Biological Drinking Water Treatment? Naturally.

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JESS BROWN, R. SCOTT SUMMERS, MARK LeCHEVALLIER, HEATHER COLLINS, J. ALAN ROBERSON, STEVE HUBBS, AND ERIC DICKENSON

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AT A 2013 AWWA SYMPOSIUM ON BIOLOGICAL TREATMENT OF DRINKING WATER, PRESENTATIONS COVERED A FULL SPECTRUM OF TOPICS; SPEAKERS OUTLINED DIFFERENT PROCESSES, DISPELLED MISCONCEPTIONS, INTRODUCED NEW RESEARCH, AND SUMMARIZED THE REGULATORY ASPECT OF BIOTREATMENT.

In March 2013, AWWA hosted its first-ever Biological Drinking Water Treatment Symposium in Denver, Colo. Approximately 200 utility personnel, academicians, regulators, consultants, and others gathered for two days to learn about the latest developments in and applications of biological drinking water treatment. Session topics covered biofiltration, monitoring tools, membrane pretreatment, passive systems, microbial ecology, trace organic and inorganic contaminant removal, and the latest research developments. The symposium kicked off with a plenary session designed to provide a general overview of biological drinking water treatment and specific discussions on aerobic biofiltration, anoxic biotreatment, natural systems, and regulatory drivers. This article provides a summary of the plenary presentations.

BIOLOGICAL DRINKING WATER TREATMENT

As illustrated in Figure 1, biological drinking water treatment relies on naturally occurring bacteria to mediate the transfer of electrons between reduced compounds (electron donors) such as dissolved organic carbon (DOC) and oxidized compounds (electron acceptors) such as oxygen. These oxidation-reduction reactions may convert contaminants to innocuous or less-toxic end-products.

The first recorded example of intentional biological drinking water treatment occurred in Scotland in the early 1800s, and there have been substantial developments since. Today, biological drinking water treatment processes are generally classified on the basis of (1) whether they are engineered or passive, (2) the design hydraulic loading rate, (3) the redox potential during treatment, and/or (4) the type of natural filtration used (passive systems). Table 1 (modified from Evans 2010) lists the potential effectiveness of these biotreatment classifications for treating various contaminants and identifies whether the associated biotreatment process is solely relied on to control the problem of concern—primary (1°)—or requires other processes to resolve the problem—secondary (2°).

AEROBIC BIOFILTRATION

Overview. ***Process definition.*** Biological treatment within a filter (i.e., a biofilter) at a drinking water treatment facility is an operational practice of managing, maintaining, and promoting biological activity on granular media in the filter to enhance the removal of organic and inorganic constituents before treated water is introduced into the distribution system. Typically, biofilters are rapid-rate filters (RRFs) in conventional surface water or groundwater treatment plants in which biomass has been allowed to accumulate by the control of any predisinfectant, most commonly chlorine, residual in the filter influent. RRFs are typically operated with hydraulic loading rates of 2–15 gpm/ft^2. If granular activated carbon (GAC) is the filter media, biological activity will occur even if chlorine is in the filter influent, as chlorine and ozone are removed by GAC at the top of the filters.

In most US surface waters, there is sufficient oxygen in the source water to serve as the electron acceptor such that the biodegradable organic or inorganic compounds can be oxidized under aerobic conditions. The relationship between electron acceptors and donors is illustrated in Figure 1. For groundwaters, this may not be the case, and preaeration may be needed to maintain aerobic conditions. Slow-sand filters, now considered an alternative biofilter, have a long history of use in the United States. Their major drawback is the large land requirement, as they are operated at hydraulic loading rates of 50 to 100 times lower than RRFs.

Contaminant coverage. An overview of the contaminant removal by biofilters is shown in Table 1.

Organic compounds. Under drinking water conditions, the biomass attached in a filter is supported by an aggregate of biodegradable organic matter (BOM). Use of biofilters in the plant helps to biostablize the water because BOM, the substrate, is removed, decreasing the biological activity in the distribution system. If the source water is not affected by anthropogenic sources, BOM is composed of complex natural organic matter (NOM) fractions—which can serve as disinfection by-product (DBP) precursors—as well as specific organic contaminants (such as geosmin, 2-methylisoborneol [MIB], and microcystins) that are biodegradable.

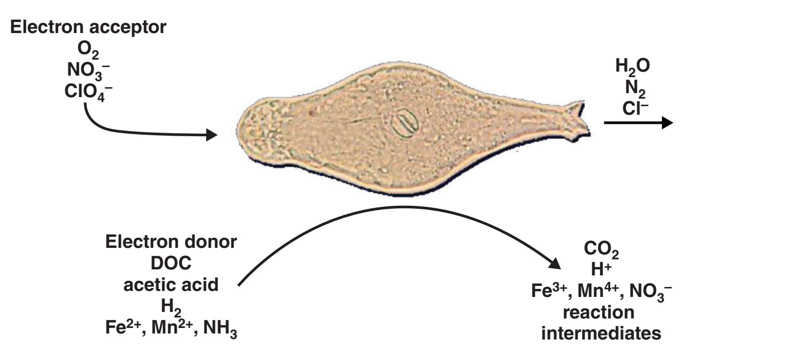
> Though aerobic biofiltration has been in use around the world for decades, there remain common misperceptions about biofilters and whether biofiltration should be considered.

If the source water is anthropogenically affected, then—in addition to the natural BOM—other specific organic contaminants, such as pharmaceuticals and personal care products, can contribute to the BOM. Furthermore, if ozone is used upstream of a biofilter, many of the ozonation by-products (OBPs) created are also biodegradable.

Inorganic compounds. Ammonia, iron, and manganese are the inorganic contaminants most commonly controlled by aerobic biofilters in drinking water treatment.

Applications. ***Traditional.*** The majority of biofilters in use have been converted from existing RRFs. Typically these filters were designed for

FIGURE 1 Bacterial mediation of electron transfer between reduced compounds (electron donors) and oxidized compounds (electron acceptors)



ClO_4^-—perchlorate, Cl^-—chlorine, CO_2—carbon dioxide, DOC—dissolved organic carbon, Fe^{2+}—iron(II), Fe^{3+}—iron(III), H^+—hydrogen ion, H_2—hydrogen, H_2O—water, Mn^{2+}—manganese(II), Mn^{4+}—manganese(IV), N_2—nitrogen, NH_3—ammonia, NO_3^-—nitrate, O_2—oxygen the sole objective of particle removal. Most often chlorine was applied upstream of the filter, and a residual was in the RRF influent. Again, if the media was GAC, bioactivity was occurring in the depth of the filter. To convert a sand or anthracite media–based RRF to a biofilter, the prechlorine dose was decreased or discontinued such that no residual was present in the RRF influent. For many utilities, this conversion was accomplished with little secondary consequences—e.g., effluent turbidity levels below the standard, no excessive head loss buildup, or no additional backwash requirements. However, some utilities have to make operational changes such as reevaluating flocculant/filter aid addition, changing manganese removal processes, and modifying the backwash regime.

Once the chlorine residual is no longer in the influent, biological activity begins immediately because the substrate and naturally occurring microorganisms are present, even if pre-disinfection was practiced, since the nonpathogenic biomass accumulating on the filter and responsible for target compound removal survives the disinfection process. While the biological activity begins immediately, it takes time for the biomass to grow and acclimate to the target substrate. Depending on the assimilable nature of the target compound, acclimation may require days (e.g., OBPs), weeks (e.g., aggregate substrate measured by DOC, shown in the top curve in Figure 2), or several months (e.g., specific contaminants occurring at very low concentrations).

If the media is fresh GAC, and if the target compound is adsorbable, the removal at the start is dominated by adsorption. However, with time the adsorption capacity is exhausted and, as illustrated in Figure 2, bioremoval eventually becomes the dominant removal mechanism. The time to exhaustion and time to bioacclimation depend on the target compound. After adsorption is exhausted, the GAC filter is often termed biologically active carbon.

New developments. The current approach is to design new filters to include biotreatment as a secondary objective. In all cases, particle removal is the primary objective, and the associated microbial control should never be affected such that safe water production is threatened. A well-designed and operated biofilter can accomplish both objectives. The role of the residence time, or empty bed contact time (EBCT), in biofilter effectiveness is becoming more apparent. EBCT is not explicitly used in the design of a filter for particle removal, but increasing EBCT can improve bioremoval. RRFs, with EBCTs of 3 to 20 min, can fully remove easily assimilated

TABLE 1 Biological drinking water treatment classifications and contaminant degradation potential[a,b]

	Generalized Potential Effectiveness				
			Specific organic contaminants		
System Classification	Biological stability (e.g., low assimilable organic carbon)	Natural organic matter, disinfection by-product precursors	Naturally occurring compounds taste and odor–causing (e.g., MIB and geosmin) microtoxins	Synthetic compounds (e.g., ozonation by-products, pharmaceutical and personal care products)	Inorganic compounds (e.g., iron, manganese, ammonia, nitrate, perchlorate)
Engineered systems					
Slow-sand filtration (1º)	High	Moderate	Moderate	High to none	Moderate
Rapid-rate filtration					
Without preozonation	Moderate (1º)	Low to moderate (2º)	Moderate to high (1º–2º)	Moderate to none (1º–2º)	High to none (1º–2º)
With preozonation	Moderate (1º)	Moderate (2º)	High (1º–2º)	High to none (1º–2º)	High to none (1º–2º)
Anoxic biological treatment	Low	Low	Low	Low	High (1º)
Natural systems					
Riverbank filtration (1º–2º)	High	Moderate	Moderate	High to none	Low
Aquifer filtration (1º–2º)	High	Moderate	Moderate	High to none	Low

MIB—2-methylisoborneol

[a]1º = primary removal process—biotreatemt process is solely relied on to control the problem of concern
[b]2º = secondary removal process—requires other processes to resolve the problem of concern

The potentials for treatment effectiveness are solely intended to be used as a general guide and are not intended to be used for design. Actual treatment effectiveness is affected by many factors including the specific contaminant, source water quality and conditions, treatment process design and operation, and presence of specific strains of bacteria.

compounds such as OBPs, and partially remove MIB and DOC. Other more recalcitrant compounds, even when acclimated, need more contact with the biomass to be effectively removed, which is associated with the longer EBCTs of slow-sand filters (5 to 10 h) and riverbank filtration (1 to 100 days).

Low temperature has also been shown to negatively affect biofilter performance. This can be illustrated, using a first-order model (Figure 3), by appropriately decreasing the rate constant at lower temperatures (Zearley & Summers 2012). As illustrated for an EBCT of 7 min, greater than 80% removal of a target compound would be expected at temperatures above 20°C, and 80–15% removal would be expected at temperatures between 20 and 10°C, while at temperatures below 10°C, less than 15% removal would be expected.

Implementation. *Monitoring.* First and foremost, monitoring of the turbidity is needed to ensure the production of safe water. Monitoring of the chlorine residual in the filter influent and backwash water is critical because the presence of chlorine in the influent will render the biofilter ineffective if the media is not GAC. If a groundwater source is used, knowledge of the dissolved oxygen level is needed for effective management. Monitoring of the influent and effluent concentrations of the target compound is needed to assess the performance. From an operational perspective, the head loss development needs to be monitored. Knowledge of the nutrient conditions will help determine whether the biofilter is being run under optimal conditions.

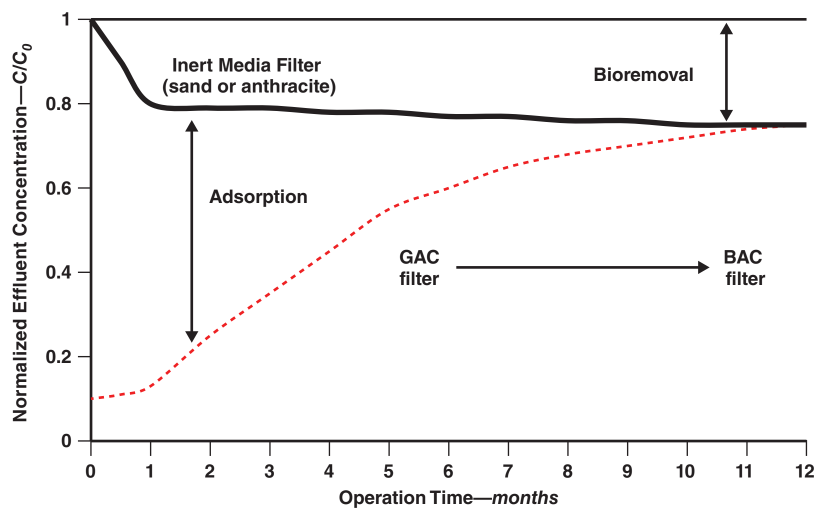
Control. Operating non-GAC biofilters without chlorine residual in the influent is critical to successful performance, which is also facilitated by limiting the chlorine or chloramine in the backwash water. The start-up process of a new biofilter, like that of any filter, needs to evaluate the pretreatment and operating conditions such that particle removal objectives are achieved. These include coagulation, flocculent/filter aid addition, and backwash conditions.

Myth busters. Though aerobic biofiltration has been in use around the world for decades, there remain common misperceptions about biofilters and whether biofiltration should be considered.

It can't be a biofilter because

- *there is no preozonation.* Preozonation is not required for a biofilter. There is enough BOM in surface waters to support biological activity in a filter. Preozonation will increase the BOM concentration by oxidizing nonbiodegradable organic matter to easily biodegradable organic matter. Depending on the treatment objective, this can be beneficial, but it is not required and may not be economical.

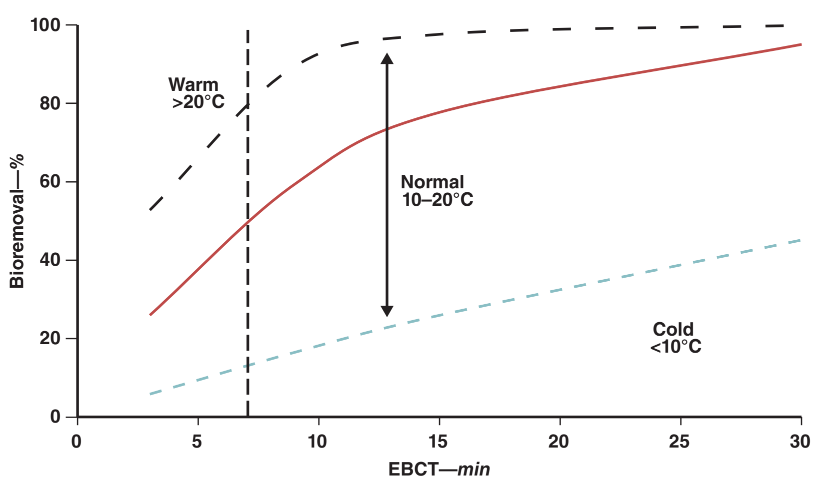
FIGURE 2 Acclimation to all RRF media types and transition from GAC[a] to BAC[b]



BAC—biologically active carbon, C/C_0—effluent concentration divided by the influent concentration, GAC—granular activated carbon, RRFs—rapid-rate filters

[a]Adsorption and bioremoval
[b]Bioremoval only

FIGURE 3 Impact of temperature on bioremoval of a range of contaminants



EBCT—empty bed contact time

- *there is a chlorine residual in the influent.* The critical issue is whether there is a chlorine residual in the effluent. In nearly all cases with inert media, like sand and anthracite, a chlorine residual in the influent will likely preclude the development of biological activity. If the media is GAC, a chlorine residual in the influent will not stop the development of biological activity in the filter, as chlorine reacts with GAC and is totally consumed in the first few inches of the media, allowing biomass to develop in the rest of the filter. All GAC filters are biofilters.
- *the backwash water has chlorine or chloramines.* Backwash water with a chlorine or chloramine residual will stymie, but not stop, the development of biological activity in the filter. This will likely lead to diminished performance for BOM removal.

I don't want a biofilter because

- *all microbes are bad because they cause diseases or taste and odor.* Not all microbes are pathogens, nor do they all cause taste and odor. Microbes will grow and slough off of biofilters, but biofilters are followed by disinfection before finished water leaves the plant.
- *biofilters will lead to higher effluent turbidity or clog my filter and lead to shorter run times.* If the operating conditions are optimized, biofilters can successfully meet effluent turbidity standards and filter run-time criteria. These optimized operating and design conditions can be developed during pilot-plant testing.
- *they are too difficult to operate.* Once biofilters are in place and optimized operating conditions are established, biofilters do not present unachievable challenges. Like all new treatment processes, training and operating experience are critical to the successful implementation of biofilters.

ANOXIC BIOTREATMENT

Overview. *Process definition.* Anoxic biotreatment involves the addition of an electron donor/carbon source (substrate), which bacteria use under low-oxygen conditions to degrade oxidized compounds (e.g., nitrate). Also distinct from aerobic biofiltration is that these processes are designed around biological contaminant degradation—not particle removal. Anoxic bioreactors can either be heterotrophic, in which organic carbon (e.g., acetic acid or ethanol) is dosed as an electron donor and carbon source, or autotrophic, in which an inorganic compound is dosed as an electron donor (e.g., hydrogen or sulfur), and inorganic carbon is added for cell synthesis (e.g., carbon dioxide). Anoxic bioreactor systems can treat a wide range of contaminants, including nitrate, perchlorate, bromate, selenate, chromate, and some volatile organic compounds.

Drivers. Though full-scale anoxic biotreatment plants have been on-line in Europe for more than 30 years, there have been limited applications in the United States. However, recent trends and drivers may change that. These include (1) the rising costs and increasing complexities of handling water treatment residuals (e.g., ion exchange brine), (2) water scarcity and the need for agencies to better leverage their own water sources, (3) the push for green technologies (biotreatment processes typically use low energy and efficiently destroy contaminants instead of concentrating them), and (4) increasing regulatory attention and support for anoxic biological processes.

Reactor configurations. *General.* There are common design considerations for all anoxic bioreactor processes, including (1) selection of media on which biofilms develop (e.g., GAC, sand, plastic, membranes), (2) substrate selection and dose, (3) nutrient dose (phosphorus, micronutrients), (4) method for biomass control, and (5) contact time. Another important consideration is the implementation of downstream treatment. In general, downstream treatment is designed to reoxygenate the water, remove any residual electron donor (particularly applicable to heterotrophic processes), filter bioreactor effluent turbidity, and disinfect. Anoxic bioreactor processes are most often configured as fixed beds, fluidized beds, or membrane-based reactors, though there are other anoxic bioreactor configurations and approaches (e.g., continuous stirred tank reactor-based systems, systems that use specialized biological media).

Fixed bed. Fixed-bed bioreactors use a stationary media bed, such as sand, plastic, GAC, or expanded clay, on which biofilms develop (similar to aerobic biofiltration). The granular media can be contained in pressure vessels or open basins. Raw water is amended with an organic substrate and then flows by gravity or is pumped across the media bed. As contaminants are degraded, growing biofilms accumulate and cause pressure drop across the bed. Thus, fixed-bed bioreactors are routinely taken off-line and backwashed to remove excess biomass from the system.

Fluidized bed. In fluidized-bed anoxic bioreactor configurations, water is pumped up-flow through the reactor to fluidize the biofilm-coated granular media (approximately 25–30% bed expansion). A portion of the bioreactor effluent flow is recycled and blended with raw water to provide the necessary fluidization velocity. An organic substrate is dosed to the combined feed flow. Excess biomass is removed from the media bed through fluid shearing forces and/or by in-line mechanical biomass/media separation devices. Thus, though fluidized-bed bioreactors require higher feed-flow capacity, they do not require an off-line backwashing step.

Membrane based. Membranes can also be used to support biofilm growth. In this case, hydrogen (electron donor) and carbon dioxide (carbon source) are delivered across a gas-transfer membrane and diffuse directly into the biofilm attached to the other side of the membrane. The membranes are submerged in a reactor vessel through which raw water passes, and contaminants diffuse from the bulk water into the biofilms, where they are degraded. Occasionally, the membranes may be chemically cleaned to remove excess biomass.

Implementation. ***Monitoring.*** Multiple parameters can be monitored in-line to provide real-time feedback on anoxic bioreactor health and performance. For example, nitrate/nitrite and perchlorate analyzers can be used to directly quantify contaminant removal and to determine the appropriate substrate dose. Raw water dissolved oxygen (DO) can be monitored as part of the substrate dose calculation, and treated water DO is monitored to track reoxygenation efficacy. Turbidity is typically measured in the system effluent to ensure that biomass stays within the treatment process, thereby limiting any demand on the final disinfection step.

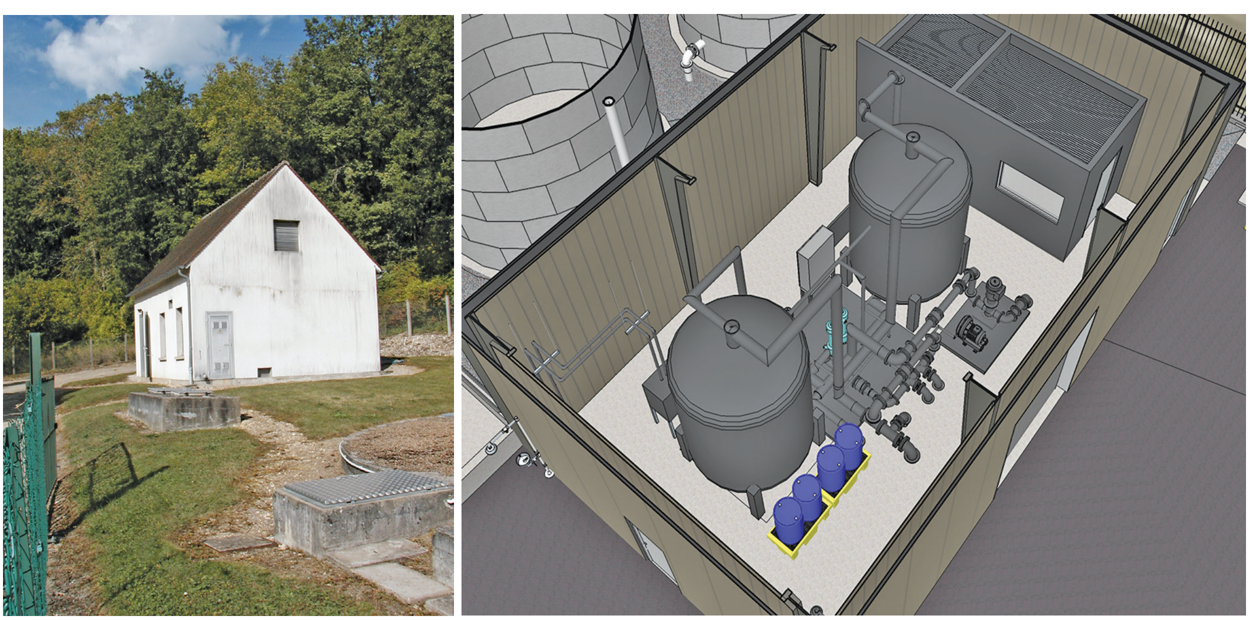
Control. Anoxic bioreactor processes rely on the addition of an external substrate to meet contaminant removal goals. Therefore, a robust chemical feed system must be integrated that not only ensures consistent substrate delivery, but also monitors raw water quality and adjusts the substrate dose as necessary. The biomass control strategy is also an important consideration, as it affects bioreactor hydraulics, which in turn drives the efficiency and efficacy of treatment. Depending on the specific bioreactor configuration, these methods may include backwashing, in-line biomass/media separators, or in-place chemical cleans.

Myth busters. While there is rapidly growing interest in anoxic biological treatment, there are limited anoxic bioreactor applications in the US drinking water industry today. In part, this is due to a handful of pervasive myths:

- ***Anoxic biological treatment applies only to wastewater.*** Dozens of successfully operating anoxic biotreatment drinking water facilities have been in operation in Europe for decades (Figure 4, part A), mainly treating for nitrate. Several biodenitrification drinking water treatment plants are being designed or are under construction in the United States (Figure 4, part B).
- ***Specialized microbial inocula are required.*** Naturally occurring bacteria from the target raw water provide the necessary microbial community. No specialized inoculum is required.
- ***Regulators will never approve full-scale anoxic biotreatment for drinking water.*** Anoxic biotreatment plants have been approved for full-scale applications in Oklahoma, Texas, California, and Minnesota. Regulatory agencies in other states

FIGURE 4 Full-scale, well head biodenitrification plant[a] (A) and 3-D model of a full-scale, well head biodenitrification plant[b] (B)

A B



3-D—three-dimensional

[a]Located in France
[b]Under construction in California's Central Valley

are also considering anoxic biotreatment applications.

- ***A substantial disinfection step is required to treat anoxic bioreactor effluent.*** Anoxic biotreatment does not increase the risk of pathogen occurrence. Low chlorine contact times have been shown to effectively disinfect effluent from anoxic biotreatment systems.
- ***The addition of an organic electron donor will lead to problems with DBP formation potential.*** A properly designed and operated anoxic bioreactor process does not increase DBP formation potential. This may mean that post-treatment processes are designed to account for substrate carryover from the bioreactor process.
- ***Anoxic biological treatment is not applicable in cold climates.*** While low temperatures tend to slow biodegradation kinetics, anoxic biotreatment can be effective even under cold-water conditions (Figure 5). Bioreactor contact time may need to increase to account for the slower biodegradation kinetics.

NATURAL BIOTREATMENT SYSTEMS

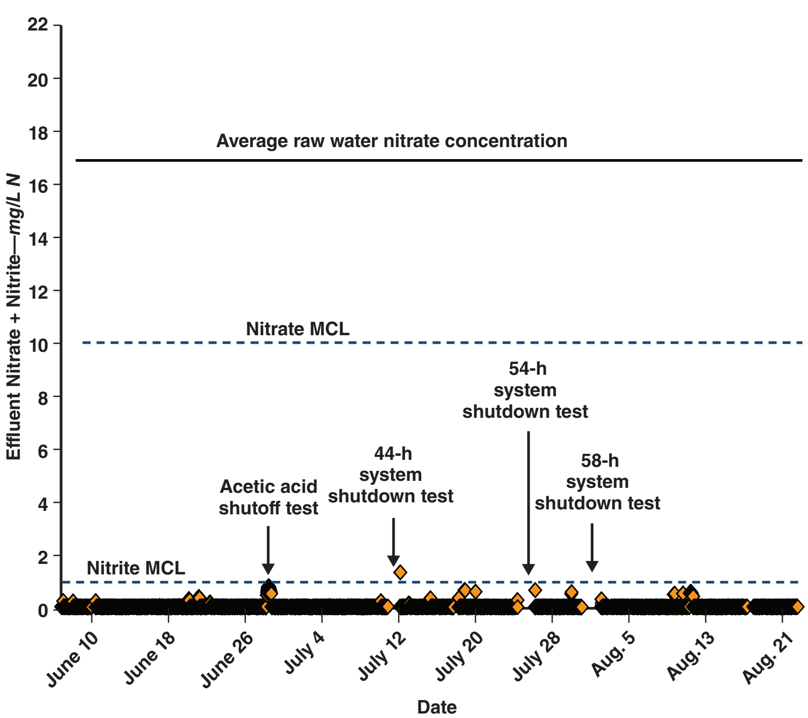
Background. Natural biological treatment processes include riverbank filtration (RBF), soil aquifer treatment, and aquifer storage and recharge. In these natural systems, the biological process is essentially uncontrolled except for the flow rate through the given media, which is controlled through the amount of water pumped out of (or into) the system. Thus, the microbes responsible for reducing the organic loading in the system originate from the source water and filtration media, and vary over time with the temperature and food source provided by the source water.

Once stable, a natural sequence of biodegradation is established as a function of travel time between source water and point of extraction, with the depletion of the food source (organics) and biochemical electron acceptors (typically oxygen, nitrate, sulfate, in sequence of travel) as the source water travels toward the point of extraction. If the time of travel is adequate, and oxygen, nitrate, and sulfate electron acceptors are depleted, the remaining organic food source may be converted to methane gas by microbial fermentation. These biotreatment regimes are illustrated in Figure 6 for a typical RBF process, with richly oxygenated source water progressing across the riverbed (aerobic degradation) and through the aquifer to an end point of methane production (methanogenesis).

System hydraulics. An understanding of hydraulic flow regimes in natural systems is important when interpreting organic reduction processes. Figure 7 illustrates the continuum of flow lines in a riverbank system in which travel times and water velocities can vary by orders of magnitude depending on the particular flow line. Shorter flow lines may have travel times to the point of extraction of less than one day, while the longer flow lines may have travel times in the hundreds of days. In lakebed systems, in which infiltration rates are typically much lower, the travel time between source and extraction can be years.

While travel times in natural systems can be expressed in terms of averages, the impact of the travel time on biological treatment along various flow lines is significant. The extent of organic removal and the specific types of organics removed greatly depends on the depletion of the electron acceptors (oxygen, nitrate, sulfate) and the subsequent microbial populations that become established in the aquifer (aerobic, anoxic, and anaerobic). Along the shortest flowpath, one might expect that most of the oxygen is depleted (which in RBF typically happens within feet of travel distance into the

FIGURE 5 Sustained biological nitrate removal and robustness treating groundwater at ~10°C

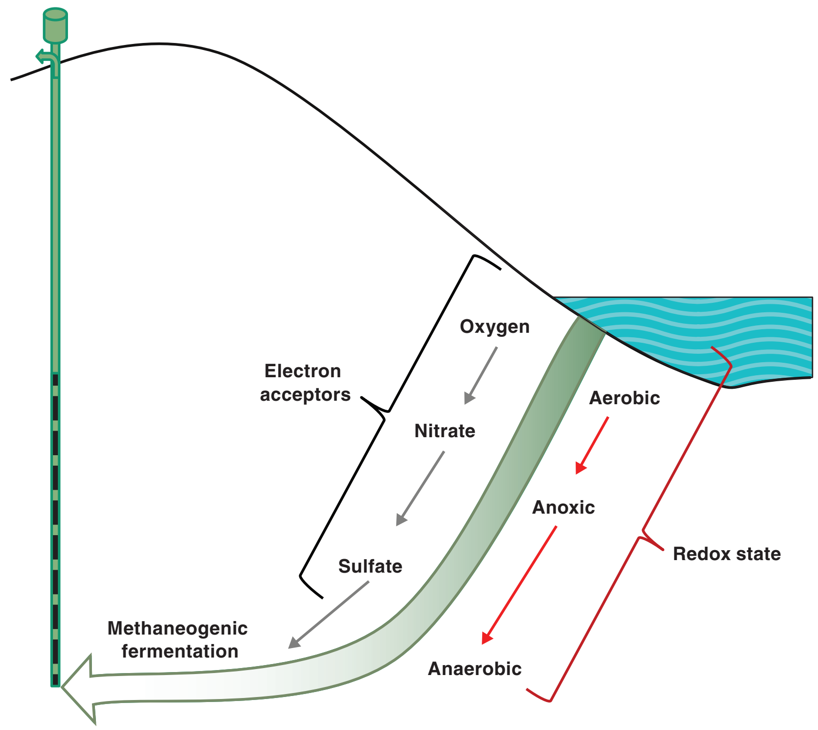


MCL—maximum contaminant level, N—nitrogen riverbed), and that organic reduction may not be as complete as might occur on the longer flowpaths. Thus, those organics that are easily biodegradable under aerobic conditions (such as the bulk measure of assimilable organic carbon) may be significantly removed along this shorter flowpath, while organics that require a greater amount of time and a less aerobic state of biodegradation (such as atrazine) may be poorly removed along this short flowpath. Conversely, along the longer flow lines in which oxygen and easily degradable organics are depleted, organics that are more resistant to biodegradation may be substantially removed.

The varying time of travel between source water and extraction due to flowpath hydraulics also provides a challenge for interpreting water quality when considering short-term contamination events, because the pulse of contamination in the stream is attenuated by the waters of various ages at the point of extraction. Dilution due to the time lag along flow lines will result in a much lower concentration of contamination than is seen in the river regardless of whether any biodegradation occurs at all. Dilution of the source water peak with land-side groundwater must thus be considered when interpreting water quality changes during short-term contamination events.

Temperature and hydraulics add a level of complication in natural systems because the viscosity of water increases (i.e., becomes "thicker") as water temperature decreases, resulting in a decrease in aquifer conductivity (i.e., ease with which water flows). In systems that experience a wide range of temperature variation (such as RBF), water temperatures at the point of infiltration can vary significantly, in some instances from near freezing to 90°F. This large temperature range results in a significant seasonal variation in the contribution to well-discharge volume along various flow lines, as contribution along shorter (colder) flow lines decreases in winter. Average

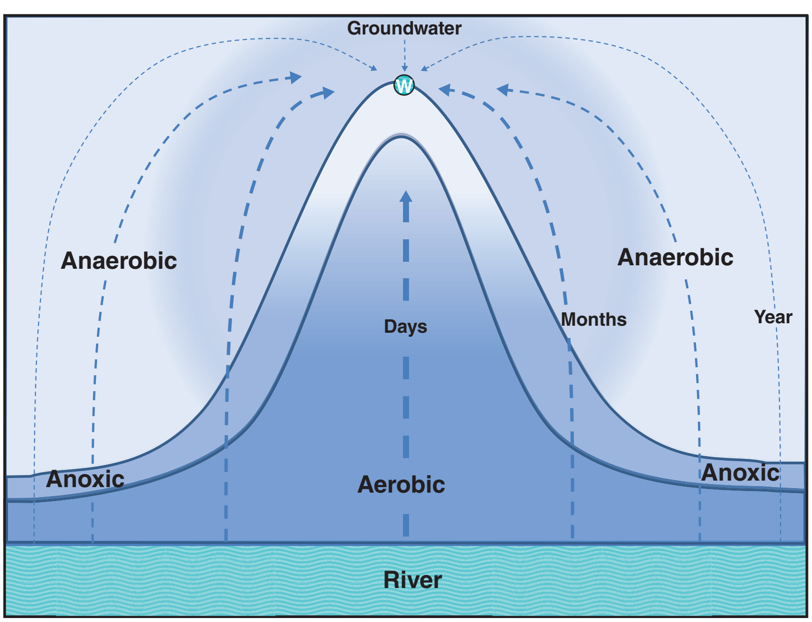
FIGURE 6 Biologic regimes in RBF



RBF—riverbank filtration

RBF acts like a plug-flow bioreactor.

FIGURE 7 Flow patterns and biologic regimes in RBF systems



RBF—riverbank filtration

well-discharge temperatures have been observed to "lag" source water temperatures by as much as three months, while along longer flow lines this lag can extend to beyond a year. Along the six-month flow line, water reaching the well is warmest in winter, thus resulting in a greater contribution to overall well output.

The impact of temperature and hydraulics on contaminant removal can be illustrated by considering the example of an atrazine spike after a short-term spring-rain runoff event. In the relatively cold stream water, surface water levels of atrazine may peak and fall within a few days, while the well is drawing water primarily along warmer flow lines of weeks and months of travel time. This results in less infiltration along shorter flow lines and a significant dilution of the atrazine spike as the aquifer is charged with atrazine-laden water. Along the longer flow lines, atrazine is significantly removed over a longer period of weeks to months. It is not uncommon for a short-term peak of 1 µg/L of atrazine in the river source to result in no observed increase in the RBF discharge.

Biodegradability of contaminants. The ease with which contaminants are biodegraded depends on chemical structure. In aerobic (oxygen-rich) systems, chemical compounds with "weaker" organic bonding are easily biodegraded and yield a relatively large amount of energy for biomass sustainability. In natural systems, this can be quantified as the assimilable organic carbon, which if not removed in treatment can support biofilm production in the distribution system. On the other end of the spectrum of biodegradability are compounds based on stronger chemical bonds, with atrazine providing the example. Table 2 provides a list of chemicals by ease of biodegradability for a soil aquifer treatment system with predominant conditions from oxic to anoxic. Many of the chemicals that are only marginally biodegradable with days of travel time are significantly removed with weeks of travel time.

In the RBF example, the oxygen and easily biodegradable compounds are found at the point of infiltration into the riverbed. The biochemistry in this zone is similar to slow-sand filtration, in which a great deal of biologic activity occurs near the surface of the filter. As the easily biodegradable compounds and oxygen are depleted, biological regimes capable of surviving in more hostile environments with lower-energy food sources tend to predominate. Along the longer flow lines, the less biodegradable compounds provide the food source for anoxic and anaerobic microbes.

Types of natural biological treatment systems. RBF is one of the more prevalent natural biological systems used for water supply, with systems dating back 100 years still in use. There are other examples of natural biological systems:

- Aquifer storage and recovery, in which water is fed directly into an aquifer for later extraction
- Soil aquifer treatment, in which surface water or reclaimed wastewater is placed in lagoons to recharge aquifers
- Infiltration galleries, in which collection pipes are laid in shallow trenches along a riverbank and backfilled with permeable media

Myth busters. ***Any filtration system will eventually clog.*** In RBF systems, riverbed scouring is critical to indefinitely maintaining a productive infiltration rate. Most natural streams with sand bottoms attain adequate scouring velocities to continuously scour the stream bed. Systems that are not characterized by a continuously scoured infiltration surface require management for sustainable production.

Water quality varies greatly depending on which well is turned on. This phenomenon is common when multiple wells are placed perpendicular to the riverbank as opposed to being spaced parallel along the riverbank. In this situation, the landward-most wells will receive a much greater contribution of groundwater (with higher levels of hardness) than will those wells closest to the river. A thorough understanding of

TABLE 2 Removal of indicator chemicals

Good Removal	Intermediate Removal	Poor Removal
>90%	**90–25%**	**<25%**
Two- to three-day travel time		
Atenolol	DEET	Carbamazepine
Caffeine	Gemfibrozil	Meprobamate
Triclosan	Ibuprofen	Sulfamethoxazole
	Naproxen	
Two-week travel time		
Atenolol		Carbamazepine
Caffeine		
DEET		
Gemfibrozil		
Ibuprofen		
Meprobamate		
Naproxen		
Sulfamethoxazole		
Triclosan		

Source: Drewes et al. 2011

DEET—*N,N*-diethyl-*meta*-toluamide

well-field hydraulics will help identify these types of problems.

HOW REGULATIONS PLAY INTO THE MOVEMENT TOWARD BIOTREATMENT

Water systems typically consider multiple factors, including regulations, when evaluating treatment options for a new and/or upgraded treatment plant. How regulations play into the movement toward biotreatment is not always a linear path. Regulations can be one of several factors affecting the trend; they are not necessarily the only factor. Water systems sometimes use a multi-attribute analysis when evaluating future treatment technologies, and regulations are typically considered as one of the attributes.

With regard to the penetration of new technologies into the water sector, regulations have been a driver in water sector adaptation of a specific treatment technology in some cases, such as ultraviolet light for *Cryptosporidium* inactivation under the Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR, 71 FR 654). However, many water systems installed ultraviolet treatment as protection against potential *Cryptosporidium* contamination—not because of the LT2ESWTR requirement. So while regulatory requirements can be a technology driver, many water systems install a specific treatment technology to meet a system-specific water quality objective that is independent of any regulatory requirement.

Since the initial Safe Drinking Water Act (SDWA) was passed in 1974, the US Environmental Protection Agency (USEPA) has finalized 19 national primary drinking water regulations (NPDWRs) that address 91 contaminants—a broad range of chemical and microbial contaminants.

The 19 regulations fall into two general groups determined by chronology—nine regulations that were finalized before and 10 that were finalized after the 1996 SDWA Amendments. The first nine regulations significantly increased the number of regulated contaminants from 22 in 1975 to 84 in 1992, almost quadrupling the number of regulated contaminants in 18 years (USEPA 2001). Most of these regulations were numerical maximum contaminant levels (MCLs) with compliance typically based on an annual average of quarterly samples. The Lead and Copper Rule and the Surface Water Treatment Rule had some complicated regulatory elements, but most systems were able to implement compliance strategies for these two regulations over time.

> An understanding of hydraulic flow regimes in natural systems is important when interpreting organic reduction processes.

The 10 regulations finalized after the 1996 SDWA Amendments are more complex regulations from two perspectives:

- The regulations address contaminants that are more difficult to treat, such as arsenic and radium. More complicated treatment technologies such as coagulation/microfiltration or ion exchange are needed, and residual-disposal issues can be complex.
- The regulations have more complex compliance monitoring requirements such as the locational running annual average in the Stage 2 Disinfection By-Products Rule (DBPR, 71 FR 388).

One additional wrinkle in the federal regulatory development process beyond the typical MCL is the treatment technique (TT). When there is no reliable method that is economically and technically feasible to measure a contaminant, USEPA establishes a TT for control of that contaminant. USEPA has developed TTs for several different contaminants in the 19 NPDWRs.

From a treatment technology perspective, USEPA lists the technologies that achieve compliance with the MCL/TT for each regulation/contaminant. USEPA publishes a list of best available technologies (BATs) for each regulation/contaminant. Biological filtration, biological treatment, or biotreatment have not been specifically listed as BATs in any of the 19 NPDWRs. While not listed as a BAT, biotreatment has been used for compliance with past regulations:

- Riverbank filtration in the toolbox for the LT2ESWTR
- Biofiltration after the use of ozone to comply with the Stage 2 DBPR
- Biological iron and manganese treatment to comply with the secondary standards for those two contaminants

Biotreatment will likely be a strategy to help some systems comply with future regulations. What USEPA is going to regulate, what the MCLs will be, and when the regulations will be finalized is a collection of moving parts that are always changing. Further complicating future regulatory predictions, USEPA is facing many resource challenges for all of its regulatory programs, including drinking water. Declining resources will likely lead to more regulatory delays and uncertainties. However, regulations addressing the contaminants listed here are possible or probable in the next five years, and biotreatment will likely be a treatment option for some of them:

- Carcinogenic volatile organic compounds
- Perchlorate
- Chlorate
- Strontium

At this time, it is not clear whether unregulated trace organics such as pharmaceuticals and personal care products and cyanotoxins will be regulated in the near future, if at all.

Biotreatment for compliance with drinking water regulations raises a couple of issues that need additional research and then some technology transfer so that utilities and regulators understand the nuances of biotreatment. First, consensus is needed on measuring biological stability after biological filtration and after determining an appropriate level of stability. Second, reducing contaminants with the addition of a carbon source is new to the drinking water community, and permitting can be challenging. Regulators and operators need to develop a comfort level with the design and operation of carbon addition for biotreatment.

Biotreatment has the potential for helping utilities achieve compliance with several future drinking water regulations, but more work is needed to increase the comfort level for utilities and regulators. Additionally, many water systems have system-specific water quality goals outside of the regulations, and biotreatment is one treatment strategy that can be used to meet those system-specific goals.

CONCLUSION

Biological processes can efficiently treat a wide range of drinking water contaminants and may provide several advantages over "conventional" treatment processes. More stakeholders in the drinking water community need to develop a deeper understanding of biotreatment—both natural and engineered systems—because there are several "myths" that are based on misunderstandings, and they need to be corrected. As more and more hard-to-treat contaminants are regulated, biotreatment is a treatment option that should be fully evaluated as part of a water system's compliance strategy.

ABOUT THE AUTHORS

__Jess Brown__ (to whom correspondence may be addressed) is director of Carollo Engineers' Research and Development Practice, 3150 Bristol St., Ste. 500, Costa Mesa, CA 92626 USA; jbrown@carollo.com. He leads Carollo's biological drinking water treatment program and has 17 years of experience in developing, testing, and implementing biological processes for drinking water applications. Brown was chair of the 2013 AWWA Biotreatment Symposium; is a former chair of the AWWA Biological Drinking Water Treatment Committee; a trustee for the AWWA Water, Science, and Research Division; and is chairing the 2016 AWWA Biotreatment Symposium (January 27–28, Long Beach, Calif.; the AWWA Reuse Symposium is January 25–26, also in Long Beach). He received a BA degree in environmental science and public policy from Harvard University, Cambridge, Mass., and a BS degree in civil engineering and MS degree and PhD in environmental engineering from the University of Illinois Urbana–Champaign. __R. Scott Summers__ is a professor at the University of Colorado, Boulder. __Mark LeChevallier__ is director of innovation and environmental stewardship at American Water in Voorhees, N.J. __Heather Collins__ is manager of water treatment at the Metropolitan Water District of Southern California in Los Angeles. __J. Alan Roberson__ is director of federal relations at AWWA in Washington, D.C. __Steve Hubbs__ was vice-president of water quality and production (now retired) at Louisville Water Co., Ky. __Eric Dickenson__ is the R&D Project Manager, Southern Nevada Water Authority, Henderson, Nev.

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