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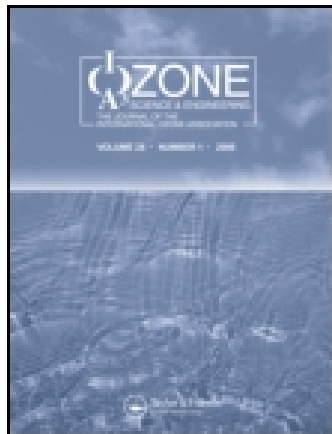
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Costs of Advanced Treatment in Water Reclamation

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The additional removal of trace organic contaminants (TOrcs) provided by advanced water and wastewater treatment inevitably requires additional financial costs, which must be estimated to support utility planning and compare alternatives. This study presents conceptual-level (Class 4) capital and annual operations and maintenance (O&M) cost curve equations to aid evaluations of advanced treatment trains for water reuse. The cost curve equations are broadly applicable to the water reuse community, particularly those interested in ozone-based treatment trains. Unit processes include microfiltration or ultrafiltration membranes (MF/UF), nanofiltration or reverse osmosis membranes (NF/RO), ozone (with or without hydrogen peroxide, H₂O₂), ultraviolet (UV) treatment with H₂O₂ (UV/H₂O₂), and biological activated carbon (BAC); all cost curves are for a unit process and can be added together to obtain costs for a combined treatment train. The cost curves indicate that at all plant capacities (1 to 500 MGD), membrane treatment (e.g., MF or RO) represents the highest cost unit process, ozone the least, and BAC or UV/H₂O₂ fall in between. Additionally, the relationship between ozone dose and TOrc removal is discussed with a demonstration of how costs change with increasing ozone dose to achieve desired TOrc destruction.

Keywords Ozone, Advanced Treatment Costs, Membranes, Trace Organic Contaminants, Water Reuse

INTRODUCTION

Trace concentrations of organic pollutants are detectable in water and wastewater due to the availability of extremely sensitive analytical methods. These trace organic contaminants

(TOrcs), including pharmaceuticals and personal care products (PPCPs) and endocrine disrupting compounds (EDCs), are of interest because of potential human health effects, demonstrated impacts on aquatic ecosystems, and increased public awareness (Benotti et al. 2009; Debroux et al. 2012; Snyder et al. 2003).

Domestic wastewater is considered the primary source of PPCPs and EDCs to the environment. They are released to wastewater during manufacturing, excretion from personal use, and disposal of unused quantities (Daughton and Ternes 1999; Hollender et al. 2009). Although wastewater is treated at municipal wastewater treatment plants (WWTPs) prior to discharge to waterways, conventional treatment trains were not designed to remove TOrcs. Wastewater-derived TOrcs therefore occur in the aquatic environment, in downstream sources of drinking water, and in (waste)water that is treated for reuse and recycling (water reclamation).

Expansion and optimization of wastewater treatment may be the most efficient strategy for minimizing the occurrence of TOrcs (Snyder et al. 2014). Multiple studies have evaluated treatment processes for their ability to remove or destroy TOrcs in drinking water and wastewater, including biological treatment (e.g., activated sludge), physicochemical treatment (e.g., media or membrane filtration), conventional oxidation (e.g., chlorine and ozone), and advanced oxidation processes (AOP) (Huber et al. 2003; Kim et al. 2007; Snyder et al. 2006, 2007; Ternes et al. 2002; Westerhoff et al. 2005). High pressure membrane filtration (e.g., reverse osmosis, nanofiltration) and AOP (e.g., UV/hydrogen peroxide [H₂O₂], ozone, ozone/H₂O₂) are considered effective alternatives for the removal of TOrcs from water or wastewater, each unit process having its own advantages and disadvantages and pretreatment requirements. Membrane and AOP technologies, here referred to as “advanced treatment,” may be added alone or together to conventional wastewater treatment as part of a treatment train for water reclamation in applications such as potable reuse.

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The additional pollutant removal provided by advanced treatment inevitably requires additional financial costs and energy consumption (Jones et al. 2007). Accurate estimates of capital costs and operations and maintenance (O&M) costs prior to construction are required for water/wastewater utilities to compare alternatives during feasibility and planning studies. Limited general information on unit process costs for advanced treatment is available in the literature (Friedler and Pisanty 2006) (e.g., USBR 2003). Planning cost estimates are typically developed by engineers using site specific conditions (like plant size) and information from vendors, past projects, and engineering experience. Individual estimates for unit process costs can vary greatly depending on assumptions made and cost items that are included or omitted depending on the level of effort and interests of the engineer or manufacturer performing the estimate (Smith 1968), and therefore synthesizing information from multiple sources is preferable.

Conceptual-level (Class 4) engineering cost estimates defined according to the American Association of Cost Estimating (AACE) are considered planning-level or order-of-magnitude costs. They provide reasonable accuracy to within -30% and $+50\%$ of actual costs and can be estimated when $\leq 1\%$ of design is completed, which is appropriate for planning and feasibility evaluations.

The objective of this study was to prepare conceptual-level capital and O&M cost curves for select advanced treatment unit processes to allow cost estimates on a per unit flow basis over a range of plant flow capacities. Unit processes included microfiltration or ultrafiltration membranes (MF/UF), nanofiltration or reverse osmosis membranes (NF/RO), ozone (with or without H_2O_2), UV with H_2O_2 (UV/ H_2O_2), and biological activated carbon (BAC). The end result is a set of formulas that the reader can use to estimate costs for their own combination of advanced unit processes for a specific flow capacity, to be added to the user's own estimate of costs for conventional treatment.

This cost evaluation was completed as part of a larger technical study of the use of ozone in water reclamation for contaminant oxidation (refer to Snyder et al. 2014). The present study developed costs for advanced treatment technologies to facilitate comparison with ozone. All costs are presented as cost curves in terms of unit cost (\$/MGD, or million US dollars per million gallons per day of treated flow) versus plant flow capacity (MGD).

METHODS

Unit Processes Selected for Cost Estimates

Cost curves were developed for the advanced treatment options listed above, selected because these technologies are generally accepted for use in water reclamation for TORCs mitigation. Costs associated with conventional wastewater treatment (primary, secondary, and tertiary) were not included in the scope of this study, and must be added if total treatment costs are desired. Depending on the treatment objectives

and size/capacity of a given facility, the individual (unit process) costs for selected advanced treatment steps may be summed to obtain an estimated cost for advanced treatment, for both capital and O&M costs. For example, if UV/ H_2O_2 is selected as the preferred AOP technology for contaminant oxidation, the treatment train may contain low- and high-pressure membranes prior to the UV/ H_2O_2 (e.g., MF followed by RO). A per gallon-treated cost estimate can be determined by adding the cost per gallon for each unit process at a given design capacity (reported in MGD).

Cost Estimation Approach

The cost estimation approach allows readers to choose one or more unit processes that achieve the water quality goals of their preliminary designs, i.e., TORCs mitigation, and compare the collective capital and O&M Class 4 estimated costs. Capital and O&M cost curves for each unit process were based on literature, past project experience, and vendor quotes. The following sections provide more details for each unit process. The cost curves and associated equations are presented in the results, with individual cost items tabulated in the Supplemental Material (SM) for each unit process.

All costs were prepared in 2011 dollars, with historical costs adjusted to the September 2011 *Engineering News-Record* (ENR) Construction Costs Index (CCI) 9116 (ENR 2011). The ENR CCI should be referenced for the preparation of conceptual costs in future years.

For capital cost estimates, estimated costs for installation, yard piping, landscaping, electrical and control construction, and engineering, legal, and administrative costs were derived from the *Cost Estimating Manual for Water Treatment Facilities* (McGivney and Kawamura 2008). Installation cost (assumed to be 30% of equipment costs), contractor overhead and profit (OH&P; 15%), and contingency (30%) were included in the capital costs. The capital costs do not include unique site considerations, access to the site, additional backup power, ancillary process steps, or treated water storage. O&M costs were based on estimated energy use, replacement part costs, and chemical usage, and depend on the system size and, for ozone, the estimated dose for the desired level of treatment. Labor is included in O&M cost estimates if it represents a significant portion. Electrical costs were adjusted to \$0.0988/kWh for 2011, which was based on the average retail price for all customer classes in 2010 (\$0.0983/kWh) according to the U.S. Energy Information Administration (USEIA 2010). For future years or project locations where higher energy costs are deemed significant, the power costs for each unit treatment process in the present study (see the Supplemental Material) can be proportionally increased to adjust the O&M cost curve equation.

The cost curves, which present the unit cost (\$/MGD) of treated flow versus plant flow capacity (MGD), were developed for systems from 1 to 80 MGD in size, though in some cases vendor data allowed the development of a wider range of capacities. In most cases, the cost estimates tend to flatten

significantly beyond 80 MGD, whereas below 10 MGD the cost curves can be quite steep.

In all cases, a curve-fitting technique was implemented to develop a cost equation for each unit process that can be used to estimate conceptual-level capital or O&M costs for a specific facility capacity. A power function curve of the form $y = ax^b$ provided the highest correlation, where y is the unit capital or O&M cost (\$/MGD) and x is the plant capacity (MGD), and a and b are empirical constants.

Ozone Cost Estimate

Ozone capital costs were based on data provided by a reputable vendor and were limited to projects designed or built within the past 3 years. The vendor provided costs for facilities ranging from 10 MGD to more than 500 MGD and specified the ozone system size in pounds per day of production. Facility costs for flows less than 10 MGD were not available because of the steep rise in cost for smaller systems.

In developing a baseline ozone dose for the cost estimate, we assumed a representative total organic carbon (TOC) in the unit process influent of 6 mg/L and a target O_3 :TOC ratio of 0.5, leading to an assumed applied ozone dose of 3 mg/L. As indicated by Snyder et al. (2014; ENR 2011), an O_3 :TOC ratio of 0.5 is quite effective in destroying a wide range of TORCs and achieving significant microbial inactivation. However, some applications will require lower or higher ozone doses, depending on the water quality and treatment objectives. The cost estimation method for ozone doses other than 3 mg/L is described later in the results. With respect to position in a treatment train, the ozone cost estimate is sized for pre-RO applications (i.e., assumes a non-RO treated water quality).

Table S-1 in the Supplemental Material presents the capital costs associated with the physical structures for the contactors. In developing these costs, it was assumed that the design would provide a hydraulic residence time (HRT) of 5 min. In water reclamation applications, the high level of effluent organic matter (EfOM) imparts a high ozone demand, which results in rapid loss of ozone residual. Typical contactor designs for drinking water applications, which may have contact times of 10 to 20 min, would often be excessive for water reclamation applications. Therefore, the 5-min HRT used for this cost estimate would generally be sufficient to allow complete ozone decay, assuming O_3 :TOC ratios less than 1.0. Table S-2 shows the vendor data for the equipment used in the cost curve development, which includes ozone generators, a liquid oxygen (LOX) system (but not LOX consumable costs), a supplemental nitrogen system, ozone injection or diffusers, ozone destruct units, monitors, and the overall control system. Redundant ozone generators were not included in the cost estimates.

The estimate assumes there is at least one contactor for each ozone generator. The contactors were designed to have a depth of 24 ft with 19 ft of submergence and 5 ft of freeboard. Each contactor had between 2 and 10 cells, with a length

of 4 ft/cell. The number of contactors for a capacity below 100 MGD was kept at one per generator, whereas the number of cells was adjusted to maintain a reasonable width (assumed to be less than 25 ft). For the larger systems, the number of contactors as well as the number of cells within each contactor was increased to maintain a reasonable contactor volume and width.

Table S-3 provides the total estimated capital costs including installation; yard piping; landscaping; electrical and control construction; and engineering, legal, and administrative costs.

For O&M, vendor-supplied costs for systems ranging from 10 to 535 MGD were limited to energy consumption associated with ozone generation and destruction (see Table S-4) and did not include maintenance or oxygen delivery or production (which may consist of a LOX, ambient air, or vacuum/pressure swing adsorption (VPSA) system). Maintenance costs and additional staff time were assumed to be minimal relative to the total energy costs. Ambient air, LOX, and VPSA will increase the unit energy cost beyond what is described herein and should be considered on a system-specific basis. Energy consumption (or energy equivalent consumption) for each type of oxygen delivery system will vary widely based on daily operating conditions, oxygen utilization efficiency, and system capacity. Detailed guidance on the costs associated with VPSA and LOX can be found in Chang et al. (2008). Even without inclusion of the maintenance and oxygen production or delivery costs, the energy costs per pound of ozone and per unit volume of treated water are still within the range reported by Chang et al. (2008).

In applications where H_2O_2 addition is warranted (e.g., reductions in contactor size or bromate mitigation), the preceding O&M costs can be adjusted to include chemical addition using a cost equation provided in the results. The modified estimate assumes that the impact of H_2O_2 addition on capital costs is insignificant for a Class 4 cost curve, and therefore only O&M costs are increased. The O&M cost estimate is based on a conservative molar H_2O_2 : O_3 ratio of 1.0. Based on an ozone dose of 3 mg/L, this leads to a target H_2O_2 dose of approximately 2 mg/L. The H_2O_2 and quenching costs were based on vendor-supplied data for UV/ H_2O_2 systems, described in the next section. The estimates were adjusted in a linear fashion to account for the different doses in the ozone/ H_2O_2 (2 mg/L) and UV/ H_2O_2 (3 mg/L) systems. The annual O&M costs for ozone/ H_2O_2 are summarized in Table S-5.

UV/ H_2O_2 Cost Estimate

Capital costs for UV/ H_2O_2 were developed from equipment cost curves provided by two major vendors. The cost curves were based on system capacities ranging from approximately 1 to 80 MGD for the first vendor and 10 to 80 MGD for the second vendor. Cost curves from a third, smaller vendor were approximately three times greater and were excluded. The systems were sized by the vendor assuming a

target 1.2-log (94%) removal of NDMA and 0.5-log (68%) removal of 1,4-dioxane per the 2008 California Department of Public Health (CDPH) Draft Groundwater Recharge Reuse Regulations (CDPH 2008). Actual system size and water quality objectives will vary by location. With changes to the 2008 Draft Regulations in 2011 (CDPH 2011), the level of required treatment remains similar. To validate their AOP, utilities can elect to satisfy the original 0.5-log reduction in 1,4-dioxane as an alternative to demonstrating specified levels of reduction for a suite of TOrCs.

Table S-6 presents the UV/H₂O₂ capital costs, including the vendor-provided equipment costs, supplemented with additional costs related to yard piping; landscaping; electrical and control construction; and engineering, legal, and administration costs.

O&M costs for UV/H₂O₂ (Table S-7) were developed from cost curves provided by the same three major vendors and include equipment replacement, energy consumption, and chemical costs. Labor is anticipated to be minimal relative to these other O&M costs and was not included. The cost curves were based on system capacities ranging from approximately 1 to 80 MGD for the first vendor and 10 to 80 MGD for the other two vendors. The O&M cost curve (see results) represents the mean of the three vendor estimates, which were fairly similar (within 20%). One vendor provided detailed costs broken down by chemicals, power, and lamp replacement (see Table S-7).

The selection of UV and H₂O₂ doses will influence the O&M costs for energy and chemicals and will vary significantly depending on the treatment application (e.g., disinfection versus chemical oxidation), source water quality, and product water quality criteria. In this case, vendors provided O&M cost estimates assuming chemical oxidation to meet water quality criteria for 1.2-log removal of NDMA and 0.5-log removal of 1,4-dioxane. The UV dose was not provided by all vendors and was selected as needed to satisfy the specific NDMA and 1,4-dioxane removal criteria. UV doses required to oxidize organic compounds are greater than typical UV doses used for disinfection only (i.e., 40 mJ/cm²) (Snyder et al. 2007). The assumed H₂O₂ dose for the AOP was in the range of 2.5 to 3.5 mg/L. The source water was assumed to be RO-treated (earlier in the treatment train), resulting in a high UV transmittance compared to non-RO-treated waters. Here we conservatively assumed a 95% transmittance for the RO-treated water (Esposito et al. 2007; Swaim et al. 2009). If post-RO water contains atypically high levels of NDMA or 1,4-dioxane, if the hydroxyl radical scavenging capacity is high, or if the UV transmittance is lower than 95%, the estimated cost curves should be recalculated with the assistance of a qualified vendor and engineer.

Low Pressure Membrane (MF or UF) Cost Estimate

MF/UF capital costs were developed based on professional engineering experience for facilities ranging 1 to 80 MGD. Costs were consistent with a recently completed MF project

which served to validate the cost curve. Table S-8 summarizes the total estimated capital costs, based on equipment plus supplemental costs for yard piping; landscaping; electrical and control construction; and engineering, legal, and administration costs.

Annual O&M costs for MF/UF are summarized in Table S-9 and include the costs for labor, chemicals, periodic membrane replacement, and energy consumption. These were developed from existing O&M cost curves for membrane treatment provided in the United States Bureau of Reclamation (USBR) Desalting Handbook for Planners (USBR 2003). The handbook provides guidelines for RO treatment of brackish water and is based on data from existing facilities supplemented with performance estimates. For this study, the energy costs from USBR were reduced by 90% to reflect the anticipated reduction in pressure and associated energy required for low-pressure membranes (MF/UF) versus high-pressure membranes (NF/RO), based on project and industry experience (WEF 2006). Other O&M costs (labor, chemicals, and membrane replacement) were assumed to be similar between low- and high-pressure membranes. For the purposes of this conceptual-level Class 4 cost estimate, feed pressure differences between MF and UF (both low-pressure membranes) were assumed to be small, and therefore the cost curve applies to both types of low-pressure membranes.

Labor costs were included in this case because they are anticipated to be significant. However, it should be noted that when O&M costs for combined low- and high-pressure membrane treatment trains (e.g., MF-RO) are summed, labor costs should only be counted once. The additional labor associated with the dual membrane system is assumed to be insignificant in comparison to a single membrane process. The labor correction is provided in the results.

The USBR O&M cost curves are available for system capacities ranging from 1.1 to 53 MGD, which is reflected in Table S-9. Although the cost curve developed for the present study is based on this capacity range, the regression equation (see results) can be used for larger facilities because of the relatively flat nature of the curve.

High Pressure Membrane (NF or RO) Cost Estimate

Capital costs for high-pressure membrane filtration, which includes RO and NF, were developed based on professional engineering experience for facilities ranging from 1 to 80 MGD. The capital costs for two recently completed RO projects were also reviewed to validate the cost curve. Pretreatment costs, including chemical addition and low-pressure membrane filtration, were not included in the estimate. Table S-10 summarizes the total estimated capital costs, based on equipment plus yard piping; landscaping; electrical and control construction; and engineering, legal, and administration costs.

Annual O&M costs for high-pressure membranes are presented in Table S-11 and include labor, chemicals, periodic membrane replacement, and energy costs. As with the

low-pressure membrane cost estimates, the NF/RO O&M costs are based on the USBR handbook (USBR 2003) for RO treatment of brackish water for system capacities ranging from 1.1 to 53 MGD. These estimates assume brackish water having 500 to 2000 mg/L of total dissolved solids (TDS), which could be greater than some lower-salinity reclaimed wastewaters. For the purposes of this conceptual-level Class 4 cost estimate, feed pressure differences due to differences between brackish and recycled water salinity are assumed to have an insignificant impact on O&M costs and are therefore not accounted for. Additionally, the cost estimate does not account for the difference in feed pressure between NF and RO membranes, also assumed to have an insignificant impact on costs.

Biological Activated Carbon Cost Estimate

The capital cost curves for BAC were based on the design of granular activated carbon (GAC) facilities in water treatment applications (McGivney and Kawamura 2008), largely because of the lack of available data and vendor experience with BAC in wastewater applications. However, filter bed volume and standard construction costs were assumed to be equivalent between the two types of installations. Costs were prepared for filter capacities ranging from 1 to 80 MGD.

Capital costs for the construction of a BAC filter include the following major components: filter structure, filter media, backwash pumping, intermediate lift pumping, yard piping, site work, and electrical and control systems. Additional assumptions and parameters are listed with the BAC capital costs summarized in Tables S-12 and S-13.

Capital costs were prepared for empty bed contact times (EBCTs) of 10 and 20 min (Tables S-12 and S-13, respectively) to allow users to select the appropriate design parameter for their BAC filter application. Separate cost curves were prepared for both small (1–10 MGD) and large systems (10–80 MGD) because the costs were noticeably impacted by economies of scale. Therefore, four different regression equations for BAC capital costs are presented in the results according to EBCT and design flow.

Annual O&M cost curves for BAC filters were based on vendor-provided GAC replacement costs (\$1.65/lb to include shipping, installation, and disposal) plus operations in water treatment applications (McGivney and Kawamura 2008) because of the lack of available data and widespread vendor experience with wastewater BAC. Although construction costs (capital) were assumed to be similar between BAC (for wastewater) and GAC (for water), the O&M costs were varied between the water and wastewater by decreasing the replacement interval of the media to once every 8 years. The replacement interval may vary considerably between facilities depending on the specific objectives at each location. Some systems may rely primarily on the biological aspect of BACs, some facilities may seek a combination of biological degradation and adsorption, and others may want to maximize the level of adsorption in the system, all of

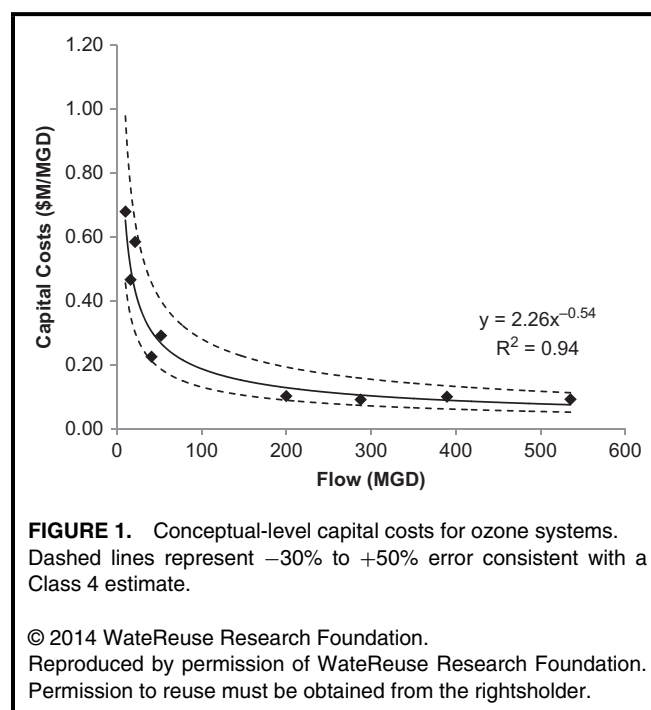
which have implications for media replacement frequency. The maintenance approach may also differ between facilities as some will purchase virgin replacement media whereas others may install on-site regeneration facilities. Because of the limited number of wastewater facilities employing BAC or GAC, it was infeasible to evaluate all of these alternatives. Therefore, the estimated costs utilized an 8-year lifespan for the media.

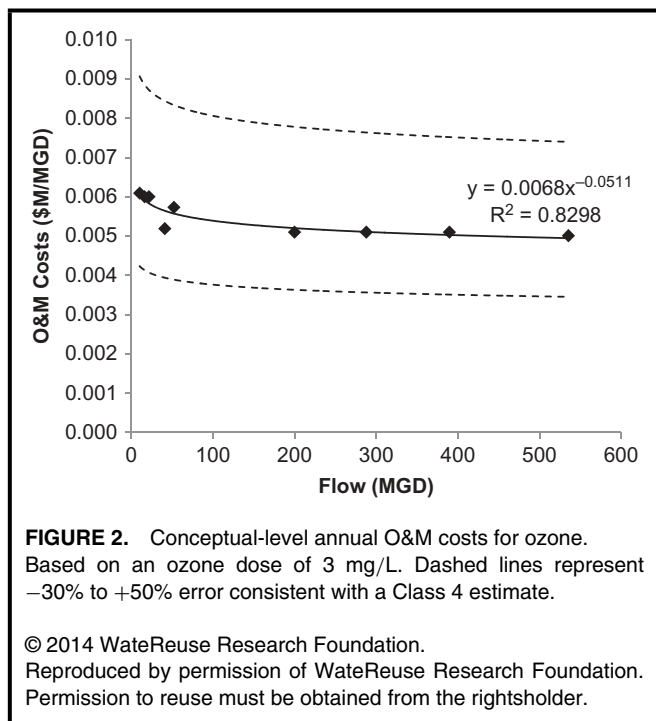
O&M costs for BAC filters include media replacement, electricity, and labor. As with the capital cost estimates, O&M cost curves were developed for two different EBCTs, and the estimates also account for the different amount of media in each configuration. Cost curves were developed for both small (1–10 MGD) and large systems (10–80 MGD) to achieve a better curve fit for approximating conceptual-level O&M costs. Unlike the capital costs prepared using the rated capacity of the filters, the O&M costs were prepared based on an average treated flow equal to half of the facility's rated capacity, to account for redundancy and overdesign, which are common in many systems. (Nevertheless, the x-axis of the cost curve is still the full design capacity.) Additional assumptions and parameters are listed with the annual BAC O&M costs summarized in Tables S-14 and S-15.

RESULTS AND DISCUSSION

Capital and O&M Cost Curves for Advanced Treatment

The capital and O&M cost curves (\$/MGD vs. MGD) for each advanced treatment unit process are shown in Figures S-1 through S-13 in the Supplemental Material. As an example, Figures 1 and 2 present the capital and O&M cost





curves for ozone. As noted earlier, the same capital cost curve (Figure 1) applies when ozone/H₂O₂ is used. The benefit of economy of scale is indicated by the significant reduction in the capital unit cost (\$/MGD) with increasing plant capacity (MGD). Separate O&M cost curves are provided for ozone alone (Figure 2) or with H₂O₂ (Figure S-3). Table 1 provides a summary of the regression equations for each of the cost curves.

To facilitate comparison of the cost curves between the different unit processes, the capital cost curves are presented together in Figure 3 and the O&M curves together in

Figure 4. At all plant capacities, membrane treatment represents the highest cost unit process, ozone the least, and BAC or UV/H₂O₂ fall in between. However, it should be noted that the UV/H₂O₂ system is sized for post-RO membrane applications and therefore does not compare directly to ozone, which here assumes lower UV transmittance (UVT) waters (pre-RO applications). Also note that Figures 3 and 4 do not show the -30/+50% error interval for each curve.

Combined Costs for Advanced Treatment Train

A wide range of unit processes have been implemented for advanced treatment in nonpotable and potable reuse applications. Some treatment trains are now regarded as industry standards (e.g., MF-RO-UV/H₂O₂ for indirect potable reuse) because of historical precedent or stringent regulatory guidelines. However, many facilities are now seeking alternatives because of a more flexible regulatory framework or unique water quality objectives. To support review of these alternatives, the cost curves presented in Table 1 can be used to develop overall conceptual-level cost estimates for a custom treatment train. The discussion that follows utilizes these cost curve regressions to estimate costs for several advanced treatment scenarios.

Calculating Baseline Costs

To illustrate the use of these cost curve equations in estimating capital and O&M costs for various process combinations, example calculations are presented in Tables 2 through 5 for the following combined systems: ozone-BAC, MF-ozone-BAC, MF-RO, MF-RO-UV/H₂O₂ and MF-Ozone-RO. With respect to the oxidation processes, the ozone system is based on an applied ozone dose of 3 mg/L, and the UV/H₂O₂ system is designed to achieve 1.2-log removal of NDMA and 0.5-log removal of 1,4-dioxane. The BAC is designed with a 10-min EBCT.

TABLE 1. Summary of Conceptual-Level Cost Curve Regression Equations

Process	Capital Cost ^a	Annual O&M Cost
	(\$/MGD)	(\$/MGD)
Ozone	$2.26 \times (\text{Plant Capacity, in MGD})^{-0.54}$	$0.0068 \times (\text{Plant Capacity, in MGD})^{-0.051}$
Ozone/H ₂ O ₂	$2.26 \times (\text{Plant Capacity, in MGD})^{-0.54}$	$0.016 \times (\text{Plant Capacity, in MGD})^{-0.020}$
UV/H ₂ O ₂	$0.474 \times (\text{Plant Capacity, in MGD})^{-0.056}$	$0.038 \times (\text{Plant Capacity, in MGD})^{-0.052}$
MF or UF	$3.57 \times (\text{Plant Capacity, in MGD})^{-0.22}$	$0.30 \times (\text{Plant Capacity, in MGD})^{-0.22}$
NF or RO	$7.14 \times (\text{Plant Capacity, in MGD})^{-0.22}$	$0.44 \times (\text{Plant Capacity, in MGD})^{-0.13}$
BAC		
10 min EBCT, 1–10 MGD	$2.92 \times (\text{Plant Capacity, in MGD})^{-0.52}$	$0.074 \times (\text{Plant Capacity, in MGD})^{-0.19}$
20 min EBCT, 1–10 MGD	$3.03 \times (\text{Plant Capacity, in MGD})^{-0.48}$	$0.085 \times (\text{Plant Capacity, in MGD})^{-0.16}$
10 min EBCT, 10–80 MGD	$1.43 \times (\text{Plant Capacity, in MGD})^{-0.17}$	$0.059 \times (\text{Plant Capacity, in MGD})^{-0.044}$
20 min EBCT, 10–80 MGD	$1.52 \times (\text{Plant Capacity, in MGD})^{-0.15}$	$0.070 \times (\text{Plant Capacity, in MGD})^{-0.036}$

Notes: ^aCapital costs include contractor OH&P and contingency.

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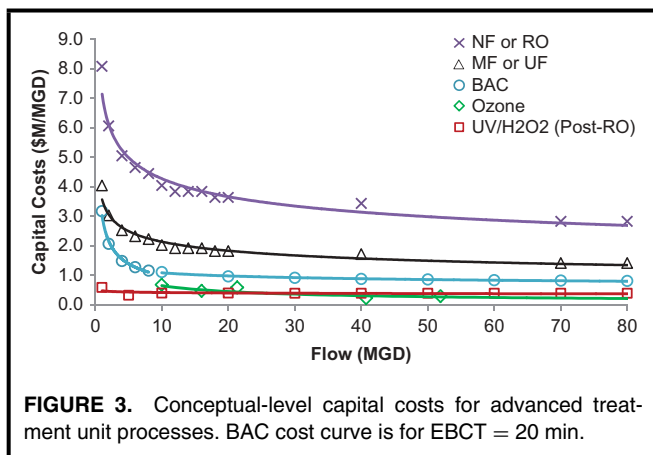


FIGURE 3. Conceptual-level capital costs for advanced treatment unit processes. BAC cost curve is for EBCT = 20 min.

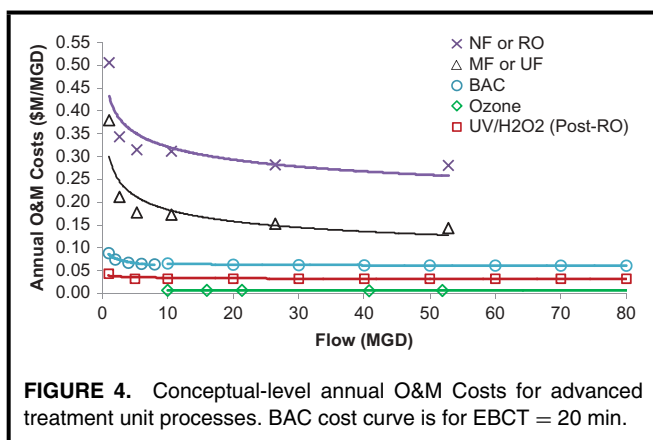


FIGURE 4. Conceptual-level annual O&M Costs for advanced treatment unit processes. BAC cost curve is for EBCT = 20 min.

Table 2 contains the capital costs for the combined process trains normalized to design flow (\$M/MGD). The costs are based on the equations in Table 1 modified by a labor correction factor (described later), where necessary. Similarly, Table 3 provides the corresponding flow-normalized annual O&M costs for the same treatment trains. Table 4 and Table 5 present these same estimates but as total capital and annual

O&M costs (\$M), respectively, by multiplying by the design capacity of the plants.

To account for redundancy in the labor costs when low- and high-pressure membranes are integrated into the same treatment train (i.e., MF pretreatment for RO), a correction factor should be applied based on a regression of the labor portion of the cost curve. This correction is described by the following regression equation:

$$\text{Membrane Labor Correction (in \$M/MGD)}$$

$$= 0.20 \times (\text{Plant Capacity, in MGD})^{-0.83}$$

The resulting membrane labor correction should be subtracted from the overall cost estimate for the facility. For example, for a facility with both MF and RO membranes, a 2 MGD facility would subtract \$0.1M/MGD from its cost estimate, whereas a 50 MGD facility would subtract \$0.008M/MGD from its cost estimate.

Ozone/H₂O₂ was not considered in the example treatment train scenarios. Ozone/H₂O₂ has been identified as a potential (AOP) candidate for the MF-RO-AOP treatment train, but few studies have been performed to identify the appropriate dosing conditions, particularly in relation to the revised CDPH regulation published in November 2011. Furthermore, ozone/H₂O₂ is not expected provide significant benefits over ozone from a wastewater treatment perspective (Pisarenko et al. 2012; Stanford et al. 2011). In applications where H₂O₂ would provide a significant benefit (e.g., reductions in contactor size or targeting bromate mitigation), users can develop costs for a custom treatment train with the information provided in Table 1.

Variable Ozone Dose Modification

The example cost estimates for the ozone-based treatment trains above were developed for an ozone dose of 3 mg/L. To allow the cost estimator to increase or decrease the ozone dose, a correction factor was developed and is described in detail in the Supplemental Material. The equations that follow can be used to adjust capital and O&M costs for a desired

TABLE 2. Flow-Normalized Capital Costs for the Combined Process Trains

Capacity (MGD)	Process Trains and Capital Costs ^a (\$M/MGD)				
	O ₃ -BAC	MF-O ₃ -BAC	MF-RO	MF-RO-UV/H ₂ O ₂	MF-O ₃ -RO (O ₃ -MF-RO)
1	\$5.18	\$8.75	\$10.7	\$11.2	\$13.0
5	\$2.21	\$4.72	\$7.52	\$7.95	\$8.46
10	\$1.62	\$3.77	\$6.45	\$6.87	\$7.11
25	\$1.22	\$2.98	\$5.28	\$5.67	\$5.67
50	\$1.01	\$2.52	\$4.53	\$4.91	\$4.80
80	\$0.89	\$2.25	\$4.08	\$4.46	\$4.30

Notes: ^aCapital costs include contractor OH&P and contingency.

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TABLE 3. Flow-Normalized Annual O&M Costs for the Combined Process Trains

Capacity (MGD)	Process Trains and Annual O&M Costs (\$/MGD)				
	O ₃ -BAC	MF-O ₃ -BAC	MF-RO	MF-RO-UV/H ₂ O ₂	MF-O ₃ -RO (O ₃ -MF-RO)
1	\$0.08	\$0.38	\$0.54	\$0.58	\$0.55
5	\$0.06	\$0.27	\$0.51	\$0.55	\$0.52
10	\$0.06	\$0.24	\$0.48	\$0.51	\$0.48
25	\$0.06	\$0.20	\$0.42	\$0.46	\$0.43
50	\$0.06	\$0.18	\$0.38	\$0.41	\$0.39
80	\$0.05	\$0.17	\$0.36	\$0.39	\$0.36

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TABLE 4. Total Capital Costs for the Combined Process Trains

Capacity (MGD)	Process Trains and Capital Costs ^a (\$M)				
	O ₃ -BAC	MF-O ₃ -BAC	MF-RO	MF-RO-UV/H ₂ O ₂	MF-O ₃ -RO (O ₃ -MF-RO)
1	\$5.2	\$9.0	\$11	\$11	\$13
5	\$11	\$24	\$38	\$40	\$42
10	\$16	\$38	\$65	\$69	\$71
25	\$31	\$75	\$132	\$142	\$142
50	\$50	\$126	\$226	\$245	\$240
80	\$71	\$180	\$327	\$356	\$344

Notes: ^aCapital costs include contractor OH&P and contingency.

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TABLE 5. Total Annual O&M Costs for the Combined Process Trains

Capacity (MGD)	Process Trains and Annual O&M Costs (\$M)				
	O ₃ -BAC	MF-O ₃ -BAC	MF-RO	MF-RO-UV/H ₂ O ₂	MF-O ₃ -RO (O ₃ -MF-RO)
1	\$0.1	\$0.4	\$0.5	\$0.6	\$0.5
5	\$0.3	\$1.4	\$2.6	\$2.7	\$2.6
10	\$0.6	\$2.4	\$4.8	\$5.1	\$4.8
25	\$1.4	\$5.1	\$11	\$11	\$11
50	\$2.8	\$9.0	\$19	\$21	\$19
80	\$4.0	\$13	\$29	\$31	\$29

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ozone dose as described by the ratio, r , of the new dose to the baseline dose of 3 mg/L (r = new ozone dose/3):

$$\Delta \text{ Capital } (\$M) = 0.0156 \times \text{Design Capacity (in MGD)}$$

$$\times (r - 1)$$

$$\Delta \text{ O\&M } (\$M) = 0.005 \times \text{Design capacity (in MGD)} \times (r - 1)$$

For example, the adjusted capital costs for a 10 MGD O₃-BAC facility operating with a 6 mg/L ozone dose would be \$11.7M + \$0.16M = \$11.9M, where \$11.7M is the cost

assuming 3 mg/L (see Table 2) and \$0.16M is the correction factor (see the Supplemental Material for equations and steps). Similarly, the adjusted annual O&M costs would be \$0.6M + \$0.05M = \$0.7M.

Relating the Level of TORC Destruction by Ozone to Cost

The costs for ozone-based treatment trains will be highly dependent on the water quality objectives in each application. Some systems will target TORC mitigation to reduce the potential impacts of their effluent on public and aquatic health,

some will determine their dosing conditions based on microbial inactivation goals, and others might design their systems based on aesthetics or odor control. The actual ozone doses in each application may vary significantly, which makes it difficult to capture all possible scenarios, water qualities, and treatment goals. For the purposes of this project, the following discussion focuses on designs targeting TOrC mitigation based on the treatment data presented by Snyder et al. (2014).

The recent regulatory trend emphasizes guidelines based on contaminant groupings rather than individual contaminants. This is evident in recent announcements by the United States Environmental Protection Agency (USEPA 2010) and the Draft Groundwater Replenishment revisions published by the CDPH (2011). Specifically, the CDPH is proposing that facilities implementing full advanced treatment (i.e., RO with an oxidation process such as MF-RO-AOP) must demonstrate specific reductions for nine structural classes. For example, the draft regulations mandate 0.5-log destruction of hydroxy aromatics, amino/acylamino aromatics, and a variety of other classes. The draft regulations also require 0.3-log destruction of saturated aliphatics and nitro aromatics. Although these guidelines only apply to full advanced treatment, a similar approach may be warranted for alternative applications, including spreading of ozone-BAC effluent in recharge basins.

Incorporating this framework, the results for TOrC destruction by ozone presented by Snyder et al. (2014) classified the target TOrCs into five groups based on their susceptibility to oxidation. The relative removal of these groups proved to be consistent regardless of secondary effluent water quality. For

example, an O_3 :TOC of 0.25 consistently achieved greater than 80% destruction of the Group 1 contaminants in all of the experimental matrices, whereas an O_3 :TOC ratio of 1.0 (i.e., a higher ozone dose for the same TOC level) achieved greater than 80% destruction of the target compounds in Groups 1, 2, and 3.

Increased ozone dose to achieve greater TOrC destruction will correspond to increased costs. To illustrate the relationship between cost and TOrC oxidation, the cost curves from the present study were used to estimate capital and annual O&M costs for a theoretical 50 MGD O_3 -BAC treatment train over a range of ozone doses, and this information is presented alongside the expected TOrC oxidation efficacy in Table 6. The facility is assumed to have a TOC concentration of 6 mg/L at the ozone dosing point and an EBCT of 10 minutes in the BAC system. As demonstrated in the literature and the project data for the City of Reno pilot (Snyder et al. 2014), downstream BAC provides substantial biodegradation and removal of TOrCs. However, it is still critical to design the upstream ozone process to provide a baseline level of TOrC mitigation because the BAC process is less predictable.

As demonstrated in Table 6, marginal increases in the capital and annual O&M costs for an O_3 -BAC process translate to significantly increased levels of contaminant oxidation. Note that these estimated mitigation levels are for the ozone unit process alone and therefore do not reflect the additional biodegradation and adsorption in the downstream BAC process, which would lead to final TOrC concentrations that

TABLE 6. Cost and Oxidation Efficacy of a Theoretical 50-MGD O_3 -BAC Treatment Train

O_3 Dose	1.5 mg/L	3 mg/L	6 mg/L	9 mg/L
O_3 :TOC Ratio	0.25	0.5	1.0	1.5
Conceptual-level cost estimate				
Capital Costs	\$49M	\$50M	\$52M	\$53M
Annual O&M	\$2.7M	\$2.8M	\$3.1M	\$3.3M
Average percent destruction of target compounds in the ozone unit process				
Group 1	>90%	>90%	>90%	>90%
Group 2	>60%	>90%	>90%	>90%
Group 3	>30%	>60%	>90%	>90%
Group 4	>15%	>30%	>60%	>80%
Group 5	<5%	>5%	>15%	>20%

Notes: 10-min EBCT for the BAC process; capital costs include contractor OH&P and contingency Group classifications from Snyder et al. (2014):

Group 1 = TOrCs with $k_{O_3} > 10^5$ and $k_{OH} > 5 \times 10^9 \text{ M}^{-1}\text{s}^{-1}$, e.g., bisphenol A, carbamazepine, estrone;
 Group 2 = TOrCs with $10 < k_{O_3} < 10^5$ and $k_{OH} > 5 \times 10^9 \text{ M}^{-1}\text{s}^{-1}$, e.g., atenolol, amikacin, benzotriazole;
 Group 3 = TOrCs with $k_{O_3} \leq 10$ and $k_{OH} > 5 \times 10^9 \text{ M}^{-1}\text{s}^{-1}$, e.g., ibuprofen, phenytoin, TCEP;
 Group 4 = TOrCs with $k_{O_3} < 10$ and $1 \times 10^9 < k_{OH} < 5 \times 10^9 \text{ M}^{-1}\text{s}^{-1}$, e.g., atrazine, iopromide, meprobamate;
 Group 5 = TOrCs with $k_{O_3} < 1$ and $k_{OH} \leq 1 \times 10^9 \text{ M}^{-1}\text{s}^{-1}$, e.g., TCEP, NDMA;
 where k_{O_3} and k_{OH} are the reaction rate constants between the TOrC and ozone or hydroxyl radical.

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may be comparable to those of MF-RO-UV/H₂O₂ (Snyder et al. 2014).

The differences in cost between O₃-BAC—regardless of ozone dose—and MF-RO-UV/H₂O₂ are staggering. The highest ozone dose described in Table 6 corresponds to conceptual-level capital and annual O&M costs of \$39M and \$3.3M, respectively, compared to capital and annual O&M costs for a 50 MGD MF-RO-UV/H₂O₂ facility of \$130M and \$21M, respectively (from Table 4 and Table 5).

CONCLUSIONS

Treatment costs are impacted by a variety of design variables including flow rate, site constraints, water quality objectives, manufacturer quotes, and other factors. Due to the large number of variables, the same treatment train may have significantly different costs from one site to another. Recognizing these limitations, conceptual-level cost estimates can be developed for use at the conceptual design stage to make relatively accurate comparisons of alternative treatment trains.

This study presented conceptual-level unit costs and cost curves to aid evaluations of advanced treatment trains over different design flows and, for ozone, dosing conditions. Potential modifications to eliminate labor redundancies in sequential membrane systems and to account for varying ozone dose were described. The models are broadly applicable to the water reuse community, particularly those interested in ozone-based treatment trains.

The choice of unit processes depends on a number of factors in addition to cost, chiefly the desired effluent quality. Membrane filtration with MF (for pretreatment prior to RO) and RO followed by UV disinfection has become a widely accepted or “industry standard” combination of technologies. However, studies indicate that ozone (in combination with appropriate pretreatment) and BAC can produce a similar effluent quality with respect to TOrCs removal at potentially a much lower cost (Snyder et al. 2014), though the removal of TDS is not achieved without the high pressure membranes. The cost curves developed in the present study confirm this expectation over a range of plant capacities, where additive costs for MF and RO result in much higher total capital and O&M costs than, for example, BAC plus ozone or MF plus ozone.

The cost for advanced treatment can be a significant portion of (or equal to) the cost for existing conventional treatment to which the advanced unit processes must be added (Friedler and Pisanty 2006; Jones et al. 2007). In questioning the excessive use of advanced treatment to remove organic micropollutants, Jones et al. (2007) note that the improvement in effluent quality comes with increased energy consumption and CO₂ emissions (in addition to large financial costs, which are passed on to the public), challenging the paradigm that increased effluent quality can only be environmentally beneficial. Recognizing the trade-offs, more engineering planning

studies for advanced water/wastewater treatment are including footprint, energy consumption, and CO₂ emissions alongside financial costs as part of a broader “triple bottom line” analysis.

However, when advanced treatment is conducted for water reuse and the costs are viewed as part of a broader (systems perspective) cost-benefit analysis, certain cost savings may be recognized, e.g., from avoided use and treatment of an alternative water source (Voulvoulis 2012). Over time, cost-benefit analysis for advanced treatment is likely to tip toward a net benefit as equipment costs continue to decline and their energy efficiency improves. Some or all of the energy demand associated with advanced treatment will be offset as more domestic wastewater treatment plants evolve to harness the energy embedded in wastewater (Crawford and Sandino 2010; WERF 2011) (e.g., methane [natural gas] generation from anaerobic digestion of biosolids produced during secondary treatment), resulting in energy neutral or even net energy positive treatment plants.

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SUPPLEMENTAL MATERIAL

Supplemental data for this article can be accessed on the publisher’s [website](#).

REFERENCES

- Benotti, Mark J., Rebecca A. Trenholm, Brett J. Vanderford, Janie C. Holady, Benjamin D. Stanford, and Shane A. Snyder. 2009. “Pharmaceuticals and Endocrine Disrupting Compounds in U.S. Drinking Water.” *Environmental Science & Technology* 43(3): 597–603.
- California Department of Public Health (CDPH). 2008. *Draft Groundwater Recharge Reuse Regulations*. Accessed July 31, 2013. <http://www.cdph.ca.gov/certlic/drinkingwater/Documents/Recharge/DraftRechargeReg2008.pdf>.
- California Department of Public Health (CDPH). 2011. *Draft Groundwater Replenishment Reuse Regulations*. Accessed July 31, 2013. <http://www.cdph.ca.gov/certlic/drinkingwater/Documents/Recharge/DraftRechargeReg-2011-11-21.pdf>.

- Chang, YuJung, David J. Reardon, Pierre Kwan, Glen Boyd, Jonathan Brant, Kerin L. Rakness, and David Furukawa. 2008. *Evaluation of Dynamic Energy Consumption of Advanced Water and Wastewater Treatment Technologies* (AWWARF Project #3056). Denver, CO: AWWA Research Foundation.
- Crawford, George, and Julian Sandino. 2010. *Energy Efficiency in Wastewater Treatment in North America: A Compendium of Best Practices and Case Studies of Novel Approaches*. Alexandria, VA: Water Environment Research Foundation (WERF).
- Daughton, C. G., and T. A. Ternes. 1999. "Pharmaceuticals and Personal Care Products in the Environment: Agents of Subtle Change?" *Environmental Health Perspectives* 107(Suppl. 6): 907–938.
- Debroux, Jean-François, Jeffrey A. Soller, Megan H. Plumlee, and Laura J. Kennedy. 2012. "Human Health Risk Assessment of Non-Regulated Xenobiotics in Recycled Water: A Review." *Human and Ecological Risk Assessment* 18(3): 517–546.
- ENR. 2011. Engineering News-Record. "Construction Cost Indices." Accessed December 12, 2011. http://enr.construction.com/economics/current_costs/.
- Esposito, Kathleen M., Patrick J. Phillips, Beverley M. Stinson, Timothy Bradley, Gary Whalen, and C. Mysore. 2007. Multiple Barrier Treatment for Indirect Potable Reuse: Considerations for Trace Contaminants of Emerging Concern. In *Proceedings of the Water Environment Federation*, San Diego, California, October 13–17.
- Friedler, Eran, and Ehud Pisanty. 2006. "Effects of Design Flow and Treatment Level on Construction and Operation Costs of Municipal Wastewater Treatment Plants and Their Implications on Policy Making." *Water Research* 40(20): 3751–3758.
- Hollender, Juliane, Saskia G. Zimmermann, Stephan Koepke, Martin Krauss, Christa S. McArdell, Christoph Ort, Heinz Singer, Urs von Gunten, and Hansruedi Siegrist. 2009. "Elimination of Organic Micropollutants in a Municipal Wastewater Treatment Plant Upgraded with a Full-Scale Post-Ozonation Followed by Sand Filtration." *Environmental Science & Technology* 43(20): 7862–7869.
- Huber, Marc M., Silvio Canonica, Gun-Young Park, and Urs von Gunten. 2003. "Oxidation of Pharmaceuticals During Ozonation and Advanced Oxidation Processes." *Environmental Science & Technology* 37(5): 1016–1024.
- Jones, Oliver A. H., Pat G. Green, Nikolaos Voulvoulis, and John N. Lester. 2007. "Questioning the Excessive Use of Advanced Treatment to Remove Organic Micropollutants from Wastewater." *Environmental Science & Technology* 41(14): 5085–5089.
- Kim, Sang D., Jaeweon Cho, In S. Kim, Brett J. Vanderford, and Shane A. Snyder. 2007. "Occurrence and Removal of Pharmaceuticals and Endocrine Disruptors in South Korean Surface, Drinking, and Waste Waters." *Water Research* 41(5): 1013–1021.
- McGivney, William, and Susumu Kawamura. 2008. *Cost Estimating Manual for Water Treatment Facilities*. Hoboken, NJ: John Wiley & Sons, Inc.
- Pisarenko, Aleksey N., Benjamin D. Stanford, Dongxu Yan, Daniel Gerrity, and Shane A. Snyder. 2012. "Effects of Ozone and Ozone/Peroxide on Trace Organic Contaminants and NDMA in Drinking Water and Water Reuse Applications." *Water Research* 46(2): 316–326.
- Smith, Robert. 1968. "Cost of Conventional and Advanced Treatment of Wastewater." *Journal Water Pollution Control Federation* 40(9): 1546–1574.
- Snyder, Shane A., Urs von Gunten, Gary Amy, and Jean Debroux. 2014. *Use of Ozone in Water Reclamation for Contaminant Oxidation*. Report No. WRF-08-05. Alexandria, Virginia: WaterReuse Research Foundation.
- Snyder, Shane A., Eric C. Wert, Hongxia Lei, Paul Westerhoff, and Yeomin Yoon. 2007. *Removal of Edcs and Pharmaceuticals in Drinking and Reuse Treatment Processes*. Denver, Colorado: American Water Works Association Research Foundation (AWWARF).
- Snyder, Shane A., Eric C. Wert, David J. Rexing, Ronald E. Zegers, and Douglas D. Drury. 2006. "Ozone Oxidation of Endocrine Disruptors and Pharmaceuticals in Surface Water and Wastewater." *Ozone: Science & Engineering* 28(6): 445–460.
- Snyder, Shane A., Paul Westerhoff, Yeomin Yoon, and David L. Sedlak. 2003. "Pharmaceuticals, Personal Care Products, and Endocrine Disruptors in Water: Implications for the Water Industry." *Environmental Engineering Science* 20(5): 449–469.
- Stanford, Benjamin D., Aleksey N. Pisarenko, R. David Holbrook, and Shane A. Snyder. 2011. "Preozonation Effects on the Reduction of Reverse Osmosis Membrane Fouling in Water Reuse." *Ozone: Science & Engineering* 33(5): 379–388.
- Swaim, P.D., R. Morgan, P. Mueller, M. Vorissis, U. Erdal, and W. Carter. 2009. "Implementing an Effective UV Advanced Oxidation Process." *Proceedings of the Water Environment Federation* 2009(1):678–688.
- Ternes, Thomas A., Martin Meisenheimer, Derek McDowell, Frank Sacher, Heinz-Jürgen Brauch, Brigitte Haist-Gulde, Gudrun Preuss, Uwe Wilme, and Ninette Zulei-Seibert. 2002. "Removal of Pharmaceuticals During Drinking Water Treatment." *Environmental Science & Technology* 36(17): 3855–3863.
- United States Department of the Interior, Bureau of Reclamation (USBR). 2003. *Desalting Handbook for Planners*, 3rd Edition. Prepared by RosTek Associates, Inc. for Desalination and Water Purification Research and Development Program, United States Department of the Interior, Bureau of Reclamation, Technical Service Center, Denver, Colorado.
- United States Energy Information Administration (USEIA). 2011. *Electric Power Annual 2010*. Washington DC: United States Energy Information Administration, United States Department of Energy.
- United States Environmental Protection Agency (USEPA). 2010. *Paradigm for Addressing Drinking Water Contaminants as Groups to Enhance Public Health Protection (EPA Draft Discussion Paper)*. Accessed July 31, 2013. http://water.epa.gov/lawsregs/rulesregs/sdwa/dwstrategy/upload/contaminant_groups_paradigm_discussion_9_17_10.pdf.
- Voulvoulis, Nikolaos. 2012. "Water and Sanitation Provision in a Low Carbon Society: The Need for a Systems Approach." *Journal of Renewable and Sustainable Energy* 4(4): 041403.
- Water Environment Federation (WEF). 2006. *Membrane Systems for Wastewater Treatment*. Alexandria, VA: Water Environment Federation (WEF) Press, McGraw-Hill.
- Water Environment Research Foundation (WERF). 2011. "Energy Production and Efficiency Research – the Roadmap to Net-Zero Energy (Fact Sheet)." Accessed July 24, 2013. Available from http://www.werf.org/c/2011Challenges/Energy_Optimization.aspx.
- Westerhoff, Paul, Yeomin Yoon, Shane Snyder, and Eric Wert. 2005. "Fate of Endocrine-Disruptor, Pharmaceutical, and Personal Care Product Chemicals During Simulated Drinking Water Treatment Processes." *Environmental Science & Technology* 39(17): 6649–6663.