CEP APRIL 2014 INDUSTRIAL WATER REUSE VOL.110/NO.4

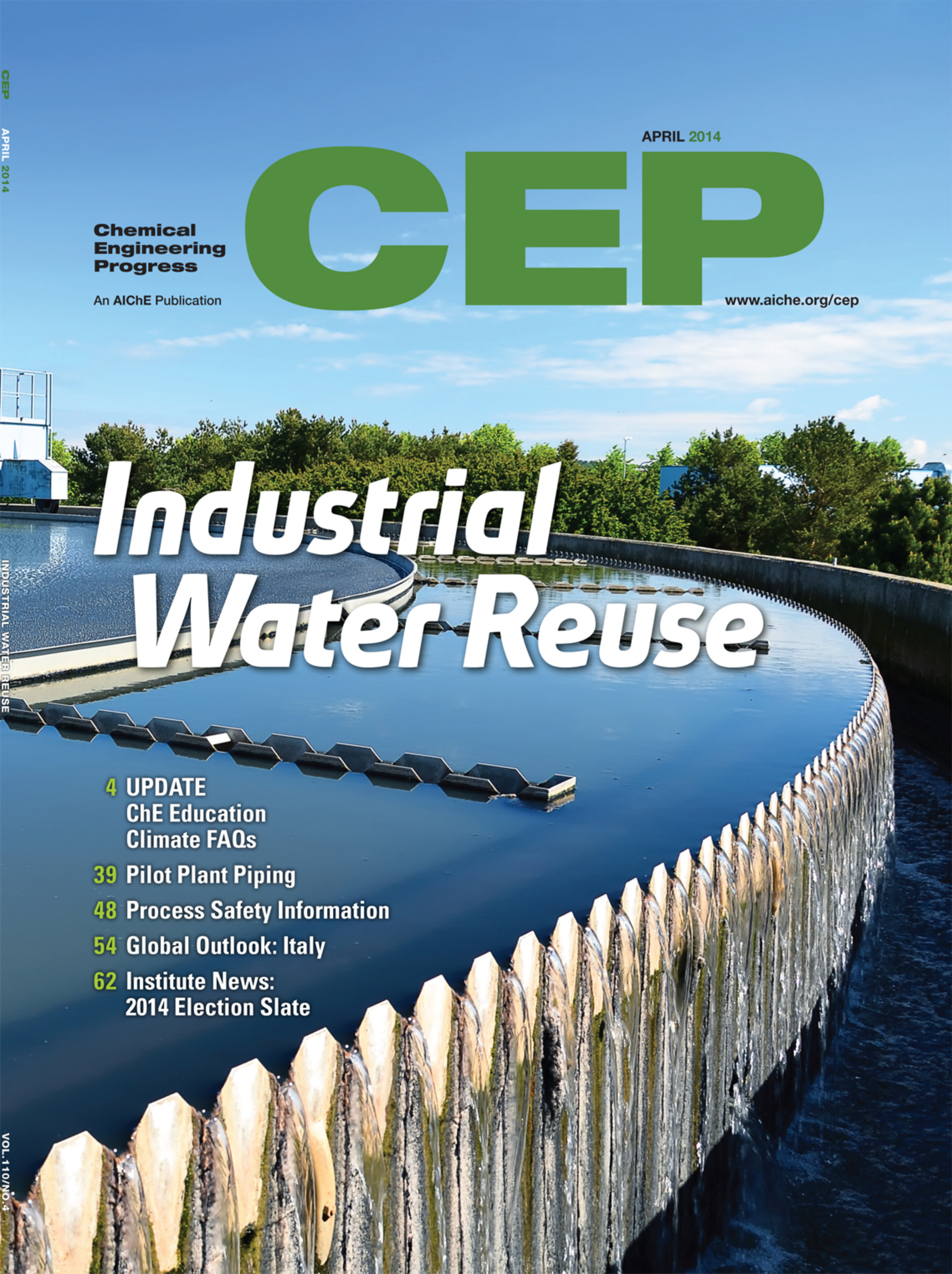
APRIL 2014

CEP

Chemical Engineering Progress

An AIChE Publication

www.aiche.org/cep



Industrial Water Reuse

Reduce Water Consumption through Recycling

Allegra K. da Silva, P.E.
Al Goodman, P.E.
CDM Smith

Industrial facilities are increasingly turning to water reuse for a wide range of purposes. This article reviews water-reclamation technologies and explains how to determine whether water reuse is a feasible option for your plant.

Industry and communities around the world are turning to water reuse. The drivers are varied and include: the need to augment strained water supplies, reduce nutrients in treated effluent, maintain ecological balance, and reduce the costs of purchased and treated water, among others. In industry, another impetus for water reuse is energy efficiency. Depending on the level of treatment required, however, water reuse can be energy intensive, and a full lifecycle analysis is required to compare overall resource costs with the costs of alternative water supplies.

Because the U.S. currently reuses only about 7–8% of municipal wastewater, there is tremendous potential to expand reclaimed water use over the coming decades. The largest freshwater demands come from thermoelectric power generation and agriculture, 49% and 34%, respectively. Industry and mining together use less than 5% of total water withdrawals, and public and domestic self-supply constitute the remaining 12% of total water demand *(1)*.

Categories of water reuse applications are listed in Table 1. As municipalities implement various types of urban water reuse, they are turning to industry and agriculture as potential customers of reclaimed water. In addition, there are significant efforts in industry to evaluate onsite water reuse for various production processes. For example, some companies are evaluating reclaiming heat from process wastewater to preheat recycled water or to reduce the energy requirements for heating incoming water.

This article focuses on applications and treatment processes for industrial reuse. Reference 2 provides more information on the full range of reuse categories and applications.

Table 1. Categories of water reuse applications.

Category of Reuse	Description
Industrial	Industrial applications and facilities (including food production and high-tech industries), power production, and extraction of fossil fuels
Urban	Non-potable applications in municipal settings
Agricultural	Irrigate food crops that may or may not be intended for human consumption
Environmental	Create, enhance, sustain, or augment water bodies, including wetlands, aquatic habitats, and stream flow
Groundwater Recharge — Non-potable	Recharge aquifers that are not used as potable water sources
Potable — Indirect Potable Reuse (IPR)	Augment a drinking water source (surface water or groundwater) with reclaimed water followed by an environmental buffer that precedes normal drinking water treatment
Potable — Direct Potable Reuse (DPR)	Introduce reclaimed water (with or without retention in an engineered storage buffer) directly into a water treatment plant, either co-located with or remote from the advanced wastewater treatment system

Source: Adapted from *(2)*.

Water reuse in cooling, heating, and high-technology manufacturing

Cooling tower makeup. Evaporative cooling systems require significant volumes of makeup water to replace water lost through evaporation. Additionally, some water must be periodically discharged (referred to as blowdown water) to prevent dissolved solids that are concentrated during evaporation from building up in the cooling water and damaging equipment. Large hyperbolic concrete cooling towers that are commonly used at utility power plants can recirculate 200,000–500,000 gpm (12,600–31,500 L/s) and evaporate approximately 6,000–15,000 gpm (380–950 L/s) of water. Smaller cooling towers recirculate flows on the order of a few thousand gpm.

Reclaimed water can be used for cooling tower makeup water. The main concerns in using reclaimed water for this application are controlling biological regrowth (which occurs when nutrients are present and an adequate disinfectant residual is not maintained) and scaling (caused by minerals, particularly calcium, magnesium, sulfate, alkalinity, phosphate, silica, and fluoride). Reference 3 explains how to determine what quality of reclaimed water is suitable and cost-effective for cooling tower makeup.

Boiler water makeup. Water for boiler makeup requires extensive pretreatment to control scale and oxygen within the boiler, whether the source is reclaimed water or conventional potable water. Because they operate at higher pressures and temperatures, boilers are even more susceptible to corrosion due to scale build-up than cooling towers. Hardness, alkalinity, silica, and alumina must be carefully removed or

Table 2. Recommended boiler water quality limits.

Drum Operating Pressure, psig	0–300	301–450	451–600	601–750	751–900	901–1,000	1,001–1,500	1,501–2,000	Once-Through Steam Generation
Steam									
TDS max, ppm	0.2–1.0	0.2–1.0	0.2–1.0	0.1–0.5	0.1–0.5	0.1–0.5	0.1	0.1	0.05
Boiler Water									
TDS max, ppm	700–3,500	600–3,000	500–2,500	200–1,000	150–750	125–625	100	50	0.05
Alkalinity max, ppm	350	300	250	200	150	100	N/A	N/A	N/A
TSS max, ppm	15	10	8	3	2	1	1	N/A	N/A
Conductivity max, μmho/cm	1,100–5,400	900–4,600	800–3,800	300–1,500	200–1,200	200–1,000	150	80	0.15–0.25
Silica max, ppm SiO_2	150	90	40	30	20	8	2	1	0.02
Feedwater (Condensate and Makeup, after Deaerator)									
Dissolved Oxygen, ppm O_2	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	N/A
Total Iron, ppm Fe	0.1	0.05	0.03	0.025	0.02	0.02	0.01	0.01	0.01
Total Copper, ppm Cu	0.05	0.025	0.02	0.02	0.015	0.01	0.01	0.01	0.002
Total Hardness, ppm $CaCO_3$	0.3	0.3	0.2	0.2	0.1	0.05	ND	ND	ND
pH @ 25°C	8.3–10.0	8.3–10.0	8.3–10.0	8.3–10.0	8.3–10.0	8.8–9.6	8.8–9.6	8.8–9.6	N/A
Nonvolatile TOC, ppm C	1	1	0.5	0.5	0.5	0.2	0.2	0.2	ND
Oily Matter, ppm	1	1	0.5	0.5	0.5	0.2	0.2	0.2	ND

Source: Adapted from *(2, 4)*.
TDS = Total Dissolved Solids. TSS = Total Suspended Solids. TOC = Total Organic Carbon.
N/A = Not Applicable. ND = Nondetectable.

controlled in boiler water makeup, because they can cause scaling, foaming, and other forms of carryover that create deposits in the boiler, superheater, reheater, and turbine units. Equipment that uses the steam from boilers and condensate-return systems can be corroded by the release of carbon dioxide from the breakdown of bicarbonate alkalinity under the influence of boiler heat. Foaming is controlled by removal of organics using carbon adsorption or ion exchange *(2).*

Table 2 *(2, 4)* presents the maximum recommended concentrations of various water quality parameters for boiler operation. Reclaimed water used as boiler makeup water is typically sent through an ion-removal process, such as ion exchange, electrodeionization, or reverse osmosis (RO), to control total dissolved solids (TDS).

Several refineries in southern California use recycled water that has gone through clarification, filtration, and RO pretreatment as their primary source of boiler makeup water, saving water as well as chemicals and energy. A municipal water utility supplies the refineries with water of two different quality levels for low-pressure and high-pressure boiler feedwater. After one pass through RO treatment and disinfection to produce the low-pressure boiler feedwater, the high-pressure boiler feedwater is treated with a second pass through the RO membranes to remove additional dissolved solids from the water. To provide a sense of the scale of operations: One of the California refineries uses about 5.8 million gal/d (254.1 L/s) of single-pass RO water for low-pressure boiler feed and an additional 2.4 million gpd (105 L/s) of double-pass RO water for high-pressure boiler feed sourced from reclaimed water *(2)*; another refinery produces 3.2 million gpd of boiler makeup water from reclaimed water in an onsite system.

At the Univ. of Connecticut Storrs campus, a two-stage RO system is used for ion removal to treat reclaimed water for boiler makeup water *(5).* This system (Figure 1) came online in 2013 and was an innovative response to local water scarcity.

RO-treated water is highly corrosive and must be stored and distributed in piping and tanks made of corrosion-resistant materials, such as stainless steel or polyvinyl chloride, or in many cases, stabilized by adding chemicals such as sodium bisulfite to balance the anions and cations and reduce corrosivity.

High-technology manufacturing. Reclaimed water is used in high-technology applications, such as in the semiconductor industry in the manufacture of microchips and circuit boards. The water quality required for circuit board manufacturing is similar to that of boiler feedwater, requiring extensive treatment. Reclaimed water is also used at the associated facilities for cooling water and site irrigation.

Intel, for example, internally recycles approximately 2 billion gal (7.6 million m^3) of water per year, the equivalent of 25% of its total water withdrawals. A large portion of this is internally generated water. After ultrapure water is used to clean silicon wafers during fabrication, the water is reused for industrial purposes, irrigation, cooling towers, scrubbers, and other facility uses through special dedicated plumbing networks *(2).*

Water reuse in prepared food manufacturing

Although the food and beverage industry was initially reluctant to use reclaimed water because of concerns about public perception, the use of highly treated, drinking-water-quality reclaimed process waters has been growing. As knowledge of water reuse principles and treatment technologies has increased, companies have become motivated to use reclaimed water at manufacturing sites, which helps minimize the total volume of fresh water used. Reuse is a green practice that reduces operating costs and a facility's water footprint and, in some cases, provides better or more-consistent water quality than that of the public water supply.

The manufacture of prepared foods is a water-intensive process, especially if irrigation used in the food chain supply is included. (In many areas of the country, 70% of water usage is for crop irrigation.) Even if irrigation is not considered, preparing food products generates large volumes of

▲ **Figure 1.** The Univ. of Connecticut Storrs campus installed a two-stage reverse osmosis system with microfiltration pretreatment to treat reclaimed water for use as boiler makeup. Shown here (left to right) are some of the components that pretreat the water prior to RO: the pump that feeds water to the microfilter system, the microfilter membrane cartridges, and the UV reactors. Photos courtesy of Jason Maskaly.

process wastewater, often measured in gallons of water per unit of production (such as gallons/case, or gallons/bird in the case of poultry). Process wastewater (Figure 2) comes from food product washing and cleaning, fluming to transport food products (such as vegetables), cooking, ingredient make-up, equipment cleaning and sanitation, housekeeping, disinfection and rinsing of process units, steam and hot water generation for processing, can and bottle conveyor-belt lubrication, can and bottle warming, and cooling. Some facilities are turning to non-rinse (*i.e.,* dry) cleaning methods to reduce operating costs and flows to the wastewater treatment process.

Food industry wastewater can contain high concentrations of fats, oils, and grease (FOG). Fryers, for instance, are typically sanitized weekly in a procedure known as a boil-out, which involves heavy cleaning with hot caustic cleaners and degreaser solutions. The oil and grease are often emulsified due to in-process and in-pipe mixing and the addition of various ingredients and detergents that act as emulsifying agents. When discharged to the process sewer, emulsified oils and greases add high loads of biochemical oxygen demand (BOD) to wastewater treatment systems.

In certain industries, valuable products and byproducts can be recaptured through reuse. For example, when containers are cleaned after the filling process, some overfill or spillage typically occurs. The wash water can be filtered through nanofiltration to recover sugars for use in animal feed or for growing yeast, while the cleaned reclaimed water can be used for any number of uses, such as pallet cleaning or conveyor lubrication.

In meat processing, blood can be recaptured from the rendering processes and resold as blood meal. While blood recapture presents value to food producers, not all blood is recaptured from wastewater, and what is not recovered presents significant loads for wastewater treatment, since blood has a chemical oxygen demand (COD) concentration of about 400,000 mg/L and a BOD of about 200,000 mg/L. In fact, the COD loads generated from blood in waste streams at meat and poultry processing facilities are some of the highest COD concentrations seen in the food industry. High-fructose corn syrup also has BOD levels in the hundreds of thousands of mg/L, depending on its concentration.

▲ **Figure 2.** This activated sludge aeration tank at a pork processing plant is equipped with floating mechanical aerators.

In 2013, the International Life Sciences Institute (ILSI) published guidelines for water use reduction (including water reuse) in the food and beverage industry *(6).* The guidelines include an 11-step procedure for implementing water reuse and meeting water quality requirements.

Produced water from oil and natural gas production

Hydraulic fracturing has made vast quantities of natural gas from shale available, reshaping the energy landscape of the U.S. *(7).* However, extracting shale gas by pumping water (and often chemicals) into subsurface deposits generates large, unavoidable volumes of wastewater — around eight times as much water is brought to the surface as oil or gas *(2).* Contrary to current perception, wells in the Marcellus formation, by far the largest shale gas resource in the U.S., produce significantly less wastewater per unit of gas recovered (approximately 35% less) than shale gas wells in other formations *(8).*

Produced water is defined as any water present in a reservoir with a hydrocarbon resource that is brought to the surface with the crude oil or natural gas during production operations. Formation water is water that flows from the hydrocarbon zone or from production activities when injected fluids and additives are introduced to the formation. The term flowback water is specific to hydraulic fracturing — it is water that returns to the surface within a few days or weeks following injection of large volumes of fracturing fluid into the hydrocarbon reservoir.

The quality of produced waters varies widely depending on the geographic location, geological formation, and type of hydrocarbon being extracted. Produced water quality ranges from water that meets state and federal drinking water standards to water having very high concentrations of TDS and hydrocarbons. Such contaminants can threaten ecological health if discharged to water bodies or used as irrigation water without treatment, or human health if untreated produced water reaches drinking water sources *(2).* As a result, produced water requires treatment, disposal, and, potentially, recycling in accordance with federal and state regulatory requirements, as described in the U.S. Dept. of Energy's (DOE) online resource, The Produced Water Management System *(9).* The reuse of produced water remains contentious and, under current regulations, can only be practiced west of the 99th meridian, which passes through North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, and Texas *(2).*

Wastewater from oil and natural gas production processes can contain the following constituents:

• oil emulsions containing amines, volatile organic compounds (VOCs), and alkanes can be adsorbed into activated sludge and adversely affect wastewater effluent quality

• phenolics may accumulate and negatively affect nitrification

• amines convert to ammonia, which if not fully treated can increase effluent toxicity

• alcohols, glycols, and ketones can deplete oxygen, enhance filament growth, and cause sludge settling problems

• residual fracturing chemicals.

As is the case with all reclaimed water, the potential uses of reclaimed produced water depend on the water quality and the level of treatment provided. Uses can include surface water flow augmentation, aquifer recharge, storage and recovery, crop irrigation, livestock watering, and a range of industrial reuse purposes. The produced water generated from coalbed methane production tends to be low in TDS, and can often be reused with very little treatment, whereas higher-TDS produced water requires a much higher level of treatment and may require disposal of residual waste (such as concentrated brine). Treatment, often conducted using modular technologies that can be mobilized in the field, may be by oil-water separators, dissolved-gas flotation or coalescing media separators, adsorption, and filtration targeted for removal of specific constituents *(2)*.

Wastewater reuse feasibility

Because each facility presents site-specific and process-specific challenges, determining the feasibility of water reuse requires thorough data collection and careful analysis of the many options available. Begin by answering the following questions.

1. What water quality is needed for reuse? Potential water reuse options at an industrial plant include, in order of increasing water quality and cost, land application/disposal, landscape irrigation, cooling, sanitation, clean-in-place (CIP), boiler makeup, food preparation, and ingredient water.

2. What are the water flows at the facility? Start with a water survey that considers daily and seasonal variations, current and future water uses (both quality and quantity), and potential sources of recoverable water.

3. What are the future water demands and available sources? Conduct a water-needs study to predict future demands, potential onsite conservation, and alternative sources that can be used to ensure sustainable operation.

4. Can wastewater segregation be achieved? Treatment requirements for a facility that can separate restroom wastewater from the process sewer system are different than those for a plant with a combined wastewater system. Older facilities often use combined sewers, which present problems for wastewater treatment plant (WWTP) sludge disposal, especially if sludge is used as animal feedstock. Additional disinfection, extensive permitting, and related perception concerns must be considered for reclamation from combined wastewater systems. Also, the segregation of oily wastewater streams may be needed to protect any downstream membranes.

5. Is flow equalization needed? Depending on flowrate variation, batch dumps to discard product that does not meet specifications, seasonal variations, and the type of sanitation processes used, equalization may be warranted. This should be considered before the treatment system components are sized, because properly designed equalization tanks can minimize downstream component sizes and costs.

6. What is in the wastewater? The composition of process streams — *e.g.,* BOD, COD, FOG, total suspended solids (TSS), pH, temperature, and salt concentrations — can vary considerably. Thus, sampling and analytical testing under various process conditions is needed to determine the minimum, maximum, and average loadings on the treatment system. Testing may include nontraditional analytical parameters, such as salts, hardness, alkalinity, silica, and cations and anions (especially if membrane systems are being considered). The concentrations and compositions of soluble versus particulate matter are also important, as these affect the choice of a treatment process. Dissolved-air floatation (DAF), for example, does not effectively remove soluble organics.

7. How much space is available? Biological treatment is generally used to remove soluble organics from food industry wastewaters. This may take place in large lagoons or concrete tanks, for which space availability needs to be considered.

8. What waste disposal options are available? Water reuse must be considered relative to alternative options, including full or partial disposal of wastewater and residual solids. Treatment technologies that will not be adversely affected by upstream processes or side-stream sludge processes should be selected. It is not uncommon for designers to underestimate the volume of sludge produced, and solids management in a WWTP can easily affect the treatment efficiency and quality of the reuse water.

In reuse scenarios that employ RO and other membrane-based processes, the concentrate stream must be carefully managed and disposed. If this stream cannot be discharged to the publicly owned treatment works (POTW), then onsite evaporation or further concentration of the reject may be required, thereby significantly increasing costs and space requirements.

9. What are the potential costs and savings? Reuse scenarios should be considered from a lifecycle cost perspective. Costs can include capital costs and operating and maintenance costs, with labor, electric/energy, chemicals, and sludge disposal being the primary ongoing operational costs. Water reuse treatment costs depend on the water quality required. As the water quality increases, the costs increase somewhat exponentially rather than linearly, and the level of technical competence required of operators increases as well.

Savings should also be addressed on a lifecycle basis. Savings can include the purchase cost of water, wastewater treatment fees to a POTW, cost of compliance monitoring, and cost of avoided treatment for the current water supply.

Technology options

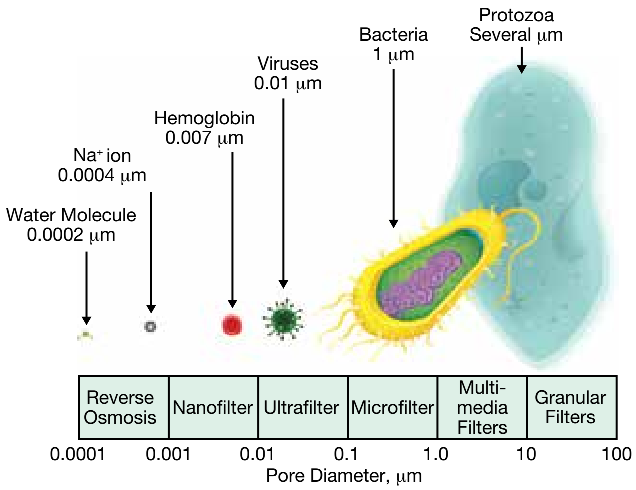
Treatment technologies are available to achieve virtually any desired level of water quality, and the level of treatment required depends on the reuse application. For most industrial uses of reclaimed water, conventional processes involving secondary treatment, filtration, and disinfection steps are sufficient to achieve the necessary water quality. In applications with the potential for human contact or with sensitive equipment, advanced treatment may be required.

It is important to remember that not all water constituents have negative impacts for all uses. For example, it may be beneficial to leave nutrients such as nitrogen and phosphorus in reclaimed water that will be used for landscape irrigation to reduce or eliminate the application of supplemental fertilizers.

Wastewater treatment for industrial reuse often employs the following major processes. Screening, equalization, and primary clarification serve as pretreatment steps that allow subsequent treatment processes to operate more efficiently.

Screening. In this pretreatment step, screens remove large solids to protect downstream equipment and to recover usable resources, such as byproducts of food processing for potential disposal as animal feed (depending on amount of debris removed by screening).

Equalization. Equalization tanks even out flow variations, as well as smooth variations in concentration, temperature, and, with the controlled addition and mixing of acids or caustics, pH.



▲ **Figure 3.** Membrane technology selection involves matching the membrane's pore diameter to the size of the molecules or biological constituents targeted for removal.

Primary clarification. Primary clarifiers work by providing sufficient hydraulic retention time, typically 1–3 hr, to allow suspended solids in the wastewater to settle and some of the floatables to separate. Thickened solids are removed from the bottom of the clarifier and further dewatered or digested to produce biogas. Some food-processing plants are able to dispose of primary sludge as animal feed.

Biological treatment. There are many types of biological treatment — such as anaerobic digestion, activated sludge, and trickling filters — as well as options for nutrient removal, different aeration systems and efficiencies, different footprints, etc. The use of certain cleaning chemicals (*e.g.,* germicides and disinfectants) and in-plant clean-in-place (CIP) processes may introduce chemicals into the wastewater that inhibit biological treatment.

Anaerobic treatment is typically considered if the BOD concentration (soluble or particulate) is more than 8,000 mg/L or, in the case of organic sludge, if the volume of organic matter is sufficient (approximately 50,000 gpd of flow to the digester) for the production of biogas. Anaerobic digestion can generate methane gas (at a concentration of more than 65% methane) and, when performed onsite, can meet some of a facility's energy requirements.

Activated sludge treatment takes place in aeration tanks fitted with diffusers and air-distribution headers (Figure 2), and involves hydraulic retention times of 4–24 hr. Biomass converts the wastewater's organic constituents to suspended solids, which are subsequently separated from the process flow by secondary clarifier(s) or membrane filtration. These solids are recycled to the aeration tank as return activated sludge (RAS) for reseeding and treating incoming flow. The biomass solids that build up, known as waste activated sludge (WAS), are periodically removed from the RAS, then dewatered and disposed (or in some cases, digested).

Dissolved-air flotation (DAF). DAF introduces fine air bubbles into the wastewater by pressure or specialized induction pumps, causing suspended solids to float. DAF is very common in meat and dairy industries, where high concentrations of fats, oils, and grease are present. Coagulation and flocculation chemicals are often added to help smaller solids to congeal and form larger particles for more-efficient separation/floatation. The floating matter, which may contain up to 15% solids, is continuously skimmed, and likewise may be used for animal feed or rendering. DAF can typically remove 90% of the influent TSS.

Membrane filtration. Membrane filtration technologies are becoming much more acceptable for use as solids-separation processes upstream of biological treatment systems. Clarifiers depend on biomass settling; if the biomass does not settle well or if hydraulic flows vary, clarifier operation is upset and becomes inefficient. Membrane treatment of the clarifier influent is sometimes used to remove constituents that hinder biomass settling.

Membranes are capable of retaining compounds of various molecular weights and even ions, depending on the membrane's porosity. The membranes used in industrial water reuse include microfilters (MF), ultrafilters (UF), nanofilters (NF), and RO membranes. Figure 3 shows the pore size range for each type of membrane.

Ultrafiltration can be used instead of clarifiers for activated sludge separation. These membranes can be configured as plates or tubular modules that are submerged in the aeration chamber, adjoining aeration section, or external steel or concrete tank(s).

Obtaining water of drinking-water quality may require activated carbon and/or RO membranes. RO can remove salts and specific ions while granular activated carbon (GAC) can adsorb potential fouling compounds upstream of the RO membranes. RO systems are often configured as tubular (Figure 4) or spiral-wound flat plate systems, and are common in desalination applications. In order to effectively determine RO system sizes, efficiencies, and suitability for a specific application, the following water quality parameters must be characterized:

- pH and alkalinity
- temperature
- COD
- TSS
- total solids
- nitrogen species (nitrate, nitrite, ammonia, total Kheldahl nitrogen)
- phosphorus species (orthophosphate and total phosphate)
- ionic species in terms of bulk measures of specific conductance, hardness, metals, and TDS
- metals and ions (aluminum, barium, calcium, chloride, copper, fluoride, iron, lead, magnesium, mercury, potassium, silica, sodium, strontium, sulfur)
- volatile solids and volatile suspended solids.

▲ **Figure 4.** This low-pressure reverse osmosis (LPRO) system can provide up to 650,000 gpd of reclaimed water to a snack foods plant.

In addition to removing salts and ions, RO can remove recalcitrant organic compounds by size exclusion. If the latter is not required, electrodialysis reversal (EDR) can be used to remove salts and ions.

Advanced oxidation processes (AOPs). AOPs can be added to the end of a treatment train to degrade recalcitrant organic compounds, such as pharmaceuticals, personal care products, and industrial compounds. AOPs use two or more components to generate powerful free radicals that oxidize chemicals, and include ultraviolet (UV) light with hydrogen peroxide (H_2O_2), ozone/H_2O_2, ozone/UV, UV with titanium dioxide (UV/Ti), and a variety of Fenton reactions using

Literature Cited

1. **Kenny, J. F., *et al.*,** "Estimated Use of Water in the United States in 2005," http://pubs.usgs.gov/circ/1344/, U.S. Geological Survey, Reston, VA (2009).
2. **U.S. Environmental Protection Agency,** "Guidelines for Water Reuse," Publication EPA/600/R-12/618, EPA, Washington, DC (Sept. 2012).
3. **Pukorius, P. R.,** "Consider Recycled Water for Your Cooling Tower Makeup," *Chem. Eng. Progress,* **109** (2), pp. 24–29 (Feb. 2013).
4. **American Boiler Manufacturers Association,** "Boiler Water Quality Requirements and Associated Steam Quality for Industrial/Commercial and Institutional Boilers," ABMA, Vienna, VA (2005).
5. **Reitz, S.,** "Water Reclamation Facility Coming Online at Storrs Campus," *UCONN Today,* http://today.uconn.edu/blog/2013/04/water-reclamation-facility-coming-online-at-storrs-campus (Apr. 22, 2013).
6. **International Life Sciences Institute,** "Water Recovery and Reuse: Guideline for Safe Application of Water Conservation Methods in Beverage Bottling and Food Processing," www.ilsi.org/ResearchFoundation/RSIA/Pages/WaterRecoveryGuideline.aspx, ILSI, Washington, DC (2013).
7. "Special Section: Energy — Shale Gas," *Chem. Eng. Progress,* **108** (8), pp. 33–64, available at www.aiche.org/resources/publications/cep/2012/august/special-section-energy-shale-gas-full-supplement (Aug. 2012).
8. **Lutz, B., *et al.*,** "Generation, Transport, and Disposal of Wastewater Associated with Marcellus Shale Gas Development," *Water Resources Research,* **49** (2), pp. 647–656 (Feb. 2013).
9. **U.S. Dept. of Energy,** "Produced Water Management Information System," www.netl.doe.gov/research/coal/crosscutting/pwmis/index (accessed Sept. 5, 2012).
10. **Oneby, M. A., *et al.*,** "Ozone Treatment of Secondary Effluent at U.S. Municipal Wastewater Treatment Plants," *Ozone: Science and Engineering,* **32** (1), pp. 43–55 (2010).
11. **Dailey, J.,** "Wastewater Treatment Plant in San Francisco is a Gorgeous Indoor Wetland," Inhabitat.com, http://inhabitat.com/wastewater-treatment-plant-in-san-francisco-is-a-gorgeous-indoor-wetland (Feb. 21, 2011).

iron (Fe/H_2O_2, Fe/ozone, Fe/H_2O_2/UV). These technologies can be used in industrial reuse to reduce the toxicity of an effluent or to process finishing water for high-tech industries. They are also valuable for potable reuse applications because of their ability to remove compounds that are not significantly removed during conventional wastewater treatment processes and to provide pathogen disinfection in addition to conventional disinfection *(2)*.

Disinfection. Disinfection is usually required as a final step in most systems to prevent the regrowth of bacteria and other microorganisms in the recycled water system. Disinfection can be achieved with UV light or with various

Table 3. Comparison of treatment processes and their effectiveness at physically removing (R) and degrading or destroying (D) specific wastewater constituents. Green indicates effective, yellow indicates partial or limited effectiveness, and red indicates not effective. Sources: *(2, 6).*

Unit Process	Relative Cost	Relative Complexity	BOD	TOC	TSS	TDS	FOG	Heavy Metals	Trace Chemicals	Pathogens[e]
Biological Treatment	$	++	D	R	R, D (Partial)	—	R, D	R	R, D (Limited)	R, D (Limited)
Dissolved-Air Flotation (DAF)	$$	++	R	R	R	—	R	R	—	—
Anaerobic Digestion	$$	++	D	D	D	—	D	R	D	D
Microfiltration (MF), Ultrafiltration (UF)	$$	++	R	R (Partial)	R	—	N/A	R	—	R
Reverse Osmosis (RO), Nanofiltration (NF)	$$$	+++	N/A	R	R	R	N/A	R	R[a]	R
Electrodialysis Reversal	$$$	+++	N/A	—	—	R	N/A	R	—	—
Advanced Oxidation Processes (AOP)	$$	+++	—	D[b]	—	—	N/A	N/A	D[b]	D
Chlorination	$	+	N/A	D (Partial)	—	—	N/A	N/A	D (Partial)	D
Ultraviolet Treatment (UV)	$$	+	N/A	—	—	—	N/A	N/A	—	D
Ozone Treatment	$$	++	D	D (Partial)	—	—	N/A	N/A	D[b]	D
Peracetic Acid (PAA)	$	++	D	D (Partial)	—	—	N/A	N/A	D (Partial)	D
Ferrate	$	++	R, D	D	R (Partial)	—	N/A	R	D (Partial)	D
Pasteurization	$$	++	D	—	—	—	N/A	N/A	D (Partial)	D
Granular Activated Carbon (GAC)	$$	++	R	R	R	—	N/A	R	R[c] (Partial)	R (Limited)
Biological Activated Carbon (BAC)	$$	++	R,D	R, D (Partial)	R	—	N/A	R	R, D[c,d] (Partial)	R, D (Limited)
Wetlands	$	++	D	R	R, D (Partial)	—	R, D	R	R, D (Limited)	R, D (Limited)

Notes:
a. The removal efficiencies of RO and NF may be less than 90% for certain chemical constituents, including nitrosodimethylamine (NDMA), 1,4-dioxane, and flame retardants. RO, with smaller-pore membranes, typically offers better removal than NF.
b. Certain compounds, such as flame retardants tris-1-chloro-2-propylphosphate (TCPP) and tris-2-chloroethylphosphate (TCEP), are resistant to oxidants.
c. TOC removal (a surrogate parameter that reflects bulk trace chemical constituent removal) is typically between 40% and 60% for GAC and BAC, compared with greater than 98% for RO and NF.
d. While BAC removes trace chemical constituents, regrowth of microorganisms may result in higher TOC in the effluent if a disinfectant residual is absent.
e. The actual removal or destruction of pathogens varies for each unit process depending on the type (*i.e.,* virus, bacteria, or protozoa), or even species, of pathogen. Furthermore, the dose and contact time (for chemical oxidants) and optimization of the process have large impacts on pathogen removal. Indicative ranges of microbial log reductions reported in the literature for different treatment processes are presented in Table 6-3 of the EPA's *Guidelines for Water Reuse (2).*

chemical oxidants, including free chlorine, chloramine, ozone, peracetic (or peroxyacetic) acid (PAA), ferrate, or bromine. Pasteurization is also an effective disinfection technique for water reuse, and has been demonstrated at the Laguna wastewater treatment plant in Santa Rosa, CA. In many industrial applications, a free-chlorine residual is often maintained to ensure quality throughout piping systems and to disinfect return piping.

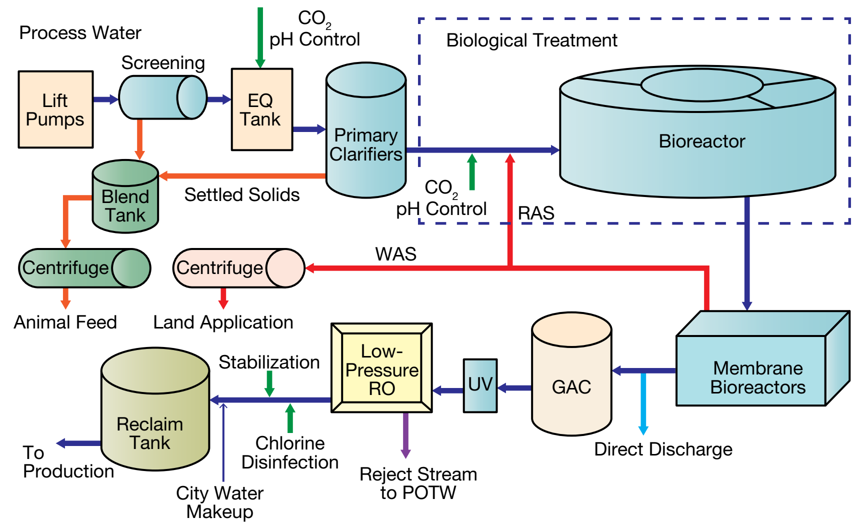
Biological activated carbon (BAC). BAC filtration is an alternative to RO and membrane-based treatment trains where a treatment objective includes removal of recalcitrant organic compounds. BAC is GAC operated as a biological filter — a layer of microorganisms colonizes the GAC surface to allow degradation of adsorbed compounds. When BAC is combined with pre-ozonation (ozone/BAC), ozone first oxidizes bulk organics to lower-molecular-weight compounds, which the BAC's biological process degrades.

BAC controls taste and odor, reduces color, and removes unwanted organic compounds that can react with chemical disinfectants to form byproducts or cause membrane fouling; BAC can also disinfect. Ozone/BAC will not reduce the TDS, so it may not be appropriate for projects where reducing the mineral content in the water is important. Ozone/BAC is already widely used in potable water plants, with about 400 installations in the U.S. and about 3,000 installations worldwide *(10).*

Natural systems. An alternative to conventional wastewater treatment for reuse applications is natural filtration through riverbanks, aquifers, and wetlands. The media in these systems — soil and plants — filter water and in some cases provide a surface for biofilm growth that can biologically oxidize or reduce contaminants *(2).* The San Francisco Public Utilities Commission, for one, uses an onsite wetland system for water reuse treatment *(11).*

Table 3 compares unit processes that can be used to treat wastewater for industrial reuse and their effectiveness at physically removing (R) and degrading or destroying (D) specific constituents in the wastewater.

Figure 5 shows how multiple unit operations may be combined in a typical water recovery and reuse system.



▲ **Figure 5.** This process is designed to produce reclaimed water that meets EPA's primary and secondary drinking water standards — suitable for reuse in food-contact applications.

Final thoughts

As technologies to reduce facility water and energy use have advanced, industry has increasingly embraced the use of reclaimed water for a wide-ranging suite of purposes: from process water, boiler feedwater, and cooling tower use, to flushing toilets and site irrigation. Current technologies produce reclaimed water that can provide the same performance as more-expensive potable water. As water resources become increasingly valued around the world, industrial water reuse is expected to expand. CEP

ALLEGRA K. DA SILVA, PhD, P.E., is an environmental engineer with CDM Smith (Email: dasilvaak@cdmsmith.com), where she was part of the CDM Smith project management team that guided the 2012 update of the U.S. Environmental Protection Agency's *Guidelines for Water Reuse (2)*. With more than 10 years of experience in water, wastewater, and water reuse and over 13 years' experience working on international collaborations, she has been involved in water reuse feasibility and regulatory assignments, assessment of drinking water and wastewater disinfection systems, development of bench-scale testing to validate novel technologies, design of point-of-use drinking water purification devices, and evaluation of wastewater collection systems. Prior to joining CDM Smith, da Silva was a water management advisor at the U.S. Agency for International Development (USAID). She has a BS from Rensselaer Polytechnic Institute in chemical engineering and an MS and PhD from Yale Univ., both in in environmental engineering. She is a licensed professional engineer in Connecticut and a member of the American Water Works Association and the Water Environment Federation.

AL GOODMAN, P.E., is a principal environmental engineer in CDM Smith's Louisville, KY, office (Phone: (502) 217-7938; Email: goodmanaw@cdmsmith.com), where his national and global projects include food and beverage (F&B) industry wastewater treatment plant design and troubleshooting, industrial water reuse, operations training, and expert testimony. He has more than 38 years of experience in F&B industrial wastewater projects, and was responsible for the two most recent and significant process-wastewater-to-drinking-water-quality reuse projects in the U.S., at Frito-Lay and J. R. Simplot. Goodman founded and was CEO of an environmental consulting firm for 20 years before selling it to CDM Smith. He has a BS in chemistry from Bellarmine Univ. in Louisville, KY, is a licensed professional engineer in Indiana, Ohio, and Kentucky, and is a certified industrial wastewater treatment operator. He is a past president of the Water Environment Federation, the Indiana Water Environment Association, and several other professional environmental organizations, and has chaired more than a dozen wastewater and environmental committees.