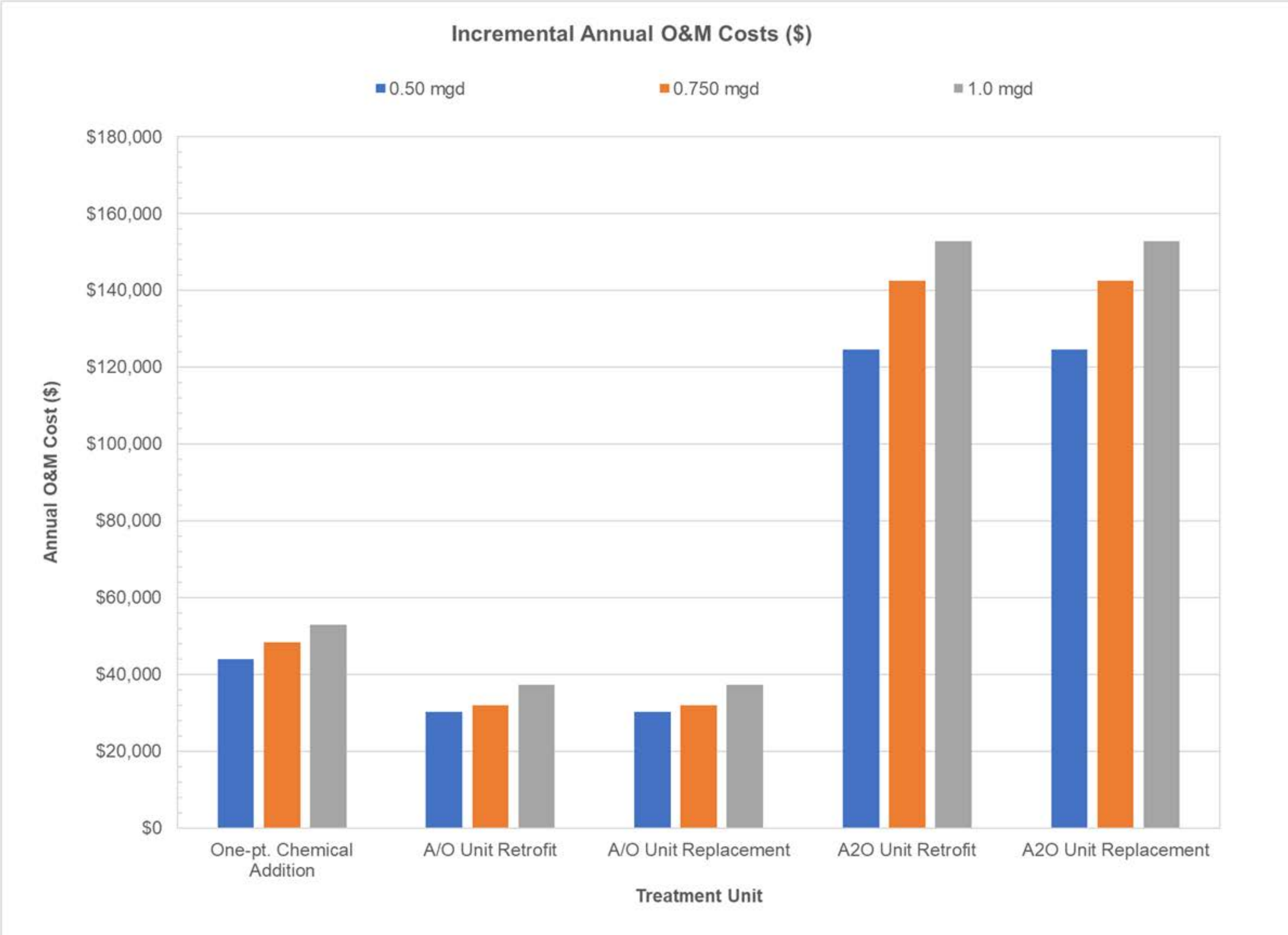

Figure 8. Facility Group 3: Estimated Incremental Annual O&M Cost ($)

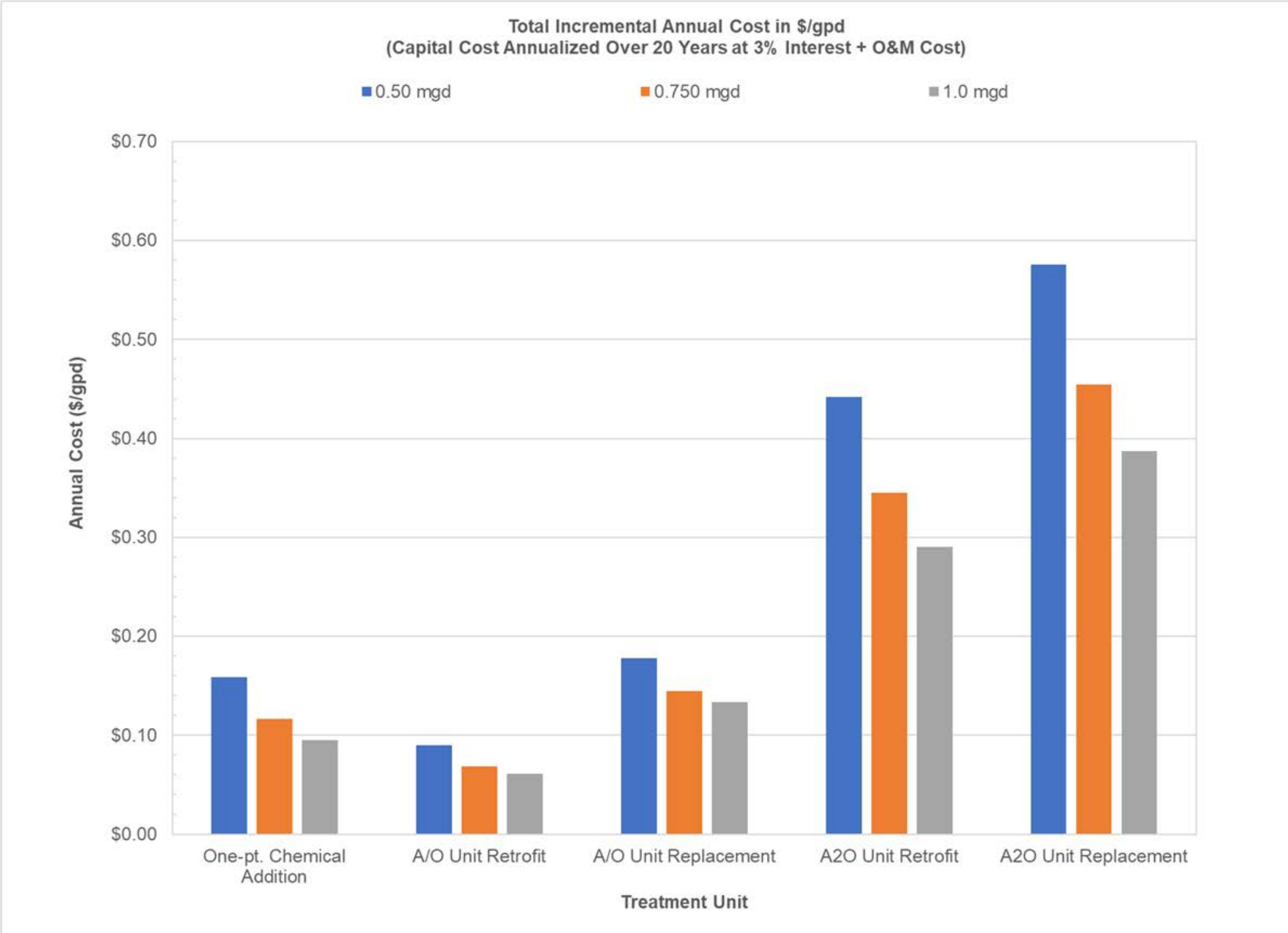

Figure 9. Facility Group 3: Incremental Annual Cost in $/gpd

3.4 OTHER COST CONSIDERATIONS

Data limitations and some features of CapdetWorks lead to some uncertainties and the need to make assumptions in the analysis of incremental costs to wastewater treatment facilities. These uncertainties and assumptions, summarized in Table 15, may cause an underestimation or overestimate on of costs.

Table 15. Cost Estimate Uncertainties and Assumptions

Uncertainty/Assumption	Likely Effect on Cost Estimate	Notes
The analysis makes assumptions regarding influent concentrations and treatment process design parameters and applies these assumptions to all modeled treatment systems.	Underestimate or Overestimate	CapdetWorks considers both influent concentrations of parameters of concern and treated effluent volume to produce estimated costs. The analysis in this report uses the same values for key influent parameters used by U.S. EPA in prior studies. CapdetWorks also allows users to modify unit process parameters that may have an impact on treatment system performance and cost. The analysis uses CapdetWorks default process design parameters with the exception of chemical dosage for alum addition. The analysis uses the same values as prior U.S. EPA studies. A specific facility may have influent concentrations or design parameters that differ from the assumptions used in the analysis and that could affect costs. For example, higher influent concentrations of total phosphorus might require higher chemical dosing for total phosphorus removal. The assumptions used in the analysis may result in underestimating or overestimating costs for a particular facility.
The analysis assumes the same baseline treatment system components for all facilities within each facility grouping.	Underestimate or Overestimate	The analysis assumes a uniform baseline treatment system for facilities in Group 1 and either the same system plus one-point chemical addition or EBPR as the baseline for Group 2 and Group 3. Treatment units at individual facilities may differ from these baseline systems; therefore, the analysis may underestimate or overestimate costs for a specific facility.
To estimate costs, the analysis assumes that all facilities will add or retrofit at least one phosphorus	Underestimate or Overestimate	Some facilities may be able to optimize existing treatment processes to achieve the target total phosphorus concentrations (e.g., optimizing solids capture in the final clarifier to remove particulate phosphorus). On the other

Uncertainty/Assumption	Likely Effect on Cost Estimate	Notes
treatment unit to a baseline treatment system to achieve additional total phosphorus removal. Cost estimates are included for some unit processes, such as fermentation and cloth filtration, that the analysis assumes will not be necessary at all facilities.		hand, some facilities may consider adding units that were not part of the analysis, such as equalization basins, to lower peak demand and provide for more cost effective treatment. The analysis also provides cost estimates for additional unit processes that may or may not be needed to achieve the required total phosphorus concentrations, such as the addition of fermentation to a system with EBPR or the addition of a cloth filter to enhance total phosphorus removal in a system employing chemical treatment. The analysis assumes that fermentation and/or cloth filtration will not be needed at all facilities. Assumptions regarding baseline systems and the selected unit process additions could either underestimate or overestimate the costs to a specific facility.
For Group 1 facilities (significant minors), the analysis makes assumptions about potential cost savings by retrofitting rather than replacing biological treatment units.	Underestimate or Overestimate	For some unit processes, an option is to retrofit, rather than replace, an existing unit to achieve better phosphorus removal. Retrofitting allows a facility to save costs by using existing tankage, piping, and other equipment. The analysis relies on assumptions from prior U.S. EPA studies, summarized in Table 7, to estimate the cost savings of retrofitting rather than replacing existing unit processes. The relative cost of retrofitting rather than replacing a unit at an individual facility may be different from these assumptions; therefore, the analysis may underestimate or overestimate costs for a specific facility.
The A2O unit process provides for additional nitrogen removal.	Overestimate	Some facilities may opt to make changes to their treatment systems to enhance both nitrogen and phosphorus removal. The analysis recognizes this possibility by including an option for facilities without specific nutrient removal technologies of retrofitting or upgrading a conventional plug-flow activated sludge unit to an A2O process for biological treatment. Because the cost of additional treatment for nitrogen removal is not part of the analysis, the costs for A2O as a unit process overestimates the costs for phosphorus removal alone at such facilities.
The analysis assumes a need to expand existing unit process capacity for some	Overestimate	The analysis assumes that a facility installing an A2O unit process for EBPR will also need to expand blower capacity and secondary clarification capacity by 50%. This assumption is consistent with U.S. EPA assumptions used in prior

Uncertainty/Assumption	Likely Effect on Cost Estimate	Notes
total phosphorus treatment unit options.		analyses. If a facility already has sufficient blower capacity and secondary clarification capacity to accommodate replacement or retrofitting an existing biological treatment process with an A2O unit, this assumption may lead to an overestimation of costs for that facility.
CapdetWorks does not include some treatment processes that were considered in the analysis (e.g., fermentation, cloth filtration).	Underestimate or Overestimate	As discussed in Section 2.3, CapdetWorks does not include all of the unit processes considered in the analysis (e.g., fermentation, cloth filtration). The analysis makes assumptions regarding the cost of these unit processes based on assumptions from prior U.S. EPA studies and best professional judgment. These assumptions could result in underestimating or overestimating costs for a particular treatment unit at a specific facility.
Key cost estimate inputs used in CapdetWorks are based on the latest values available and, where possible, for the State of Ohio.	Underestimate or Overestimate	The analysis modifies selected cost calculation inputs in CapdetWorks to update costs as close as possible to 2022 dollars; however, the inputs are from data published in different months and, in some cases, the latest available data are from 2021. As labor rates and prices (e.g., equipment costs, energy costs) change over time, the cost estimates in the analysis could increase or decrease. For example, labor rates may be higher than what is reflected by the latest available data at the time of the analysis; conversely, energy costs may be slightly lower. In addition, while cost estimate inputs were modified to reflect values for Ohio where possible, local values might be different. Thus, costs could be either underestimated or overestimated for a specific locality.
The analysis assumes that capital costs are financed over 20 years at 3% interest.	Underestimate or Overestimate	The financing period and interest rate for an individual facility may differ from those used in the analysis. Depending on the actual financing period and interest rate, the annualized costs presented in the analysis may underestimate or overestimate actual costs.
CapdetWorks does not break out other direct and indirect capital costs by treatment unit.	Underestimate or Overestimate	As discussed in Section 2.4.1, the estimated incremental capital cost for each additional treatment unit is based on the estimated cost of the treatment unit itself plus other direct and indirect capital costs attributed to installation of that treatment unit. Because CapdetWorks does not break out these costs by treatment unit, the analysis pro-rates other

Uncertainty/Assumption	Likely Effect on Cost Estimate	Notes
		direct and indirect capital costs by treatment unit using the process described in Section 2.4.1. The formula could overestimate or underestimate costs for a specific facility. For example, considering facility Group 1 and Group 2, the model predicts that the capital cost of adding one-point chemical addition to an EBPR facility is less at some higher design flow rates than it is at some lower design flow rates. This can be attributed to the formula used to assign other direct and indirect capital costs to a particular treatment unit in proportion to that treatment units share of the overall cost of all treatment units.
Sludge handling costs are not considered in the analysis.	Underestimate	Chemical precipitation of total phosphorus increases sludge generation and limits disposal options for facilities. Also, sludge treatment processes may liberate phosphorus, resulting in high phosphorus recycle streams, and could require more process upgrades for nutrient removal in some instances. Sludge handling costs are not considered in the analysis; therefore, facilities adding chemical treatment for phosphorus removal may be underestimated.

4.0 REFERENCES

AACEI. 2005. *Cost Estimate Classification System—As Applied in Engineering, Procurement, and Construction for the Process Industries*. AACE International Recommended Practice No. 18R-97. TCM Framework: 7.3 – Cost Estimating and Budgeting. Association for the Advancement of Cost Engineering International.

U.S. Army Corps of Engineers and U.S. Environmental Protection Agency. 1979. *Computer-Assisted Procedure for the Design and Evaluation of Wastewater Treatment Systems: Users Guide*. Department of the Army, Corp of Engineers. U.S. EPA, Office of Water. Washington, D.C. May 1979.

U.S. Bureau of Labor Statistics (BLS). 2022. Occupational Employment and Wage Statistics Data. https://www.bls.gov/oes/tables.htm. November 28, 2022.

U.S. Energy Information Administration (EIA). 2022. *Electric Power Monthly with Data for May 2022.* July 2022. https://www.eia.gov/electricity/monthly/. November 28, 2022.

U.S. Environmental Protection Agency (U.S. EPA). 2008. *Municipal Nutrient Removal Technologies Reference Document*. EPA 832-R-08-006. U.S. EPA, Office of Wastewater Management, Municipal Support Division, Municipal Technology Branch. Prepared by Tetra Tech, Inc., Fairfax, VA. September 2008. https://www.epa.gov/sustainable-water-infrastructure/municipal-nutrient-removal-technologies-reference-document. November 28, 2022.

-----. 2021. *Life Cycle and Cost Assessments of Nutrient Removal Technologies in Wastewater Treatment Plants*. U.S. EPA, Office of Water, Office of Science and Technology, Standards and Health Protection Division. Prepared by Eastern Research Group, Inc., Lexington, MA. August 2021. https://www.epa.gov/system/files/documents/2021-08/life-cycle-nutrient-removal.pdf. November 28, 2022.