

WMOST

- Watershed Management Optimization Support Tool -

Watershed Management Optimization Support Tool Benefits Module: Theoretical Documentation

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by

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Abstract

The Watershed Management Optimization Support Tool (WMOST) was developed by the United States Environmental Protection Agency (US EPA) to facilitate integrated water resources management. The new Benefits Module for WMOST enables stakeholders to calculate the value of additional water-quality benefits associated with water resource management as well as additional co-benefits. Water quality benefits (or costs) include both changes in costs of drinking water treatment and total nonmarket benefits (i.e., use and nonuse) of water quality changes. Co-benefits valued include (1) change in housing property value due to improved aesthetic quality of the landscape from increases in green space, (2) air pollution removal and energy savings benefits related to canopy cover, and (3) air pollution removal and energy savings benefits related to green roofs.

1 Introduction

The Watershed Management Optimization Support Tool (WMOST) was developed by the United States Environmental Protection Agency (US EPA) to facilitate integrated water resources management (IWRM; Detenbeck et al. 2018 a,b,c). It enables users to find the least-cost solution to meet water quantity and water quality related objectives, considering practices within stormwater, wastewater, drinking water, and land conservation programs. By adopting an integrated water management approach, WMOST promotes cost efficiencies and helps users to avoid unintended consequences, e.g., increased algal blooms associated with increased retention time following decisions to maximize surface water supply in reservoirs. In addition, the flooding module within previous versions of WMOST allowed users to consider some ancillary benefits of management actions such as reductions in flood-related costs. However, other ancillary water quality benefits and cobenefits of IWRM were not captured in previous versions of WMOST. Increasingly, municipalities are adopting a more holistic approach to IWRM, and doing comprehensive evaluations of environmental, social, and economic consequences of their decisions (Stratus Consulting Inc. 2009).

The new Benefits Module for WMOST is designed to assess potential water quality-related benefits and non-water quality co-benefits associated with IWRM decisions. Additional water quality-related benefits include avoided costs for drinking water treatment to reduce suspended solids (US EPA 2009) as well as values assigned by the general public to water quality improvements (U.S. EPA, 2015). The latter values are calculated based on a meta-analysis of willingness-to-pay, using the Water Quality Index (WQI) approach (U.S. EPA, 2015). Co-benefit values monetized within the Benefits Module include:

- 1) changes in water treatment costs
- 2) changes in total nonmarket benefits of water quality changes
- 3) improved aesthetic quality of the landscape from increases in green space leading to changes in property values (Mazzotta et al. 2014),
- 4) avoided human health damages associated with reduced exposures to criteria air pollutants related to canopy cover (Nowak et al. 2014),
- 5) increased carbon sequestration related to canopy cover (IWGSCC 2016, U.S. EPA, 2019a),
- 6) reduction in heating and cooling needs associated with canopy cover (Nowak et al. 2017) and green roofs (<https://sustainability.asu.edu/urban-climate/green-roof-calculator/>), and
- 7) avoided emissions from power plants associated with lessened energy costs.

Although there are other potential benefits and co-benefits associated with watershed management practices (including green infrastructure; Tzoulas et al. 2007, Meerow and Newell 2016, Environmental Finance Center 2017), we chose to highlight this subset of benefits because of the availability of published methods to assign monetary values to this specific set. The Benefits Module is built upon a Microsoft Excel interface, using the skeleton of EPA's ScenCompare utility for WMOST to import results log files from WMOST runs and extract decision variables of interest from the WMOST results (US EPA 2020).

Instructions for running the WMOST Benefits Module in the ScenCompare interface are provided in a separate User Guide (US EPA 2020). In the current document, we provide additional background on the

calculation of benefits and cobenefits. In Section 2 of this document, we provide additional background on the theoretical basis for each of these benefits and co-benefit categories. In Section 3, we introduce a stand-alone spreadsheet that illustrates the behind-the-scene calculations included in the Benefits Module, and then describe the underlying calculations and data sources in greater detail.

2 Overview of Benefits and Co-benefits Calculated by the Module

2.1 Overview

Figure 1 below summarizes the benefit calculations and associated WMOST management practices included in the standalone spreadsheet (Appendix A).

2.2 Water Quality Benefits

2.2.1 Avoided drinking water treatment costs

We can calculate the benefit of improved source surface water quality¹ by estimating the reduction in water treatment costs associated with lower total suspended solids (TSS) concentrations. The methodology for this is laid out in the documentation for the 2009 Final Effluent Limitation Guidelines and Standards for the Construction and Development Industry (US EPA 2009). The treatment costs depend on turbidity levels and the costs of coagulants as turbidity is treated with varying doses of chemical coagulants.

2.2.2 Nonmarket value of water quality changes

The US EPA has used the Water Quality Index (WQI) as a water quality metric in benefit cost analysis for several rulemakings (U.S. EPA 2009, 2015). The WQI was developed to communicate complex water quality information in valuation exercises (McClelland 1974). The WQI is a composite indicator that combines information from multiple water quality parameters into a single overall value expressed on a 0 - 100 scale. Creating the WQI involves three main steps (US EPA 2009): (1) obtaining measurements on individual water quality indicators, (2) transforming measurements into “subindex” values to represent them on a common scale, and (3) aggregating the individual subindex values into an overall WQI value (Walsh and Wheeler 2013). We base the use and non-use value of water quality improvements on the methodology from the 2015 Steam Electric Rule (SE ELG) (U.S. EPA 2015), which used a meta-regression model (MRM) of the public’s willingness-to-pay (WTP) for water quality improvements. The SE ELG analysis expressed water quality improvements in WQI terms, calculated mean household annualized WTP for water quality improvements on an annual and census block group (CBG) basis, and multiplied the household WTP by the number of households that value the affected resources to estimate the total annualized benefits. Some methodological updates were incorporated to address the following critical elements of the approach.

¹ This benefit calculation is limited to source surface water quality (flows to the water treatment plant from the surface water and reservoir). It will not account for improvements to groundwater water quality.

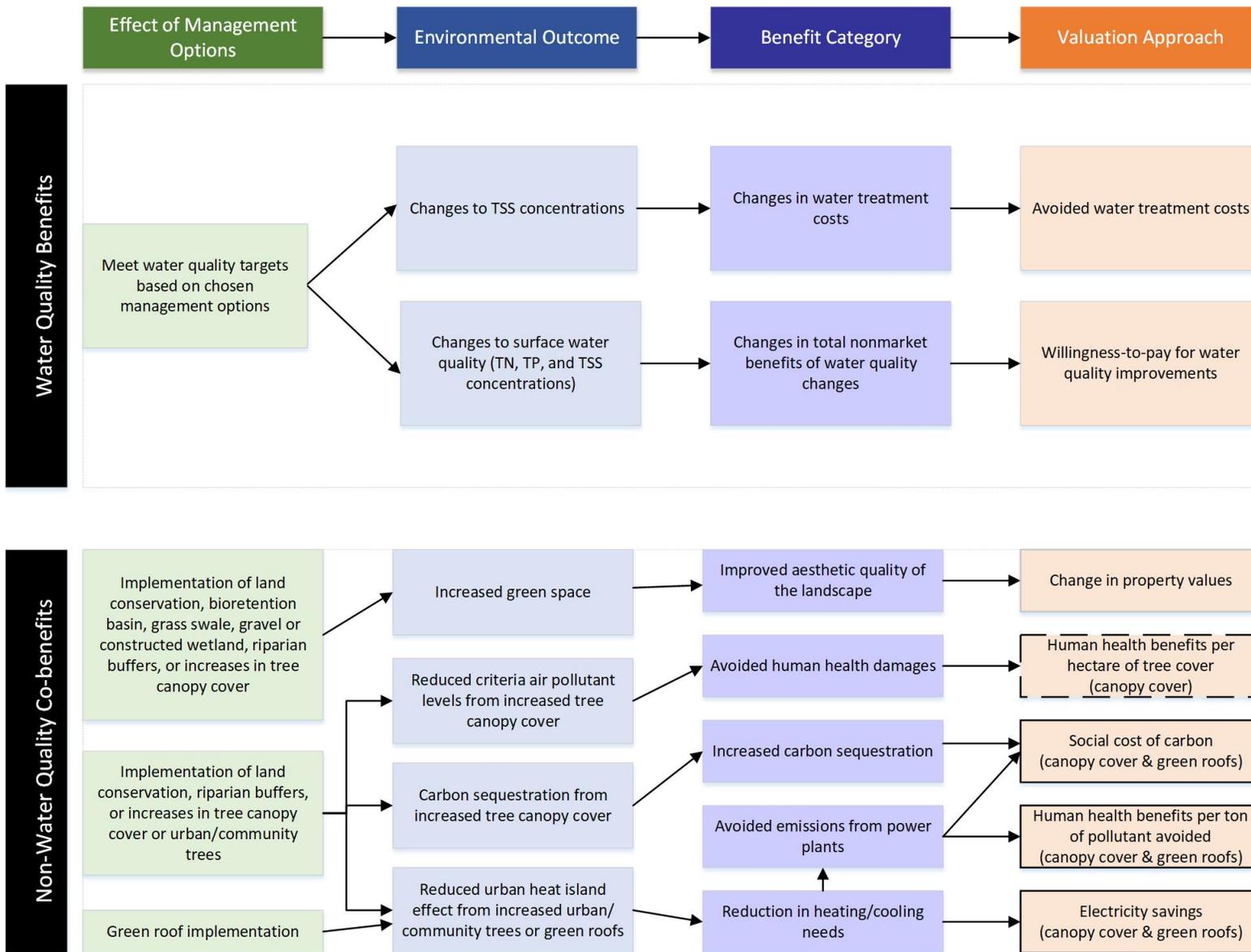


Figure 1. Benefit and co-benefit categories and valuation methodologies included in the Benefits Module.

2.2.2.1 *Water quality changes*

The WQI used in the benefits assessment for the Construction and Development Rule (US EPA 2009) included six parameters (US EPA 2009): dissolved oxygen (DO), biochemical oxygen demand (BOD), fecal coliform (FC), total nitrogen (TN), total phosphorus (TP), and total suspended solids (TSS). The WQI aggregates these multiple parameters into a single index value expressed on a 0-100 scale. For use within the Benefits Module, we chose to use this six-parameter WQI, because of the greater simplicity of use than the seven-parameter WQI used in the SE ELG.

Of the six parameters used in the WQI calculation, WMOST is capable of modeling three: TN, TP, and TSS. Users can access USGS's National Water Information System (NWIS)² for concentration data for the other three parameters (DO, BOD, and FC). WMOST is used to estimate changes in values of TN, TP and TSS, with the other three parameters assumed to remain constant. For example, if a user is using WMOST to determine management options for reducing TN loads, the user can then also run WMOST in simulation mode to understand how the same chosen management option(s) affect TP and TSS concentrations and use USGS's NWIS to obtain data for DO, BOD, and FC for the same time period. Please see the Benefits Module User Guide for more details (US EPA 2020b).

2.2.2.2 *Estimating per household WTP*

Our chosen approach applies the estimate per household WTP to all households residing in the affected watershed, like the approach taken for the C&D Rule (2009). WMOST does not have the capability to model water quality changes outside of the model study area. This limitation affects the substitute sites variable (see Section 3.3.2) and the number of households that value the affected resource. The substitute site proportion variable is set to one to indicate no substitute sites as WMOST cannot quantify water quality changes outside of the study area. In addition, the number of households that value the affected resource will be limited to households within the watershed boundary. Setting the substitute sites variable to one may overestimate the per household WTP estimate by not accounting for effects of available substitutes outside the watershed. However, limiting the number of households to those within the watershed boundary will likely underestimate total WTP since households from surrounding watersheds may also value the water quality improvements. Since we expect the number of households to have a greater effect on the total WTP estimate than the substitute sites variable, this methodology will likely produce a conservative estimate.

Overall, we have not made any changes to the benefit function used to estimate total WTP for a change in water quality. Instead, we have made changes to the data sources and hard-coded values for the meta-analysis function input variables (as shown in the tables in Section 3.3.2).

² USGS's NWIS dataset provides information on the occurrence, quantity, quality, distribution, and movement of surface and underground waters based on data collected at approximately 1.5 million sites in all 50 States, the District of Columbia, and U.S. territories. More information on NWIS can be found at <http://waterdata.usgs.gov/nwis/>

2.3 Non Water Quality Co-benefits

2.3.1 Change in property values associated with green space

The calculation of increased housing prices resulting from increased green space (both natural and constructed green infrastructure) uses the coefficients from a meta-regression of results in existing hedonic literature from Mazzotta et al. (2014) to estimate the anticipated percent change in housing prices per HUC12 or HUC10. Following the methodology in Mazzotta et al. (2014), the percentage change in annual rental value of a property is dependent on the percentage change in green space, distance of green space from residences, characteristics of the changed green space, and population density. We have adjusted in calculations and underlying data to account for differences in the effects of changes to green space for land uses with varying population densities and within varying distances from residences.

2.3.2 Canopy cover benefits

Canopy cover benefits are based on increased acres of overall canopy cover and whether this increase includes urban/community trees. Increased acres of canopy cover results in increased carbon sequestration and increased removal of criteria air pollutants³ that cause negative human health impacts (NO₂, SO₂, O₃, PM_{2.5}). Increased acres of urban/community trees also result in energy cost savings for nearby buildings and subsequent reductions in criteria air pollutants (NO_x, SO₂, and PM_{2.5}) and carbon dioxide from avoided power plant emissions.⁴ Table 1 describes the canopy cover benefits in more detail, along with the sources used to quantify and monetize each benefit and the region type of each source (e.g., national, state-level, local).

Table 1. Canopy cover benefits and descriptions of the quantification/monetization sources

Environmental Outcome	Benefit	Source(s)	Region Type
Increased acres of canopy cover	Increased carbon sequestration	Social Cost of Carbon: Global: IWGSCC (2016) Domestic: U.S. EPA (2019a)	National
	Avoided human health damages resulting from tree removal of air pollutants (NO ₂ , SO ₂ , O ₃ , PM _{2.5})	Nowak et al. (2014)	National (regressions); county-level (population density)
Increased acres of urban/community trees	Electricity savings	Nowak et al. (2017); personal communication with authors	State-level
	Avoided human health damages from avoided NO _x , SO ₂ , and PM _{2.5} emissions from power plants	Quantification: Nowak et al. (2012); Nowak et al. (2017) Monetization: U.S. EPA (2018)	Quantification: State-level Monetization: National

³ EPA has established national ambient air quality standards (NAAQS) for six of the most common air pollutants—carbon monoxide (CO), lead (Pb), ground-level ozone (O₃), particulate matter (PM_{2.5}), nitrogen dioxide (NO₂; NO_x), and sulfur dioxide (SO₂; SO_x) — known as “criteria” air pollutants. The primary NAAQS are set to protect public health.

⁴ Avoided human health damages for acres of tree canopy overall and acres of urban/community trees differ because power plants do not emit ground-level ozone.

Table 1 (Continued)

Environmental Outcome	Benefit	Source(s)	Region Type
Increased acres of urban/community trees	Avoided CO ₂ emissions from power plants	Quantification: Nowak et al. (2012); Nowak et al. (2017) Monetization: IWGSCC (2016), U.S. EPA (2019a)	Quantification: State-level Monetization: National

2.3.2.1 Increased acres of canopy cover

Increased carbon sequestration

Management actions that will increase carbon sequestration in the landscape include riparian buffer restoration, increasing canopy cover to developed land, and conserving forested land areas. While other green infrastructure practices could also increase carbon sequestration, carbon sequestration values for other constructed green infrastructure practices are not readily available and are likely of smaller magnitude than those associated with changes in canopy cover. Calculating the value of annual carbon sequestration is a two-step process: (1) multiplying the increase in tree cover by the rate of carbon sequestration to obtain the annual amount of carbon sequestered by the additional canopy cover; and (2) multiplying the annual amount of carbon sequestered by the social cost of carbon. EPA is currently using interim values of the domestic social cost of carbon (SC-CO₂) to inform Federal regulatory analyses (U.S. EPA, 2019). For this application, we are giving the WMOST user the option to calculate co-benefits using either the interim domestic or global social cost of carbon or both. We propose giving the user these options for several reasons. First, available domestic social cost of carbon values are unpublished; interim values have been developed under Executive Order 13783 (82 FR 16093, March 31, 2017) for use in regulatory analyses until an improved estimate of the impacts of climate change to the United States can be developed based on the best available science and economics. Second, Executive Order 13783 required the use of domestic SC-CO₂ in regulatory impact analyses only. WMOST users may use the tool for non-regulatory purposes, so they can decide whether domestic or global SC-CO₂ values are appropriate for their analysis.

Avoided human health damages resulting from tree removal of air pollutants

Increased canopy cover results in increased removal of pollutants by trees and other plants. To quantify the reduction in air pollutants due to trees, the Benefits Module multiplies the number of increased canopy cover acres by pollutant removal rates from Nowak et al. (2014) and determines the pollutant reductions in metric tons. To monetize the reduction in air pollutants due to trees, the benefits module applies regression equations from Nowak et al. (2014) that estimate dollars per metric ton based on population density.

2.3.2.2 Increased acres of urban/community trees

Electricity savings

In Nowak et al. (2017), calculations for energy savings from canopy cover first divide estimated total energy savings from urban/community trees (MWh) in the United States by the number of acres of urban/community trees in the United States to determine average electricity savings per acre of trees. The calculations then multiply the average nationwide price of a megawatt hour of residential electricity by the electricity savings per acre of urban/community trees to determine the dollar value of electricity

savings per acre. Finally, the dollar value of electricity savings per acre is multiplied by the number of increased canopy cover acres expected under the optimization scenario to estimate the total value of energy savings from canopy cover.

We substitute state-level per hectare values for residential energy conservation from Nowak et al. (2017) instead of calculating a national-level per hectare value. Although the Nowak et al. (2017) paper only provides average national per hectare benefit values in 2009 dollars (\$455 for energy conservation, \$228 for avoided power plant emissions) and a range for the per hectare energy conservation values by state (low of \$123 in Montana to a high of \$1,811 in Washington, DC),⁵ the authors provided state-level values via personal communication.

Avoided human health damages from avoided emissions from power plants

We also add human health benefits from avoided power plant emissions related to reduced heating and cooling energy requirements, using EPA-vetted benefit per ton values to monetize human health benefits from avoided power plant emissions.⁶ Instead of using the state-level per hectare benefit values for avoided power plant emissions provided by the authors of Nowak et al. (2017), which are based on European willingness-to-pay values, we calculate state-level per hectare values using national-level, EPA-vetted benefit per ton values. To develop state-specific per hectare values of avoided emissions, we combine national-level benefits per ton estimates with the state-level estimates of avoided emissions and hectares of urban/community trees.

Avoided CO₂ emissions from power plants

Reductions in energy use associated with heating and cooling costs also leads to reductions in CO₂ emissions from power plants. Residential building energy conservation and avoided power plant emissions by urban and community trees in the United States are obtained from Nowak et al. (2017) and the social cost of carbon is defined as described above (IWGSCC 2016, U.S. EPA 2019a).

2.3.3 Green roofs

Like canopy cover, green roofs provide value by reducing energy requirements associated with heating and cooling. In turn, those reductions in energy use lead to avoided human health damages from avoided NO_x, SO₂, and PM_{2.5} emissions. CO₂ emissions from power plants are reduced as well (Table 2).

⁵ The large range is attributable to factors that can affect energy savings, including density of residential buildings, energy usage between heating and cooling seasons, local energy costs, and presence (or density) of tree cover in the vicinity of residential buildings (Nowak et al., 2017).

⁶ We note that Nowak et al. (2017) includes national level per hectare values of avoided power plant emissions. The authors also provided state-level values via personal communication. However, both national-level and state-level values are based on air pollution cost factors from Europe that may not be appropriate for the U.S. due to differences in population characteristics (e.g., perceived values of the same benefit).

Table 2. Green roof benefits and descriptions of the quantification/monetization sources

Benefit	Source(s)	Region Type
Electricity savings	State-level: U.S. EIA (2018)	State-level (you can provide local values)
Avoided human health damages from avoided NO _x , SO ₂ , and PM _{2.5} emissions from power plants	Quantification: U.S. EPA (2019b) Monetization: U.S. EPA (2018)	Quantification: Regional (AVERT regions) Monetization: National
Avoided CO ₂ emissions from power plants	Quantification: U.S. EPA (2019b) Monetization: IWGSCC (2016), U.S. EPA (2019a)	Quantification: Regional (AVERT regions) Monetization: National

To calculate green roof benefits, the user will determine green roof energy savings by inputting information about potential green roofs into Arizona State University’s Green Roof Energy Calculator tool.⁷ The calculator tool requires green roof characteristics and location, using the closest available city to the study watershed of interest.

To quantify reductions in criteria air pollutants (SO₂, NO_x, PM_{2.5}) and carbon dioxide (CO₂) from reduced energy consumption due to the installation of green roofs, the Benefits Module applies regional AVERT⁸ emission rates (U.S. EPA, 2019b) to convert energy savings into avoided emission of criteria air pollutants (in lbs of SO₂, NO_x, and PM_{2.5}) and carbon dioxide (in tons of CO₂). The contiguous United States is divided into ten AVERT regions. Four different types of regional AVERT emission rates are available: wind, utility-scale photovoltaic, portfolio energy efficiency, and uniform energy efficiency.

3 Calculation of Benefits

3.1 Stand-alone Spreadsheet

A subset of the calculations of co-benefits related to canopy cover and green roofs is illustrated in a stand-alone spreadsheet (Appendix A). This resource is provided to make calculations and associated data sources more transparent to the user and to enable exploration of scenarios outside of those associated with WMOST optimizations. It could also be used in conjunction with other regional decision support tools requiring access to these calculations and look-up tables.

3.2 Calculating Benefits - Dollar Year

Within the Benefits Module, benefits are calculated using various costs that are either defined by the user, the literature, or a government data source. As a result, benefit values are calculated in a variety of dollar years. The table below summarizes the various cost data sources and associated dollar year for each of the benefit calculations.

⁷ <https://sustainability.asu.edu/urban-climate/green-roof-calculator/>

⁸ AVoided Emissions and geneRation Tool

As shown, benefit values are in a variety of dollar years. To streamline the calculation of benefits for users, ensure benefit calculation consistency, and confirm the accuracy with which the benefit values can be compared to WMOST outputs, the following approach is adopted. Users have the option to adjust the default dollar year value (2016 – 2019) on the Benefits Module interface. The specified dollar year will then be used in ScenCompare’s background programming. For any benefits that include costs or data input by users (e.g., avoided water treatment costs or value of energy savings), the user will specify the dollar year of their data and the appropriate conversion will be made by the module’s background programming.

Table 3. Cost data sources and associated dollar years.

Benefit Valuation	Dollar Year	Cost	User Input	Literature Value	Government Data Source
Avoided water treatment costs	Set by user	Cost of alum	X		
Use and non-use of water quality improvements	2007\$	Mean income (converted to 2007\$ from user-specified year)	X		X
Green space	2013\$	Median home value (converted to 2013\$ from 2017\$)			X
Carbon sequestration benefits	2016\$	Global social cost of carbon			X
Carbon sequestration benefits	2017\$	Domestic social cost of carbon			X
Avoided CO ₂ emissions from avoided power plant emissions	2016\$	Global social cost of carbon			X
Avoided CO ₂ emissions from avoided power plant emissions	2017\$	Domestic social cost of carbon			X
Human health benefits from increased canopy cover (tree uptake of pollutants)	2010\$	Benefit per ton estimates, using a regression equation based on population density		X	
Human health benefits from increased canopy cover (avoided power plant emissions)	2015\$	Benefit per ton estimates for PM _{2.5} , SO ₂ , NO _x			X
Human health benefits from green roof implementation (avoided power plant emissions)	2015\$	Benefit per ton estimates for PM _{2.5} , SO ₂ , NO _x			X
Value of energy savings from increased canopy cover	2009\$	Energy savings per hectare of tree cover		X	
Value of energy savings from green roof implementation	Set by user	Price of a MWh of residential electricity	X		X

3.3 Water Quality Benefits

3.3.1 Changes in water treatment costs

This benefit requires a comparison of TSS concentrations before (i.e., baseline) and after the implementation of management options. We can convert our pre- and post- management practice TSS concentrations (mg/L) to turbidity (nephelometric turbidity units [NTU]) using the following relationship from EPA (2009):

$$T = \frac{\left(\frac{L_{SwWtp,t} + L_{ResWtp,t}}{bQ_{SwWtp,t} + bQ_{ResWtp,t}} \right) \times \left(\frac{3.79 \times 10^6}{9.07 \times 10^8} \right)}{b} \quad (3.1)$$

where variables are defined as follows:

Table 4. Definition of variables in equation 3.1

Variable	Definition	Value	Source
T	turbidity (NTU)	> 0	Calculated from WMOST results
$L_{SwWtp,t}$	TSS loadings from surface water to the water treatment plant (tons)	> 0	WMOST results
$L_{ResWtp,t}$	TSS loadings from the reservoir to the water treatment plant (tons)	> 0	WMOST results
$bQ_{SwWtp,t}$	Flows from surface water to the water treatment plant (MG)	> 0	WMOST results
$bQ_{ResWtp,t}$	Flows from the reservoir to the water treatment plant (MG)	> 0	WMOST results
b	estimated ratio of turbidity to TSS	1.5 by default, can be edited by user ⁹	EPA (2009)

The values 3.79×10^6 and 9.07×10^8 correspond to the conversion factors of liters per million gallons and milligrams per ton, respectively.

Once we have calculated baseline and post-management practice implementation levels of turbidity, we can calculate the baseline and post-management practice implementation dosage of the coagulant used to treat turbidity (alum). The dosage of alum used to treat water of a given turbidity can be approximated by the following relationship from EPA (2009):

$$Al = 33 \log(T) - 28 \quad (3.2)$$

where variables are defined as follows:

Table 5. Definition of variables in equation 3.2

Variable	Definition	Value	Source
Al	alum dose (mg/L)	> 0	Calculated from WMOST results
T	turbidity (NTU)	> 0	Calculated from WMOST results

⁹ The 2009 C&D rule used 0.8, 1.5, and 2.2 for low, midpoint, and high benefit estimates. We recommend using 1.5 as the default value but allow users to adjust it in the interface. As discussed in EPA (2009), “as the value of b decreases, a given level of TSS generates more turbidity, leading to higher treatment costs”.

If the calculated alum dose is negative, the value is adjusted to 0.

Finally, the cost of the alum required before and after the TSS reduction can be calculated for a given volume of intake flow using a calculation from EPA (2009):

$$TC_{Al} = \sum_{t=1}^{ndays} (Q_{SwWtp,t} + Q_{ResWtp,t}) \times \left(\frac{Al \times (3.79 \times 10^6)}{9.07 \times 10^8} \right) \times C_{Al} \quad (3.3)$$

where variables are defined as follows:

Table 6. Definition of variables in equation 3.3.

Variable	Definition	Value	Source
TC_{Al}	total annual alum cost (\$/year)	> 0	Calculated from WMOST results
$Q_{SwWtp,t}$	daily flow from surface water system to water treatment plant (MG/day)	> 0	WMOST results
$Q_{ResWtp,t}$	flow from reservoir to water treatment plant (MG/day)	> 0	WMOST results
Al	alum dose (mg/L)	> 0	Calculated from WMOST results
C_{Al}	cost of alum (\$/ton)	> 0	Set by the user
$ndays$	number of days in the year	> 0	WMOST results

The values 3.79×10^6 and 9.07×10^8 correspond to the conversion factors of liters per million gallons and milligrams per ton, respectively.

By calculating this value before and after the implementation of any management practices, the difference can be used to measure the benefit of reduced water treatment costs due to TSS reductions within the watershed.

3.3.2 Changes in total nonmarket benefits of water quality

After obtaining water quality levels for each of the six parameters included in the WQI, WMOST transforms the parameter measurements into subindex values expressed on a common scale and aggregates the subindices to obtain a daily or monthly overall WQI value. Table 7 summarizes the weights used to aggregate the subindices to an overall WQI value using a geometric mean function (see equation below the table).

Table 7. Parameter weights for WQI calculation.

Parameters	Weights
Dissolved oxygen	0.24
Fecal coliform	0.22
Biochemical oxygen demand	0.15
Total nitrogen	0.14
Total phosphorus	0.14
Total suspended solids	0.11

$$WQI = \prod_{i=1}^n Q_i^{W_i} \quad (3.4)$$

- WQI = the multiplicative water quality index (from 0 to 100)
 Q_i = the water quality subindex measure for parameter i
 W_i = the weight of the i -th parameter
 n = the number of parameters (i.e., six)

The marginal household willingness to pay calculation is as follows:¹⁰

$$\ln(MWTP) = -2.30 + 1.18 \times northeast + 0.561 \times central + 1.4 \times south + 0.333 \times \ln(income) - 0.827 \times mult_type - 0.079 \times river - 0.271 \times \ln(agricultural) - 0.034 \times \ln(ar_ratio) + 1.1 \times substitutes - 0.015 \times Q \quad (3.5)$$

where variables are defined as follows:

Table 8. Definition of variables in equation 3.5

Variable	Definition	Value	Source
<i>northeast</i>	binary variable indicating that the affected population is in a Northeast U.S. state, defined as ME, NH, VT, MA, RI, CT, and NY.	0, 1	Set by the user
<i>central</i>	binary variable indicating that the affected population is in a Central U.S. state, defined as OH, MI, IN, IL, WI, MN, IA, MO, ND, SD, NE, KS, MT, WY, UT, and CO.	0, 1	Set by the user
<i>south</i>	binary variable indicating that the affected population is in a Southern U.S. state, defined as NC, SC, GA, FL, KY, TN, MS, AL, AR, LA, OK, TX, and NM.	0, 1	Set by the user
$\ln(income)$	natural log of median household income values for the watershed area. (\$/year)	> 0, calculated by user	Set by the user; 2015 ACS 5-Year Estimates ¹¹
<i>mult_type</i>	binary variable indicating that multiple waterbody types are affected (e.g., river and lakes).	0	Hard-coded ¹²
<i>river</i>	binary variable indicating that rivers are affected.	1	Hard-coded ¹³

¹⁰ Meta-analysis documentation for the SE ELG analysis describes additional methodological variables that characterize features of the source studies included in the meta-analysis, such as the year in which the study was conducted, payment vehicle, elicitation format, WTP estimation method, and publication type. These variables are included to explain differences in WTP across studies but are not expected to vary across different management scenarios. The equation accounts for these hard-coded variables in the intercept coefficient.

¹¹ https://factfinder.census.gov/bkmk/table/1.0/en/ACS/15_5YR/B19001

¹² WMOST is a lumped model so this variable will be set to zero.

¹³ WMOST can route flows through a surface water component and reservoir component. For the purposes of this benefit calculation, the reservoir component is assumed to represent a dammed river so this variable will be set to one.

Table 8. (Continued)

Variable	Definition	Value	Source
$\ln(\text{agricultural})$	natural log of the proportion of the watershed area which is agricultural.	> 0, calculated by user	Set by the user; NLCD
$\ln(\text{ar_ratio})$	ratio of the sampled area, in km ² , relative to the affected resource area. For WMOST purposes, the sampled area is equal to the affected resource area.	1	Hard-coded
<i>substitutes</i>	size of the affected resources relative to available substitutes. Calculated as the proportion of water bodies of the same hydrological type affected by the water quality change within the affected resource area	1	Hard-coded
Q	Water quality changes due to the implementation of the management practice, $Q = WQI_{\text{Scenario}} - WQI_{\text{Baseline}}$.	0-100	Calculated from WMOST results

After calculating marginal willingness-to-pay, we can calculate annual household WTP for the change in water quality due to the implemented management practice(s):

$$HWTP = MWTP \times Q \quad (3.6)$$

where variables are defined as follows:

Table 9. Definition of variables for equation 3.6

Variable	Definition	Value	Source
$HWTP$	annual household WTP for households located within the WMOST watershed area (\$/year)	> 0	Calculated from WMOST results
$MWTP$	marginal WTP for water quality estimated by the meta-analysis function	> 0	Calculated from WMOST results (see above)
Q	estimated annual average water quality change: $Q = WQI_{\text{Scenario}} - WQI_{\text{Baseline}}$ Where WQI_{MO} is the annual average water quality index value resulting from the management option implementation and WQI_{BL} is the annual average water quality index value for the baseline	> 0	Calculated from WMOST results (see above)

Once household willingness-to-pay has been calculated, we can calculate total willingness-to-pay (TWTP) for water quality improvements by multiplying the number of households (HH) within the watershed by the household willingness-to-pay value (HWTP):

$$TWTP = HWTP \times HH \quad (3.7)$$

3.4 Non Water Quality Co-benefits

3.4.1 Improved aesthetic quality of the landscape from increases in green space leading to changes in property values

3.4.1.1 Benefit equations

Benefits for three different residential land use types (low, medium, and high density) are estimated based on equations from Mazzotta et al. (2014). Changes in home price are calculated for two buffer zones: (1) for increases in green space occurring within 250 meters of residences and (2) for increases in green space occurring at distances of 250 – 500 meters. These estimates are then combined to estimate the total benefits to affected homeowners:

$$\begin{aligned} \% \Delta \text{homeprice}_{250m} = & 0.039 + 0.169 \times P_{inc_250} - 0.063 \times P_{popdens} + 0.252 \times \text{riparian} - \\ & 0.013 \times \text{wetland} + 0.245 \times \text{trees} + 0.392 \times \text{protected} + 0.081 \times \text{recreational} - \\ & 0.018 \times \ln(\text{lotsize}) - 0.0009 \times \text{homeprice} \end{aligned} \quad (3.8)$$

$$\begin{aligned} \% \Delta \text{homeprice}_{500m} = & 0.039 + 0.102 \times P_{inc_500} - 0.063 \times P_{popdens} + 0.252 \times \text{riparian} - \\ & 0.013 \times \text{wetland} + 0.245 \times \text{trees} + 0.392 \times \text{protected} + 0.081 \times \text{recreational} - \\ & 0.018 \times \ln(\text{lotsize}) - 0.0009 \times \text{homeprice} \end{aligned} \quad (3.9)$$

Because long-term home price trends are difficult to predict, before applying the calculated percent change in home price, we convert the overall present-day median housing values to annual rental-equivalent home values to calculate an annualized value by multiplying median housing values by a discount rate (3% in Mazzotta et al. (2014)):

$$\text{median home value} \times .03 = \text{annual rental equivalent value} \quad (3.10)$$

The percentage change in home prices can be applied to this annual rental-equivalent value to estimate the monetary benefits to homeowners from increased green space within the defined buffer distance.

$$\% \Delta \text{homeprice}_{250m} \times \text{annual rental equivalent value} \times \text{housing units}_{250m} \quad (3.11)$$

Variables are defined as follows¹⁴:

Table 10. Definition of variables for equation 3.11

Variable	Definition	Value	Source – Riparian Buffer BMP ¹⁵	Source – All Other Green Space BMPs
P_{inc_250}	Percentage increase in open space within 250 meters of residences (%).	0-100	WMOST results, (based on Tables 11,12) WMOST Green Space Values Database (<i>AD</i> variable), and riparian contribution lookup table	WMOST results (based on Table 12)
P_{inc_500}	Percentage increase in open space between 250 and 500 meters of residences (%).	0-100	WMOST results, (based on Tables 11, 12) WMOST Green Space Values Database (<i>AD</i> variable), and riparian contribution lookup table	WMOST results (based on Table 12)
$P_{popdens}$	Percentage increase in open space if watershed had ≥ 800 people per square mile in 2011; zero if watershed has < 800 people per square mile in 2011 (%).	0-100	WMOST Green Space Values Database (based on <i>PD10p900</i> variable, using WMOST results value if watershed has ≥ 800 people per square mile)	WMOST Green Space Values Database (based on <i>PD10p900</i> variable, using WMOST results value if watershed has ≥ 800 people per square mile)
<i>riparian</i>	One if riparian buffer area is expected to increase; zero otherwise.	0, 1	WMOST results	Hard-coded as 0 as they are non-riparian buffer BMPs
<i>wetland</i>	One if wetland area is expected to increase; zero otherwise.	0, 1	Set by the user	Set by the user
<i>trees</i>	Percentage of the increase in open space that is tree cover	0-100	Default values set or suggested by WMOST (see Section 4.4.1.2), can be adjusted by the user	Default values set or suggested by WMOST (see Section 4.4.1.2), can be adjusted by the user

¹⁴ EPA developed a Green Space Values Database to aid users with the data input required for the calculation of this co-benefit. Its implementation is discussed in more detail in Section 4.4.1.2.

¹⁵ The WMOST Green Space Values Database includes more detailed information on residential land uses within the defined buffer distances (0-250 meters and 250-500 meters) from a riparian zone. As a result, the data sources for riparian buffer BMPs is slightly different from the data sources for other green space BMPs (see Table 13 for the additional green space BMPs).

Table 10. (Continued)

Variable	Definition	Value	Source – Riparian Buffer BMP ¹⁶	Source – All Other Green Space BMPs
<i>protected</i>	One if open space associated with development practice is typically permanently protected; zero otherwise.	0, 1	WMOST results; 1 if land conservation BMP implemented	WMOST results; 1 if land conservation BMP implemented
<i>recreational</i>	One if recreational amenities are included in development practice; zero otherwise.	0, 1	Set by the user	Set by the user
$\ln(\textit{lotsize})$	Natural log of median lot size	> 0	WMOST Green Space Values Database (<i>hh</i> variable)	WMOST Green Space Values Database (<i>haphu10</i> variable)
<i>homeprice</i>	Median home value	> 0 (\$thousands)	WMOST Green Space Values Database (<i>MHVK</i> variable)	WMOST Green Space Values Database (<i>MHVK</i> variable)
<i>housing units</i>	Number of housing units within defined buffer distance	> 0	WMOST Green Space Values Database (<i>m2</i> and <i>hu</i> variables)	WMOST Green Space Values Database (<i>AREAM2</i> and <i>hu10pha</i> variables)

The percentage increase in open space within the two defined buffers (0-250 m and 250-500 m from residences) would be determined based on the scale of the implemented BMPs. Table 11 below summarizes available WMOST management practices and their associated assumed distance from residences. All other WMOST management practices either do not involve changes in green space or would be expected to occur more than 500 meters from residences and therefore would have no impacts on property values.

Table 11. WMOST management practice and assumed distance from residences

WMOST management practice	0-250 meter buffer	250-500 meter buffer
Land Conservation		X
Bioretention Basin		X
Grass Swale	X	
Gravel Wetland		X
Direct Reduction Tree Canopy	X	
Riparian Buffer	X	X

¹⁶ The WMOST Green Space Values Database includes more detailed information on residential land uses within the defined buffer distances (0-250 meters and 250-500 meters) from a riparian zone. As a result, the data sources for riparian buffer BMPs is slightly different from the data sources for other green space BMPs (see Table 13 for the additional green space BMPs).

Only riparian buffers are assumed to potentially affect values of properties within both 0-250 meters and 250-500 meters. For other BMPs, implementation is assumed to occur within either the 0-250 meter or 250-500 meter buffer. For example, if WMOST chose to implement a grass swale BMP, the percentage increase in open space within 250 meters from residences would be nonzero and used to calculate the percentage change in home prices. The grass swale BMP would not increase the percentage of open space within 250 to 500 meters from residences and WMOST would not calculate associated benefits on that basis.

3.4.1.2 WMOST Green Space Values Database

EPA developed the WMOST Green Space Values Database to aid users with obtaining input data required for the calculation of this co-benefit. This section describes how WMOST will use the database, especially when applied to WMOST model runs that span multiple HUC12s. Table 12 summarizes the relevant database variables and how WMOST will utilize them for the co-benefit calculation.

Table 12. Green Space Values Database variable summary

Variable Name ¹⁷	Variable Description	WMOST Usage
MHVK	Median home value (\$thousand) in land use class in HUC12	Used directly; area-weighted average if study area spans multiple HUC12s
PD10p900	Average population density per 900 m2 in land use class in HUC12	Used to determine if variable should be 0 or the percent increase in open space; area-weighted average if study area spans multiple HUC12s
AD	Average distance (m) of building centroid from riparian zone for each land use class if within buffer distance of riparian zone in HUC12	Used as a crosswalk with the riparian contribution lookup table. The distance will be rounded to the nearest tenth to crosswalk with the lookup table and identify the fraction of the building radius that intersects with the riparian zone; area-weighted average distance if study area spans multiple HUC12s
hu10pha	Housing units per hectare in land use class in HUC12	Used directly; area-weighted average if study area spans multiple HUC12s
haphu10	Average hectares per housing unit in land use class in HUC12	Used directly; area-weighted average if study area spans multiple HUC12s

¹⁷ The truncated variable name is used within this table. The full variable name includes indicators of the associated land use area type or riparian zone buffer distance.

Table 13. Default percent tree canopy values for each BMP associated with the increase in green space benefit calculation.

Associated BMP	Default Percent Tree Canopy	Rationale
Land conservation	Variable based on conserved land use	This should vary based on the land use chosen to be conserved. Default values for each NLCD land use/land cover class are summarized in Appendix B of the Benefits Module User Guide: Default Percent Tree Canopy Values by Vegetated NLCD Land Cover Class
Bioretention basin	50%	According to North Carolina’s Department of Environmental Quality’s (NCDEQ) Stormwater Design Manual ¹⁸ , bioretention cells should be designed to have a maximum tree or shrub canopy of 50 percent at five years after planting.
Grass swale	0%	The assumed vegetation is grass.
Gravel wetland	0%	This should vary based on native wetland vegetation, but the default value assumes that the implemented gravel wetland is dominated by grasses and shrubs.
Constructed wetland	30%	This should vary based on native wetland vegetation, but the default value is based on a constructed <i>forested</i> wetland. According to a U.S. Army Corps of Engineers (USACE) performance standards for nontidal wetland mitigation banks guide ¹⁹ , canopy cover should be at least 30 percent. Users will be notified that they should adjust this value if implementing constructed wetlands dominated by grasses or shrubs.
Riparian buffer implementation	100%	The default value assumes that the user will implement forested riparian buffers ²⁰ , but users will be notified that they should adjust this value if implementing riparian buffers dominated by grasses or shrubs.
Direct reduction tree canopy	100%	This BMP is intended to represent increases in tree canopy in urban areas.

¹⁸<https://files.nc.gov/ncdeq/Energy+Mineral+and+Land+Resources/Stormwater/BMP+Manual/C-2%20%20Bioretention%201-19-2018%20FINAL.pdf>

¹⁹https://www.nab.usace.army.mil/Portals/63/docs/Regulatory/Mitigation/IRT_NT_WetlandBuffer_Monitoring_Protocol_Bank_10_28_16.pdf?ver=2017-11-13-163628-277

²⁰ Based on a U.S. Department of Agriculture Natural Resources Conservation Service (USDA-NRCS) riparian forest buffer specification guide sheet (<https://efotg.sc.egov.usda.gov/references/public/VT/VTSpec391-0109.pdf>), canopy density should be at least 80 percent coverage. We will include this lower bound in the theoretical documentation.

3.4.2 Canopy cover benefits

3.4.2.1 Increased acres of canopy cover

Increased carbon sequestration

Calculating the value of annual carbon sequestration is a two-step process (see example equation below): (1) multiplying the increase in tree cover by the rate of carbon sequestration to obtain the annual amount of carbon sequestered by the additional canopy cover; and (2) multiplying the annual amount of carbon sequestered by the social cost of carbon.

$$V_{TCS} = A_{TC} \times R_{CS} \times C_{SCC} \times GPDIPD \quad (3.12)$$

where variables are defined as follows:

Table 14. Definition of variables in equation 3.12

Variable	Definition	Value	Source
V_{TCS}	total value of annual carbon sequestration (\$/year)	> 0, calculated by user	n/a
A_{TC}	increase in tree cover (acres)	> 0, calculated by WMOST	WMOST results
R_{CS}	rate of carbon sequestration (metric ton C acre ⁻¹ year ⁻¹)	0.77	US EPA (2019) ²¹
C_{SCC}	Domestic social cost of carbon (2016\$/metric ton C) OR		WMOST look-up table ²²
C_{SCC}	Global social cost of carbon (2007\$/metric ton C)		WMOST look-up table ²³
$GPDIPD$	GPD Implicit Price Deflator		WMOST look-up table

Avoided human health damages resulting from tree removal of air pollutants

The Benefits Module uses both pollutant removal rates for criteria air pollutants (NO₂, O₃, PM_{2.5}, and SO₂) and population density-based regression equations from Nowak et al. (2014), as shown in Equation 3-13 below. The Benefits Module performs the calculations for each of the air pollutants and sums the values to obtain the total value of avoided human health damages resulting from tree removal of air pollutants.

$$V_{TAHD} = (A_{TC} \times PR_x) \times PDR_x \quad (3.13)$$

where variables are defined as follows:

²¹ https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references#_ftn1

Please note that this is an estimate for “average” U.S. forests in 2017; i.e., for U.S. forests as a whole in 2017. Significant geographical variations underlie the national estimates, and the values calculated here might not be representative of individual regions, states, or changes in the species composition of additional acres of forest. Nowak et al. (2013) also reports rates of carbon sequestration per unit of tree cover for specific cities and states.

²² https://www.epa.gov/sites/production/files/2019-06/documents/utilities_ria_final_cpp_repeal_and_ace_2019

²³ https://19january2017snapshot.epa.gov/sites/production/files/2016-12/documents/sc_co2_tsd_august_2016.pdf

Table 15. Definition of variables in equation 3.13

Variable	Definition	Value	Source
V_{TAHD}	total value of avoided human health damages from increased tree removal of air pollutants (\$/year)	> 0, calculated by the Benefits Module	n/a
A_{TC}	increase in tree cover (acres)	> 0, calculated by WMOST	WMOST results
PR_x	pollutant removal rate for NO ₂ , O ₃ , PM _{2.5} , and SO ₂ (converted from g/m ² to metric tons/acre)	Varies by pollutant	Nowak et al. (2014)
PDR_x	population density-based regressions estimating avoided human health damages per metric ton (population density is X variable)	Varies by pollutant	Nowak et al. (2014)

3.4.2.2 Increased acres of urban/community trees

Reduction in heating/cooling needs

The Benefits Module uses state-level per hectare energy conservation values to calculate total annual energy savings due to increased acres of urban/community trees:

$$V_{TES} = A_{TC} \times Conv_{ha} \times V_{ES} \quad (3.14)$$

where variables are defined as follows:

Table 16. Definition of variables in equation 3.14

Variable	Definition	Value	Source
V_{TES}	total value of energy savings due to increase in urban/community trees (\$/year)	> 0, calculated by the Benefits Module	n/a
A_{TC}	increase in urban/community trees (ac)	> 0, calculated by WMOST	WMOST results
V_{ES}	state-level value of energy savings (\$/ha)	Varies by state	Nowak et al. (2017)
$Conv_{ha}$	Converts acres to hectares	0.405	n/a

Avoided human health damages from avoided emissions from power plants

We quantify human health benefits from air pollution reduction related to reduced energy consumption using estimates of national monetized benefits per ton (BPT) of avoided NO_x, SO₂, and PM_{2.5} for the Electricity Generating Unit sector. Several adverse health effects have been associated with PM_{2.5} and its precursors (NO_x and SO_x), including premature mortality, non-fatal heart attacks, hospital admissions, emergency department visits, upper and lower respiratory symptoms, acute bronchitis, aggravated asthma, lost workdays and acute respiratory symptoms. All these health effects were included in the estimation of benefits that went into the calculation of benefits per ton (U.S. EPA, 2018). A very large percentage, 98 percent, of the total monetized benefits of reducing PM_{2.5} concentrations are attributable to avoided premature mortality. U.S. EPA (2018) estimated two sets of BPT values from two different epidemiology studies (Krewski et al., 2009; Lepeule et al., 2012). Using both values provides low and high estimates for air pollution reduction benefits and informs the user of the potential range for these benefit estimates.

The Benefits Module uses the following calculation for each of three air quality pollutants (PM_{2.5}, SO₂, NO_x) and sums the values to calculate total avoided human health damages from avoided power plant emissions:

$$V_{TAE} = \frac{AE_{state} \times Conv_{ton}}{UC_{state}} \times A_{TC} \times Conv_{ha} \times V_{BPT} \quad (3.15)$$

where variables are defined as follows:

Table 17. Definition of variables in equation 3.15

Variable	Definition	Value	Source
V_{TAE}	total value of avoided criteria air pollutant emissions due to increase in urban/community trees (\$/year)	> 0, calculated by the Benefits Module	n/a
AE_{state}	Avoided emissions (metric tons of PM _{2.5} , SO ₂ , NO _x) from power plants due to urban/community trees	Varies by state	Nowak et al. (2017)
$Conv_{ton}$	Converts metric tons (tonnes) to U.S. tons (short tons)	1.1023	n/a
UC_{state}	urban/community tree cover (ha)	Varies by state	Nowak et al. (2012)
A_{TC}	increase in urban/community tree cover (acres)	> 0, calculated by WMOST	WMOST results
$Conv_{ha}$	Converts acres to hectares	0.405	n/a
V_{BPT}	National-level benefit per ton values for PM _{2.5} , SO ₂ , NO _x	Low and high estimates for each pollutant	U.S. EPA (2018)

Increased carbon sequestration

To calculate benefits from avoided CO₂ emissions from power plants, the Benefits Module uses state-level per hectare values of avoided CO₂ emissions and multiplies the value by the increased hectares of urban/community trees associated with WMOST-prescribed management practices, including land conservation, riparian buffer restoration, and selected green infrastructure practices. The Benefits Module then uses either the global or domestic SC-CO₂ values (see Section 2.3.2.1) to monetize the avoided CO₂ emissions from power plants, as shown in Equation 3.16.

$$V_{TAC} = \frac{AE_{state}}{UC_{state}} \times A_{TC} \times Conv_{ha} \times C_{SCC} \quad (3.16)$$

where variables are defined as follows:

Table 18. Definition of variables in equation 3.16

Variable	Definition	Value	Source
V_{TAC}	Total value of avoided CO ₂ emissions due to increase in urban/community trees (\$/year)	> 0, calculated by the Benefits Module	n/a
AE_{state}	Avoided metric tons of CO ₂ from power plants due to urban/community trees	Varies by state	Nowak et al. (2017)
UC_{state}	urban/community tree cover (ha)	Varies by state	Nowak et al. (2012)
A_{TC}	increase in urban/community tree cover (acres)	> 0, calculated by WMOST	WMOST results
$Conv_{ha}$	Converts acres to hectares	0.405	n/a
C_{SCC}	Domestic social cost of carbon (\$/metric ton C) OR		U.S. EPA (2019a)
C_{SCC}	Global social cost of carbon (\$/metric ton C)		IWGSCC (2016)

3.4.3 Green roofs

3.4.3.1 Reduction in heating/cooling needs from green roofs

We add energy cost reductions by multiplying the megawatt hour electricity savings by the price of a megawatt hour of residential electricity. Users can access state-level average prices for residential electricity through the U.S. Energy Information Administration (2018)²⁴, or they can use local values for the price of a MWh of residential electricity, if available.:

$$V_{TES} = ES_{kWH} \times Conv_{MWH} \times V_{MWH} \quad (3.17)$$

where variables are defined as follows:

Table 19. Definition of variables in equation 3.17

Variable	Definition	Value	Source
V_{TES}	total value of energy savings from green roofs (\$/year)	> 0, calculated by the Benefits Module	n/a
ES_{kWH}	annual electrical savings (kWh)	> 0, calculated by user	Green roofs calculator ²⁵
$Conv_{MWH}$	Convert kilowatt hours to megawatt hours	0.001	n/a
V_{MWH}	price of a MWh of residential electricity	Varies	Set by the user; U.S. Energy Information Administration (2018) ²⁶

3.4.3.2 Avoided human health damages from avoided NO_x , SO_2 , and $PM_{2.5}$ emissions from power plants

To quantify reductions in criteria air pollutants (SO_2 , NO_x , $PM_{2.5}$) from reduced energy consumption due to the installation of green roofs, the Benefits Module applies regional AVERT emission rates (U.S. EPA, 2019b) to convert annual energy savings into avoided emission of criteria air pollutants and then monetizes the reductions using benefit per ton estimates (U.S. EPA, 2018), as shown in Equation 3.18:

$$V_{TAHD} = (ES_{kWH} \times Conv_{MWH}) \times (AVERT_X \times Conv_{tons}) \times V_{BPT} \quad (3.18)$$

where variables are defined as follows:

²⁴ If the study watershed spans more than one state, we propose averaging the appropriate state-level values

²⁵ <https://sustainability.asu.edu/urban-climate/green-roof-calculator/>

²⁶ Values provided in cents per kilowatt hour for years 2001 through 2018.

Table 20. Definition of variables in equation 3.18

Variable	Definition	Value	Source
V_{TAHD}	total value of avoided human health damages from avoided power plant emissions (\$/year)	> 0, calculated by the Benefits Module	n/a
ES_{kWH}	annual electrical savings (kWh)	> 0, calculated by user	WMOST results, green roofs calculator ²⁷
$Conv_{MWH}$	convert kilowatt hours to megawatt hours	0.001	n/a
$AVERT_X$	AVERT regional emission rate for SO ₂ , NO _x , PM _{2.5} (lbs/MWh)	Varies by pollutant, region, and rate type ²⁸	U.S. EPA (2019b)
$Conv_{tons}$	convert pounds to tons	0.0005	n/a
V_{BPT}	National-level benefit per ton values for SO ₂ , NO _x , PM _{2.5}	Low and high estimates for each pollutant	U.S. EPA (2018)

The Benefits Module uses the same methodology for applying the U.S. EPA (2018) benefit per ton estimates as described in Section 3.4.4.2. U.S. EPA (2018) provides benefit per ton estimates for the three pollutants for years 2016, 2020, 2025, and 2030. We use linear regression to calculate values for the years in between the reported values. The Benefits Module then uses the value that corresponds to the study period, averaging values if the study period is longer than one year, and then applies the value corresponding to the year of the analysis.

3.4.3.3 Avoided CO₂ emissions from power plants

To quantify reductions in carbon dioxide (CO₂) from reduced energy consumption due to the installation of green roofs, the Benefits Module applies regional AVERT emission rates (U.S. EPA, 2019b) to convert annual energy savings into avoided carbon dioxide emissions and then monetizes the reductions using either global or domestic SC-CO₂ values, as shown in Equation 3.19:

$$V_{TAC} = (ES_{kWH} \times Conv_{MWH}) \times (AVERT_X \times Conv_{tons}) \times C_{SCC} \quad (3.19)$$

where variables are defined as follows:

²⁷ <https://sustainability.asu.edu/urban-climate/green-roof-calculator/>

²⁸ The contiguous United States is divided into ten AVERT regions. Four different types of regional AVERT emission rates are available: wind, utility-scale photovoltaic, portfolio energy efficiency, and uniform energy efficiency.

Table 21. Definition of variables in equation 3.19

Variable	Definition	Value	Source
V_{TAC}	total value of avoided CO ₂ emissions from avoided power plant emissions (\$/year)	> 0, calculated by the Benefits Module	n/a
ES_{kWh}	electrical savings (kWh)	> 0, calculated by user	WMOST results, green roofs calculator ²⁹
$Conv_{MWh}$	convert kilowatt hours to megawatt hours	0.001	n/a
$AVERT_x$	AVERT regional emission rate for CO ₂ (tons/MWh)	Varies by pollutant, region, and rate type ³⁰	U.S. EPA (2019b)
$Conv_{tons}$	convert U.S. tons to metric tons	0.907185	n/a
C_{SCC}	Domestic social cost of carbon (\$/metric ton C) OR		U.S. EPA (2019a)
C_{SCC}	Global social cost of carbon (\$/metric ton C)		IWGSCC (2016)

²⁹ <https://sustainability.asu.edu/urban-climate/green-roof-calculator/>

³⁰ The contiguous United States is divided into ten AVERT regions. Four different types of regional AVERT emission rates are available: wind, utility-scale photovoltaic, portfolio energy efficiency, and uniform energy efficiency.

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Appendix A. Illustrative calculations for cobenefits ([link to spreadsheet](#))

Appendix B. Shapefile and metadata for green values dataset
