

User's Manual for Integrated Treatment Train Toolbox - Potable Reuse (IT³PR) Version 2.0

FINAL

by
Eva Steinle-Darling, PhD, PE
Andrew Salveson, PE
Caroline Russell, PhD, PE
Qun (Charlie) He
Chao-An Chiu
Dylan Lesan

Texas Water Development Board

P.O. Box 13231, Capitol Station
Austin, Texas 78711-3231

December 2016



This page is intentionally blank.



Texas Water Development Board Contract # 1348321632

User's Manual for Integrated Treatment Train Toolbox - Potable Reuse (IT3PR) Version 2.0



Eva Steinle-Darling, PhD, PE
Andrew Salvesson, PE
Caroline Russell, PhD, PE
Qun (Charlie) He
Chao-An Chiu
Dylan Lesan
Carollo Engineers, Inc.

FINAL

December 2016

This page is intentionally blank.

Acknowledgements

The original development of the IT³PR model was funded by the Water Environment and Reuse Foundation (WE&RF, formerly WateReuse Research Foundation, or WRRF) as part of Project WRRF 11-02, in cooperation with in-kind contributions from a number of participating agencies, project sponsors and partners that are gratefully acknowledged and can be found listed in the publications from the WRRF 11-02 project.

Updates to the model for Version 2.0 were funded by WateReuse Texas. Version 2.0 is a required submittal under Texas Water Development Board (TWDB) Project "Direct Potable Reuse Monitoring: Testing Water Quality in a Municipal Wastewater Effluent treated to Drinking Water Standards" (TWDB Contract #1348321632).

Table of Contents

Executive Summary	1
1 Introduction.....	3
1.1 Model Overview	3
1.2 Version 2.0 Updates.....	7
2 Step-By-Step Guide to Using the Model	7
2.1 Start Page	7
2.2 Icon Navigation and User Inputs	8
2.3 Initial Input Page.....	8
2.4 Treatment Train Builder	12
2.5 Adding a Second (and Third) Train.....	18
2.6 Remove a Train.....	18
2.7 Treatment Train Comparison Page.....	18
3 Model Structure	21
3.1 Internal Structure Overview.....	21
3.2 Basis for Unit Process Models.....	28
3.3 Process Train Options.....	45
3.4 Calculating Overall Process Train Performance.....	47
3.5 Basis for Unit Cost Models.....	48
4 Summary and Conclusions	59
5 References.....	62

Attachments

Appendix A Visual Basic Code used by the Texas Commission on Environmental Quality to Calculate Virus and Giardia Log Inactivation for Chlorine and Chloramines

List of Figures

Figure 2.1	Start Page.....	7
Figure 2.2	Initial Input Page.	9
Figure 2.3	Treatment Train Builder Internal Logic	13
Figure 2.4	Example Train Builder Page, Input Portion.	15
Figure 2.5	Example Input Error Notification.....	15
Figure 2.6	Example Train Builder Page, Output Portion.	16
Figure 2.7	Example Quality and Treatment Goal Summary.	18
Figure 2.8	Example Train Comparison Summary from the Bottom Section of the Train Comparison Page.	20
Figure 3.1	Screen Shot of the Master Table.	27
Figure 3.2	Screen Shot of the Unit Process Table for UV Disinfection.	27
Figure 3.3	Planning-Level Cost Curve for Conventional Filters.	55
Figure 3.4	Planning-Level Cost Curve for Hydrogen Peroxide Dosing Systems.	59

List of Tables

Table 3.1	Default Treatment Goals for Chemical Parameters	22
Table 3.2	Default values for Wastewater Effluent Concentrations by Treatment Type	25
Table 3.3	Unit Process Performance Parameter Values for Wastewater Processes.....	29
Table 3.4	Unit Process Performance Parameter Values for Media Filtration Processes.....	30
Table 3.5	Unit Process Performance Parameter Values for Membrane Filtration Processes.	31
Table 3.6	Unit Process Performance Parameter Values for Membrane Desalination Processes.	32
Table 3.7	Unit Process Performance Parameter Values for Oxidative Processes.....	33
Table 3.8	Unit Process Performance Parameter Values for Other Treatment Processes.	35
Table 3.9	Unit Process Performance Parameter Values for Treatment in Engineered Storage Buffers.	36
Table 3.10	Unit Process Performance Parameter Values for Environmental Buffers.	36
Table 3.11	Secondary Treatment Performance as a Function of Solids Retention Time ^a	39
Table 3.12	Chlorination Performance as a Function of Ct - California Version ^a	40
Table 3.13	Ozone Disinfection Performance as a Function of Ct ^a	41
Table 3.14	Ozone Advanced Oxidation Process (AOP) Performance as a Function of O ₃ :TOC ^a .	41
Table 3.15	UV Performance as a Function of Dose (without Oxidant Addition) ^a	42
Table 3.16	UV Performance as a Function of Dose (with Peroxide Addition) ^a	43
Table 3.17	Processes that Affect Total Flow Rate.	49
Table 3.18	Processes that are Dependent on User Inputs and Incoming Water Quality.....	50
Table 3.19	Effluent Characteristics of Relevant Unit Processes.....	51
Table 3.20	Unit Cost Model Summary Table.	55
Table 3.21	Planning-Level Membrane Equipment Costs.....	56
Table 3.22	Planning-Level Project Cost of UV Systems in \$1000's.	57
Table 3.23	Planning-Level Project Cost of Chlorine Dosing Systems in \$1000's.	58
Table 3.24	Planning-Level Project Cost of Ozone Systems in \$1000's.....	58

Executive Summary

The Integrated Treatment Train Toolbox - Potable Reuse (IT³PR) Excel tool and this User's Manual were originally developed as one of several deliverables for Water Environment and Reuse Foundation (WE&RF, formerly WateReuse Research Foundation, or WRRF) Project 11-02, Equivalency of Advanced Treatment Trains for Potable Reuse, which focused on supporting the evolution from IPR to DPR by assessing the effectiveness of advanced treatment trains in removing microbial and chemical contaminants that are or may become a concern with respect to drinking water quality. The project centered on identifying and assessing treatment trains that satisfy stringent public health criteria under development for DPR, but do not necessarily include the use of reverse osmosis (RO), a frequently employed but cost- and energy-intensive unit process.

The WRRF 11-02 study consisted of three main phases: (i) identification of performance criteria that protect public health in DPR reuse situations, (ii) development of a toolbox model that calculates the efficacy of user-selected treatment alternatives including treatment trains that incorporate RO, and (iii) pilot-, full- and/or near-full-scale evaluation of the most promising reuse treatment trains. This User's Manual and the IT³PR Excel tool that accompanies it were developed as project deliverables for the second phase of the WRRF 11-02 project, and then updated as part of a TWDB project to facilitate application for Texas DPR projects.

The tool allows a user to establish treatment goals for pathogens, trace chemicals, and total organic carbon and develop up to three advanced treatment trains for potable reuse. The tool outputs include an estimate of the treatment provided by each train relative to the treatment goals provided by the user, and planning-level cost estimates for the advanced treatment portions of the overall treatment trains, broken down by individual treatment process. This User's Manual provides both step-by-step guidance in the use of this Excel tool and also documents the construction of the tool, including model assumptions on treatment efficacy, cost tables, and model limitations.

The tool and its underlying models were developed in a number of steps. The first step consisted of developing a list of relevant unit processes, which included conventional and membrane bioreactor-based secondary treatment, various membrane processes (micro-, ultra-, and nano-filtration as well as RO), oxidative processes (ultraviolet irradiation or photolysis, ozonation, UV or ozone with peroxide addition, and conventional chlorination), biological filtration (media and carbon-based), and several types of environmental buffers.

Each of these unit processes was evaluated for its efficacy for the removal and/or destruction of microbial and chemical contaminants as a function of important operational and feed water quality parameters. The result was the development of a unit process model (i.e., a performance curve) for each process studied. A planning-level cost model is also included for each of the advanced unit processes based on current manufacturer and project cost information. The cost information is designed to be included as default values and can be overridden by future users with more up-to-date cost information.

A user interface was constructed around these unit process models such that a user of the program can assemble them into potable reuse treatment train alternatives, based on a limited number of

process flow options defined in Figure 2.3. The model allows for evaluation of environmental buffers for indirect potable reuse scenarios, simulating the additional treatment achieved through groundwater attenuation, soil aquifer treatment, or surface water augmentation. Based on inputs with respect to influent water quality, flow rate, and other design choices, users can customize each treatment train and receive information on the approximate cost of their alternative, as well as how well it performs with respect to the performance criteria set by the user.

Version 2.0 includes several additional features, including additional parameters that are tracked through the treatment trains, additional train options, and a feature to select between two regulatory paradigms for defining treatment goals for potable reuse: The approach used in the original IT³PR tool developed for WRRF 11-02 and a Texas-specific approach, developed in collaboration with the Texas Commission on Environmental Quality.

This User's Manual provides both step-by-step guidance in the use of this Excel tool and also documents the construction of the tool, including model assumptions on treatment efficacy, cost tables, and model limitations.

1 Introduction

Indirect potable reuse (IPR) has been an important part of the nation's water supply portfolio and planned IPR projects are more prevalent throughout the U.S. and the world due to a combination of increased demand and uncertain supply. The reuse discussion is now expanding to include direct potable reuse (DPR), which eliminates the environmental buffers characteristic of the current IPR paradigm.

An Excel-based tool was developed as part of WateReuse Research Foundation Project 11-02, Equivalency of Advanced Treatment Trains for Potable Reuse, to allow users to assess and compare the performance and costs of different potable reuse treatment trains, IPR and DPR. The model was updated as part of a Texas Water Development Board (TWDB) project facilitating use to plan for Texas potable reuse projects and to include additional performance parameters that could be of interest for all users, regardless of geography.

This manual describes the treatment toolbox model constructed for WRRF 11-02 project, and updates incorporated through the TWDB project.

1.1 Model Overview

The model was developed in a number of steps. The first step consisted of developing a list of relevant unit processes, which included conventional and membrane bioreactor-based secondary treatment, various membrane processes (micro-, ultra-, and nano-filtration as well as reverse osmosis (RO)), oxidative processes (ultraviolet (UV) irradiation or photolysis, ozonation, UV or ozone with peroxide addition, and conventional chlorination), biological filtration (media and carbon-based), and several types of environmental buffers.

Each of these unit processes was evaluated for its efficacy for the removal and/or destruction of microbial and chemical contaminants as a function of important operational and feed water quality parameters. The result was the development of a unit process model (i.e., a performance curve) for each process studied. A planning-level cost model is also included for each of the advanced unit processes based on current manufacturer and project cost information. The cost information is designed to be included as default values and can be overridden by future users with more up-to-date cost information.

A user interface was constructed around these unit process models such that a user of the program can assemble them into potable reuse treatment train alternatives, based on a limited number of process flow options. These include an advanced treatment train consisting of microfiltration, RO, and advanced oxidation (UV/peroxide) following conventional primary and secondary treatment, which is considered the baseline alternative. Several alternatives that do not contain RO are included.

For IPR scenarios, environmental buffers can be added to the end of the treatment trains to simulate the additional removal achieved through groundwater injection, soil

aquifer treatment, or surface water augmentation. Comparison of performance with and without the buffer can be used to assess the impact of the environmental buffer in terms of potential reduced reliance on the engineered processes. In Texas, reliance on these buffers is generally only considered if discharges are occurring to water bodies that are not designated “waters of the state” as the typical DPR paradigm does not apply in indirect reuse cases where discharges to waters of the state, as water quality requirements in that case are based on conventional discharge requirements and downstream withdrawals of that water are subject to a complex set of water rights considerations, but no specific additional treatment requirements. The treatment benefit provided by the environmental buffers should be considered an estimate and will not necessarily reflect the actual removal credits, if any, attributed by the Texas Commission on Environmental Quality (TCEQ).

Based on inputs with respect to influent water quality, flow rate, and other design choices, a user can customize each treatment train and receive information on the approximate cost of their alternative, as well as how well it performs with respect to the performance criteria set by the user.

1.1.1 Performance Parameters

The performance parameters are intended to be measures of treatment achieved by the train(s) constructed by users of the toolbox. Ten total performance parameters were chosen, four microbial-based parameters to assess the effectiveness of treatment trains with respect to pathogen inactivation / removal, and six chemical-based parameters to assess the trains’ effectiveness with respect to chemical contaminants.

The microbial performance parameters are virus (based on MS2 bacteriophage or adenovirus), *Giardia* and *Cryptosporidium*. These parameters were chosen in accordance with the microbial performance goals specified in California and determined on a case-by-case basis by TCEQ in Texas. An additional, optional performance parameter for bacteria (based on total coliform) is also included, as recommended by a National Water Research Institute (NWRI) Panel that was convened for WRRF 11-02.

The chemical performance parameters are total organic carbon (TOC), nitrate, “trace organic chemicals” (TOrcs), “estradiol equivalency” (EEQ), *N*-nitrosodimethylamine (NDMA), and perfluorinated compounds with established health advisory levels (HALs). These six chemical performance parameters exhibit a range of concentration levels (e.g., parts per million to parts per trillion), chemical characteristics impacting treatability, and health impacts (e.g., acute versus chronic). Their inclusion facilitates a broad assessment of whether a proposed treatment train can achieve recommended goals to minimize adverse health impacts associated with exposure to chemical constituents in the water.

- TOC removal serves as an indication of bulk organics removal and can be used as a general indication of whether sufficient organics are removed to facilitate free chlorine disinfection without forming concentrations of

regulated disinfection byproducts (DBPs) above the respective maximum contaminant levels (MCLs). As a reference point, California set a 0.5 mg/L TOC goal for potable reuse projects injecting purified water for groundwater replenishment.

- Nitrate is used as a performance parameter for the model since it is only removed through a few processes (e.g., biological denitrification, RO, and to a lesser extent, nanofiltration, NF) and is regulated in drinking water by a 10 mg/L MCL based on acute health impacts.¹
- The very general category of TOxCs serves to encompass chemical microconstituents typically observed at parts per billion concentrations in reclaimed water and which exhibit a wide range of physical chemical properties and susceptibilities to treatment.
- The more specific category EEQ serves to quantify the estrogenic effect of water and is distinguished from the general TOxCs category by a much lower concentration goal (5 ng/L compared to 1 ug/L, see Section 3.1.2).
- NDMA is a probable carcinogen with a 10^{-6} cancer risk at low part per trillion concentrations (e.g., 0.7 ng/L based on EPA Integrated Risk Information System data; USEPA, 1987). NDMA can occur in wastewater treatment effluent and form during ozonation or chloramination at potable reuse plants. It is only well-removed by a few advanced treatment technologies (e.g., biological filtration, UV photolysis).
- The USEPA recently finalized HALs for perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS) at 70 ng/L individually or at a combined concentration. PFOA and PFOS typically occurs in groundwater or surface waters contaminated from anthropogenic sources including firefighting foams, non-stick coating, textile coatings, and mist suppressants. However, PFOA and PFOS can occur at concentrations above the HALs in wastewater effluent used as a potable reuse supply depending on upstream industrial discharges. For this reason, and because PFOA and PFOS are only removed by a few advanced technologies (i.e., GAC, RO, and IX in the case of PFOS), these perfluorocompounds are included as a performance parameter.

¹ Nitrite is also regulated in drinking water, at a 1 mg/L MCL. The model assumes as a rough estimate that removal of nitrate generally serves as an indication that the treatment train will achieve adequate removal of nitrite; however, that assumption must be confirmed for a given potable reuse application.

The choice of chemical performance parameters reflects a compromise between the large number of compounds and surrogates chosen for tracking by the NWRI Panel, and keeping the scope of the model realistic, based on available literature data. A more detailed discussion of the microbial and chemical performance parameters and the associated treatment goals are provided in Sections 3.1.1 and 3.1.2 for, respectively.

1.1.2 Unit Processes

The unit processes included in the toolbox range from standard secondary treatment steps (activated sludge) to advanced treatment steps (advanced oxidation) and encompass a thorough, yet realistically limited set of proven technologies for treatment of water for reuse. An effort was made to include processes used by utilities currently practicing indirect potable reuse (IPR). Three types of environmental buffers were also included. Technologies included within the model are:

- Wastewater Treatment Processes
 - Conventional Activated Sludge (CAS) Secondary Treatment, with
 - BOD removal only
 - nitrification, or
 - denitrification through biological nutrient removal (BNR)
 - Membrane Bioreactors (MBR), which are producing either
 - nitrified, or
 - denitrified effluent.
- Media Filtration Processes
 - Media Filters
 - Deep Bed Filtration (denitrifying)
 - Biologically Active Filtration
- Membrane Filtration
 - Microfiltration
 - Ultrafiltration
- Membrane Desalination
 - Nanofiltration
 - Reverse Osmosis
- Oxidative Processes
 - Chlorination
 - Ozonation
 - UV Irradiation or Photolysis (with and without peroxide)
- Environmental Buffers
 - Soil Aquifer Treatment (SAT)
 - Direct Injection / Subsurface Migration
 - Surface Water Augmentation
- Engineered Buffers
 - Engineered Buffer with Chlorine Disinfection (TCEQ model)
 - Engineered Buffer with Chloramines Disinfection (TCEQ model)

1.2 Version 2.0 Updates

Version 2.0 includes several additional features, including additional parameters that are tracked through the treatment trains (Giardia, TOC, nitrate, and PFOS+PFOA), and additional train options illustrated in Figure 2.3.

The most prominent addition to the model in this version is the ability to select between two regulatory paradigms: The approach used in the original IT³PR tool developed for WRRF 11-02, which is closely aligned with the California regulatory paradigm for potable reuse projects, and the approach to permitting DPR projects taken by the Texas Commission on Environmental Quality (TCEQ).

2 Step-By-Step Guide to Using the Model

A note on format: This chapter is written in second person because it is intended to serve as a set of simple instructions for users. Writing instructions in third person (“the user may...”) can be awkward and interferes with the intended simplicity of the message.

Should questions remain, please contact the authors of this publication, using one of the following email addresses: asalveson@carollo.com or esd@carollo.com.

2.1 Start Page

Upon opening the model Excel file, you will be presented with the Start Page. Before proceeding, please be sure that macros are enabled; otherwise key features of the model will not work.

The start page provides a starting point to launch the model. This page also provides credit to the major sponsors and collaborators associated with the model. Click anywhere on the start page to begin.



Figure 2.1 Start Page

2.2 Icon Navigation and User Inputs

Throughout the model, the “help” and “print” icons appear in the program header:



If you are unsure how to proceed at any point, you can click the help icon to be redirected to the quick-start guide.



If you would like to print the page, click on the print icon at any time.

Additional icons are used to link back to previous pages, and are explained in the sections below.

Gray buttons at the bottom of some screens provide additional navigational help. These are labeled with their function, such as “Build a Treatment Train,” “Go to Train Comparison,” or “Reset Default Inputs.” Examples of these buttons are shown at the bottom of Figure 2.2.

2.2.1 User Input Boxes in Blue

Throughout the tool, user input boxes are shown with a blue background. These are the only cells within the Excel sheets that you will be able to edit. Inputs come in the form of cells in which you input a number, or select from multiple choice drop-down menus. For example, in Figure 2.2, the cell indicating “Primary Effluent” is a drop-down menu; all other cells are input boxes with default values that you can choose to edit.

2.2.2 Saving Your Input Data

You may save the Excel file at any time, so you can continue where you left off the next time you open the file, as you would with any regular Excel file.

2.3 Initial Input Page

The purpose of the Initial Input Page is to gather basic information about the project, including

- name,
- size,
- influent water quality, and
- treatment goals.

Figure 2.2 shows an example of the Initial Input Page, with step-by-step input instructions shown in red. Note that the appearance of the Initial Input Page changes depending on whether the “California” or “Texas” button is highlighted, reflecting different inputs required to reflect Texas’ approach to evaluating potable reuse projects as discussed below.

The first step is to enter a project name and the proposed project capacity. Note that the capacity is defined as the final finished water flow target. Input of the wastewater treatment plant flow for advanced treatment will result in a reduced amount of flow produced by the advanced treatment system due to backwash flows and other reject

streams. The two input tables define the influent water quality and the treatment goals for microbial (upper table) and chemical (lower table) performance parameters, respectively.

2.3.1 Choosing Your Regulatory Approach

Buttons are provided to allow the user to choose between two regulatory approaches: The approach used in the original IT³PR tool developed for WRRF 11-02, which is closely aligned with the California regulatory paradigm for potable reuse projects, and the approach to permitting DPR projects taken by the Texas Commission on Environmental Quality (TCEQ).

The distinction is provided since the Texas Commission on Environmental Quality (TCEQ) has been establishing pathogen log inactivation / removal requirements based on measured concentrations in the source water to the potable reuse treatment plant (e.g, secondary effluent), whereas California has set pathogen log removal based on typically-observed (not site-specific) pathogen concentrations in the raw wastewater. Other states are considering various combinations of the two approaches.

The recently published TWDB *Direct Potable Reuse Resource Document* (APAI, 2016) is recommended for further reading to gain a better understanding of the distinctions between the two regulatory paradigms.

Toggling between the California and Texas buttons changes the defaults for target removal of microbial parameters and the available user inputs for microbial removal requirements.

1. Input Facility Name and Size

2. Choose California or Texas as your Regulatory Approach

3. Input Water Quality and Treatment Goals for Microbial and Chemical Parameters. Default values are provided. (Options vary)

4. Choose your existing wastewater treatment process (options vary)

5. Add optional water treatment plant credits (click on button to make input table appear)

6. Click here to start building treatment trains.

Water Quality and Treatment Goal Inputs - Microbial Parameters:

	Bacteria	Virus	Cryptosporidium	Giardia
Secondary Effluent Concentration	Not Applicable	100 MPN/L	50 oocysts/L	230 cysts/L
Purified Water Concentration		2.2E-07	3.0E-05	6.8E-06
Target Removal*	7-log	9-log	6-log	8-log

*Microbial target removal includes secondary treatment log removal credits (National case only)

Water Quality and Treatment Goal Inputs - Chemical Parameters:

	TOC	Nitrate as N	TOxCs	EEQ	NDMA	PFOS+PFOA
Secondary - Denitrified	20 mg/L	8 mg/L	3 ug/L	2 ng/L	80 ng/L	50 ng/L
Treatment Goal	1.5 mg/L	8 mg/L	1 ug/L	1 ng/L	8 ng/L	50 ng/L
Target Removal	93%	0%	67%	50%	90%	0%

*Choose "Primary Effluent" or "Secondary Effluent" as your initial monitoring point for chemical parameters.

Water Treatment Plant Log Credits

	Bacteria	Virus	Cryptosporidium	Giardia
Plant Log Removal	0.0-log	4.0-log	3.0-log	2.5-log

Figure 2.2 Initial Input Page.

2.3.2 Water Quality and Treatment Goal Inputs - Microbial Parameters

For microbial parameters, treatment goals are defined in relative terms as log-removal goals, to be attained over the course of the treatment train, from primary or secondary effluent to final product depending on the selection for California-type and Texas-type projects.

- The default values provided for the treatment goals for California-type projects are those determined by the NWRI Panel that was convened specifically for WRRF 11-02. The default values of 9-log bacteria (total coliform), 10-log protozoa (*Cryptosporidium*), and 12-log enteric virus are the recommended levels of treatment from raw wastewater to potable standards.
- The default values provided for the treatment goals for Texas-type projects are based on maximum TCEQ requirements for potable reuse projects implemented to date, specifically: 9-log virus, 6-log *Cryptosporidium*, and 8-log *Giardia*. Default values for bacteria are 7-log. These can be changed if desired. You are also able to input site-specific maximum concentrations of pathogens measured in the source water to the potable reuse train under evaluation. If you choose this option, the model will calculate the log removal requirements based on the following finished water targets:
 - 2.2×10^{-7} /L for viruses (per Regli et al., 1991),
 - 6.8×10^{-6} cysts/L for *Giardia* (per Regli et al., 1991), and
 - 3×10^{-5} oocysts/L for *Cryptosporidium* (per Haas et al., 1996),

following TCEQ's approach for determining site-specific microbial removal requirements for potable reuse projects.

2.3.3 Water Quality and Treatment Goal Inputs - Chemical Parameters

For chemical parameters, treatment goals are defined in terms of target concentrations in the potable reuse product water. The default treatment goals are chosen to reflect most closely the goals for various chemical parameters determined by the NWRI Panel for WRRF 11-02 (see Section 3.1.2). Since nitrate has an acute health endpoint and DPR treatment trains often only provide one barrier for its removal, a 30% safety factor is proposed, resulting in a treatment goal of 7 mg/L as N. Chronic, rather than acute, exposure to NDMA has been attributed to increased cancer risk; however, concentrations can fluctuate depending on relative industrial discharges, water quality characteristics, and treatment performance. Therefore, a 20% safety factor is proposed to meet the California NL of 10 ng/L, resulting in a default goal of 8 ng/L. The specified treatment targets for these performance parameters can be changed as desired by the user to reflect site-specific objectives.

Because the removal efficiencies for the unit process models are defined in terms of relative removal (i.e., a percent removal), an input of initial concentrations is needed

for the model to provide useful outputs. The model approach for providing initial concentrations of the chemical parameters varies depending on whether the "California" or "Texas" button is highlighted.

Chemical Parameter Input Values for the California Scenario

Two input options are available if you select the "California" button: primary effluent or secondary effluent. Note that primary effluent is functionally equivalent to raw wastewater for the purposes of this tool, because no removal credit is given for primary treatment.

If you choose "primary effluent" as the point where initial concentrations are measured, the secondary processes you choose during the next step (Treatment Train Builder) will influence the total removal achieved for the chemical parameters.

If you choose "secondary effluent" as the point where initial concentrations are measured, only additional treatment specified beyond conventional activated sludge (i.e., for BOD removal) will factor into any additional chemical removal achieved at the WWTP. *Your choice of secondary unit processes will still affect the total removal achieved for microbial parameters (since these are always measured with respect to raw wastewater influent for the California scenario).*

The default influent concentrations provided change depending on which "starting point" you choose, and reflect values obtained from the currently available literature (see Section 3.1.3).

Chemical Parameter Input Values for the Texas Scenario

If you select the "Texas" button, the chemical water quality is specified depending on the secondary or tertiary treatment you select from the drop down menu. For example, if you select Tertiary Denitrification to reflect effluent from a wastewater treatment plant that incorporates this treatment step (or which may incorporate that step in the future as part of an upgrade to facilitate potable reuse), the input parameters show lower nitrate concentrations than if one of the options for Conventional Activated Sludge is selected. The default influent concentrations provided change depending on which wastewater treatment process you choose, and reflect values obtained from the currently available literature (see Section 3.1.3).

Note that in the Texas scenario no chemical (*nor* microbial) removal is calculated by the model for wastewater treatment processes. Rather, the Input page is set up for you to specify the water quality at the end of the wastewater treatment plant. For chemical parameters, the input page allows you to specify the water quality at the end of the WWTP by carefully selecting the final WWTP process from the dropdown menu. This modeling framework mirrors the approach taken by TCEQ for regulatory review of proposed potable reuse projects, essentially drawing a line in the sand on where wastewater treatment ends and where advanced treatment for potable reuse begins, and carefully characterizing the corresponding "source" water quality for the advanced treatment plant.

2.3.4 Taking into Account Water Treatment Plant Credits

If your project feeds into a surface water treatment plant, some of the LRV credits from that existing plant may be applicable to the potable reuse project. The default is to assume no credit, but if you click on the "WTP - Log Credits" button at the bottom of the page, a window will pop up asking you whether the treated water will go to an existing water treatment plant. If you click "yes," an additional table will appear that allows you to enter the LRV credits obtained by your water treatment plant. A typical surface water treatment plant is required to provide at minimum 4-log virus, 3-log Giardia, and 2.5-log Cryptosporidium LRV.

Note: You may reset the default values for the inputs on this page at any time by clicking the gray "Reset Default Inputs" button.

Note: After every input, the model recalculates the remaining allowable unit processes, causing the page to flicker momentarily while it refreshes. This behavior is normal and expected, and should stop after a few seconds.

2.3.5 Navigating to the Next Page


After completing the information on the Initial Input Page the first time, you should click on the "Build a Treatment Train" button on the bottom right. (The "Go to Train Comparison" button is only useful if you have already built one or more treatment trains and have returned to the Initial Input Page to review or adjust your inputs.)

2.4 Treatment Train Builder

Your most significant interaction with the toolbox model takes place on the Treatment Train Builder pages. Before you begin building your treatment trains, however, it is important to note that the logic within the tool restricts the unit processes available to you based on your previous unit process selections.

The model is set up with this restriction for a number of reasons, which are discussed in more detail in Section 3. The simple explanation is that it does not make good process sense to allow a random ordering of unit processes. In fact, only a limited number of combinations are reasonable from an overall process perspective. A graphical representation of the logic that defines the allowable combinations of unit processes into treatment trains is shown in Figure 2.3.

2.4.1 Input Instructions

You can choose to build and then compare up to three treatment trains, as described in the step-by-step instructions below. The graphics in this section (including instructions shown in red font) are copied from the "Help" sheet in the tool, which can be accessed from any page by clicking on the help icon:  Input fields are marked by a light blue background. If a cell does not have a light blue background, it will be locked and cannot be edited.

There are two parts to each Treatment Train Builder page, (1) the top, where the train is defined based on your inputs ("input portion"), and (2) the bottom, where its calculated performance is displayed ("output portion").

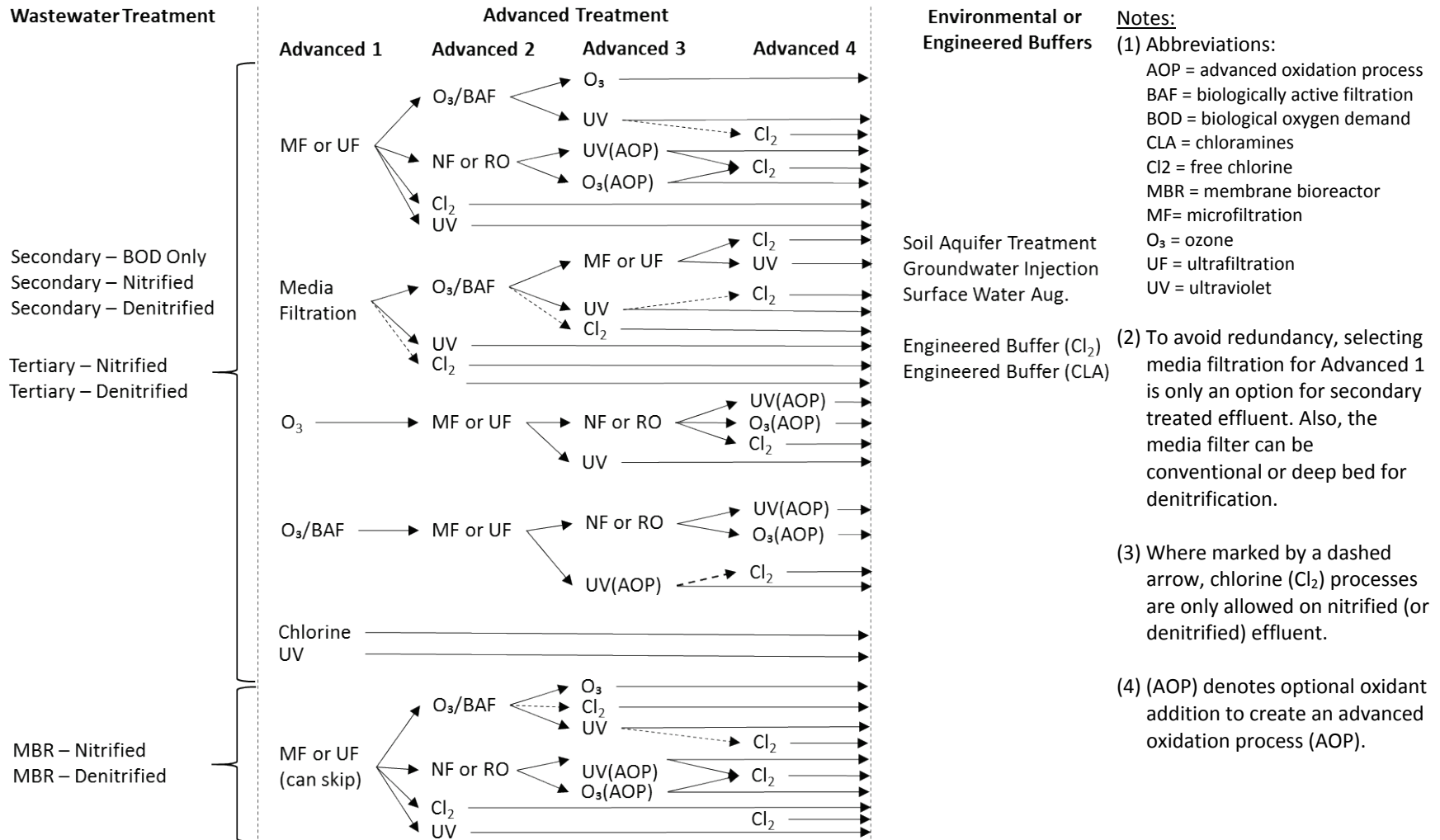


Figure 2.3 Treatment Train Builder Internal Logic

The input portion a Treatment Train Builder page, with step-by-step instructions in red, is shown in Figure 2.4. With guidance from Figure 2.3, you should be able to plan out your desired process train(s), and then build them as follows:

1. From the initial input screen, click on the “Build a Treatment Train.”
2. This brings up the treatment train builder page for Train No. 1 (see Figure 2.4). The facility name and size will carry over from what you entered on the initial input screen.
3. If you selected the California button, you begin to “build” your first treatment train by selecting a wastewater treatment process (see Figure 2.4, Step 1). Note that if you selected secondary effluent as the starting point on the Input page, the selection of a wastewater treatment process affects only the log removals assigned to that process step. For chemical parameters, the model will use the effluent concentrations that were entered on the Input page. For suggestions on alternative water quality assumptions for the Input page, refer to Table 3.2

If you selected the "Texas" button, your selection from the Input page is indicated and cannot be changed on the Train tab.

4. For the California scenario, you should then enter a solids retention time (SRT) in the input box to the right of the drop-down menu for the secondary process. As indicated by a small pop-up box that appears when you select the input box for SRT (see Figure 2.4, Step 2), the value entered must be within a certain range. A default value is provided. If you enter a value outside the given range, you will get an error message and will be asked to enter a different value. A sample input error box is shown in Figure 2.5.

If you selected the "Texas" button, the model still allows you to enter a value in the SRT box; however, the value does not impacted calculations for microbial or chemical treatment through the proposed train(s). This is a legacy feature that will likely be removed in the next version.

5. After completing the inputs for the secondary treatment process, you may choose the first advanced treatment step by selecting an option from the drop-down menu for the “Advanced 1” treatment step. Depending on the unit process you choose, another pop-up box may appear, in which you can specify operational information (such as chemical dose). Whenever such an input box appears and you select it, a small pop-up box will appear with an input message that provides some guidance on the expected range of inputs.
6. Continue selecting unit process options until you have completed your desired treatment train (with up to four advanced treatment unit processes). To construct a train with fewer than four advanced treatment steps, simply select “NONE” for the steps after you have completed your train.
7. Finally, you may choose to add an environmental buffer if the scenario you are considering includes such an option. For these, the input box allows you to enter a travel time.

Facility Name: Hypothetical Springs, TX
 Facility Size: 5 mgd
 SELECT YOUR TREATMENT TRAIN:

1. Select secondary treatment process → Secondary Treatment: Secondary - Denitrified

2. Select first advanced treatment process → Advanced 1: Ozone/BAF

3. Enter operational parameters (or leave default values) → SRT: 10 days; Contact Time: 0.0 (min); Influent TOC = 20.0 mg/L

Advanced 1: Ozone/BAF (Ozone Bromate Warning), Ozone:TOC Ratio: 0.8, Level of C_{NDMA(O3)}: 10 (C_{NDMA(O3)} = NDMA Concentration Formed During Ozonation)

Advanced 2: UF

4. Continue selecting unit processes and entering operational parameters. → Advanced 3: UV/H2O2, UV Dose: 1000 ml/cm2

Advanced 4: Cl2, Cl2 CT: 10 mg-min/L, Contact Time: 5 (min), Initial Cl2 Demand = 2.0 mg/L

Optional Environmental Buffers: Engineered Storage Buffer - Chloramines, Chloramine CT: 450 mg-min/L, Water pH: 7, Contact Time: 90 (min), Initial Cl2 Demand = 0.0 mg/L, Water Temperature: 20.0 °C, Residual Conc = 2.0 mg/L

5. Scroll down to review removal calculations, which are updated with each change to the treatment train.

Figure 2.4 Example Train Builder Page, Input Portion.

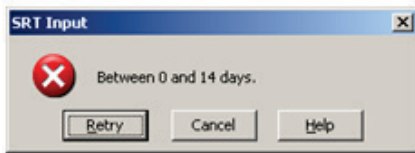


Figure 2.5 Example Input Error Notification

2.4.2 Pop-up Warning for Bromate

A pop-up warning appears when you select ozone as a treatment process. This is due to the potential to form bromate during ozonation in the presence of background bromide concentrations. The tool does not account for bromate formation. Additional analysis should be conducted on incoming bromide concentrations and the potential for bromate formation if ozonation is a selected unit process.

2.4.3 Reviewing the Treatment Train Performance

Once you have completed all the inputs related to your treatment train, you may wish to review the calculated performance of the train you have just built.

The tool instantly calculates the current performance of your treatment train and a planning-level cost after each input. The results of those calculations are shown in the two tables in the “output portion” at the bottom of the Treatment Train Builder page (see Figure 2.6). Depending on the size of your screen (and the zoom factor at which you are working in Excel), you may have to scroll down to see both tables completely.

Removal Summary includes:
Total removal achieved
At-a-glance performance indicators

Overall Performance of this Train:

	Treatment Goal	Influent Water Quality	Effluent Water Quality	Total Achieved Removal	Performance	
Bacteria	7-log			14.0-log	✓	meets goal
Virus	9-log			14.0-log	✓	meets goal
Cryptosporidium	6-log			13.0-log	✓	meets goal
TOC	93%	20 mg/L	10.8 mg/L	46%	✗	fails to meet goal
Nitrate as N	0%	8 mg/L	8 mg/L	0%	⚠	at goal
TOrcs	67%	3 ug/L	0.3 ug/L	92%	✓	meets goal
EEQ	50%	2 ng/L	0.0 ng/L	100%	✓	meets goal
NDMA	90%	80 ng/L	2 ng/L	98%	✓	meets goal
PFOS+PFOA	0%	50 ng/L	50 ng/L	0%	⚠	at goal

Breakdown of Train Performance by Unit Process:

Categories	Wastewater Treatment	Advanced 1	Advanced 2	Advanced 3	Advanced 4	Buffer	Water Treatment Plant Credits
Selected Process	Secondary - Denitrified	Ozone/BAF	UF	UV/H2O2	Cl2	Engineered Storage Buffer - Chloramines	User-Defined
Bacteria	Not Accounted	0.0-log	4.0-log	6.0-log	4.0-log	0.0-log	0.0-log
Virus	Not Accounted	0.0-log	0.0-log	4.0-log	6.0-log	0.0-log	4.0-log
Cryptosporidium	Not Accounted	0.0-log	4.0-log	6.0-log	0.0-log	0.0-log	3.0-log
TOC	Not Accounted	40%	0%	10%	0%	0%	NA
Nitrate as N	Not Accounted	0%	0%	0%	0%	0%	NA
TOrcs	Not Accounted	70%	30%	60%	0%	0%	NA
EEQ	Not Accounted	98%	30%	80%	0%	0%	NA
NDMA	Not Accounted	50%	0%	95%	0%	0%	NA
PFOS+PFOA	Not Accounted	0%	0%	0%	0%	0%	NA
Cost - Subtotal	Not Available	\$4,463,870	\$12,500,000	\$24,619,000	\$268,000	Not Available	NA

Build Another Treatment Train Remove This Train Go to Train Comparison

6a. Click here to build another train.

OR

6b. Click here to the train comparison page.

Removals and costs broken down by unit process. Note costs only available for advanced treatment processes.




Figure 2.6 Example Train Builder Page, Output Portion.

2.4.4 Reviewing the Outputs

As shown in Figure 2.6, the rows in the output tables on the Train Builder page represent the ten performance criteria, and the columns represent the performance metric with respect to the selected treatment train.

Top Output Table: Overall Performance of the Train

The top output table shows summary information that compares the total removal achieved by the selected treatment train to the treatment goals you defined on the Initial Input page. The icons in the right-most column give you a quick and easy visual indicator of whether your treatment train has met the performance criteria you specified with respect to each performance parameter.

In the example shown in Figure 2.6, the train meets the specified criteria for most parameters as indicated by the  icon in each row. A  symbol indicates the train has not met the treatment goal for TOC, and two  symbols indicates that the train is right at the limit of meeting the treatment goals for nitrate and PFOS+PFOA.

If one or more of the parameters do not meet a goal, it might prompt you to take a look at the contribution of the individual unit processes to the overall performance of the treatment train with respect to the specific parameter, thinking, for example “Where can I make a change that will increase my TOC removal efficiency by 10%?”, or “do I really need to achieve 99% removal?”

Bottom Output Table: Breakdown of Train Performance by Unit Process

The bottom output table breaks down the total performance of the treatment train with respect to each performance parameter into the individual contributions made by each unit process. In the example provided in Figure 2.6, TOC removal is attributed to the ozone/BAF (40%), and UV/H₂O₂ (10%). No additional removals are achieved through ultrafiltration (UF) or chlorination (Cl₂). Together, these removals result in the 46% removal shown in the Top Output Table.

The bottom line in the bottom output table is, quite literally, the bottom line. This line shows the estimated project capital costs for each unit process as sized for the proposed train. Note that costs are provided *only* for advanced treatment processes and are not available for secondary treatment or the optional environmental buffer steps.

With these data, you may now choose to implement different unit processes, or simply adjust the inputs for the given parameters, e.g., increase the UV dose or add peroxide to transform the UV process into an advanced oxidation process.

2.4.5 Generating a Treatment Train Report



Once you are satisfied with the treatment train and its modeled performance (and cost), you may want to capture the information in a one-page handout. You can do this by clicking on the print icon (shown above), which will provide you with a printable version of the Treatment Train Builder page with its current inputs and outputs.

2.5 Adding a Second (and Third) Train

To create a second treatment train, click on the “Build Another Treatment Train” button at the bottom of the output portion of the first Treatment Train Builder page, and complete all the steps described in Section 2.4. You may build up to three trains to compare. Once you have completed all of your trains, click on the “Go to Train Comparison” button at the bottom of any Treatment Train Builder page. This will take you to the Treatment Train Comparison page.

2.6 Remove a Train


To remove a treatment train from the comparison page, click on the “Remove this Train” button at the bottom of the output portion of the Treatment Train Builder pages. This will remove this train from the Train Comparison summary. Do not hide the train workbook. You may remove one, two or all three trains.

2.7 Treatment Train Comparison Page

The Treatment Train Comparison page provides a summary of all the inputs and outputs from the current model run. An example of a Treatment Train Comparison page is shown in Figure 2.7 and Figure 2.8.

2.7.1 Water Quality and Treatment Goal Summary

The top two tables on this page show the treatment goals and influent concentrations for the ten performance parameters that you provided on the Initial Input page.

Water Quality and Treatment Goal Summary  Edit inputs

	Bacteria	Virus	Cryptosporidium	Giardia
Secondary Effluent Concentration	Not Applicable	100 MPN/L	50 oocysts/L	230 cysts/L
Target Removal*	7-log	9-log	6-log	8-log

*Microbial target removal includes secondary treatment log removal credits (National case only)

	TOC	Nitrate as N	TOrCs	EEQ	NDMA	PFOS+PFOA
Secondary -	20 mg/L	8 mg/L	3 ug/L	2 ng/L	80 ng/L	50 ng/L
Treatment Goal	2 mg/L	8 ug/L	1 ug/L	1 ng/L	8 ng/L	50 mg/L
Target Removal	93%	0%	67%	50%	90%	0%

Figure 2.7 Example Quality and Treatment Goal Summary.



To edit any of the input parameters or treatment goals, click on the “Edit Inputs” icon. This will take you back to the Initial Input Page.

2.7.2 Train Comparison Summary

The bottom two tables on the Treatment Train Comparison page show a summary of the selected treatment trains (without specific operational parameters), and a summary of their performance with respect to the ten performance parameters, respectively. At-a-glance icons provide a quick indication of which treatment trains are meeting goals with respect to which performance parameters. In the example provided in Figure 2.8, Train 1 meets the performance goals with respect to all

parameters. Train 2 meets performance goals for nine parameters, but is right on the border for nitrate and PFOS+PFOA and fails to meet the removal goal for TOC. Train 3 is similar to Train 2 but provides slightly more removal for nitrate.

A legend at the bottom of the page explains the meaning of the at-a-glance icons.

The right-hand column of the upper train comparison table also shows the total flow required coming into advanced treatment that is needed to achieve the desired finished flow rate (5 mgd in all the examples provided in this manual). This column provides an indication of the various overall process recoveries of each advanced treatment train. The quantity (flow) of RO or NF concentrate requiring disposal is also provided to facilitate a comparison of treatment trains in terms of potential residuals handling issues. Other residuals streams are not included in the analysis since they are either substantially lower flow (e.g., membrane clean-in-place wastes) and/or are suitable for recycling to the headworks of the WWTP or other locations within the treatment train.

The right-hand column of the lower train comparison table provides the total estimated planning-level cost for each train. While these should not be given the same credibility as a real engineer's planning-level estimate, they serve to provide an approximate total project cost and also provide good *relative* indications of cost between the trains shown. Note that the costs do *not* include the cost of treatment residual (e.g., RO concentrate) treatment or disposal, permitting, or any other site-specific considerations.

To review and/or edit any of the three treatment trains, simply click on the links provided as shown in Figure 2.8. The links will take you back to the Treatment Train Builder page for the selected train.

2.7.3 *Generating a Treatment Train Comparison Report*



Once you are satisfied with the water quality inputs, goals, treatment trains, and their modeled performance, you may want to capture the information in a one-page handout. You can do this by clicking on the print icon (shown above), which will provide you with a printable (pdf) version of the Treatment Train Comparison page.

Train Comparison Summary

	Secondary	Advanced 1	Advanced 2	Advanced 3	Advanced 4	Optional Environmental Buffers	Required Influent Flow Rate	RO Concentrate Produced
Train 1	Secondary - Denitrified	MF	RO	UV/H2O2	Cl2	Engineered Storage Buffer - Chloramines	6.6 mgd	1.3 mgd
Train 2	Secondary - Denitrified	Ozone/BAF	UF	UV/H2O2	Cl2	Engineered Storage Buffer - Chloramines	5.3 mgd	NA
Train 3	Secondary - Denitrified	Tertiary Media Filtration	Ozone/BAF	UF	UV	Engineered Storage Buffer - Cl2	5.5 mgd	NA

	Bacteria	Virus	Cryptosporidium	Giardia	TOC	Nitrate as N	TOCs	EEQ	NDMA	PFOA+PFOA	Estimated Total Costs
Target Removal	7-log	9-log	6-log	8-log	93%	0%	67%	50%	90%	0%	
Train 1	✔ 13.0-log	✔ 14.0-log	✔ 12.0-log	✔ 12.3-log	✔ 97.8%	✔ 90.0%	✔ 98.2%	✔ 99.3%	✔ 95.0%	✔ 99.0%	\$ 42,305,000
Train 2	✔ 14.0-log	✔ 14.0-log	✔ 13.0-log	✔ 13.5-log	✘ 46.0%	⚠ 0.0%	✔ 91.6%	✔ 99.7%	✔ 97.5%	⚠ 0.0%	\$ 41,850,870
Train 3	✔ 14.0-log	✔ 12.0-log	✔ 13.0-log	✔ 12.8-log	✘ 56.8%	✔ 80.0%	✔ 92.1%	✔ 99.7%	✔ 97.5%	⚠ 0.0%	\$ 38,204,633

✔ Meets Goal ⚠ Near Goal ✘ Does not meet goal

Figure 2.8 Example Train Comparison Summary from the Bottom Section of the Train Comparison Page.

3 Model Structure

The main body of the model's performance parameters and assumptions are stored on sheets hidden from the user during normal use of the toolbox. This section describes how the information on these sheets was obtained, and how it works together to produce performance and cost data for user-chosen treatment trains.

Because many of the unit treatment processes are still the subject of considerable research and costs will change over time, advanced users may wish to edit model inputs. Many aspects of the toolbox, specifically the input values for performance parameters can be edited readily by reasonably proficient Excel users, even if they do not have any macro programming or editing experience. Therefore, this chapter also explains how to (and how **NOT** to) edit these values without damaging the model's functionality.

The model contains many default parameters, most of which can be overridden by the user. However, a significant amount of background information was included in the determination of those default parameters, so the project team recommends that default values only be overridden if a compelling reason exists to do so.

3.1 Internal Structure Overview

The model is built on four main components:

1. Unit process models, which describe the efficiency of each unit process as a function of relevant operational parameters;
2. Combination of the unit process models into treatment trains, for which an overall performance can be calculated;
3. Unit cost models, which describe the cost of each unit process as a function of relevant operational parameters, including the level of treatment preceding a given unit process within the chosen treatment train; and
4. Combination of the unit cost models into total costs for a given treatment train, based on unit cost models.

3.1.1 Target Removals for Microbial Parameters

As described briefly in Section 2.3.22, default treatment goals for microbial parameters if the "California" button is selected are taken directly from the recommendations of the NWRI Panel for WRRF 11-02, which include 9-log removal of bacteria (based on total coliform), 12-log virus inactivation (based on MS-2 bacteriophage), and 10-log removal of protozoa (both *Giardia* and *Cryptosporidium*). These goals are based on pathogen inactivation / removal from raw wastewater to achieve potable water goals. The rationale behind these choices is described in detail in the NWRI Panel's report (NWRI, 2013).

The default treatment goals for microbial parameters if the "Texas" button is selected are based on the difference between microbial goals for finished drinking water and 95th percentile values

for secondary effluents as reported by Rose et al (2004) and Olivieri et al (2007).¹ Should you have different pathogen log removal goals based on site-specific effluent sampling data, you can input those log removal values (or the corresponding source water microbial concentrations) on the Input page (see Section 2.3.2) and continue to build your treatment train.

3.1.2 Treatment Goals for Trace Chemical Parameters

As described briefly in Section 1.1.1, treatment goals for chemical parameters are defined differently than for microbial parameters. The default treatment goals for trace chemicals are defined based on (1) recommendations made by the NWRI Panel convened for WRRF 11-02, which describes treatment goals for chemical parameters in terms of maximum recommended final concentrations in potable water (NWRI, 2013), (2) regulations, where applicable, and (3) engineering experience. Table 3.1 lists the default goals for the six chemical parameters incorporated in the model. The following paragraphs provide background on the selection of the default goals. Additional explanation for each parameter and the choice of default treatment goal are provided below.

Table 3.1 Default Treatment Goals for Chemical Parameters

Chemical Parameter	Default Treatment Goal
Total Organic Carbon (TOC)	1.5 mg/L
Nitrate	7 mg/L as N
TOrCs	1 µg/L
Estradiol Equivalency (EEQ)	1 ng/L
N-nitrosodimethylamine (NDMA)	8 ng/L
Perfluorooctane sulfonate and perfluorootanoate (PFOS + PFOA)	50 ng/L

1. Total Organic Carbon (TOC)

While the appropriate threshold TOC concentration is still the subject of active research (Water Environment and Reuse Foundation Project No. 15-04), **the default concentration goal for TOC in potable water was set at 1.5 mg/L**. Note that this may not be the appropriate goal in all locations. For example, groundwater injection projects in California must achieve 0.5 mg/L TOC. Further, the target concentration to maintain compliance with the Stage 2 DBPR will vary depending on the site-specific characteristics and resulting reactivity of the organic matter with chlorine to form regulated DBPs.

TOC differs from the “TOrCs” category in that it captures all of the organic constituents in the water, including the humic and fulvic structures that constitute the bulk of the effluent organic

¹ Drinking water goals are based on concentrations of rotavirus, *Cryptosporidium*, and *Giardia* correlated to a 1 in 10,000 risk of annual infection from consumption of 2 liters of drinking water based on dose-response curves for the respective microorganisms.

matter (EfOM) and are qualitatively similar (though not identical) to the constituents of natural organic matter (NOM) found in conventional surface water sources. The TOrC contribution to TOC is generally negligible, as reflected in the 500-fold difference in the goal concentrations established for the tool.

2. Nitrogen Species

The default removal goal for nitrate is based on achieving an average concentration of 7 mg/L or less (as nitrogen) in potable water, providing a 30% safety factor for meeting the 10 mg/L primary MCL for drinking water. A margin of safety is incorporated into the model for nitrate since it poses an acute (rather than chronic) health risk. To reduce the number of total parameters tracked, the default removal goal for nitrate is assumed to be sufficient to reduce concentrations of nitrite below its MCL of 1 mg/L as nitrogen.

3. Trace organic chemicals (TOrCs)

“TOrCs removal” is the most broadly defined chemical performance parameter, and was chosen to reflect a wide range of compounds with different physical and chemical properties. Percent removal credits were therefore assigned relatively conservatively to each unit process, especially for advanced treatment processes. This is because the *relative* mixture of TOrCs will evolve over the course of treatment to contain more recalcitrant compounds, necessitating more conservative percent removal estimates for those processes that are used toward the end of a treatment train (i.e., most of the “advanced treatment” processes included here) as opposed to the beginning (i.e., the secondary processes included here).

Based on a conservative survey of the NWRI Panel’s recommendations for maximum final concentrations in potable water across the wide range of trace organic compounds listed, **the default concentration goal for TOrCs in potable water was set as 1 ug/L.**

This level is defined on a per-compound level (i.e., the concentration of any given TOrC should be less than 1 ug/L, unless it is listed separately below), and was chosen because the concentration limits recommended by the Panel for most individual trace chemical compounds were equal to or greater than 1 ug/L, with the exception of estrogens, NDMA and perfluorochemicals (see below for all).

4. Estradiol Equivalency (EEQ)

“EEQ removal” is a much more narrowly defined performance parameter that is specifically intended to track the hormonal activity of the treated water. This parameter was chosen due to the more specific effects of estrogenicity on both human health and the environment, and the WRRF 11-02 NWRI Panel’s recommendation that estrogen concentration goals in potable water be set significantly lower than most other trace compounds.

The Panel recommended that 17 β -estradiol concentrations be in the “low nanogram per liter” concentrations or less in potable water. The California Contaminants of Emerging Concern (CECs) Panel defines a monitoring trigger level (MTL) of 0.9 ng/L for 17 β -estradiol (Drewes et al., 2010). As implied by its name, EEQ is given in units of estradiol equivalents. Therefore, **the default concentration goal for EEQ in potable water was set as 1 ng/L as estradiol.**

5. N-Nitrosodimethylamine (NDMA)

“NDMA removal” was chosen as a fourth performance parameter, for three reasons. First, the Panel recommended a significantly lower maximum concentration goal in potable water than for most other TOrCs. Second, NDMA can be formed from ozonation or chloramination of the wastewater effluent, in addition to occurring as a potential industrial contaminant for WWTPs receiving industrial discharges. Third, NDMA is notoriously difficult to remove using certain advanced treatment processes, which has resulted in its use as a performance parameter (or even design parameter) for several potable reuse systems.

Based on the Panel’s recommendation that maximum concentration goals in potable water reflect current standards and/or monitoring guidelines, **the default concentration goal for NDMA in potable water was set as 8 ng/L**, providing a 20% safety factor for meeting the California State Water Resources Control Board Division of Drinking Water (DDW) Notification Level (non-enforceable). NDMA is not currently regulated by a federal MCL.

6. Perfluorooctane sulfonate (PFOS) and Perfluorooctanoic Acid (PFOA)

Similar to NDMA, perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA) were included because their EPA health reference level of 70 ng/L (EPA, 2016), is significantly below the 1 µg/L general TOrCs threshold and they are also difficult to remove. They are tracked in the model as the sum of both individual concentrations, PFOS+PFOA, as this is how the 2016 EPA Health Advisory of 70 ng/L is defined. This reference level supersedes those provided by NWRI (2013).

It is important to note that science on the health impacts of exposure to PFOS and PFOA in drinking water is still emerging, and some state standards (e.g., Vermont at 20 ng/L) and findings from the New Jersey Drinking Water Quality Institute Health Effects Subcommittee (Gleason et al., 2016) suggest that a significantly lower concentration goals may be appropriate. However, at the time of this writing, and in accordance with the development of the other concentration goals under WRRF 11-02, the current Health Advisory level of 70 ng/L for PFOS+PFOA is considered the appropriate benchmark. Using this value as a starting point, a 30% safety factor was used to develop the **model default goal of 50 ng/L**.

Explanations for the Omissions of Additional Parameters of Interest in DPR Scenarios

The following parameters are of interest in DPR scenarios and were the subject of one or more PAC comments on Version 1.0 of this toolbox. Therefore, their omission from the tool is explained in more detail below:

Total dissolved solids (TDS). TDS is of critical importance to many DPR projects because the human use of water adds salts and the source waters used in water-scarce regions are often already near or at the regulatory limits for salinity. The reason TDS was not included in the toolbox, however, is that of the processes in the toolbox only high-pressure membrane processes (NF and RO) can remove salt, and its removal is very simple to track. RO will remove approximately 99% of TDS, whereas NF membranes range in their ability to remove TDS between 25% and 75%. If you need to desalt for your project, you need a desalination membrane step, which could include NF or RO.

Priority pollutants. All DPR source water should be screened for regulated chemicals as a matter of due diligence. However, few of these compounds are present at concentrations exceeding MCLs even in secondary effluent (Trussell et al., 2014). The six primary groups of chemical

contaminants, i.e., TOC, nitrate, TOxCs. EEQ, NDMA, and PFOS and PFOA, capture a broad range of chemical characteristics and treatability. Treatment trains capable of meeting performance goals for these parameters would be expected to address all known chemicals of concern, with the exception of TDS, and assuming the default goals are as recommended within this User's Manual. As highlighted in Section 2.4.2, bromate should be carefully considered for treatment trains using ozone.

3.1.3 Initial Concentration Default Values for Chemical Performance Parameters

The removal efficiencies for the unit process models are defined in terms of relative removal (i.e., percent removal). This requires input of initial concentrations such that the model can provide final concentrations calculated based on those percent removals (see Section 3.4). Default values for concentrations of the chemical performance parameters in wastewater treatment are provided in Table 3.2.

Table 3.2 Default values for Wastewater Effluent Concentrations by Treatment Type

Effluent Type	EEQ^a	TOxCs^a	Nitrate^b	TOC^b	NDMA^c	PFOS+PFOA^d
Primary Effluent	50 ng/L	10 ug/L	50 mg/L ^e	50 mg/L		
Conventional Secondary (BOD Removal Only)	5 ng/L	10 ug/L	30 mg/L ^e	30 mg/L		
Conventional Secondary (Nitrified)	3 ng/L	6 ug/L	30 mg/L	25 mg/L		
Secondary (Denitrified)	2 ng/L	3 ug/L	8 mg/L	20 mg/L		
Tertiary (Nitrified)	5 ng/L	5 ug/L	30 mg/L	20 mg/L	80 ng/L	50 ng/L
Tertiary (BNR or Denitrifying Filters)	5 ng/L	3 ug/L	5 mg/L	5 mg/L		
MBR (nitrified)	5 ng/L	5 ug/L	10 mg/L	4 mg/L		
MBR (with BNR)	5 ng/L	3 ug/L	5 mg/L	3 mg/L		

^a Default values based on Salveson et al (2012).

^b Default values based on Asano et al (2007), Table 3-14 and Table 8-3. Nitrate is given as N.

^c Default value for NDMA is based on work by Sedlak and Kavanaugh (2006) for concentrations in raw wastewater. Some removal in secondary treatment was observed by these authors at some facilities but it was extremely variable. Other facilities experienced no removal during secondary treatment.

^d Default values for PFOS+PFOA are relatively arbitrary, but reflective of a general observation that they are rarely present at concentrations above the EPA Health Advisory Level of 70 ng/L.

^e While nitrate concentrations in effluent that is not fully nitrified may be significantly lower than that of fully nitrified effluent, the ammonia present in non-nitrified effluent has the potential to be transformed into nitrate, and the default value chosen reflects this formation potential.

3.1.4 The Hidden Master Tab

Note: the IT³PR tool is designed to be modified and updated by the user. Overall, the user is encouraged to modify the tool as needed based upon the constant evolution of knowledge. However, the “user-friendly” focus on the tool is in the use of the tool and not in the modification of the tool. This and the subsequent section are designed to assist the proactive user in how to modify the tool.

All the built-in model inputs for the unit process models are stored in the hidden “Master” tab, which consists of the Master Input Table, and a number of lookup tables for individual processes (Unit Process Tables) that are linked from the Master Input Table. The Master Input Table, a copy of which is shown in Figure 3.1, has columns for each of the performance parameters (bacteria, virus, *Giardia*, *Cryptosporidium*, TOC, nitrate, TOrCs, EEQ, NDMA, and PFOS+PFOA), and rows for each unit process. Each row of the table represents the unit process model for a unit process with respect to the ten performance parameters.

In the simplest of cases, the unit process model is simply composed of ten constant values. This is the case where operational parameters are not expected to have a significant effect on the unit process with respect to removal effectiveness for the performance parameters. For example, the operation of membrane processes is subject to a very limited number of operational parameters, none of which – to a first level of approximation – affects the performance of the membranes with respect to the performance parameters of interest for this model. Therefore, the unit process models for membrane processes contain constant values for all ten performance parameters.

For example, the unit process model for RO membranes is defined by: 95% removal of TOC, 90% removal of nitrate, 95% removal of TOrCs and EEQ, 50% removal of NDMA, and 99% removal of PFOS+PFOA. For the California scenario, RO membranes are allocated 2-log removal credit for each of the microbial parameters, whereas no credit is allocated for the Texas scenario reflecting the state-specific approach for providing microbial removal credit for that unit process.¹

For unit processes where performance is a strong function of one or more operational variables (SRT for secondary processes, chemical dose for oxidation processes, UV fluence, or travel time in environmental buffers), the cells within the master input table link to a variety of unit process tables (also located on the Master tab). Each Unit Process Table provides performance with respect to one or more of the performance parameters, as a function of the relevant operational parameter. The sources of the values and functions contained within the Master Input Table, including the Unit Process Tables, are described in detail in Section 3.2, in the subsection corresponding to each unit process in question.

¹ While RO has been demonstrated to achieve more than 6 log removal of MS2 macrophage (Steinle-Darling et al, 2016), the Texas Commission on Environmental Quality (TCEQ) has set a precedent whereby microbial removal credit will only be recognized for RO (or NF) if the water utility, its consultant, or the membrane supplier can demonstrate through challenge testing or alternate methods that the removal is achieved and can be monitored in real time.

Texas Water Development Board Contract # 1348321632

Master Input Table										
Treatment Process	Microbial Inactivation - Potential Credits ⁽¹⁾				Microconstituent Removals ⁽¹⁾				TOC (mg/L)	
	Bacteria (total coliform)	Virus (MS-2)	Protozoa (Crypto)	Giardia	EEQ	TOrCs (ng/L)	NDMA (ng/L)	Nitrate as N	% removal	PFOS+PFOA
Secondary Processes										
Conventional Activated Sludge	SRT Dependent	2-log	0	0	SRT Dependent	0	0	50%	0%	
Conventional Activated Sludge - Denitrified		2	0	0	SRT Dependent	0	0	90%	90%	0%
Tertiary Nitrification	3	2	0	0	90	70	0	0%	95%	0%
Tertiary Denitrification	3	2	0	0	90	70	0	90%	95%	0%
MBR	5-log	3-log	0	0	SRT Dependent	0	0	0	95%	0%
MBR - Denitrified	5-log	3-log	0	0	SRT Dependent	0	0	90%	95%	0%
Tertiary Media Filtration	0	0	0	0	40%	30%	0	0	20%	0
Tertiary Media Filtration - Denitrification	0	0	0	0	40%	30%	0	95%	20%	0
Membrane Processes										
MF	3.0-log	0-log	4.0-log	4-log	50%	40%	0	20%	5%	0%
UF	4.0-log	3.0-log	4.0-log	4-log	50%	50%	0	30%	15%	0%
"loose" NF (Note (3))	1-log	1-log	1-log	1-log	75%	75%	7.50%	75%	95%	90%
Texas NF and RO get no credit	0	0	0	0						
BWRO and "tight" NF	2-log	2-log	2-log	2-log	95%	95%	50%	75%	99%	99%
Oxidation Processes										
Chlorination					Ct-Dependent					0%
Ozone					see green box in "ozone" tab			Formation	0%	5%
Ozone / H2O2					all the same as above			0%	0%	0%
UV		"UV disinfection" Table				see UV-H2O2 Table		20%	0%	0%
UV/H2O2		"UV disinfection" Table				see UV-H2O2 Table		30%	0%	0%
Fixed-Film Biological Processes										
Biofilter (with Pre-Ozonation)	0	0	0	0	50%	50%	50%	50%	30%	0%
Environmental Buffers										
SAT	4 log + 1 log per month	4 log + 1 log per month	4 log + 1 log per month	4 log + 1 log per month	0%	0%	50%	50%	50%	0%
Injection / subsurface migration (log units per month of travel time)	1-log	1-log	1-log	1-log	0	0	0	0	0%	0%
Surface Water Augmentation	0	0	0	0	1/2-Life of 10d	1/2-Life of 14d	1/2-Life of 3d	0%	0%	0%
Engineered Storage Buffer with Cl2	4	3	0	0	1/2-Life of 10d	1/2-Life of 14d	1/2-Life of 3d	0%	0%	0
Engineered Storage Buffer with Chloramines	4	3	0	0	1/2-Life of 10d	1/2-Life of 14d	1/2-Life of 3d	0%	0%	0

Figure 3.1 Screen Shot of the Master Table.

UV Disinfection: UV Dose versus Removal						
Dose (mJ/cm2)	Bacteria / E. Coli	Virus/Adeno	Giardia	Protozoa/Crypto	NDMA	Nitrate as N
1-5	2-log	0.00-log	0.0-log	0.0-log	0%	0%
5-10	4-log	0.00-log	2.0-log	2.0-log	0%	0%
10-20	5-log	0.00-log	3.0-log	3.0-log	0%	0%
20-50	6-log	0.00-log	6.0-log	6.0-log	0%	0%
50-100	6-log	1.00-log	6.0-log	6.0-log	10%	10%
100-200	6-log	2.00-log	6.0-log	6.0-log	25%	25%
200-250	6-log	4.00-log	6.0-log	6.0-log	60%	60%
250-500	6-log	6.00-log	6.0-log	6.0-log	65%	65%
500-800	6-log	6.00-log	6.0-log	6.0-log	80%	80%
800-1000	6-log	6.00-log	6.0-log	6.0-log	90%	90%
>1000	6-log	6.00-log	6.0-log	6.0-log	95%	95%

Figure 3.2 Screen Shot of the Unit Process Table for UV Disinfection.

3.1.5 *Editing the Unit Process Models*

Changes to unit process models must be made in the hidden Master sheet. Note that this sheet is called by several other hidden sheets (Master_lookup(1), (2) and (3)) when treatment trains are constructed by the user. This means it is very important not to make any changes to the Master sheet beyond what is described below.

To edit or update any unit process model, it is important to check whether the Master Input Table calls any Unit Process Tables before editing. For example, if a user wanted to update the destruction of TOrCs by a UV/AOP process, it would be important to make those changes in the UV/AOP Unit Process Table (as a function of UV fluence), as opposed to assigning a blanket value in the Master Input Table and thereby overriding the dependence on UV fluence.

In contrast, if a user wanted to override the log removal credit given to RO for pathogens (because, for example, a reliable method for integrity testing had been developed and so a greater log removal credit was reasonable), this could be done simply by overwriting the values shown for log removals in the Master Input Table.

3.1.6 *Master Cost Table*

Costs are stored in lookup tables in a hidden CostMaster tab. These lookup tables are based on vendor cost estimates, proprietary sizing tools, and cost multipliers all derived from project experience. These cost tables are very general and should not be seen as providing an accurate cost for any particular design condition. However, in sum aggregate, they provide an order of magnitude estimate of cost for various treatment trains, which can be used for comparison purposes. These cost tables are reproduced in Section 3.5.5. ***In the application and use of these costs, it is important to note that ancillary and site-specific costs, in particular, the cost of RO or NF concentrate disposal, is not included in the estimates.***

To protect the intellectual property on which the cost numbers are based, the master cost tables contain only dollar amounts without further justification of those amounts. If a user would like to customize the inputs on the cost side, he or she can update the values in the existing tables and all the updates will carry through.

Changes to unit process cost models must be made in this hidden CostMaster sheet. Note that this sheet is called by several other hidden sheets (Master_lookup(1), (2) and (3)) when treatment trains are constructed by the user. This means it is very important not to make any changes to the CostMaster sheet beyond replacing numerical values in the existing tables.

3.2 **Basis for Unit Process Models**

The unit processes available for the user to incorporate into the model are described below. A comprehensive summary of the references for the built in performance values is provided in Tables 3.3 through 3.10. Tables 3.11 through 3.16 provide additional detail on a process-by-process basis as a function of specific process parameters.

**Table 3.3 Unit Process Performance Parameter Values for Wastewater Processes.
(Pertains only to California Regulatory Paradigm)**

Input Parameter	Value	Reference
Conventional Activated Sludge (CAS) log removal for virus	2-log	Francy et al, 2012 found median 2.61-log, minimum 0.92-log removal of adenovirus (see Table 2). Rose et al. (2004) found a mean of approximately 2-log reduction of enteric viruses.
CAS log removal for total coliform, as a function of SRT	2- to 3-log (see Table 3.11)	EPA, 1986 (see Table 2-1). Log removals supported by Francy et al. 2012 with median 2.89-log and minimum 1.96-log removal of fecal coliforms. Rose et al. (2004) found a mean total coliform removal of 2-log across six CAS facilities.
MBR log removal for virus	2-log	Francy et al, 2012 found median 3.40-log and minimum 2.38-log removal of adenovirus (see Table 2). Note that California will not allow any virus log reduction credits for microfiltration membranes (CDPH, 2010) but has granted virus credit for secondary treatment.
MBR removal for fecal coliform	5-log	Francy et al, 2012 found median >6.73-log and minimum 5.34-log removal of fecal coliforms (see Table 2).
MBR removal of protozoa	4-log	Reardon et al., 2005 (based on removal achieved by microfiltration; not specific to MBRs)
TOC removal in Conventional Wastewater Treatment ^a	<i>Secondary only:</i> 50% (BOD only) 50% (nitrified) 70% (BNR) <i>Secondary and Tertiary:</i> 60% (nitrified) 90% (BNR)	Asano, 2007 (see Table 3-14).
TOC removal in MBRs ^a	60% (nitrified) 90% (BNR)	Asano, 2007 (see Table 3-14).
Nitrate removal in Wastewater Treatment ^a	0% (BOD only) 0% (nitrified) 80% (BNR)	Values shown at left are from Asano (2007, see Table 3-14). While the model tracks a parameter named "nitrate" in accordance with the chemical regulated in drinking water at 10 mg/L, it is best described as a "nitrate formation potential" - or the total organic nitrogen present in the water.

Input Parameter	Value	Reference
TOrC removal in both secondary processes, as a function of SRT ^a	10%-70% (see Table 3.11)	Salveson et al., 2012a (see Table 5.7 and text associated with EEQ)
EEQ removal in both secondary processes, as a function of SRT ^a	10%-90% (see Table 3.11)	Salveson et al., 2012a (see text associated with EEQ) and Baronti et al. (2000)
NDMA removal in secondary processes, as a function of SRT ^a	None	Sedlak et al (2006). Some removal in secondary treatment was observed at some facilities but it was extremely variable. Other facilities experienced no removal during secondary treatment.
PFOS+PFOA Removal ^a	None	Literature does not support PFOS or PFOA removal through secondary treatment.

^a Chemical removal percentages are only applicable if Primary Effluent has been selected as the starting point on the Input Page.

Table 3.4 Unit Process Performance Parameter Values for Media Filtration Processes.

Input Parameter	Value ^a	Reference
Microbial removals	None	Asano et al., 2007 (Figure 8-18). Rose et al (2004) indicate a mean of 2-log removal of total coliform, but removals vary significantly (compare Figures 3-8 and 3-14). Without the other components of conventional water treatment (coagulation, flocculation, and sedimentation) there is no established mechanism for attributing log removal credits to media filtration alone.
TOC Removal	20%	Asano et al (2007)
Nitrate Removal, conventional	none	Literature does not support removal of nitrate in conventional media filtration.
Nitrate removal, deep bed denitrifying filter	80%	Based on a review of literature on biological nitrate removal (Mohseni-Bandpi et al., 2013)
TOrC removal	none (conventional) 20% (denitrifying)	Reungoat et al. (2009) and Falas et al. (2016)
EEQ removal	none (conventional) 20% (denitrifying)	Reungoat et al. (2009) and Falas et al. (2016)
NDMA removal	none	Literature does not support removal of NDMA in conventional media filtration.
PFOS+PFOA Removal	none	Literature does not support PFOS or PFOA removal through media filtration.

Table 3.5 Unit Process Performance Parameter Values for Membrane Filtration Processes.

Input Parameter	Value	Reference
<i>Microfiltration</i>		
Virus removal	none	Limited literature (Lovins et al. 2002, Drury et al, 2012) suggests that 2-log virus removal can be achieved. However, pore sizes in clean MF membranes are too large to effectively retain virus. Neither California nor Texas allow any virus log reduction credits for microfiltration membranes.
Protozoa removal	3-log	Reardon et al., 2005. Additional removal may be demonstrated through challenge testing and ongoing direct integrity tests but is not relied upon during the initial planning phases for which this tool is designed.
TOC Removal	none	Literature and industry experience does not support significant TOC removal through membrane filtration processes unless operated as direct filtration with upstream coagulant addition.
Nitrate removal	none	Asano et al (2007), Table 8-21
TOrC removal	10%	Value chosen to be slightly lower removal than for UF. Some removal is expected due to particle association of TOrCs.
EEQ removal	30%	Linden et al., 2012 (based on limited data)
NDMA removal	none	No removal expected due to pore size of membranes and lack of particle association.
PFOS+PFOA Removal	none	Literature does not support PFOS or PFOA removal through microfiltration.
<i>Ultrafiltration</i>		
Virus removal	none	Several sources indicate 3-log or more virus removal can be achieved by UF membranes (EPA, 2008; Reardon et al., 2005). Lovins et al, (2002) indicate 6-log may be achievable. However, existing direct integrity testing protocols for low pressure membranes cannot detect breaches the size of viruses so no credit can be obtained..
Protozoa removal	4-log	Reardon et al., 2005 and Lovins et al, 2002.
TOC Removal	none	Literature and industry experience does not support significant TOC removal through membrane filtration processes unless operated as direct filtration with upstream coagulant addition.
Nitrate removal	none	Asano et al (2007), Table 8-21
TOrC removal	30%	Salveson et al, 2010
EEQ removal	30%	Salveson et al, 2010
NDMA removal	none	No removal expected due to pore size of membranes and lack of particle association.
PFOS+PFOA Removal	none	Literature does not support PFOS or PFOA removal through ultrafiltration.

Table 3.6 Unit Process Performance Parameter Values for Membrane Desalination Processes.

Input Parameter	Value	Reference
<i>Nanofiltration^a</i>		
Microbial removals	None	Schäfer et al., (2005) and Lovins et al, (2002), indicate significant removals could be achieved. However, there is no precedent in California or Texas for assigning LRV credit for NF.
TOC Removal	93%	Asano et al (2007), Table 9-3
Nitrate removal	25%	Asano et al (2007), Table 9-3
TOrC removal	75%	Schäfer et al., 2005, Steinle-Darling et al., 2010
EEQ removal	75%	Schäfer et al., 2005
NDMA removal	5%	Miyashita et al., 2009
PFOS+PFOA Removal	90%	Steinle-Darling and Reinhard (2008)
<i>Reverse Osmosis</i>		
Microbial removals	2-log (California) None (Texas)	Schäfer et al., (2005) and Reardon et al., (2005), indicate significant removals could be achieved. California has credited between 1- and 2-log for all pathogens. However, no direct integrity tests exists with which NF or RO membranes can be monitored, precluding any credit for pathogen removal at this time, so Texas does not provide any LRV credit for NF or RO
TOC Removal	95%	Asano et al (2007), Table 9-6
Nitrate removal	90%	Asano et al (2007), Table 9-6
TOrC removal	95%	Schäfer et al., 2005
EEQ removal	95%	Racz and Goel, 2010
NDMA removal	50%	Steinle-Darling et al., 2007, Plumlee et al., 2008
PFOS+PFOA Removal	99%	Removal expected due to relative size of PFOS and PFOA, as demonstrated by Tang et al (2006) and others.

^a There is potential for ambiguity between membranes designated "NF" versus "RO" by various manufacturers. Percent removals shown in this table for NF membranes as for those that differ significantly from typical RO membranes in their ability to reject monovalent salts.

Table 3.7 Unit Process Performance Parameter Values for Oxidative Processes.

Input Parameter	Value	Reference
<i>Chlorination</i>		
California version - Log removal of viruses, as a function of Ct	0- to 6-log (see Table 3.12)	Bandy, 2009 (see Table 2.2), which is based on: Asano et al., 2007 and Meng, 1996 and Tang et al., 2010 (see Table E15, with some interpolation).
Texas Version - Log removal of virus and Giardia cysts, as a function of Ct, pH, and temperature.	0- to 6 log (see Appendix A)	TCEQ inactivation equations that interpolate between the US EPA Ct tables are used to calculate Ct requirements. Visual basic code was provided by TCEQ (see Appendix A) and directly incorporated into the model. Credits are capped at 6-log.
Log removal of Cryptosporidium oocysts	None	Literature does not support inactivation of <i>Cryptosporidium</i> by chlorine.
TOC Removal	none	Literature does not support TOC removal through chlorination.
Nitrate removal	none	Literature does not support nitrate removal through chlorination.
Removal of TOrCs, as a function of Ct	0-25% (see Table 3.12)	Linden et al., 2012 (range 0% to 99% at Ct 100 mg-min/L); Tang et al, 2010 (insignificant to moderate removal of TOrCs at 120 mg/L-min Ct)
Removal of EEQ, as a function of Ct	0-25% (see Table 3.12 Error! Reference source not found.)	Linden et al., 2012 (range 20% to 99% at Ct 100 mg-min/L); Tang et al, 2010 (70% removal of estrone at 120 mg/L-min Ct)
NDMA Removal	none	Literature shows that chlorine oxidation can reduce concentrations of chloramine-reactive NDMA <i>precursors</i> , but not NDMA itself
PFOS+PFOA Removal	none	Literature does not support PFOS or PFOA removal through chlorination.
<i>Ozonation</i>		
O ₃ :TOC versus Ct correlations for ozonation	0 to 10 mg/min-L for 0.25 to 1.5 O ₃ :TOC	Snyder et al, 2012. (see minimum representative values from Table 3.78)
Log microbial inactivation as a function of O ₃ :TOC ratio for:		Snyder et al, 2012
Bacteria	1- to 6-log (see Table 3.13)	Snyder et al, 2012 (see Table 3.88)
Virus	2- to 6-log (see Table 3.13)	Snyder et al, 2012 (see Table 3.89)

Input Parameter	Value	Reference
		Note: Removal of virus is consistent with US EPA Ct tables for ozone at 15C, based on O ₃ :TOC versus Ct correlations (see below).
Ozone log removal for Protozoa and virus as a function of Ct	0- to 2-log (see Table 3.13)	For <i>Cryptosporidium</i> : EPA, 1999 (see Table 3-8) For <i>Giardia</i> and virus inactivation, see EPA 1991, (Tables E-10 and E-11, respectively) O ₃ :TOC versus Ct correlations (see above), are used to “translate” inactivation data from Ct tables
TOC Removal	none	Literature does not support TOC removal through ozonation.
Nitrate Removal	none	Literature does not support nitrate removal through ozonation. In fact, nitrite oxidation during ozonation can produce nitrate.
TOrCs	15%-85% (see Table 3.14)	Snyder et al, 2012 (see Table 3.86; Group 4 indicator)
EEQ	60%-99% (see Table 3.14)	Snyder et al, 2012 (see Table 3.86; Group 3 indicator)
NDMA – destruction	none	Gerrity et al. (2012) and Snyder et al (2012) show formation of NDMA during ozonation of effluent. See Section 3.2.20 for additional discussion and references.
NDMA – formation	Low – 10 ng/L Med – 50 ng/L High -150 ng/L	
PFOS+PFOA Removal	none	Literature does not support PFOS or PFOA removal through ozonation.
<i>UV Irradiation or Photolysis</i>		
Pathogen log inactivation as a function of UV fluence:	0- to 6-log (see Table 3.15)	Fluence values are taken from UV Disinfection Guidance Manual (UVDGM; US EPA, 2006). Reactor design will also be based on the UVDGM validations. In order to achieve more than 4-log inactivation, more than one reactor in series is needed.
TOC Removal	none	Literature does not support bulk TOC removal through UV irradiation / photolysis; TOC is a hydroxyl radical scavenger during UV advanced oxidation (Kommineni et al., ;
Nitrate Removal	none	Literature does not support nitrate removal through UV irradiation / photolysis; note that nitrate is a hydroxyl radical scavenger during UV advanced oxidation.
Destruction of TOrCs (without peroxide addition) as a function of UV fluence	0%-25% (see Table 3.15)	Snyder et al, 2012 (see Table 3.87)

Input Parameter	Value	Reference
Destruction of TOxCs with 5-10 mg/L peroxide addition as a function of UV fluence	0%-62% (see Table 3.15)	Bandy, 2009 (averages for Tables 4.3 through 4.6) and Snyder, 2012 (averages for Table 3.87 at 10 mg/L peroxide)
Destruction of EEQ (without peroxide addition) as a function of UV fluence	0%-25% (see Table 3.15) Error! Reference source not found.)	Snyder et al, 2012 (see Table 3.87)
Destruction of EEQ with 5-10 mg/L peroxide addition as a function of UV fluence	0%-80% (see Table 3.15)	Bandy, 2009 (averages for Tables 4.3 through 4.6) and Snyder, 2012 (averages for Table 3.87 at 10 mg/L peroxide)
Destruction of NDMA as a function of UV fluence	0%-92% (see Table 3.15)	Bandy, 2009 (averages calculated from Tables 4.3 through 4.6)
PFOS+PFOA Removal	none	Literature does not support PFOS or PFOA removal through UV/hydrogen peroxide based AOP. AOP with stronger radicals (sulfate radical) has been shown to defluorinate PFOS and PFOA (Song et al, 2013; Qian et al, 2016)

Table 3.8 Unit Process Performance Parameter Values for Other Treatment Processes.

Input Parameter	Value	Reference
<i>Biologically Active Filtration</i>		
Pathogen removal (all types)	None	Some removal demonstrated by Burr, 2000, but as with media filtration above, no credit can be obtained without preceding conventional water treatment processes.
TOC Removal	40%	Trussell et al., 2016
Nitrate removal	none	Biofilters typically operate aerobically and are therefore not designed for denitrification.
EEQ and TOxC removal	50% each	Snyder et al., 2007
NDMA removal	50%	Reported removals vary. Reno pilot study indicates post-ozone BAF reduces NDMA from 7.9 ng/L to <0.28 ng/L (Drinkwater, 2011). Pilot work at higher NDMA concentrations (up to 250 ng/L) in RO concentrate indicates 75% to >95% removal may be achieved (Carollo, 2013)
PFOS+PFOA Removal	none	Literature does not support PFOS or PFOA removal through media filtration or biodegradation.

Table 3.9 Unit Process Performance Parameter Values for Treatment in Engineered Storage Buffers.

Input Parameter	Value	Reference
<i>Free Chlorine Contact – same as Table 3.7</i>		
<i>Chloramines Contact (TCEQ model)</i>		
Log removal of viruses, as a function of Ct, pH, and temperature	0- to 6-log (see equation)	Extensive literature supports virus inactivation with chloramines, though significantly higher Cts are needed than for free chlorination. TCEQ inactivation equations are used to calculate Ct requirements. Visual basic code provided by TCEQ (see Appendix A) was incorporated into the model. Credits are capped at 6-log.
Log removal of Giardia cysts, as a function of Ct, pH, and Temperature	0- to 6-log (see equation)	Visual basic code provided by TCEQ (see Appendix A) was incorporated into the model. Credits are capped at 6-log.
TOC Removal	none	None expected, similar to chlorine.
Nitrate removal	none	None expected, similar to chlorine.
EEQ, TOrC, NDMA removal	none	Some NDMA formation may be possible but is not accounted for in this model.
PFOS+PFOA Removal	none	None expected, similar to chlorine.

Table 3.10 Unit Process Performance Parameter Values for Environmental Buffers.

Input Parameter	Value	Reference
<i>Percolation during Soil Aquifer Treatment (SAT)</i>	<i>To obtain removals for SAT, the removals for percolation shown below are added to those given for direct injection. The limit of 6-log reduction credit applies to the full SAT process, i.e., the sum of credits for percolation and subsurface transport cannot exceed 6-log.</i>	
Bacteria reduction	4-log	Kazner et al., 2012; Note that California determined log reductions for SAT on a travel-time basis only (see Section 3.2.3)
Virus and protozoa reduction	4-log	Hogg et al., 2012; Note that California determined log reductions for SAT on a travel-time basis only (see Section 3.2.3)
TOC removal	50%	Based on calculations from values shown in Figure 1.5 in Asano, T. (1998).

Input Parameter	Value	Reference
Nitrate removal	50%	Nitrate removal varies. SAT sites in Mesa, AZ indicate significant / near complete removal of nitrate. Lower value chosen to be conservative.
TOrC reduction	50%	Mansell and Drewes, 2004
EEQ reduction	95%	Mansell and Drewes, 2004
NDMA reduction	Half-life of 30d	Variable removals reported, with half-lives ranging from < 7 days (Drewes, 2006) to 9 days (Bradley et al., 2005) in laboratory studies and 70 days in one full-scale investigation (Zhou et al, 2009). Removal rates were obtained under anaerobic conditions with NDMA-adapted soil. A compromise value was selected.
PFOS+PFOA Removal	none	Literature does not support removal of PFOS or PFOA through SAT as indicated by recalcitrant contaminant plumes in several locations within the U.S.
<i>Direct Injection / Subsurface Migration</i>		
Bacteria reduction	1-log per month travel time	EPA, 2008; also in analogy to credit given by CDPH (2014) for other pathogen groups. .
Virus reduction	1-log per month travel time	CDPH, 2014, see also Section 3.2.3.
Protozoa reduction	1-log per month travel time / none for DDW	Hogg et al., 2012. Note that California will not give credit for protozoa removal for direct injection projects (CDPH, 2014). See Section 3.2.3
TOC removal	None	None presumed based on calculations from values shown in Figure 1.5 in Asano, T. (1998).
Nitrate removal	None	None expected.
TOrC, EEQ, and NDMA reduction	None	Literature does not support a definitive removal value for these constituents, none is given to be conservative.
PFOS+PFOA Removal	None	Literature does not support removal of PFOS or PFOA through subsurface migration (or direct injection)
<i>Surface Water Augmentation</i>		
Bacteria reduction ^b	None	No credit due to ubiquity of bacteria in surface waters and lack of specific literature addressing the issue.
Virus reduction ^b	None	Limited data exist to suggest 0.5-log/day virus inactivation can be achieved in surface waters (Azadpour-Keeley et al., 2003). However, the general applicability of this inactivation rate is not demonstrated.

Input Parameter	Value	Reference
Protozoa reduction ^b	None	No credit due to ubiquity of protozoa in surface waters and lack of specific literature addressing the issue.
TOC removal	0%	Effects on TOC of effluent origin after mixing with TOC in surface water have not been determined.
Nitrate removal	None	Nitrate removal in surface waters is site-specific (Mulholland et al., 2009). No removal is assumed to maintain general applicability.
TOrC reduction	Half-life of 10 d	Fono et al, 2006
EEQ reduction	Half-life of 14 d	Racz and Goel, 2010
NDMA reduction	Half-life of 3 d	Plumlee and Reinhard, 2007
PFOS+PFOA Removal	None	Literature does not support a concrete removal value.

^a Log reduction credits have been rounded to the nearest integer number.

^bAdvanced-treated water that enters a surface water body (and most groundwater aquifers) will have to undergo subsequent water treatment processes to address water quality issues before entering a distribution system. These additional processes are not accounted for in the model.

3.2.1 Removal in Secondary Processes as a Function of SRT

As indicated in Section 2.3, the selection of secondary treatment processes is handled differently by the model depending on whether you select the California or Texas button. Refer to that section to review the model approach to assigning initial concentrations for chemical parameters and calculating microbial and chemical removals depending on the selection.

Only two secondary treatment processes, conventional activated sludge (CAS), and membrane bioreactors (MBRs) were chosen for inclusion in this toolbox model. This is because, compared to many of the advanced treatment processes discussed below little research has been conducted regarding the performance of secondary treatment processes with respect to the performance parameters used in this tool. Trickling filters were not explicitly included in this toolbox; however, as a rough first estimate, a low-solids retention time (SRT) CAS can be substituted for a trickling filter.

CAS was selected because it is currently the most prevalent form of secondary treatment employed at wastewater treatment facilities, which means that this process is the most relevant to most users and most of the research investigating the performance of secondary processes with respect to the performance parameters has been conducted on this process. MBRs were also included because literature on their performance with respect to the performance parameters was available.

For bacteria, TOrCs, and EEQ, a significant correlation between SRT and removals were found in the literature (as cited in Table 3.3). Therefore, the unit process models for CAS and MBR are defined as a function of SRT, as shown in Table 3.11.

For protozoa, virus, and TOC, the literature reports average removals through secondary treatment. Rose et al. (2004) indicate some trend of increasing pathogen removal with SRT, but the trend is not as well characterized. Therefore, the unit process models for those parameters for both CAS and MBRs are provided simply as the number shown in Table 3.3.

Table 3.11 Secondary Treatment Performance as a Function of Solids Retention Time^a.

Solids Retention Time (SRT)	Bacteria	TOrCs	EEQ
< 4 days	2-log	10%	10%
4 – 7 days	2-log	50%	50%
> 7 days	3-log	70%	90%

^a See Table 3.3 for the sources of the data presented in this table. Log reduction credits have been rounded to the nearest integer number.

3.2.2 Removal in Advanced Processes as a Function of Operating Parameters

The unit process models for a number of advanced processes were determined based on a comprehensive literature review, as shown and cited in Table 3.3. For several of these, the literature indicated a relatively constant removal of the various performance parameters by each unit process, irrespective (in general) of the operating conditions. Therefore, these unit processes are not revisited again in this section. The list of unit processes for which the preceding is true includes:

- Sand/Media Filtration,
- Microfiltration,
- Ultrafiltration,
- Nanofiltration, and
- Reverse Osmosis.

Additional information on the advanced treatment processes where removal of the performance parameters is a strong function of operating conditions, such as chemical dose, contact time and/or irradiation, is provided below.

Removal by Chlorination as a Function of Ct - California Version

Microbial inactivation by chlorination is a well-understood phenomenon, and is a strong function of the product between chlorine concentration (C) and contact time (t), or Ct, as codified in the US EPA Ct tables.

Table 3.12 shows the removal of microbial and chemical performance parameters as a function of Ct, as it is built into the model. Note that some regulators require significantly higher Ct values (450 mg/L-min for California Title 22 reclaimed water for unrestricted non-potable reuse). However, the literature reviewed does not support a change in log inactivation above approximately 100 mg/L-min.

For the chemical parameters TOrCs and EEQ, the removal as a function of chlorine Ct is effectively a step function, based on data collected by Linden et al (2012) at 100 mg/L-min. Below this Ct, removals for TOrCs and EEQ cannot be verified.

No removal of preformed NDMA by chlorination was supported by the literature reviewed.¹ Similarly, no removal of nitrate or PFOS+PFOA from chloramines oxidation is supported by the literature.

Table 3.12 Chlorination Performance as a Function of Ct - California Version^a.

Ct (mg/L-min)	Bacteria	Virus ^b	Giardia	Crypto	TOrCs	EEQ	TOC
1-3	2-log	None	None	None	None	None	None
3-5	3-log	2-log	None	None	None	None	None
5-10	3-log	3-log	None	None	None	None	None
10-30	4-log	4-log	None	None	None	None	None
30-50	4-log ^c	4-log	None	None	None	None	None
50-80	5-log ^c	5-log ^d	1-log	None	None	None	None
80-100	6-log ^c	6-log	1-log	None	None	None	None
> 100	6-log ^b	6-log	2-log	None	25%	25%	None

^a See Table 3.7 for the sources of the data presented in this table. Log reduction credits have been rounded to the nearest integer number. A temperature of 5°C is assumed.

^b pH 6-9 assumed.

^c Log removal as a function of Ct for bacteria beyond 4-log is not demonstrated by the literature cited in this report. However, as a conservative estimate, the same log inactivation was provided for bacteria as for virus.

^d Log reduction value at Ct of 50-80 mg/L-min is interpolated between data provided by Bandy (2009) and Tang et al (2010).

Removal by Chlorination as a Function of Ct - Texas Version

The Texas Commission on Environmental Quality (TCEQ) applies inactivation equations that interpolate between the US EPA Ct tables to calculate Ct requirements. Visual basic code was provided by the TCEQ (Appendix A) and directly incorporated into the model. LRV credits are capped at 6-log per process.

Removal by Ozone as a Function of O₃:TOC and/or Ct

Microbial inactivation by ozonation is also well understood and codified in US EPA Ct Tables for ozonation. The distinction between ozonation and chlorination lies in the former's efficacy at destroying chemical contaminants much more effectively than the latter. In addition, recent

¹ Note that chlorine oxidation can reduce concentrations of NDMA precursors resulting in lower concentrations if chloramines are used after chlorine as a disinfectant. This complex series of reactions (chlorine oxidation of NDMA precursors and subsequent formation of NDMA from reaction of remaining precursors with chloramines) is not incorporated in the model. NDMA formation from reaction with chloramines would require further study by the user for a site-specific reuse application that incorporates longer chloramine contact time than those typically observed if chloramines are only used for membrane biofouling control (i.e., not for disinfection credits).

research suggests that Ct may be an incomplete measure by which to gauge the behavior of chemical parameters under ozonation, as significant attenuation is achieved through ozonation in some cases even when no ozone residual can be measured (i.e., at an ozone Ct of zero). The ozone dose for the model was therefore framed both in terms of Ct as well as in terms of a mass ratio of ozone to total organic carbon (O₃:TOC) in the unit process influent, which much more accurately predicts the destruction of chemical parameters (Gerrity et al., 2012).

The user will specify an ozone Ct and these data will apply to the disinfection of pathogens as shown in Table 3.13, which is based on the US EPA Ct tables at 5 °C.

Table 3.13 Ozone Disinfection Performance as a Function of Ct^a.

Ct	Virus	Giardia	Cryptosporidium	Bacteria ^c
0.5	1-log	0-log	0-log	1-log
1	3-log	1-log	0-log	3-log
5	6-log ^b	3-log	0-log	6-log
10	6-log ^b	3-log	0-log	6-log
15	6-log ^b	3-log	1-log	6-log

^a Virus, *Giardia*, and *Cryptosporidium* inactivations based on US EPA Ct tables at 5°C; bacteria inactivation capped at values used for virus due to lack of data and higher susceptibility to ozonation than viruses.

^b Derived from results from WRRF 11-02 (Trussell et al., 2016)

^c Bacteria are more susceptible to ozone disinfection than virus (Lechevalier and Au, 2004); the values reflect a conservative assumption that bacterial inactivation is equivalent to observed and documented inactivation for virus.

For the destruction of organic constituents, the ozone dose is translated into O₃:TOC using the TOC concentrations in upstream unit process effluents provided in Table 3.13. The TO_{OC}s and EEQ destruction is then calculated as shown in Table 3.14. This correlation is based on measurements conducted by Snyder et al. (2013).

Table 3.14 Ozone Advanced Oxidation Process (AOP) Performance as a Function of O₃:TOC^a.

O ₃ :TOC	TO _{OC} s	EEQ	NDMA ^b	TOC
0.25	15%	60%	None	None
0.5	40%	95%	None	None
1	70%	99%	None	None
1.5	85%	99%	None	None

^a See Table 3.7 for the sources of the data presented in this table. Log reduction credits have been rounded to the nearest integer number.

^b Ozonation in potable reuse applications can form NDMA (as presented in Section 3.2.2).

NDMA Formation During Ozonation

The formation of NDMA is a significant concern during ozonation of wastewater that has not already undergone advanced treatment by NF or RO, which removes precursor compounds. Due

to the wide variability in NDMA formation observed with ozonation (Gerrity et al., 2012 and Dickenson et al., 2013), it is difficult to build in a “standard” amount of NDMA formation that will be representative of all treatment scenarios. We therefore allow the user to choose from one of three NDMA formation “levels” (low = 10 ng/L, medium = 50 ng/L, or high = 150 ng/L) in order to explore the potential ramifications of NDMA formation on selected treatment trains. Because of this unique formation step (none of the other unit processes allow for formation of any of the performance parameters), the total removal of NDMA must be calculated differently than for the other performance parameters (see Section 3.4).

Ultraviolet Irradiation

Ultraviolet irradiation (UV) is another process traditionally employed in disinfection, and is particularly effective against protozoa. While less effective than ozone with respect to most chemical contaminants, UV is one of few advanced treatment processes that has been shown – at fluences above typical germicidal doses – to provide robust destruction of NDMA. Inactivation of microbial parameters and destruction of chemical parameters by UV alone are shown in Table 3.15. No removal is assumed for nitrate.

Table 3.15 UV Performance as a Function of Dose (without Oxidant Addition)^a.

UV Dose (mJ/cm ²)	Bacteria	Virus	Protozoa	EEQ	TOrC	NDMA	TOC
5-10	2-log	None	1-log	None	None	None	None
10-20	5-log	None	3-log	None	None	None	None
20-50	6-log	None	6-log	None	None	None	None
50-100	6-log	1-log	6-log	5%	5%	10%	None
100-200	6-log	2-log	6-log	10%	10%	25%	None
200-300	6-log	5-log	6-log	15%	15%	60%	None
300-500	6-log	6-log	6-log	20%	20%	65%	None
500-800	6-log	6-log	6-log	25%	25%	80%	None
800-1000	6-log	6-log	6-log	25%	25%	90%	None
> 1000	6-log	6-log	6-log	25%	25%	95%	None

^a See Table 3.7 for the sources of the data presented in this table. Log reduction credits have been rounded to the nearest integer.

The UV reactor performance, both in terms of disinfection and destruction of various chemicals, is dose dependent. The efficiency (energy, # lamps) of a UV system to meet a target dose is based upon UV transmittance (UVT). The model includes an estimation of UVT as function of upstream treatment processes.

The economics of incoming water quality (and thus, the dependence on the location of the unit process within a treatment train), are realized within the cost estimating portion of the model, in which the first calculation to determine size of a given UV system is to calculate the total UV reactor size (and energy needed) to achieve a certain UV fluence, based on total flow rate and incoming water quality. Poorer incoming water quality translates to more UV equipment to achieve the same UV fluence (and thus the same performance) compared to the case where the incoming water quality is higher.

Ultraviolet Irradiation with Advanced Oxidation

As noted above, while a very effective disinfectant, UV alone is relatively inefficient at removing trace chemical contaminants (TOrcs and EEQ, see Table 3.15). However, the addition of hydrogen peroxide (H₂O₂) transforms UV into an advanced oxidation process (AOP), in which hydroxyl radicals break down chemical constituents very effectively. The required dose of H₂O₂ is very much dependent upon the corresponding UV dose. Higher UV dose allow for less H₂O₂ dose, and vice-versa. Many post-RO UV/ H₂O₂ processes employ 3 to 5 mg/L of H₂O₂. Such UV systems have a UV dose in excess of 350 mJ/cm². Lower dose UV systems will need significantly higher H₂O₂ doses to attain a similar level of hydroxyl radical formation. Since hydrogen peroxide conversion to hydroxyl radicals is inefficient in UV advanced oxidation, some downstream step to quench peroxide is typically needed prior to distribution. Note that the cost of a peroxide quenching step is not incorporated in the cost model.

Table 3.16 provides the unit process performance for UV/H₂O₂ as a function of UV dose with a moderate peroxide dose. While the microbial inactivation (and NDMA destruction) are effectively unchanged with the addition of peroxide, comparison of Table 3.15 and Table 3.16 **Error! Reference source not found.** illustrates the advantage of peroxide addition for the destruction of EEQ and TOrcs.

Table 3.16 UV Performance as a Function of Dose (with Peroxide Addition)^a.

UV Dose (mJ/cm ²)	Bacteria	Virus	Protozoa	EEQ	TOrc	NDMA	TOC
5-10				None	None		
10-20				None	None		
20-50				None	15%		
50-100				20%	25%		
100-200	Same as Table 3.15			40%	35%	Same as Table 3.15	
200-500				60%	50%		
500-800				80%	60%		
800-1000				80%	60%		
>1000				80%	60%		

^a See Table 3.7 for the sources of the data presented in this table. Log reduction credits have been rounded to the nearest integer.

3.2.3 Environmental Buffers

The primary purpose of the IT³PR model is to provide a toolbox with which advanced treatment processes and trains can be evaluated against one another for application in direct potable reuse scenarios. However, the treatment value of environmental buffers may be of interest to utilities that are already using an environmental buffer, or are located in a suitable geographic area to do so and wish to evaluate such an environmental buffer as part of their treatment train. In addition, it is illustrative to collect, in one place, data on the actual treatment value that can be assigned to environmental buffers (which is in addition to providing response retention time and/or their role in the public perception of potable reuse), as one looks toward replacing that environmental buffer with an engineered system in DPR applications. Therefore, three basic types of

environmental buffers were included in the toolbox: direct injection into groundwater, soil aquifer treatment (SAT), and surface water augmentation. Any one of these environmental buffers can be appended to the end of a chosen engineered treatment train.

Direct Injection into Groundwater

Groundwater aquifers have long been used as both natural storage reservoirs and environmental buffers in potable reuse systems. In direct injection processes, advanced-treated water is injected directly into the water-bearing portion of the aquifer, essentially bypassing the vadose zone. Direct injection is favorable (as compared to infiltration) if the target aquifer is separated by the surface from one or more aquitards, or if conditions are not conducive to percolation.

Advanced treated water that is injected directly into the target aquifer mingles with the natural groundwater and migrates with it along natural (though locally injection-influenced) gradients. The “treatment” that occurs in such a scenario occurs generally under low-nutrient, anoxic conditions during subsurface migration. California DDW provides 1-log removal credit for each month of travel time in the aquifer, for both bacteria and viruses. For protozoa, they provide no credit for direct injection, though literature suggests that at least a similar inactivation compared to virus can be assumed (Hogg et al., 2012).

Therefore, the model assumes a 1-log inactivation of all microbial parameters per month of subsurface travel time (see Table 3.10).

Very little literature exists that can confirm the reduction in chemical parameters through subsurface migration alone, i.e., without the benefit of vadose-zone travel. Though one would expect some measure of removal as a function of subsurface travel time, the model assumes no removal of chemical parameters occurs during subsurface migration as a conservative estimate. Additional research is currently underway (e.g., WateReuse Research Foundation Project No. 10-05) that aims to determine more precise values for TOrC removal during subsurface travel (in the vadose and saturated zones).

Soil Aquifer Treatment

Soil aquifer treatment provides the same subsurface migration benefit as direct injection, plus the treatment that occurs during the percolation process in which the water travels from the ground surface through the vadose zone, which is effectively a biologically active filter, until it reaches the water table. The model therefore provides additive removal credits associated with the percolation process and the subsurface migration process.

Based on the literature reviewed (see Table 3.10), percolation alone provides approximately 4-log removal of bacteria and viruses, and significant reductions in TOrCs and EEQ. The literature regarding removal of NDMA during percolation (and SAT as a whole) is contradictory, with half-lives ranging from < 7 days (Drewes, 2006) to 9 days (Bradley et al., 2005) in laboratory studies and 70 days in one full-scale investigation (Zhou et al, 2009). In both bench and full-scale studies, removal rates were obtained under anaerobic conditions with NDMA-adapted soil.

For the model, the removals achieved through percolation are added to the removal credits given for subsurface migration (as described above). One should note that this method of awarding LRV credits is not in accordance with the process allowed by the California DDW for SAT (CDPH, 2014), which include 1-log per month of subsurface travel time (without regard to the percolation process as separate from subsurface migration), and a lump-sum 10-log reduction credit for protozoa (both *Cryptosporidium* and *Giardia*) once the subsurface travel time exceeds 6 months.

One should also note that the model caps all microbial log removal credits at 6-log per unit process. This is both to ensure that sufficient redundancy is built into the toolbox such that multiple barriers have to be implemented to meet log removal requirements, but also such that the model does not extrapolate past the range of values supported by the literature should a user choose to enter a long-term travel time.

Surface Water Augmentation

Surface water storage can provide additional treatment through a number of mechanisms, including sorption to sediments, solar photolysis at or near the water's surface, and biodegradation in both water and sediment. These processes are dependent on many specific parameters related to the characteristics of the surface water body, such as oxygen content and re-aeration rate, rate of mixing, depth and clarity of the water, the organic fraction of the sediments, and many other factors.

Due to the challenge of consolidating the effects of a large and variable number of processes over a large and variable group of surface water body types, the attenuation proposed in this model for surface water bodies can only be a very high-level overview. In addition, for microbial parameters in particular, one must consider that even the highest quality advanced-treated water that enters a surface water body will have to undergo subsequent water treatment processes to address water quality issues inherent in surface water.

For these reasons, relatively little credit is provided for microbial inactivation/removal during surface water augmentation, and the focus is on the attenuation of chemical parameters, which may be significant with sufficient residence time in surface waters (see Table 3.10).

3.3 Process Train Options

Figure 2.3 is a graphical representation of the logic that defines the allowable combinations of unit processes into treatment trains. This train building logic was based on some basic assumptions regarding what process options can potentially achieve the desired DPR treatment goals, and include a number of the processes piloted as part of this project, including the full-advanced treatment process defined by California DDW (i.e., membrane filtration, RO, UV advanced oxidation), as well as several non-RO based alternatives. The process train options were also chosen such that users have sufficient flexibility to model a number of common advanced treatment processes that may not meet DPR treatment goals, but may be sufficient for other uses of reclaimed water, or can meet potable reuse standards in conjunction with a suitable environmental buffer.

A few basic considerations drove the arrangement of unit processes into treatment trains:

- Generally (but not always) it makes sense to lead with physical separation processes (membrane or non-membrane filtration) followed by chemical unit processes, in order to reduce the dose requirements for chemical processes.
- Pretreatment requirements were considered, such that high-pressure membranes (NF and RO) are always preceded by a low-pressure membrane (MF or UF) to reduce membrane fouling potential.
- No “duplicate” steps placing two identical unit processes in a row were allowed, as this would effectively violate the diverse barrier principle that limits pathogen log removal credits for any one unit process to 6-log units.

Additional considerations and constraints are described in the following sections.

3.3.1 Independence of Unit Process Order

The unit process models were explicitly designed such that the performance of the unit processes is independent of the order in which they are incorporated into the treatment train.

This was accomplished by a combination of controls:

1. Users are limited by the model in the way they can combine treatment steps. Examples include:
 - a. A user may not choose to implement NF or RO without a membrane pretreatment step.
 - b. Chlorination is only allowed as a disinfection method if the wastewater has been fully nitrified. If this constraint did not exist, ammonia and chlorine would combine to form chloramines, which are a substantially less effective disinfectant than free chlorine. Besides being undesirable on its own, this would necessitate the distinction of two separate unit processes (chlorination versus chloramination) in the model, to preserve the general independence of unit process models on location within treatment trains.
2. For the unit processes whose performance efficiency varies with incoming water quality, user inputs were intentionally framed in quantities that take such dependence into account. Examples include:
 - a. The user input for ozone dose is defined as a ratio of ozone to TOC. Recent research (Snyder et al, 2012) has shown that normalizing the ozone dose by the TOC concentration provides relatively consistent results across a variety of water qualities in terms of both disinfection and trace organics removal.
 - b. As described in Section 3.2.2, the user input for the UV step is framed in terms of UV dose, which decouples the influence of water quality from the effectiveness of the unit process. The effects of water quality are borne during the cost-estimating step, which calculates required lamp output based on flow rate, water quality, and the user-specified UV dose and uses that output to estimate a system cost.
 - c. The dependence on water quality parameters (TOC and/or UVT) is shifted to the cost models, which take into account the typical TOC or UVT produced by a preceding unit process, calculate the actual ozone dose or UV irradiance needed to produce the desired removals, and calculate costs from there.

3.3.2 DBP Formation

The model does not contain a general mechanism to account for the formation of disinfection byproducts (DBPs), except for the specific case of NDMA formation during ozonation. Chlorination is only allowed as a disinfection method if the wastewater has been fully nitrified (see Note (3) on Figure 2.3). As explained above, this is in part because the chlorination of wastewater containing ammonia leads to the formation of chloramines, which are a significantly less effective disinfectant. However, this also reduces the formation of nitrosamines (NDMA, e.g.), which are very difficult to remove, and may otherwise drive the need for additional processes or process capacity.

3.4 Calculating Overall Process Train Performance

Once all the unit process models have been defined, providing the performance of a user-chosen treatment train is a simple case of concatenating the performance of each step. For microbial parameters, this is simply a question of adding the log removal credits obtained by each process step to obtain the final log removal credit.

For chemical parameters, the calculation is only slightly more complicated. The performance of each unit process with respect to the chemical parameters is given as a percent removal. The concentration remaining after each unit process step is calculated by multiplying the incoming concentration by (1 – percent removed).¹

This means that the final concentration of any given chemical parameter (C_F) can be calculated from the initial concentration (C_I) and the percent removals achieved by n unit processes (R_j for j from 1 to n), as:

$$C_F = C_I \prod_1^n (1 - R_j)$$

The overall removal percentage, R_T is simply calculated as:

$$R_T = 1 - \prod_1^n (1 - R_j) \\ = 1 - C_F / C_I$$

These calculations are only possible because the unit process models were constructed such that they are independent of the order in which they appear, as described above.

3.4.1 NDMA as a Special Case

NDMA is unique among the performance parameters used in this model because unlike the other microbial or chemical parameters, it can be formed as a byproduct of treatment. While it is now well understood that NDMA formation occurs frequently during ozonation of wastewater, recent research has shown that the amount formed varies significantly (Snyder et al., 2012 and

¹ For a given unit process step i , the effluent concentration (C_i) can be calculated given an influent concentration that is the same as the effluent concentration from the previous unit process (C_{i-1}) and a removal percentage of r_i (expressed as a fraction).

$$C_i = C_{i-1} (1 - R_i) = C_{i-2} (1 - R_i)(1 - R_{i-1}) = C_{\text{incoming}} (1 - R_i)(1 - R_{i-1}) \dots (1 - R_1)$$

Dickenson et al., 2013). The current state of research does not provide sufficient quantitative data on the level of formation, and on what conditions it depends. Therefore, the model allows the user to assign three levels of NDMA formation: high (150 ng/L formed), medium (50 ng/L formed), and low (10 ng/L formed).

Including NDMA formation in the calculations for the tool requires re-working the overall formation equation slightly. There are only two cases that must be considered (see Figure 2.3): ozonation as either the first (Advanced 1) or second (Advanced 2) advanced treatment step, as no significant formation of NDMA is expected during ozonation after NF or RO.

The final concentration of NDMA is therefore calculated as follows:

$$C_F = \begin{cases} (C_i(1 - R_{secondary}) + C_{formed})(1 - R_{ADV2})(1 - R_{ADV3})(1 - R_{ADV4})(1 - R_{buffer}) & \text{for } ADV1 = O_3 \\ (C_i(1 - R_{secondary})(1 - R_{ADV1}) + C_{formed})(1 - R_{ADV3})(1 - R_{ADV4})(1 - R_{buffer}) & \text{for } ADV2 = O_3 \\ C_i \prod_1^n (1 - R_j) & \text{for all other cases} \end{cases}$$

where C_{formed} is the concentration formed during ozonation, and all the other parameters are as described above in the general removal equations. Implied in these two special cases is that no NDMA is destroyed during ozonation, so $R_{O3}=0$, and the term associated with the ozonation step (ADV1 in the first case, ADV2 in the second) reduces to a unity multiplier.

3.5 Basis for Unit Cost Models

Unit cost models are developed for each unit process. These unit cost models are constructed such that they take the output of the unit process models based on the user inputs and assign a planning-level cost to each unit process. Unlike the unit process models, some unit cost models are dependent on incoming water quality and therefore require knowledge of the preceding unit process. In addition, *all* unit process costs are dependent on the flow rate at each step, which is often also a function of the prior treatment steps.

Note that unit cost models were developed only for the advanced treatment steps, as this is the focus of the research study. The target audience for this model is the utility manager (or a consultant working for a utility client) that has an existing wastewater treatment facility and is considering advanced treatment for potable reuse. Therefore, the unit process models for secondary treatment are very general and serve to bridge gaps between the data available on the existing process. Cost models for secondary treatment were not included here.

The cost of environmental buffers was also not developed in this tool. This was done for two reasons (1) the focus of this research is primarily on direct potable reuse, in which there is no environmental buffer, and (2) the cost and scope of environmental buffers and their associated conveyance infrastructure varies widely and is very project-specific.

3.5.1 Flow Rate and Recovery Assumptions

The cost of each unit process is most heavily dependent on the flow rate through that process. The user specified the desired flow rate of finished water (Q_{out}).

The flow rate at each unit process Q_i , is defined as the effluent flow rate from that unit process. The cost models are constructed such that each unit cost model depends on the effluent flow rate from that unit process.

Many unit processes do not significantly affect the flow rate through the system, but others, mainly the physical separation processes, have return or reject flows. Table 3.17 lists these unit processes and their assumed recoveries.

Table 3.17 Processes that Affect Total Flow Rate.

Unit Process	Recovery
Biologically Active Filtration ^a	95%
Microfiltration ^a	95%
Ultrafiltration ^a	95%
Nanofiltration	80%
Reverse Osmosis	80%

^a Recoveries assume no treatment and recycling of waste streams such as filter backwash. If waste streams are recycled, recoveries will be higher than indicated.

The total flow rate coming into the treatment process (Q_{in}) therefore relates to the total flow rate out of the treatment process, Q_{out} , as follows:

$$Q_{out} = Q_{in} \prod_1^n r_i$$

where r_i is the recovery of the i^{th} of n unit processes. For example, treating 10 MGD of secondary effluent with full advanced treatment consisting of MF ($r_{MF}=95\%$), RO ($r_{RO}=85\%$), and UV AOP ($r_{AOP}=100\%$) would result in a finished water flow rate $Q_{out} = (10 \text{ MGD})(0.95)(0.85) = 8.1 \text{ MGD}$.

Similarly, the flow rate at any point within the treatment train, Q_j , can be calculated as a truncated version of the same equation:

$$Q_j = Q_{in} \prod_1^j r_i$$

Using the above example, one would calculate the flow rate leaving the MF process and entering the RO process as $Q_{MF} = (10 \text{ MGD})(0.95) = 9.5 \text{ MGD}$.

The model also provides the volume of NF or RO concentrate as an output since this residual stream would need to be handled in some manner (e.g., deep well injection, land evaporation, discharge to an acceptable surface water receiving system), as opposed to recycling to the headworks (or alternate location) within the WWTP or advanced treatment train. The concentrate flow is calculated as the difference between the feed flow to the NF or RO process and the permeate flow.

3.5.2 Unit Process Effluent Characteristics

In order to size the unit treatment processes correctly, some additional information on water quality parameters is needed. Specifically, the sizing of the unit process models in this tool depends on the following water quality parameters:

- ultraviolet transmittance (UVT),
- total organic carbon (TOC),
- initial Cl demand (Cl₂), and
- peroxide dose requirement (H₂O₂).

TOC is tracked as a performance parameter in the model and thus no additional assumptions must be made for it. However, the model must make assumptions with respect to the other three water quality parameter in order to correctly size various unit processes. **Error! Reference source not found.** lists the unit processes and indicates the linkage between processes, water quality parameters, and user inputs.

Table 3.18 Processes that are Dependent on User Inputs and Incoming Water Quality.

Process	Dependent on these Water Quality Parameters:	
	Water Quality	User Input
Chlorination	initial Cl ₂ demand	Ct
Ozonation	TOC	O ₃ :TOC
UV Irradiation	UVT	UV fluence
Peroxide Addition	dose needed for AOP	--

Based on the above and the possible process train combinations shown in Figure 2.3, the effluent quality must be defined for the unit process / water quality parameter pairings listed in Table 3.19, which shows the values of the relevant water quality parameters.

Table 3.19 Effluent Characteristics of Relevant Unit Processes.

Process	Effluent Characteristics ^a			
	UVT (%)	Initial Cl ₂ Demand (mg/L)	Peroxide Dose for AOP (mg/L)	Ozone Demand (mg/L)
Secondary (BOD only)	60	--	--	
Secondary (nitrified/denitrified)	70	5	--	
MBR	70	4	15	
Tertiary Media Filtration	60/70 ^c	5	15	
Biologically Active Filtration ^d	85	2	--	Same as TOC (to achieve O ₃ :TOC = 1) ^h
Microfiltration	65/75 ^c	See note ^e	15	
Ultrafiltration	65/75 ^c	See note ^e	15	
Nanofiltration	90	--	3(UV) ^f	
Reverse Osmosis	95	--	3(UV) ^f	
Ozonation	--	3	--	
UV(AOP)	--	See note ^e		
Total Possible Range	60 - 95	2 –5^g	3-15	

Notes

^a Effluent characteristics are based on project experience where not otherwise referenced. Effluent characteristics are only needed for those processes that potentially precede process steps affected by water quality parameters, per the allowable process combinations shown on Figure 2.3. For process / effluent characteristics pairings that are not needed for the model, "--" is shown.

^c For sand, micro-, and ultrafiltration, the effluent UVT and TOC depend on the upstream secondary process. The higher UVT and lower TOCs are achieved in the fully nitrified effluent.

^d Values shown here represent characteristics of post-ozone engineered biofiltration, as this is the only combination in which engineered biofiltration occurs within the model.

^e For micro-, ultrafiltration, , the effluent initial chlorine demand depends on the upstream processes as follows: CAS (12 mg/L), NAS (4 mg/L), ozonated secondary effluent (3 mg/L), O₃/BAF treated water (2 mg/L).

^f There are two AOP options post-NF and post-RO, UV-based and O₃-based. The peroxide dose needed for post-NF and post-RO UV-based AOP is shown in the table above. For O₃-based AOP, the required dose depends on the ozone concentration. The US EPA Drinking Water Treatability Database (US EPA, 2013) indicates that optimal range for removing most trace organic compounds is an H₂O₂ to O₃ ratio between 0.3 and 0.6. This model assumes H₂O₂ : O₃ = 0.5.

^g Note that the initial Cl₂ demand as shown in this table is not the total Cl₂ dose needed. The values shown in this table must be added to the dose that is required to meet the user-defined Ct.

^h Achieving an O₃:TOC ratio of 1:1 has been demonstrated to break through most of the ozone demand exerted by wastewater effluents, though some additional demand is exerted by nitrite, which is not directly tracked in this tool (Salveson and Fontaine, 2014). The model assumes that any *transferred* ozone dose in excess of the TOC concentration will be available to provide a Ct.

3.5.3 Processes Dependent Only on Flow Rate

The project team recognizes that membrane process flux is influenced by water quality. However, insufficient predictive information exists to model flux as a function of secondary process effluent quality. Thus, many unit processes are modeled only as a function of flow rate (Q) for costing purposes. These include:

- BAF,
- MF,
- UF,
- NF, and
- RO.

General cost curves as a function of flow rate are included for these unit processes (see Section 3.5.5). Some influence of water quality parameters (e.g., solids loading on filters, hardness / scaling potential for high-pressure membranes impacting recovery) might be expected on the total project cost for some of these unit processes, but these are considered second-order effects for the purpose of this tool. Most of the effect of those parameters would likely be seen in the operating costs of those processes (filter backwashing frequency, membrane cleaning and replacement, etc.), which are not considered in this cost model.

3.5.4 Calculating Doses for Disinfection and AOP Processes

The advanced treatment steps not listed in Section 0 are processes that require water quality information to determine the dose of chemical (or UV irradiation) needed to achieve a given result. These processes and their water quality parameter dependencies are described separately below.

Chlorine Dose

The unit process model for chlorination is dependent on a user-defined input of the Ct, which is the product of chlorine concentration and contact time. The cost of a chlorination system, on the other hand, is dependent on the total chlorine dose that must be added. To calculate the latter from the former requires an assumption regarding contact time as well as a means of calculating chlorine concentration from chlorine dose.

The chlorine dose needed (Cl_2^{dose}) is calculated from the initial chlorine demand (Cl_2^{demand}), the chlorine decay expected over the course of the contact time, and the final chlorine concentration:

$$Cl_2^{dose} = Cl_2^{demand} + Cl_2^{decay} + Cl_2^{final}$$

The initial chlorine demand is shown in Table 3.19, the chlorine decay is dependent on the assumed decay rate (r_{decay}) and the contact time (t) the final chlorine concentration must be defined by the user input of Ct and an assumption of contact time:

$$Applied\ Cl_2^{dose} = Cl_2^{demand} + r_{decay}t + \frac{Ct}{t}$$

A contact time of 90 minutes is assumed.

For example, to achieve a Ct of 450 mg/L-min per California Title 22 regulations, if the disinfection follows on ozonation with an initial chlorine demand of 3 mg/L and assuming a chlorine decay rate of 3 mg/Lh (the model default), the approximate total chlorine dose required for this unit process would be:

$$\text{Applied } Cl_2^{\text{dose}} = 3 \frac{\text{mg}}{\text{L}} + \left(\frac{3\text{mg}}{\text{Lh}} \right) (1.5 \text{ h}) + 450 \frac{\text{mg}}{\text{L}} \text{min}/90\text{min} = 12.5 \text{ mg/L}$$

Ozone Dose

Users have two options to input ozone dose. They can either input a O₃:TOC dose, or they can specify a Ct.

For an O₃:TOC input, the ozone dose needed is calculated from the user input of the ozone to TOC ratio (ranges from 0.5 to 1.5), and the incoming TOC as shown in Table 3.11 (ranges from 0.5 mg/L for RO permeate to 20 mg/L for non-nitrified secondary effluent), with an ozone transfer efficiency $\eta = 75\%$, which is representative of the efficiencies achieved in ozone reactors with bubble diffusers. Note that pipeline reactors may be able to achieve transfer efficiencies as high as 90%, but the lower value is chosen to be conservative. The applied ozone dose is calculated as follows:

$$\text{Applied } O_3 \text{ dose} = \frac{(O_3:\text{TOC}) \times \text{TOC}}{\eta}$$

For a Ct input, the initial ozone demand is determined from the incoming TOC as shown in Table 3.19. After an initial rapid attenuation phase based on initial demand (modeled as equal to the TOC concentration), ozone decays in water in a pseudo-first order process with a half-life of approximately 20 minutes (at 20C and a pH=7). To avoid accounting for decay (beyond the initial demand exerted by the effluent) a contact time of maximally 2 minutes is allowed. The same transfer efficiency of 75% is assumed. Thus, the applied ozone dose is calculated as follows:

$$\text{Applied } O_3 \text{ dose} = \frac{\text{TOC} + Ct/t}{\eta}$$

Calculating pathogen log reduction credits require a Ct, and calculating chemical destruction requires an O₃:TOC ratio. Therefore, the two quantities must be “translated” between one another to give the remaining necessary dataset for removal. Setting the applied ozone dose from the two above equations equal to one another:

$$O_3:\text{TOC} = 1 + \frac{Ct/t}{\text{TOC}}$$

and

$$Ct = (O_3:\text{TOC} - 1)(\text{TOC})t$$

Note that in order to have any Ct, one must have O₃:TOC > 1.

UV Irradiation

Users input a desired UV fluence, which is dependent on UVT. The relationship between the two is not a straightforward algebraic expression and is dependent on proprietary UV equipment information. The unit cost table presented in Section 3.5.6 incorporates that information.

Peroxide Dose for UV-Based AOP

The peroxide dose for UV-based AOP is defined in Table 3.19, so no further calculations are necessary.

Peroxide Dose for Ozone-Based AOP

The US EPA Drinking Water Treatability Database (US EPA, 2013) indicates that optimal range for removing most trace organic compounds is an H₂O₂ to O₃ ratio between 0.3 and 0.6. This model assumes H₂O₂:O₃ = 0.5. Addition of H₂O₂ will also reduce bromate formation.

The ozone dose is calculated from the user input of the ozone to TOC ratio (ranges from 0.5 to 1.5), and the incoming TOC (3 mg/L from RO, 5 mg/L from NF). Therefore, the peroxide dose required for ozone-based AOP is calculated as follows:

$$H_2O_2 \text{ dose} = 0.5 (O_3:TOC)(TOC)$$

For example, a post-NF ozone AOP system with user input of O₃:TOC = 1.5 requires a peroxide dose of 0.5 x 1.5 x 5 mg/L = 3.75 mg/L.

3.5.5 Cost Data

Table 3.20 lists the unit cost models for each of the unit processes. For the unit processes listed in Section 0, the cost is modeled as a simple function of a set cost per flow rate. For the chemical oxidation processes, the models are also a function of the respective chemical doses. For UV, the model required application of proprietary sizing information for various reactors models to achieve the cost lookup table shown in Section 3.5.6.

All unit cost models were assembled with respect to 2013 or 2014 equipment cost estimates and/or cost curves and were not updated for Version 2.0. Therefore, costs should be escalated to the present or future estimates outside of this tool.

Table 3.20 Unit Cost Model Summary Table.

Process	Cost Function	Reference
Filtration (Conventional or Bio-)	$\$725,570 \times (\text{flow in mgd})^{0.5862}$	See Figure 3.3
Microfiltration / Ultrafiltration	$\$2,500,000 \times \text{flow in mgd}$	See Table 3.21
Nanofiltration / Reverse Osmosis	$\$3,750,000 \times \text{flow in mgd}$	See Table 3.21
Chlorination	See Table 3.23	
Ozonation	See Table 3.24	
UV Irradiation	See Table 3.22	
Hydrogen Peroxide (for AOP)	See equation in Section 3.5.6	See Figure 3.4

3.5.6 Unit Cost Models

Conventional Filtration

The cost of a biologically active filtration (BAF) system is assumed for the purposes of this study to be well represented by the cost of conventional mixed media filtration. A cost curve for this type of filter is applied for this work, based on a proprietary filter sizing tool used to size and cost filters for real projects across the U.S. This cost curve is shown in Figure 3.3. A power function fit (Project Cost for Filter = $\$725,570 \times (\text{flow in mgd})^{0.5862}$ with $R^2 = 0.996$) appropriately interpolates the cost between the individual cost points, however it should not be used to extrapolate beyond the range shown below.

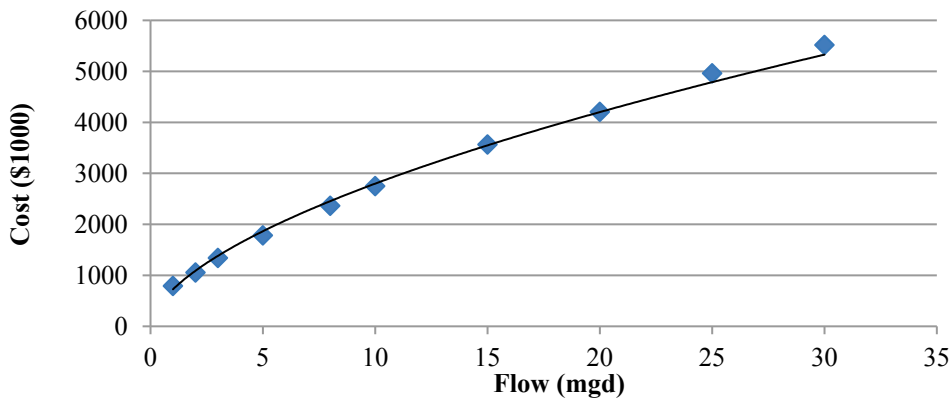


Figure 3.3 Planning-Level Cost Curve for Conventional Filters.

Membrane Filtration and Desalination

The planning-level cost of membrane equipment for water reclamation is based on project experience and is tabulated in Table 3.21. The total project cost is estimated based on these values and a multiplier of 5 to obtain total project cost from equipment costs. This relatively high multiplier is necessary to account for inter-stage pumping, tanks, plumbing, as well as a building over the membrane facility.

Table 3.21 Planning-Level Membrane Equipment Costs.

Unit Process	Cost
Microfiltration or Ultrafiltration	\$500,000 / mgd
Nanofiltration or Reverse Osmosis	\$750,000 / mgd

Note that these costs do not include the disposal of waste streams. This is especially important for high-pressure membrane systems, as concentrate disposal costs can be very expensive and in many cases higher than the treatment costs. **The cost of concentrate disposal was not included as it is very location-specific.**

UV Costs

As with the other unit cost models, the UV cost model is intended as a planning-level tool only. The unit costs provided in Table 3.22 may not be accurate for any given project, especially at the low and high end of the flow/RED spectrum, but given the range of design conditions spanned, the estimates are relatively reasonable.

Assumptions:

- Unit cost models are based on sizing of four different real low pressure high output (LPHO) UV reactor models with proprietary sizing algorithms (two each from ETS, now Neptune-Benson, an Evoqua brand, and WEDECO, a Xylem brand).
- Each "design" includes either one redundant reactor per train, or a redundant train, whichever resulted in fewer total reactors. If the total number of reactors in a train, or the number of trains exceeds 10, an additional redundant reactor per train (or an additional redundant train) is included.
- Equipment costs for the four reactors used were multiplied by a factor of 2.5 to arrive at total project cost for the UV system as a whole.

Table 3.22 Planning-Level Project Cost of UV Systems in \$1000's.

RED (mJ/cm ²)	Flow (mgd)	Feed UVT							
		55%	60%	65%	70%	75%	85%	90%	95%
10	1	\$521	\$521	\$521	\$521	\$521	\$415	\$415	\$415
	3	\$781	\$781	\$781	\$781	\$781	\$415	\$415	\$415
	5	\$781	\$781	\$781	\$781	\$781	\$415	\$415	\$415
	10	\$1,301	\$1,301	\$1,301	\$1,301	\$1,301	\$623	\$623	\$623
	25	\$2,863	\$2,863	\$2,863	\$2,863	\$2,863	\$1,850	\$1,850	\$1,850
20	1	\$521	\$521	\$521	\$521	\$521	\$415	\$415	\$415
	3	\$781	\$781	\$781	\$781	\$781	\$415	\$415	\$415
	5	\$781	\$781	\$781	\$781	\$781	\$623	\$415	\$415
	10	\$1,301	\$1,301	\$1,301	\$1,301	\$1,301	\$830	\$623	\$623
	25	\$3,019	\$2,415	\$1,811	\$1,811	\$1,811	\$1,850	\$1,850	\$1,850
50	1	\$1,041	\$911	\$781	\$651	\$521	\$415	\$415	\$415
	3	\$1,811	\$1,510	\$1,208	\$1,562	\$1,041	\$623	\$623	\$415
	5	\$2,415	\$2,113	\$1,811	\$1,687	\$1,562	\$830	\$623	\$623
	10	\$3,623	\$3,019	\$2,415	\$2,113	\$1,811	\$1,110	\$1,110	\$1,110
	25	\$7,245	\$6,038	\$4,830	\$3,925	\$3,019	\$1,850	\$1,850	\$1,850
100	1	\$1,811	\$1,510	\$1,208	\$995	\$781	\$623	\$415	\$415
	3	\$1,811	\$1,510	\$1,208	\$1,208	\$1,208	\$830	\$623	\$623
	5	\$4,830	\$3,925	\$3,019	\$2,717	\$2,415	\$1,038	\$830	\$830
	10	\$7,245	\$6,038	\$4,830	\$4,227	\$3,623	\$2,220	\$2,220	\$1,110
	25	\$14,490	\$12,075	\$9,660	\$7,849	\$6,038	\$3,700	\$3,700	\$3,700
200	1	\$2,415	\$2,113	\$1,811	\$1,510	\$1,208	\$830	\$623	\$623
	3	\$3,019	\$2,717	\$2,415	\$2,113	\$1,811	\$1,245	\$1,038	\$830
	5	\$8,453	\$7,246	\$6,038	\$5,132	\$4,226	\$1,480	\$1,110	\$1,110
	10	\$16,905	\$13,887	\$10,868	\$9,057	\$7,245	\$2,960	\$2,960	\$2,220
	25	\$33,810	\$28,678	\$23,546	\$18,113	\$12,679	\$5,550	\$5,550	\$3,700
300	1	\$3,623	\$3,019	\$2,415	\$2,113	\$1,811	\$1,038	\$830	\$623
	3	\$4,830	\$4,227	\$3,623	\$3,019	\$2,415	\$1,480	\$1,480	\$1,480
	5	\$12,075	\$10,868	\$9,660	\$7,849	\$6,038	\$1,850	\$1,850	\$1,480
	10	\$21,735	\$19,018	\$16,301	\$12,981	\$9,660	\$3,700	\$3,700	\$2,960
	25	\$51,319	\$43,772	\$36,225	\$28,980	\$21,735	\$7,400	\$7,400	\$5,550
500	1	\$3,623	\$3,019	\$2,415	\$2,113	\$1,811	\$1,453	\$1,038	\$830
	3	\$10,868	\$9,057	\$7,245	\$6,038	\$4,830	\$2,960	\$1,850	\$1,850
	5	\$16,905	\$13,887	\$10,868	\$9,057	\$7,245	\$2,590	\$2,590	\$2,220
	10	\$30,188	\$24,754	\$19,320	\$15,698	\$12,075	\$5,180	\$5,180	\$4,440
	25	\$62,790	\$52,527	\$42,263	\$33,207	\$24,150	\$11,840	\$10,360	\$8,880
800	1	\$5,434	\$4,830	\$4,226	\$3,623	\$3,019	\$1,850	\$1,850	\$1,850
	3	\$19,320	\$16,905	\$14,490	\$10,868	\$7,245	\$4,440	\$4,440	\$2,590
	5	\$27,169	\$23,245	\$19,320	\$15,094	\$10,868	\$6,660	\$5,180	\$5,180
	10	\$50,715	\$43,470	\$36,225	\$27,773	\$19,320	\$11,840	\$8,880	\$8,880
	25	\$108,675	\$90,563	\$72,450	\$57,960	\$43,470	\$18,500	\$14,800	\$13,320
1000	1	\$7,245	\$6,038	\$4,830	\$4,227	\$3,623	\$2,220	\$2,220	\$2,220
	3	\$24,150	\$19,320	\$14,490	\$11,472	\$8,453	\$5,180	\$5,180	\$5,180
	5	\$36,225	\$30,188	\$24,150	\$19,320	\$14,490	\$8,880	\$7,770	\$7,770
	10	\$67,620	\$55,545	\$43,470	\$35,320	\$27,169	\$14,800	\$14,800	\$11,840
	25	\$144,900	\$118,637	\$92,374	\$73,658	\$54,941	\$26,640	\$24,420	\$22,200

Chlorine Costs

As with the other unit cost models, the chlorine cost model is intended as a planning-level tool only. The unit costs provided below may not be accurate for any given project but represent a reasonable planning-level estimate for the purposes of providing costs for an overall treatment train. Costs include only the chemical feed equipment needed to deliver the dose shown. The model assumes that significant additional contact time is available downstream of the chlorine feed point such that a dedicated chlorine contact basin is not necessary. Multipliers are used to account for unspecified items and project overhead.

Table 3.23 Planning-Level Project Cost of Chlorine Dosing Systems in \$1000's.

Flow (mgd)	Applied Chlorine Dose (mg/L)				
	1	5	10	15	25
1	\$600	\$1,400	\$2,000	\$2,000	\$4,000
3	\$1,000	\$3,000	\$4,400	\$4,400	\$5,200
5	\$1,400	\$4,000	\$5,000	\$5,000	\$6,000
10	\$2,000	\$5,000	\$5,400	\$5,400	\$7,000
25	\$4,000	\$6,000	\$7,000	\$7,000	\$8,000

Ozone Costs

Ozone costs include the cost of the ozone generator and reactor, plus multipliers to account for unspecified items and project overhead.

Table 3.24 Planning-Level Project Cost of Ozone Systems in \$1000's.

Flow (mgd)	Applied Ozone Dose (mg/L)					
	1	5	10	15	20	25
1	\$1,000	\$2,000	\$3,000	\$4,000	\$5,300	\$6,700
3	\$2,000	\$4,000	\$6,000	\$8,000	\$10,000	\$13,000
5	\$2,600	\$6,000	\$9,000	\$12,000	\$16,000	\$20,000
10	\$3,500	\$7,500	\$10,500	\$14,000	\$19,000	\$23,000
25	\$4,000	\$9,500	\$13,000	\$17,000	\$23,000	\$28,000

Hydrogen Peroxide Costs

Costs include the chemical dosing equipment only, plus multipliers to account for unspecified items and project overhead, with the assumption that the reactor cost is included in the UV cost and therefore not repeated for the addition of hydrogen peroxide. A logarithmic relationship (Project Cost (\$1,000) = 1,418*ln(Dose(lb/day))-3,831) with R²= 0.9822) appropriately interpolates the cost interpolated between the individual cost points, however it should not be used to extrapolate beyond the range shown below.

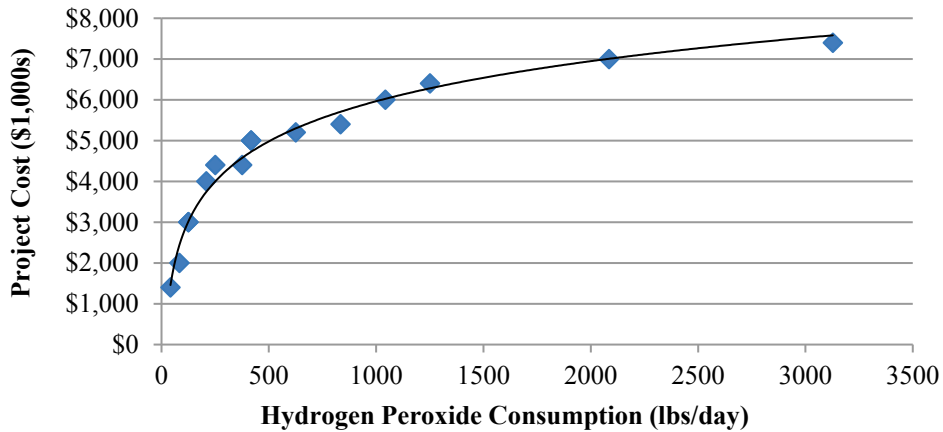


Figure 3.4 Planning-Level Cost Curve for Hydrogen Peroxide Dosing Systems.

4 Summary and Conclusions

The primary purpose of the Integrated Treatment Train Toolbox for Potable Reuse (IT³PR) Version 2.0 Excel tool is to provide a user-friendly means to evaluate advanced treatment processes and trains against one another for application in potable reuse scenarios. As presented in Section 2 of this manual, the IT³PR model allows the User to evaluate the performance and order of magnitude costs of different treatment trains through the following steps:

1. The User provides information on the project under consideration on the Input Tab of the model, including the target produced water capacity, the regulatory paradigm (i.e., California or Texas) under which the project is being evaluated, the target pathogen log/inactivation removal requirements, and the influent and target chemical microconstituent concentrations.
2. Current or planned secondary and tertiary wastewater treatment processes are defined by the User and the model assigns / calculates effluent water quality information based on that selection. The approach for this step differs depending on the regulatory paradigm selected. Information to guide the User through this selection is provided in Section 2 and further explained in Section 3 of this manual.
3. The User then builds up to three different treatment trains for comparison. On the Train Tab, the User selects different treatment processes, inputting process specifications where applicable.

Based on those selections, the model calculates the virus, *Cryptosporidium*, *Giardia*, and bacteria log inactivation /removal (LRV) achieved by individual treatment processes as well as for the full treatment train. The model also calculates the percent removal of the six chemical performance parameters - TOC, nitrate, TOrCs, estrogenicity (EEQ), NDMA, and PFOA+PFOS - for individual treatment processes as well as for the full treatment train. The model output provides visual indicators of whether the designated treatment train meets (default or user-defined) treatment goals for microbial LRVs and chemical water quality. The model also calculates order of magnitude costs based on cost models built into the model for individual treatment processes. The costs are determined based on calculated unit process flows centered on input values for produced water capacity, and modeled process feed water quality driving design specifications for a given process, where applicable. Section 3 of this manual provides details on the model-defined process performance values, which were based on an extensive literature review conducted for WRRF 11-02 and significantly augmented for version 2.0. Section 3 also provides information on the cost data that is incorporated in the model.

The Train Comparison tab provides information contrasting the performance and costs of different user-defined treatment trains. The required influent flow for each train to achieve the specified produced water capacity is listed, along with the quantity of NF or RO concentrate produced for trains that include these processes. The NF and RO concentrate flow is listed to facilitate evaluation of residuals handling considerations that will need to be factored into permitting and budgetary cost opinions depending on the treatment train. Note that costs for residuals handling are not included in the calculated treatment train costs, since the costs vary substantially depending on site-specific discharge options.

Applicability

The IT³PR Version 2.0 is foremost a potable reuse planning tool. It is not intended to supplant source water characterization, pilot testing and design steps that are critical to successful implementation of a potable reuse project. However, we encourage the User to try it out for these and other planning-level applications:

Treatment alternatives evaluations.

- The model can be used to compare IPR and DPR options in terms of advanced treatment required to meet water quality goals depending on the integration of an environmental buffer. The model can also be used to demonstrate at a planning level that a DPR train can provide equivalent pathogen and chemical contaminant removal as IPR by substituting engineered treatment for the treatment achieved by an environmental buffer.
- The model can be used to compare candidate treatment trains and as a tool to shortlist treatment alternatives that meet water quality goals. The applicability of the model for this type of application would be strengthened by incorporation of User-defined influent water quality as well as site-specific treated water goals. Additionally, the User is encouraged to carefully consider some of the information in the Hidden Master tab to assess whether the specified performance values and unit process recoveries correspond to informed site-specific expectations.
- Output from the model can be used to facilitate workshop discussions on treatment alternatives evaluations and cost implications of selecting different treatment trains

Initial regulatory discussions.

- The tool can be used to provide information on expected microbial and chemical removals for different trains to facilitate discussions with state or local agencies on regulatory considerations for various candidate treatment trains. Information on estimated residuals produced help inform initial discussions regarding residuals disposal options.
- The model can also be used to illustrate to regulators that the selected treatment train is expected to meet microbial and chemical requirements for drinking water, with performance simulation derived from extensive literature on chemical and microbial removal provided by selected unit treatment processes. This type of information can be used to facilitate discussion with regulators on expected additional data they will need to see at the next phase of the project, as well as initial expectations the utility should have in terms of monitoring and reporting, depending on the treatment train.

Water balance and residuals permitting assessment.

- Model-generated information on the influent flow required to achieve target produced water capacity can be used to conduct preliminary water balances that would factor into conceptual level design. In contrast, if the reclaimed water available for reuse is limited, the tool can be used to estimate the amount of purified water that could be produced depending on the treatment train.
- Residuals flow information generated from the model can be used to conduct a planning level evaluation of residuals handling options. For example, the residuals flow can be used to estimate the acreage required for land evaporation.

Conceptual level design.

- The model provides various data that can be used to facilitate conceptual level (10%) design of a proposed advanced water treatment plant for a potable reuse project:
 - Sizing information (e.g., feed water flow) to achieve produced water capacity requirements.
 - Conceptual level design criteria for unit processes, e.g., the ozone dose depending on influent TOC and a target O₃:TOC ratio to achieve target performance, or the UV dose to meet target water quality goals.
 - Concentrate flow requiring discharge / handling.
 - Order of magnitude costs. The costs calculated by the model are best used as a comparative feature to understand the cost of one alternative *relative to others calculated by the model*. They were developed with 2012 and 2013 cost data and were not updated for Version 2.0. They should not be used to replace site-specific planning-level cost estimates. Users should consider carefully what is included in the costs calculated by the model and then add in costs for additional components that can drive budgetary cost opinions, including residuals handling and conveyance costs.

In summary, the IT³PR Version 2.0 Excel tool is intended to provide water professionals evaluating potable reuse scenarios with a means to conduct initial planning level evaluations of treatment options and order of magnitude costs.

5 References

- APAI (Alan Plummer Associates, Inc.), 2016. Direct Potable Reuse Resource Document, Final Report for Texas Water Development Board Project No. 1248321508.
- Asano, T. (Ed), 1998. Wastewater Reclamation and Reuse: Water Quality Management Library, Volume 10, CRC Press.
- Asano, T., F. Burton, H Leverenz, R. Tsuchihashi, and G. Tchobanoglous, 2007. *Water Reuse: Issues, Technologies, and Applications (Metcalf & Eddy AECOM)*, McGraw Hill.
- Azadpour-Keeley, A., B. Faulkner, and J. Chen, 2003. Movement and Longevity of Viruses in the Subsurface, USEPA Ground Water Issue Report No. 540S03500
- Bandy, J., 2009. Innovative Treatment Technologies for Reclaimed Water, doctoral dissertation at Duke University
- Baronti, C., R. Curini, G. D'Ascenzo, A. DiCoricia, A. Gentili, and R. Samper, 2000. Monitoring Natural and Synthetic Estrogens at Activated Sludge Sewage Treatment Plants and in a Receiving River Water, Environmental Science and Technology, 34(24), 5059-5066.
- Bradley, P.M., Carr, S.A., Baird, R.B., Chapelle, F.H., 2005. Biodegradation of *N*-nitrosodimethylamine in soil from a water reclamation facility. Bioremediation Journal 9(2), 115–120.
- Burr, M. 2000. Colonization of Biologically Active Filter Media With Pathogens American Water Works Association Research Foundation (AwwaRF, now WateRF) Project 90805 Final Report.
- California Department of Public Health (CDPH), 2010. California Surface Water Treatment Rule Alternative Filtration Technology Summary, CDPH DDDWEM Technical Programs Branch, April 2010.
- California Department of Public Health (CDPH), 2014. Groundwater Replenishment Reuse Regulations, June 2014.
- Carollo, 2013. *City of Phoenix / Subregional Operating Group Salinity Research and Concentrate Minimization Demonstration Study Pilot Testing Report*, by C. He, J. Wang, and G. Carpenter, in press.
- Dickenson, E., 2013, personal communication regarding results of ongoing WateReuse Research Foundation Project No. 11-08, 10 January 2013.
- Drewes, J., P. Fox, M. Reinhard, A. Sarikaya, J. Montgomery-Brown, and A Soellner, 2001. Removal of Organics in Indirect Potable Reuse Systems: A Comparison of Efficiencies of Long-term Soil-Aquifer Treatment (SAT) and Best Available Technologies (BAT),

- Final Report for National centers of Water Treatment Technologies Project No. NCWTT 699-799-005.
- Drewes, J. E., C. Hoppe, and T. Jennings, 2006. Fate and transport of N-nitrosamines under conditions simulating full-scale groundwater recharge operations. Water Environment Research, 78(13):2466-73
- Drewes, J. E., P. Anderson, N. Denslow, A. Olivieri, D. Schlenk, S. Snyder, 2010. *Monitoring Strategies for Chemical of Emerging Concern (CECs) in Recycled Water, Recommendations of a Science Advisory Panel* convened by the California State Water Resources Control Board.
- Drinkwater, M, 2011. *Indirect Potable Reuse (IPR): Reno-Stead WRF Pilot Test Results*, presentation at NDEP Workshop on August 10, 2011.
- Drury, D., Risso, L., Shepherd, B., 2012. Disinfection Capabilities of Membranes as Tertiary Filters, Presented at the 2012 AWWA/AMTA Membrane Technology Conference & Exposition in Glendale AZ.
- EPA, 1986. Design Manual: Municipal Wastewater Disinfection, Office of Research and Development, Water Engineering Research Laboratory, EPA/625/1-86/021, October 1986.
- EPA, 1991. Guidance Manual for Compliance with the Filtration and Disinfection requirements for Public Water Systems using Surface Water Sources, March 1991.
- EPA, 1999. Guidance Manual for Alternative Disinfectants and Oxidants, April 1999.
- EPA, 2008. Ground Water Rule Source Assessment Guidance Manual, Office of Water, EPA 815-R-07-023, July 2008.
- Falás, P., Wick, A., Castronovo, S., Habermacher, J., Ternes, T.A., Joss, A. 2016. Tracing the Limits of Organic Micropollutant Removal in Biological Wastewater Treatment, *Water Research*, 95:240-249.
- Fono, L, Kolodziej, E., Sedlak, D. 2006. Attenuation of Wastewater-Derived Contaminants in an Effluent-Dominated River; Environ. Sci. Technol., 40, 7257–7262
- Francy, D., E. Stelzer, R. Bushon, A. Brady, A. Williston, K Riddell, M. Borchardt, S. Spencer, T Gellner, 2012. Comparative effectiveness of membrane bioreactors, conventional secondary treatment, and chlorine and UV disinfection to remove microorganisms from municipal wastewaters, Water Research, 46, 4164-4178.
- Gerrity, D., Gamage, S., Jones, D., Korshin, G.V., Lee, Y., Pisarenko, A., Trenholm, R.A., von Gunten, U., Wert, E.C., Snyder, S.A. 2012. Development of Surrogate Correlation Models to Predict Trace Organic Contaminant Oxidation and Microbial Inactivation during Ozonation, *Water Research*, 46:19:6257-6272.

- Gleason, J.A., Cooper, K.R., Klotz, J.B., Post, G.B., Van Orden, G., 2016. Health-Based Maximum Contaminant Level Support Document: Perfluorooctanoic Acid (PFOA), Presentation provided on September 22, 2016 by the New Jersey Drinking Water Quality Institute Health Effects Subcommittee: <http://www.nj.gov/dep/watersupply/pdf/pfoa-hb-talk.pdf>.
- Glober, C., Quinones, O., Dickenson, E. 2016. Fate of Perfluoroalkyl Substances in Full- and Pilot-Scale Potable Reuse Facilities, *Proceedings* from AWWA WQTC: Indianapolis, IN.
- Goren, U., A. Aharoni, M. Kummel, R. Messalem, I. Mekmenev, A. Brenner, and V. Gitis, 2008. Role of membrane pore size in tertiary flocculation/adsorption/ultrafiltration of municipal wastewater, *Separation and Purification Technology* 61, 193–203.
- Haas, C.N., Crocket, C.S., Rose, J.B., Gerba, C.P., Fazil, A.M., 1996. Assessing the Risk Posed by Oocysts in Drinking Water, *J. Am. Water Works Assoc.*, 88:9:131-136.
- Hijnen, W., E. Beerendonk, and G. Medema, 2006. Inactivation credit of UV radiation for viruses, bacteria and protozoan (oo)cysts in water: A review, *Water Research* 40: 3-22.
- Hogg, S., Lau-Staggs, R., Uota, D., Salveson, A., Fontaine, N., Swanback, S., Mackey, E., Danielson, R., and Cooper, R. 2012. Demonstration of Filtration and Disinfection Compliance through Soil-Aquifer Treatment. WateReuse Research Foundation Project 10-10, Final Report.
- Kazner, C, T. Wintgens, and P Dillon, Eds., 2012. *Water Reclamation Technologies for Safe Managed Aquifer Recharge*, IWA Publishing, April 15, 2012, ISBN: 9781843393443.
- LeChevalier, M. and Au, K.-K., 2004. Water Treatment and Pathogen Control, IWA Publishing.
- Linden, K., Salveson, A., and J. Thurston, 2012. *Innovative Treatment Technologies for Reclaimed Water*. WateReuse Research Foundation Project 02-009 Final Report
- Lovins III, W.,J. Taylor, and S. Hong, 2002. Micro-organism Rejection by Membrane Systems. *Environmental Engineering Science*, 19(2): 453-465.
- Mansell, J. and J. Drewes, 2004. Fate of Steroidal Hormones During Soil-Aquifer Treatment, *Groundwater Monitoring and Remediation*, 24(2), 94-101.
- Meng, Q. and C. Gerba, P., 1996. Comparative inactivation of enteric adenoviruses, polioviruses, and coliphages by ultraviolet irradiation; *Water Research* 30: 2665-2668.
- Mohseni-Bandpi, A., Elliot, D.J., Zazouli, M.A. 2013. Biological Nitrate Removal Processes from Drinking Water Supply - A Review, *J. Environ. Health Sci. Eng.*, 11:35.
- Mulholland, Patrick J.; Hall, Robert O. Jr; Sobota, Daniel J.; Dodds, Walter K.; Findlay, Stuart E.G.; Grimm, Nancy B.; Hamilton, Stephen K.; McDowell, William H.; O'Brian,

- Jonathan M.; Tank, Jennifer L.; Ashkenas, Linda R.; Cooper, Lee W.; Daham, Clifford N.; Gregory, Stanley V.; Johnson, Sherri L.; Meyer, Judy L.; Peterson, Bruce J.; Poole, Geoffrey C.; Valett, H. Maurice; Webster, Jackson R.; Arango, Clay P.; Beaulieu, Jake J.; Bernot, Melody J.; Burgin, Amy J.; Crenshaw, Chelsea L.; Helton, Ashley M.; Johnson, Laura T.; Niederlehner, B.R.; Potter, Jody D.; Sheibley, Richard W.; Thomas, Suzanne M., 2009. Nitrate removal in stream ecosystems measured by ¹⁵N addition experiments: denitrification. *Limnology and Oceanography*, 54(3), 666-680.
- Plumlee, M. and M. Reinhard, 2007. Photochemical Attenuation of *N*-Nitrosodimethylamine (NDMA) and other Nitrosamines in Surface Water, *Environmental Science and Technology*, 41(17):6170-6176.
- Plumlee M, M. López-Mesas, A. Heidlberger, K. Ishida, and M. Reinhard, 2008. *N*-nitrosodimethylamine (NDMA) removal by reverse osmosis and UV treatment and analysis via LC-MS/MS, *Water Research* 42(1-2): 347-55.
- Qian, Y., Guo, X., Zhang, Y., Peng, Y., Sun, P., Huang, C-H., Niu, J., Zhou, X., Crittenden, J.C., 2016. Perfluorooctanoic Acid Degradation Using UV-Persulfate Process: Modeling of the Degradation and Chlorate Formation, *Environ. Science and Technol.*, 50:2:772-781.
- Qin J.-J., Oo M.H., Wai, M.N., Kekre, K., 2005. TOC removal in reclamation of municipal wastewater by RO, *Separation and Purification Technology*, 46, 125.
- Racz, L. and R. Goel, 2010. Fate and Removal of Estrogens in Municipal Wastewater, *Journal of Environmental Monitoring*, 12:58-70.
- Reardon, R., F. DiGiano, M. Aitken, S. Paranjape, J. Kim, S. Chang, 2005. Membrane Treatment of Secondary Effluent for Subsequent Use, Water Environment Research Foundation Project 01-CTS-6 Final Report.
- Regli, S., Rose, J.B., Haas, C.N., Gerba, C.P., 1991. Modeling the Risk from *Giardia* and Viruses in Drinking Water, *J. Am. Water Works Assoc.*, 83:11:76-84.
- Reungoat, J., Macova, M., Escher, B.I., Carswell, S., Mueller, J.F., Keller, J. 2009. Removal of Micropollutants and Reduction of Biological Activity in a Full Scale Reclamation Plant Using Ozonation and Activated Carbon Biofiltration, *Water Research*, 1-13.
- Rochelle, P., S. Upton, B. Montelone, and K. Woods, 2005, The response of *Cryptosporidium parvum* to UV Light, TRENDS in Parasitology, 21(12): 81-87.
- Rose, J., S. Farrah, V. Harwood, A. Levine, J. Lukasik, P. Menendez, and T. Scott, 2004. Reduction of Pathogens, Indicator Bacteria, and Alternative Indicators by Wastewater Treatment and Reclamation Processes, Final Report for Water Environment Research Foundation Project 00-PUM-2T.

- Schäfer, A.I., Fane, A.G., and Waite, T.D., Eds., 2005, Nanofiltration, Principles and Applications, Elsevier.
- Salveson, A., J. Brown, Z. Zhou, and J. Lopez, 2010. Monitoring for Microconstituents in an Advanced Wastewater Treatment Facility and Modeling Discharge of Reclaimed Water to Surface Canals for Indirect Potable Reuse, WateReuse Research Foundation Project 06-019, Final Report.
- Salveson, A., T. Rauch-Williams, E. Dickenson, J. Drewes, d. Drury, D. McAvoy, and S. Snyder, 2012a. A Proposed Suite of Indicators for Assessing the Efficiency of Secondary Treatment for the Removal of Organic Trace Compounds, Water Environment Research Foundation Project CEC4R08 Final Report.
- Salveson, A. and N. Fontaine, 2014. H₂O Engineering TOrCsOX Ozonation System Validation Report, for WateReuse Research Foundation Project 11-02, April 2014.
- Sedlak, D. and M. Kavanaugh, 2006. Removal and Destruction of NDMA and NDMA Precursors during Wastewater Treatment, Final Report for WateReuse Research Foundation Project 01-002.
- Snyder, S., P. Westerhoff, Y. Yoon, and D. Sedlak, 2003. Pharmaceuticals, Personal Care Products, and Endocrine Disruptors in Water: Implications for the Water Industry. Environmental Engineering Science, 20:449–469.
- Snyder, E., R. Pleus, and S. Snyder, 2005. Pharmaceuticals and EDCs in the US Water Industry— An Update. Journal AWWA, 97(11):32–36.
- Snyder, S., E. Wert, H. Lei, P. Westerhoff, and Y. Yoon. 2007. Removal of EDCs and Pharmaceuticals in Drinking and Reuse Treatment Processes. American Water Works Association Research Foundation (AwwaRF, now WateRF) Project 9188 Final Report.
- Snyder, S.A., G. Korshin, D. Gerrity, and E. Wert, 2012. Use of UV and Fluorescence Spectra as Surrogate Measures for contaminant Oxidation and Disinfection in the Ozone/H₂O₂ Advanced Oxidation Process, WateReuse Research Foundation Project 09-10-01 Final Report.
- Song, Z., Tang, H., Wang, N., Zhu, L., 2013. Reductive Defluorination of Perfluorooctanoic Acid by Hydrated Electrons in a Sulfite-Mediated UV Photochemical System, *J. of Hazardous Materials*, 262:332-338.
- Steinle-Darling, E., M. Zedda, M. Plumlee, H. Ridgway, and M. Reinhard, 2007. Evaluating the Impacts of Membrane Type, Coating, Fouling, Chemical Properties, and Water Chemistry on Reverse Osmosis Rejection of Seven Nitrosoakylamines, including NDMA, Water Research, 41: 3959-3967.

- Steinle-Darling, E., E. Litwiller, and M. Reinhard, 2010. Effects of Sorption on the Rejection of Trace Organic Contaminants during Nanofiltration, Environmental Science and Technology, 44(7): 2592-2598.
- Steinle-Darling, E. Salveson, A., Sutherland, J., Dickenson, E., Hokanson, D., Trussell, R.S., Stanford, B. 2016. Direct Potable Reuse Monitoring: Testing Water Quality in a Municipal Wastewater Effluent Treated to Drinking Water Standards, Final Report to Texas Water Development Board.
- Surampalli, E. and Tyagi, Eds., 2004. Advances in Water and Wastewater Treatment, ASCE Publications, Jan 1, 2004 - Technology & Engineering, page 539.
- Tang, C. S. Fu, A. Robertson, C. Criddle, and J. Leckie, 2006. Use of Reverse Osmosis Membranes to Remove Perfluorooctane Sulfonate (PFOS) from Semiconductor Wastewater, *Environmental Science and Technology*, 40(23), 7343-7349.
- Tang, C-C, N Munakata, S-J Huitric, A Garcia, S Thompson, J. Kuo, 2010. Combining UV and Chlorination for Recycled Water Disinfection, WaterReuse Research Foundation Project 06-015 Final Report.
- Tobiason, J., G. Nabo bidnehndi, A. Torabian, A. Ghadimkhani, and H. Etemadi, 2008. Preozonation and Prechlorination Effects on TOC Removal by Nanofiltration in Water Treatment, *Int. J. Environ. Res* 2 (3) 269-274.
- Trussell, R.R., Salveson, A., Snyder, S., Trussell, R.S., Gerrity, D. 2016. Equivalency of Advanced Treatment Trains for Potable Reuse, Water Environment & Reuse Foundation Project Reuse-11-02-4 Final Report.
- U.S.EPA, 2013. Drinking Water Treatability Database entry on “Ozone + Hydrogen Peroxide” last updated on 5/31/2013 ([link](#)).
- USEPA, 2016. Lifetime Health Advisories and Health Effects Support Documents for Perfluorooctanoic Acid and Perfluorooctane Sulfonate, 81 FR 33250, May 25, 2016.
- Yoo, L. 2016. Effective Monitoring and Removal of Nitrosamines Using RO Membranes, Proceedings, AWWA WQTC, Indianapolis, IN, Nov. 14-16, 2016.
- Zhou, Q., S. McCraven, G. Carcia, M. Casca, T. Johnson, W. Motzer, 2009. Field evidence of biodegradation of N-Nitrosodimethylamine (NDMA) in groundwater with incidental and active recycled water recharge, Water Research, 42:793-805.

Appendix A

Visual Basic Code used by the Texas Commission on Environmental Quality to Calculate Virus and Giardia Log Inactivation for Chlorine and Chloramines

Visual Basic Code used by the Texas Commission on Environmental Quality to Calculate Virus and Giardia Log Inactivation for Chlorine and Chloramines

This appendix contains the Visual Basic for Applications (VBA) functions, or programs, used by the TCEQ to calculate the values of CT_{required} and log-inactivation in their Surface Water Monthly Operational Report (SWMOR) spreadsheets. Only the portions relevant to chlorine and chloramines disinfection were applied to the IT3PR v.2.0; those components of the VBA code are reproduced here.

The description below and the code that follows was provided by the TCEQ.

Giardia and Virus Inactivation

The equations for Giardia and viruses are based on an analysis of the CT Tables contained in 40 CFR §141.74(b)(3) and the EPA's "Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources, March 1991 Edition" (the SWTR Guidance Manual). Because neither of these two sources provided the equations used to generate the values shown in the CT tables, the TCEQ developed some empirical equations that produce results that closely match those in the EPA CT tables. These equations and calculations were submitted to EPA, who reviewed and approved them as part of the TCEQ's primacy package for the first Surface Water Treatment Rule (SWTR).

It should be noted that some of the CT_{required} values for free chlorine that are produced by the TCEQ equations are not identical to the corresponding values shown in the EPA's CT tables. However, most of TCEQ values are within 1% of the EPA values and the maximum difference between the two is about 5%.

Function CT_Giardia(D, log, t, pH, Optional c)

```
' Calculate the CT Required for a given log inactivation of Giardia lamblia.
' D = disinfectant used in the disinfection zone
'   Case 1: Free Chlorine
'   Case 2: Chlorine Dioxide
'   Case NA: Ozone (First)
'           (Disinfection credit for the first zone (cell) where ozone
'           is applied is based only on the ozone concentration and pH
'           level at the end of the zone.)
'   Case 3: Ozone (Later)
'   Case 4: Chloramine
' log = log inactivation required
' T = water temperature at the end of the disinfection zone
' pH = pH of water at the end of the disinfection zone
' C = disinfectant residual concentration at the end of the disinfection zone
'   Required if free chlorine is the disinfectant
'   Optional for other disinfectants

' Validate that C is supplied for Free Chlorine (Case 1).
If D = 1 And IsMissing(c) Then
    CT_Giardia = CVErr(xlErrValue)
    Exit Function
End If

' Validate the input value for D.
If IsEmpty(D) Or Not (D = 1 Or D = 2 Or D = 3 Or D = 4 Or D = 99) Then
    CT_Giardia = CVErr(xlErrNum)
    Exit Function
End If

' Validate the input value for log.
If IsEmpty(log) Or Not log >= 0 Then
    CT_Giardia = CVErr(xlErrNum)
    Exit Function
End If

' Validate the input value for T.
If IsEmpty(t) Then
    CT_Giardia = CVErr(xlErrNum)
    Exit Function
End If

' Validate the input value for pH.
If IsEmpty(pH) Or Not (pH >= 0 And pH <= 14) Then
    CT_Giardia = CVErr(xlErrNum)
    Exit Function

End If
' Validate the input value for C.
```

```
If Not IsMissing(c) Then
  If (D = 1 And IsEmpty(c)) Or Not c >= 0 Then
    CT_Giardia = CVErr(xlErrNum)
    Exit Function
  End If
End If

' Select the routine for Free Chlorine (Case 1).
If D = 1 Then

  ' Restrict T to a minimum of 0.5C.
  If t < 0.5 Then
    t = 0.5
  End If

  ' Restrict C to between 0.4 and 4.0 mg/L.
  If c < 0.4 Then
    c = 0.4
  ElseIf c > 4 Then
    c = 4
  End If

  ' Restrict pH to between 6.0 and 9.0 units.
  If pH < 6 Then
    pH = 6
  ElseIf pH > 9 Then
    CT_Giardia = "NA"
    Exit Function
  End If

  ' Calculate CT_Giardia using the CT functions fit to the CT Tables by the method of least squares.

  ' Select the CT function for T < 5C, developed from the CT Tables at 0.5C and 5C.
  ' CT is assumed to be a linear function of T, a 3rd order polynomial function of pH, and a 2nd order polynomial
function of C.
  ' a1, a2, ..., a11, a12, b1, b2, ..., b11, b12 represent the coefficients.
  If t < 5 Then
    a1 = 2.20458615882522E-02
    a2 = -0.13356398880381
    a3 = 3.61416515404341E-02
    a4 = -0.421536275903192
    a5 = 2.54735789871617
    a6 = -1.4769699386405
    a7 = 2.74573965142833
    a8 = -17.0859074129604
    a9 = 11.3773966198665
    a10 = -6.03759922155278
    a11 = 38.243635110616
    a12 = -31.1142455449685
    B1 = -3.39169605490086E-03
```

b2 = 0.199565956682756
b3 = 1.1101342481704
b4 = -1.30676143474112
b5 = 3.53427320863038
b6 = -13.7296456750459
b7 = 17.9892622133178
b8 = -64.2159942320124
b9 = 94.5224909110151
b10 = -60.8462321743804
b11 = 234.909138076742
b12 = -179.06192867364

CT_Giardia = log / 3 * ((a1 * t + B1) * pH ^ 3 * c ^ 2 + (a2 * t + b2) * pH ^ 3 * c + (a3 * t + b3) * pH ^ 3 + (a4 * t + b4) * pH ^ 2 * c ^ 2 + (a5 * t + b5) * pH ^ 2 * c + (a6 * t + b6) * pH ^ 2 + (a7 * t + b7) * pH * c ^ 2 + (a8 * t + b8) * pH * c + (a9 * t + b9) * pH + (a10 * t + b10) * c ^ 2 + (a11 * t + b11) * c + (a12 * t + b12))

' Select the CT function for T >= 5C, developed from the CT Table at 5C.

' CT is assumed to be an exponential function of T where CT is halved for each 10C increment, a 3rd order polynomial function of pH, and a 2nd order polynomial function of C.

' b, a1, a2, ..., a11, a12 represent the coefficients.

Else

b = -6.93147180559945E-02
a1 = 0.151091243475099
a2 = -0.662211276295901
a3 = 1.82552705197187
a4 = -4.82875232358584
a5 = 23.0107606342222
a6 = -29.8604073668406
a7 = 44.8559772206124
a8 = -211.630762887835
a9 = 214.125343939493
a10 = -128.741858325607
a11 = 602.635082651133
a12 = -473.242778464651

CT_Giardia = log / 3 * Exp(b * t) * (a1 * pH ^ 3 * c ^ 2 + a2 * pH ^ 3 * c + a3 * pH ^ 3 + a4 * pH ^ 2 * c ^ 2 + a5 * pH ^ 2 * c + a6 * pH ^ 2 + a7 * pH * c ^ 2 + a8 * pH * c + a9 * pH + a10 * c ^ 2 + a11 * c + a12)

End If

' Select the routine for Chlorine Dioxide (Case 2).

Elseif D = 2 Then

' Restrict T to between 1 and 25 degrees C.

If t < 1 Then

t = 1

Elseif t > 25 Then

t = 25

End If


```
' Restrict pH to between 6.0 and 9.5 units.
If pH < 6 Then
  CT_Giardia = "NA"
  Exit Function
Elseif pH >= 9.5 Then
  CT_Giardia = "NA"
  Exit Function
End If

' Calculate CT_Giardia for T < 5C using linear interpolation between the CT values at 1C and 5C.
If t < 5 Then
  CT_Giardia = log / 3 * (62.775 - (62.775 - 26.55) / (5 - 1) * (t - 1))

' Calculate CT_Giardia for T >= 5C using the CT function fit to the CT values at 5C, 15C, and 25C by the method of
least squares linear regression.
Else
  CT_Giardia = log / 3 * (-0.79875 * t + 30.73125)

End If

' Select the routine for Ozone (First) (Case NA)
' This routine was not necessary because the disinfection credit for the
' first zone (the contactor cell where ozone is first applied) will be
' either 0.5-log or 0.0-log based on whether C >= 0.3 mg/L. Consequently,
' the calculations are incorporated directly into the SWMOR spreadsheet.
Elseif D = 99 Then

  ' Restrict pH to between 5.5 and 9.5 units.
  If pH < 5.5 Or pH >= 9.5 Then
    CT_Giardia = "NA"
    Exit Function

  ' If 5.5 < pH < 9.5, show CT_Giardia as "NA O3 Cell 1".
  Elseif pH >= 5.5 And pH < 9.5 Then
    CT_Giardia = "NA; O3 Cell 1"

  End If

' Select the routine for Ozone (Later) (Case 3).
Elseif D = 3 Then
  ' Restrict T to a minimum of 1C.
  If t < 1 Then
    t = 1
  End If

  ' Restrict pH to between 5.5 and 9.5 units.
  If pH < 5.5 Then
    CT_Giardia = "NA"
    Exit Function
  Elseif pH >= 9.5 Then
```

```
CT_Giardia = "NA"
Exit Function
End If

' Calculate CT_Giardia for T < 5C using linear interpolation between the CT values at 1C and 5C.
If t < 5 Then
  CT_Giardia = log / 3 * (2.88 - (2.88 - 1.92) / (5 - 1) * (t - 1))

' Calculate CT_Giardia for T >= 5C using the CT function developed from the CT value at 5C.
' CT is assumed to be an exponential function of T where CT is halved for each 10C increment.
Else
  CT_Giardia = log / 3 * 2.71529003975634 * Exp(-6.93147180559945E-02 * t)

End If

' Select the routine for Chloramine (Case 4).
Elseif D = 4 Then

' Restrict T to between 1 and 25 degrees C.
If t < 1 Then
  t = 1
Elseif t > 25 Then
  t = 25
End If

' Restrict pH to between 5.5 and 9.5 units.
If pH < 5.5 Then
  CT_Giardia = "NA"
  Exit Function
Elseif pH >= 9.5 Then
  CT_Giardia = "NA"
  Exit Function
End If

' Calculate CT_Giardia for T < 5C using linear interpolation between the CT values at 1C and 5C.
If t < 5 Then
  CT_Giardia = log / 3 * (3750 - (3750 - 2145) / (5 - 1) * (t - 1))

' Calculate CT_Giardia for T >= 5C using the CT function developed from the CT values at 5C and 15C.
' CT is assumed to be a linear function of T.
Else
  CT_Giardia = log / 3 * (-69 * t + 2490)

End If

End If

End Function
```

Function CT_Virus(D, log, t, pH)

```
' Calculate the CT Required for a given log inactivation of viruses.
' D = disinfectant used in the disinfection zone
'   Case 1: Free Chlorine
'   Case 2: Chlorine Dioxide
'   Case NA: Ozone (First)
'           (Disinfection credit for the first zone (cell) where ozone
'             is applied is based only on the ozone concentration and pH
'             level at the end of the zone.)
'   Case 3: Ozone (Later)
'   Case 4: Chloramine
' log = log inactivation required
' T = water temperature at the end of the disinfection zone
' pH = pH of water at the end of the disinfection zone

' Validate the input value for D.
If IsEmpty(D) Or Not (D = 1 Or D = 2 Or D = 3 Or D = 4 Or D = 99) Then
    CT_Virus = CVErr(xlErrNum)
    Exit Function
End If

' Validate the input value for log.
If IsEmpty(log) Or Not log >= 0 Then
    CT_Virus = CVErr(xlErrNum)
    Exit Function
End If

' Validate the input value for T.
If IsEmpty(t) Then
    CT_Virus = CVErr(xlErrNum)
    Exit Function
End If

' Validate the input value for pH.
If IsEmpty(pH) Or Not (pH >= 0 And pH <= 14) Then
    CT_Virus = CVErr(xlErrNum)
    Exit Function
End If

' Select the routine for Free Chlorine (Case 1).
If D = 1 Then

    ' Restrict T to a minimum of 0.5C.
    If t < 0.5 Then
        t = 0.5
    End If

    ' Restrict pH to less than 10.5 units.
    If pH >= 10.5 Then
```

```
CT_Virus = "NA"  
Exit Function  
End If
```

' Calculate CT_Virus for T < 5C using linear interpolation between the CT values at 0.5C and 5C.

```
If t < 5 Then  
  If pH < 9.5 Then  
    CT_Virus = log / 4 * (11.475 - (11.475 - 7.65) / (5 - 0.5) * (t - 0.5))  
  Else  
    CT_Virus = log / 4 * (86.85 - (86.85 - 57.9) / (5 - 0.5) * (t - 0.5))  
  End If
```

' Calculate CT_Virus for T >= 5C using the CT function developed from the CT value at 5C.

' CT is assumed to be an exponential function of T where CT is halved for each 10C increment.

```
Else  
  If pH < 9.5 Then  
    CT_Virus = log / 4 * 10.8187337521542 * Exp(-6.93147180559946E-02 * t)  
  Else  
    CT_Virus = log / 4 * 81.8829652614024 * Exp(-6.93147180559946E-02 * t)  
  End If
```

```
End If
```

' Select the routine for Chlorine Dioxide (Case 2).

```
Elseif D = 2 Then
```

' Restrict T to a minimum of 1C.

```
If t < 1 Then  
  t = 1  
End If
```

' Restrict pH to between 6.0 and 9.5 units.

```
If pH < 6 Then  
  CT_Virus = "NA"  
  Exit Function  
Elseif pH >= 9.5 Then  
  CT_Virus = "NA"  
  Exit Function  
End If
```

' Calculate CT_Virus using the CT functions fit to the CT Table by the method of least squares.

' Select the CT function for T < 5C, developed from the CT values at 0.5C and 5C.

' CT is assumed to be a power function of log, and a linear function of T.

```
If t < 5 Then  
  CT_Virus = log ^ 2.5888984295084 * (-0.118847145326634 * t + 1.54501288924624)
```

' Select the CT function for T >= 5C, developed from the CT values at 5C.

Texas Water Development Board Contract # 1348321632

' CT is assumed to be a power function of log, and an exponential function of T where CT is halved for each 10C increment.

Else

$$CT_Virus = \log ^ 2.5888984295084 * 1.344601958162 * \text{Exp}(-6.93147180559945E-02 * t)$$

End If

Function Log_Giardia(D, log, t, pH, c, T10)

```
' Calculate the number of log inactivations for Giardia lamblia.
' D = disinfectant used in the disinfection zone
'   Case 1: Free Chlorine
'   Case 2: Chlorine Dioxide
'   Case NA: Ozone (First)
'           (Disinfection credit for the first zone (cell) where ozone
'             is applied is based only on the ozone concentration and pH
'             level at the end of the zone.)
'   Case 3: Ozone (Later)
'   Case 4: Chloramine
' log = log inactivation required
' T = water temperature at the end of the disinfection zone
' pH = pH of water at the end of the disinfection zone
' C = disinfectant residual concentration at the end of the disinfection zone
' T10 = contact time, or T10, for the disinfection zone

' Validate the input value for D.
If IsEmpty(D) Or Not (D = 1 Or D = 2 Or D = 3 Or D = 4 Or D = 99) Then
    Log_Giardia = CVErr(xlErrNum)
    Exit Function
End If

' Validate the input value for log.
If IsEmpty(log) Or Not log >= 0 Then
    Log_Giardia = CVErr(xlErrNum)
    Exit Function
End If

' Validate the input value for T.
If IsEmpty(t) Then
    Log_Giardia = CVErr(xlErrNum)
    Exit Function
End If

' Validate the input value for pH.
If IsEmpty(pH) Or Not (pH >= 0 And pH <= 14) Then
    Log_Giardia = CVErr(xlErrNum)
    Exit Function
End If

' Validate the input value for C.
If IsEmpty(c) Or Not c >= 0 Then
    Log_Giardia = CVErr(xlErrNum)
    Exit Function
End If

' Validate the input value for T10.
If IsEmpty(T10) Or Not T10 >= 0 Then
```

```
Log_Giardia = CVErr(xlErrNum)
Exit Function
End If
' Calculate the Actual CT achieved.
Actual_CT = c * T10

' Calculate the CT Required to achieve the given log inactivation of Giardia lamblia, or a 1-log inactivation if the log
inactivation required is zero.
If (log = 0 And (D = 1 Or D = 2 Or D = 3 Or D = 4)) Then
    CT_Required = CT_Giardia(D, 1, t, pH, c)
Elseif (log = 0 And D = 99) Then
    CT_Required = "NA-O3 Cell 1"
Else
    CT_Required = CT_Giardia(D, log, t, pH, c)
End If

' Calculate Log_Giardia.
If CT_Required = "NA" Then
    Log_Giardia = 0
Elseif (log = 0 And (D = 1 Or D = 2 Or D = 3 Or D = 4)) Then
    Log_Giardia = Actual_CT / CT_Required
Elseif (D = 99 And c >= 0.3) Then
    Log_Giardia = 0.5
Elseif (D = 99 And c <= 0.3) Then
    Log_Giardia = 0#
Else
    Log_Giardia = Actual_CT / CT_Required * log
End If

End Function
```

Function Log_Virus(D, log, t, pH, c, T10)

```
' Calculate the number of log inactivations for viruses.
' D = disinfectant used in the disinfection zone
'   Case 1: Free Chlorine
'   Case 2: Chlorine Dioxide
'   Case NA: Ozone (First)
'           (Disinfection credit for the first zone (cell) where ozone
'           is applied is based only on the ozone concentration and pH
'           level at the end of the zone.)
'   Case 3: Ozone (Later)
'   Case 4: Chloramine
' log = log inactivation required
' T = water temperature at the end of the disinfection zone
' pH = pH of water at the end of the disinfection zone
' C = disinfectant residual concentration at the end of the disinfection zone
' T10 = contact time, or T10, for the disinfection zone

' Validate the input value for D.
If IsEmpty(D) Or Not (D = 1 Or D = 2 Or D = 3 Or D = 4 Or D = 99) Then
    Log_Virus = CVErr(xlErrNum)
    Exit Function
End If

' Validate the input value for log.
If IsEmpty(log) Or Not log >= 0 Then
    Log_Virus = CVErr(xlErrNum)
    Exit Function
End If

' Validate the input value for T.
If IsEmpty(t) Then
    Log_Virus = CVErr(xlErrNum)
    Exit Function
End If

' Validate the input value for pH.
If IsEmpty(pH) Or Not (pH >= 0 And pH <= 14) Then
    Log_Virus = CVErr(xlErrNum)
    Exit Function
End If

' Validate the input value for C.
If IsEmpty(c) Or Not c >= 0 Then
    Log_Virus = CVErr(xlErrNum)
    Exit Function
End If

' Validate the input value for T10.
```



```
If IsEmpty(T10) Or Not T10 >= 0 Then
  Log_Virus = CVErr(xlErrNum)
  Exit Function
End If
```

```
' Calculate the Actual CT achieved.
Actual_CT = c * T10
```

```
' Calculate the CT Required to achieve the given log inactivation of viruses, or a 1-log inactivation if the log inactivation required is zero.
```

```
If (log = 0 And (D = 1 Or D = 2 Or D = 3 Or D = 4)) Then
  CT_Required = CT_Virus(D, 1, t, pH)
Elseif D = 99 Then
  CT_Required = "NA-O3 Cell 1"
Else
  CT_Required = CT_Virus(D, log, t, pH)
End If
```

```
' Calculate Log_Virus.
```

```
If CT_Required = "NA" Then
  Log_Virus = 0
Elseif (log = 0 And (D = 1 Or D = 2 Or D = 3 Or D = 4)) Then
  Log_Virus = Actual_CT / CT_Required
Elseif D = 99 And c >= 0.1 Then
  Log_Virus = 1#
Elseif D = 99 And c < 0.1 Then
  Log_Virus = 0#
Else
  Log_Virus = Actual_CT / CT_Required * log
End If
```

```
End Function
```