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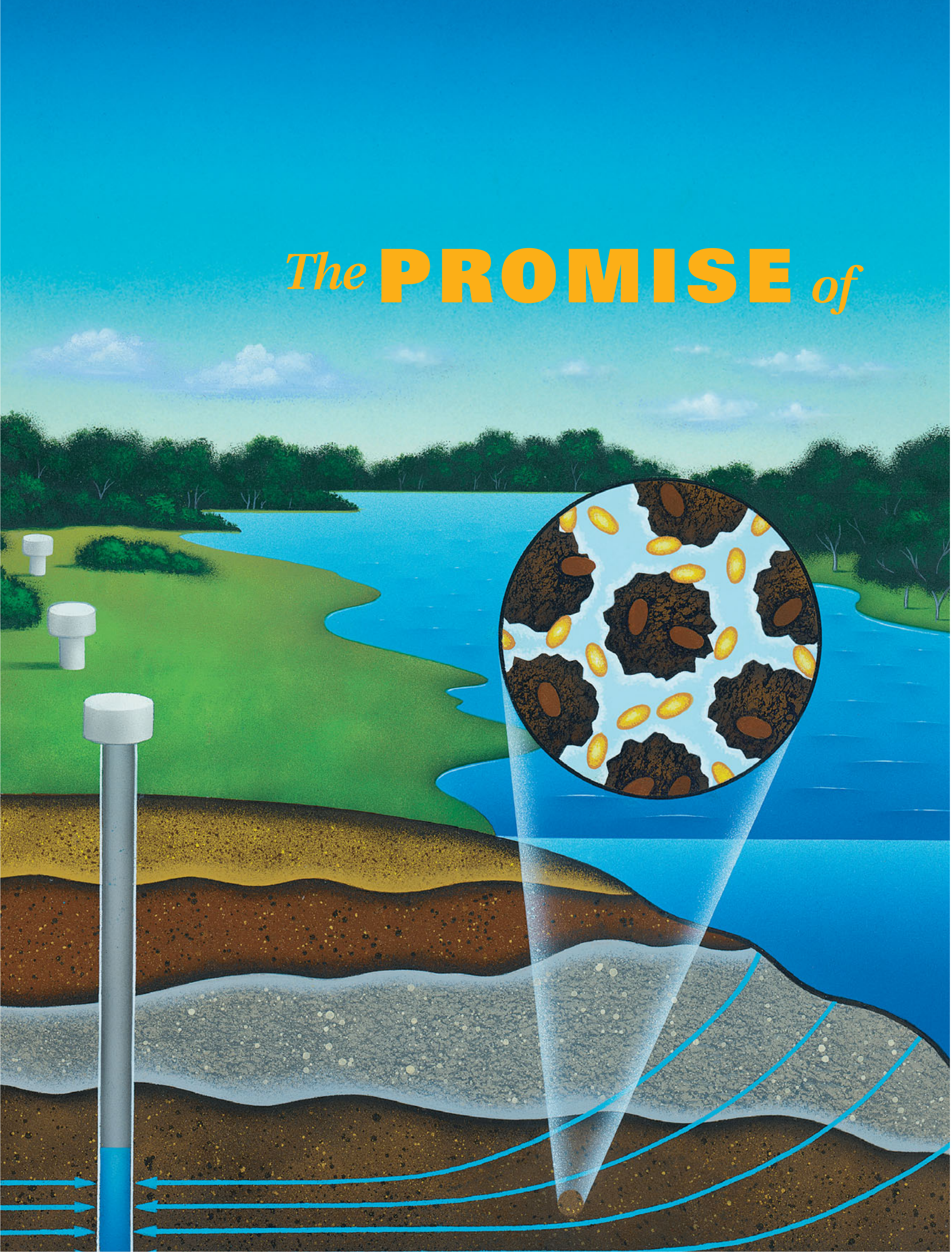

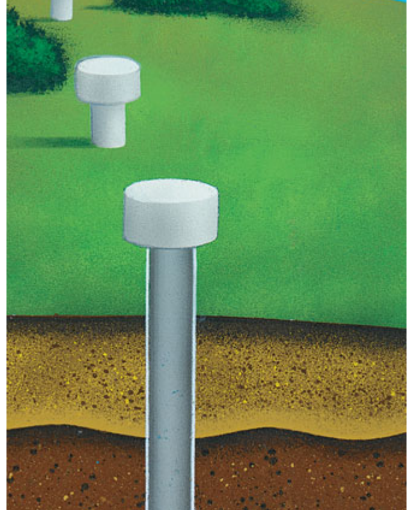

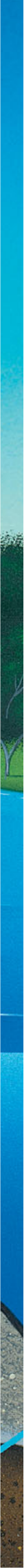

Bank FILTRATION

A simple technology may inexpensively clean up poor-quality raw surface water.

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Clean drinking water is one of the most pressing global environmental and health problems of our time. As the world's growing population puts greater demands on the available supply of high-quality drinking water, water utilities have developed new technologies for treating waters of degraded quality, such as membrane filtration, soil aquifer treatment, and advanced oxidation. But an old method called riverbank filtration is increasingly being used because it is a relatively inexpensive and sustainable means to improve the quality of surface waters (see Figure 1). Much like the reactive barriers currently being used to remediate contaminated groundwater, bank filtration provides passive exposure to various processes—such as adsorption, reduction, physicochemical filtration, and biodegradation—and produces water that is relatively consistent in quality and easier to treat to higher levels of finished quality.

The effectiveness of bank filtration has long been recognized in Europe. Many utilities in North America are interested in bank filtration because it has the potential to remove pathogenic microbes from surface water, thus improving raw water quality and reducing costs of in-plant conventional treatment. However, the complex setting of alluvial valley aquifers makes interpretation of the limited data on microbe transport during bank filtration a daunting task. Aside from quantifying the effectiveness of riverbank filtration in these diverse and heterogeneous hydrogeological settings, water

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utility engineers and scientists must learn how to predict the removal of pathogenic microbes and other key contaminants in the riverbank environment so that regulators can establish reasonable standards.

A European history

Some European countries use this technology to augment the removal of natural organic matter (NOM), organic contaminants, and pathogenic microbes from as much as 80% of their drinking water (Netherlands, 7%; Germany, 16%; Hungary, 40%; Finland, 48%; France, 50%; Switzerland, 80%) (*1–5*). In the rest of the world, bank filtration is not as common because surface water and groundwater of adequate quality are more readily available.

Scientists and engineers have only recently begun to understand the complex geochemical, biological, and hydrologic factors that control contaminant removal during bank filtration. On the basis of a century of successful riverbank filtration in Europe and improved understanding of the contaminant removal processes, utilities outside Europe are moving to capitalize on the benefits of riverbank filtration. In most European countries, there are no specific regulations regarding the implementation of bank filtration; rather, local authorities recommend guidelines to water utilities to help ensure acceptable drinking water quality. In the United States, EPA and state environmental agencies are reluctant to grant "credit for riverbank filtration", which would allow a reduction in the amount of in-plant treatment to remove pathogenic microbes and other contaminants, without results showing the effectiveness of riverbank filtration. Moreover, most utilities are reluctant to invest in the site-specific testing needed to demonstrate that riverbank filtration is effective. Current efforts to address the regulation of bank filtration focus on the removal of microbial pathogens and are contained in a preliminary draft of EPA's Long-Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) (*6*).

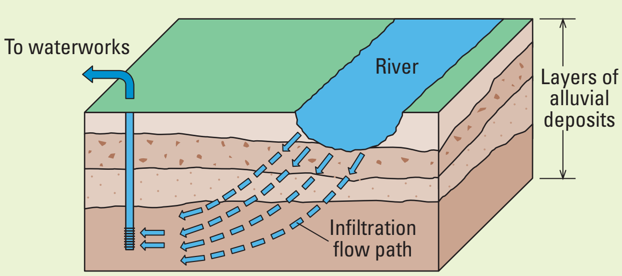
Alluvial valley aquifers are natural filters

Riverbank filtration is typically conducted in alluvial valley aquifers, which are complex hydrologic systems that exhibit both physical and geochemical heterogeneity. In most alluvial valley aquifers, sand and gravel predominate, but floodplain deposits also leave layers of silts and clays in the stratigraphy (*7*). The size, uniformity, and distribution of aquifer sediments are dependent on the type and source of the original rock and on the degree of glacial or fluvial action (*8*). Both grain size and distribution of sediments are particularly important characteristics with respect to permeability and filtration efficiency. For example, permeability may be especially low in the upper layers of the riverbed owing to deposition of fine sediment, a condition that may lead to particle straining and may vary seasonally with the river sediment load.

FIGURE 1

A schematic illustration of riverbank filtration

A wide range of contaminants are naturally filtered as surface water flows from the river through an alluvial valley aquifer to the pumping well. This process reduces the amount of treatment needed at a drinking water plant.



The hyporheic zone as a biogeochemical reactor

The interface between surface water and groundwater within alluvial valley aquifers has been recognized as a distinct biogeochemical environment. This dynamic transition zone or "hyporheic zone", commonly characterized by gradients in light, temperature, pH, redox potential, oxygen, and organic carbon, controls the quality of bank filtrate (*9*). As water infiltrates through the riverbank into the aquifer, it experiences chemical changes described by four general types of reactions: electron transfer, weathering, ion exchange, and gas exchange (*10*). In numerous studies, the most significant chemical changes were related to microbial activity, such as degradation of organic matter or organic pollutants, and were found to occur in the early stages of infiltration (*1, 11, 12*). When this intense microbial activity in the riverbed sediments consumes more oxygen than is supplied by the infiltrating river water, a "reduced zone" develops (*1, 11, 12*).

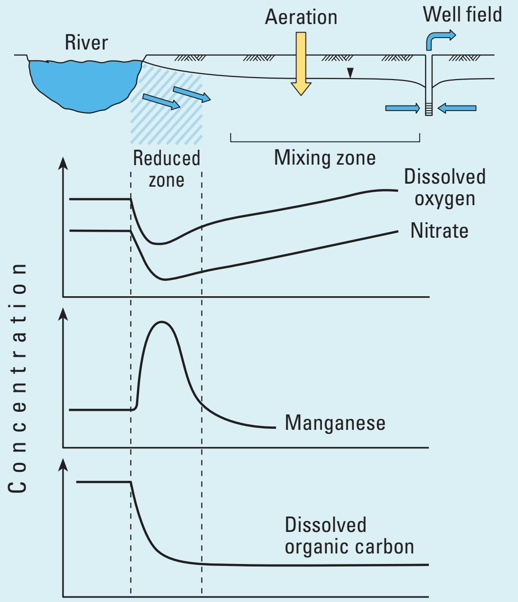
Figure 2 qualitatively illustrates how oxygen becomes significantly depleted in the bed sediments after only a few meters of filtration. Under these anoxic conditions, the microbial activity of denitrifying and sulfate-reducing bacteria further decreases the redox potential of the system (*1*). The resulting highly reduced environment usually affects the stability of mineral surface coatings (*12, 13*), such as ferric and manganese oxyhydroxides, that often play an important role in the natural filtration of microbial pathogens (*14, 15*). In addition, mobilized manganese and iron can lead to a significant deterioration of water quality (*16*). Thus, although the riverbed sediments may act as an effective filter medium in removing various water contaminants, the development of the reduced zone can be detrimental to the quality of bank filtrate.

At a certain distance from the river's edge, where microbial activity diminishes as a result of a deficiency in electron donors and the aquifer is reaerated, the reducing conditions decrease in intensity (*12*). Manganese and iron can then be removed from solution by a series of precipitation reactions. Hence, the breadth of the reduced zone can be determined by considering the evolution of manganese and iron along the infiltration flow path. The location of this zone, however, may exhibit spatial and temporal variability due to seasonal fluctuations in microbial activity and water-pumping patterns in the well field (*11*).

FIGURE 2

Water chemistry changes when moving away from the river

A schematic diagram qualitatively depicts the evolution of dissolved oxygen, nitrate, dissolved manganese, and dissolved organic carbon in the infiltration flow path during riverbank filtration.



Source: Adapted from Reference (*12*).

Riverbank sediment clogs during infiltration

Microbial activity may also decrease permeability at the surface water–groundwater interface as a result of biofilm formation (*17*). Increasing evidence shows that the accumulation of biofilm extracellular polymeric substances, as well as bacterial cells and their gaseous degradation products, can reduce the hydraulic conductivity of the sediment layers (*17, 18*). The retention of fine particles (<2 mm) in hyporheic interstices is another major contributor to the clogging of riverbank sediments (*9, 19*). Under low-flow conditions, the settling of fine particles can cause external clogging of the riverbed. More important, internal clogging of the interstices directly below the gravels and stones of the uppermost "armor" layer may form a slight seal that separates surface water from hyporheic water (*19*). Finally, fine particles that penetrate the armor layer but do not contribute to clogging the upper layer may be transported deeper into the interstitial layers of the alluvial aquifer by a process referred to as depth filtration (*19*). Although clogged riverbank sediments may increase the efficiency of natural filtration, the loss in permeability can significantly reduce the productivity of the well field.

Removing natural organic matter

NOM is a complex mixture of dissolved and particulate humic and nonhumic organic substances. The motivation for removing NOM during bank filtration is threefold: NOM contributes to odor and the deterioration of taste in drinking water, can facilitate the transport of toxic contaminants in groundwater, and is the main precursor for disinfection and oxidation byproducts. Different components of NOM exhibit different transport behavior during surface water infiltration. Several studies have indeed demonstrated that the mobility of NOM in the subsurface increases with decreasing molecular weight and hydrophobicity (*20–22*). These results suggest that the smaller and more hydrophilic fraction of NOM may dominate the NOM-facilitated transport of contaminants in groundwater.

Retention time is another important factor controlling the removal efficiency of riverbank filtration (*2, 23*). Figure 3 illustrates the influence of subsurface retention time on the mean annual dissolved organic carbon concentrations of bank filtrate from the Rhine River (*23*). The data clearly demonstrate the favorable effect of increased retention time on water quality. However, the influence of dilution with groundwater must also be considered, as it becomes particularly significant for wells located farther from the river.

Degrading organic contaminants

Groundwater is particularly vulnerable to contamination by organic compounds, especially if biological transformations are slow because of lower temperatures and decreased enzymatic activity (*24*). Thus, numerous studies have focused on the fate of organic pollutants such as herbicides, pesticides, pharmaceuticals, and odorous compounds during riverbank filtration (*23–30*).

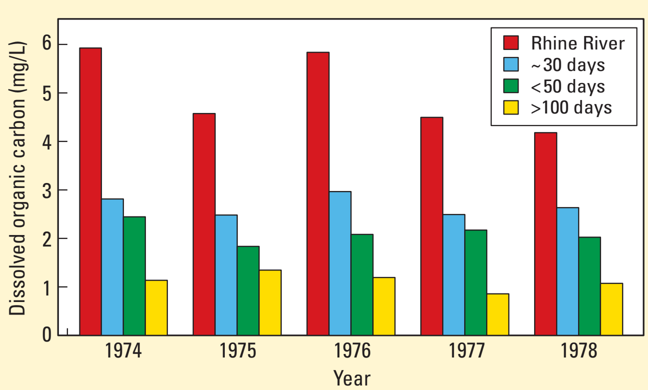
Juttner investigated the efficiency of riverbank filtration in eliminating odorous compounds in the Ruhr River in central Germany (*27*). Up to 99% of the more polar contaminants (e.g., linalool, isobornyl acetate, and menthol) were removed in the anoxic part of the aquifer. Natural odorous compounds (geosmin) were also effectively eliminated.

In a similar study conducted at the River Neckar in southwestern Germany, Juttner demonstrated the efficiency of riverbank filtration in reducing the concentrations of fragrance compounds (e.g., menthol, limonene, α-terpineol) and aromatic hydrocarbons

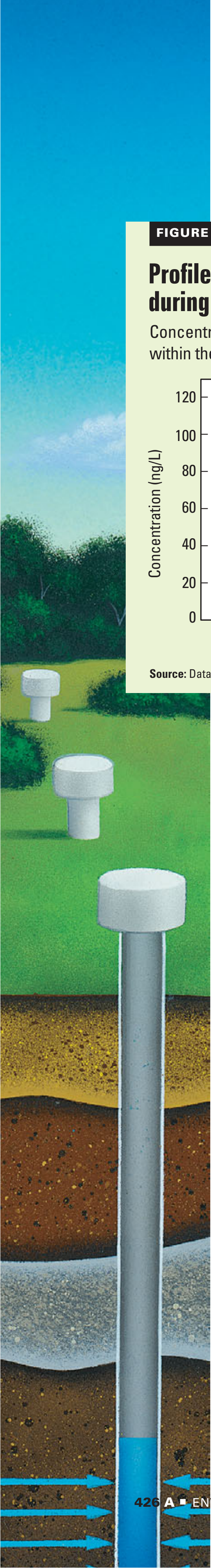
FIGURE 3

Mean annual dissolved organic carbon in the Rhine River

Riverbank filtration causes concentrations (measured in milligrams per liter) to decrease with retention time.



Source: Data from Reference (*23*).

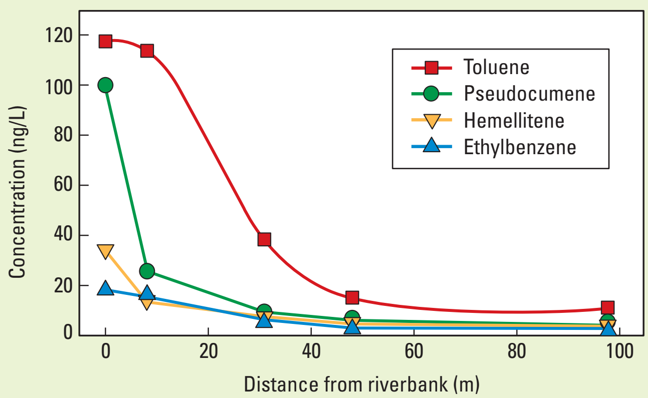


(*25*). Figure 4 illustrates the importance of the first few meters of the aquifer with respect to microbial degradation of such contaminants. These observations are consistent with those made by Schwarzenbach et al. at the River Glatt in northern Switzerland concerning compounds such as alkylated and chlorinated benzenes (*26*). However, Schwarzenbach and colleagues also identified a group of organic chemicals (chloroform, 1,1,1-trichloroethane, trichloroethylene, and tetrachloroethylene) that were resistant to biological transformation and thus ineffectively removed by riverbank filtration. Indeed, some compounds are less affected by natural filtration, such as certain pesticides (*24, 29, 31*), pharmaceuticals (*2, 30, 32*), and halogenated organic compounds (*23, 28*).

FIGURE 4

Profiles of aromatic hydrocarbon concentrations during riverbank filtration from the River Neckar

Concentrations measured in nanograms per liter decreased rapidly within the first few meters of filtration, but leveled off after 50 meters.



Source: Data from Reference (*25*).

Several studies have shown that certain organic contaminants are less prone to removal during riverbank filtration, but very few have addressed plausible explanations for this disparate behavior. Although it is well known that removal of organic contaminants is dependent on compound hydrophobicity and the organic carbon content of aquifer material, other factors such as sorption onto inorganic minerals, microbial activity, biodegradability, rate of infiltration, and dilution with groundwater also play an important role.

Behavior of inorganic pollutants

Human activities such as mining, wastewater discharge, road salting, and agriculture often lead to elevated concentrations of inorganic contaminants in surface waters. Pollutants such as heavy metals, nitrate, and sulfate are harmful to humans and animals, but may also be toxic to microorganisms that play an important role in controlling the quality of bank filtrate (*33*). Hence, the mobility and fate of dissolved inorganic contaminants during surface water infiltration have been studied extensively (*5, 10–13, 33–36*).

Several interacting processes control the transport, fate, and reactivity of inorganic pollutants in bank filtration, including sorption, precipitation, redox reactions, complexation with organic matter, microbial degradation of NOM, and dilution (*10–12, 33, 34, 37*). The effects of individual mechanisms on the transport behavior of different metals were studied on the banks of the Glatt River (*10, 34*). Results suggest that microbial degradation of organic matter mobilizes metals, such as copper and cadmium, which are known to strongly associate with NOM. On the other hand, oxide-forming metals, such as manganese, are readily mobilized because of decreased redox potential and subsequent reductive dissolution of manganese oxyhydroxides. Under more oxidizing conditions, which are typically found at the outer limit of the surface water–groundwater interface and at extended distances from the river, sorption onto or coprecipitation by manganese oxides could significantly inhibit the transport of trace metals (*33*). Adsorption or precipitation onto aquifer sediments has been identified as an important removal mechanism for metals such as zinc and cadmium (*10, 12, 34, 35*).

Natural filtration of microbial pathogens

Surface waters are often contaminated with microbial pathogens as a result of discharges of municipal wastewater effluents, as well as runoff of livestock wastes and from fields receiving manure. Under certain conditions, these pathogens may be effectively removed by underground passage of surface water. In EPA's proposed LT2ESWTR, riverbank filtration has been recognized as one way to improve *Cryptosporidium* removal (*38*). EPA is proposing to grant additional *Cryptosporidium* treatment credit to water utilities using bank filtration that meet a set of specified design criteria (*6*). Because the efficiency of this natural filtration process depends on site-specific factors—such as raw water quality, characteristics of the bed sediments, and retention time—there is no standard protocol for assessing bank filtration credit. Thus, each site must be evaluated separately (*2*).

The fate and transport of pathogenic microorganisms in the subsurface are controlled by several processes, including advection, dispersion, physicochemical filtration, straining, inactivation, dilution, and possibly grazing by higher trophic levels (*8*). Of these, physicochemical filtration and inactivation are believed to play a significant role in the removal of microbes from the pore fluid. Several filtration mechanisms, which are highly dependent on the pathogen size, govern particle removal. These mechanisms include gravitational sedimentation, interception, and Brownian diffusion. In gravitational sedimentation, the gravitational forces acting on the microbe cause it to settle onto a grain "collector". In interception, the microbe's size and trajectory are such that it will encounter the collector grain while flowing past it. Through a diffusion mechanism, the microbe is brought into contact with a collector because of its Brownian motion (*39*). Microbes can also be inactivated on the grain surface and in bulk solution or detached from sediment grains.

The most commonly used model for describing particle filtration was developed by Yao et al. (*40*). In this approach, the removal rate of particles is expressed in terms of a single collector efficiency, η, and a collision (or attachment) efficiency, α. The parameter η represents the frequency at which approaching particles will strike the collector grain, whereas α is the probability that such collisions will result in attachment. Brownian diffusion is the dominant mechanism responsible for bringing viruses into contact with sediment grains because of their small size (typically <200 nm). On the other hand, the filtration of microbial pathogens such as *Cryptosporidium* oocysts (4–6 μm) and *Giardia* cysts (9–12 μm) is controlled by interception and gravitational sedimentation. According to filtration theory, microbes on the order of 1 μm in size, such as bacteria, experience the fewest collisions with sediment grains and, hence, exhibit the greatest mobility.

The design criteria specified by EPA in LT2ESWTR are based on conservative estimates drawn from colloid filtration theory and an analysis of microbial monitoring data from existing bank filtration sites. Only unconsolidated, granular aquifers—which means those comprising sand, clay, silt, rock fragments, and pebbles—would be eligible for bank filtration credit (*6*). EPA proposes that horizontal and vertical wells drilled into these types of aquifers would be eligible for 0.5 log (68%) removal credit or 1.0 log (90%) removal credit when located at least 25 or 50 feet (7.6 or 15.2 m) from the source, respectively.

A summary of microbial removal data obtained from various field studies on riverbank filtration in the Netherlands is presented in Table 1. According to these data, riverbank filtration effectively removes bacteriophages, which are considered to be good surrogates for pathogenic viruses. Interestingly, the degree of removal of the various microorganisms is remarkably similar at the three sites in the Netherlands for a travel distance of about 25–30 m from the river, despite large variations in retention time. This result contradicts predictions based on colloid filtration theory, which suggest that microbial transport is dependent on pore water velocity (or retention time for a given travel distance), and is surprising because the inactivation of microbial pathogens is known to depend on retention time. Hence, the data in Table 1 demonstrate how the confluence of various hydrological and biogeochemical factors, such as variations in pore water velocity, degree of groundwater dilution, solution chemistry, aquifer media surface characteristics, and inherent heterogeneities in the microbial population, can significantly complicate predictions of microbial transport.

The concentrations of parasitic protozoa such as *Cryptosporidium* and *Giardia* in surface waters are commonly much lower than those of other microorganisms, including algae, diatoms, crustacea, and rotifers, and are therefore hard to detect with current analytical techniques. Thus, using these microorganisms as surrogates and bioindicators plays an important role in evaluating the natural filtration efficiency and hence the risk of cyst or oocyst breakthrough at a particular riverbank filtration site. A major problem associated with the use of surrogates and bioindicators is the lack of data correlating the occurrence of *Cryptosporidium* and *Giardia* with other microorganisms found in groundwater (*8*). Schijven et al. present data which show that diatoms often concurrently appear with cyst or oocyst breakthrough at different riverbank filtration sites (*41*). One advantage of using algae and diatoms as surrogates is that they have the same size range as cysts and oocysts. In fact, in a study completed for Casper Public Utilities (Casper, Wyo.), algae was selected as a surrogate indicator for *Cryptosporidium* and *Giardia* (*8*).

Hydrology influences performance

The growing body of recent field-scale investigations suggests that bank filtration can be an effective means of improving the quality of surface waters (*23, 25–27, 42, 43*). However, the dynamic nature of these complex hydrologic systems is a major obstacle for the reliable implementation of this technology.

The transient behavior of the river stage influences the flow and transport characteristics of the system, which may, in turn, affect the quality of the bank filtrate. For example, a rise in river level can result in water infiltrating a previously unsaturated region, which may not exhibit the same removal properties as the permanently saturated zone (*44*). Variability in pore water velocity and the corresponding retention time, caused by changes in both the hydraulic gradient and the alluvial hydraulic conductivity, may also limit biogeochemical activity in the hyporheic zone (*45*). Furthermore, in a study conducted in the riverbed of the Rhine River at the Flehe waterworks in central Germany, Schubert et al. found that the river flow dynamics influenced the breadth and permeability of the clogged regions (*44*). These findings may have serious implications for the efficiency of bank filtration and the productivity of the well field.

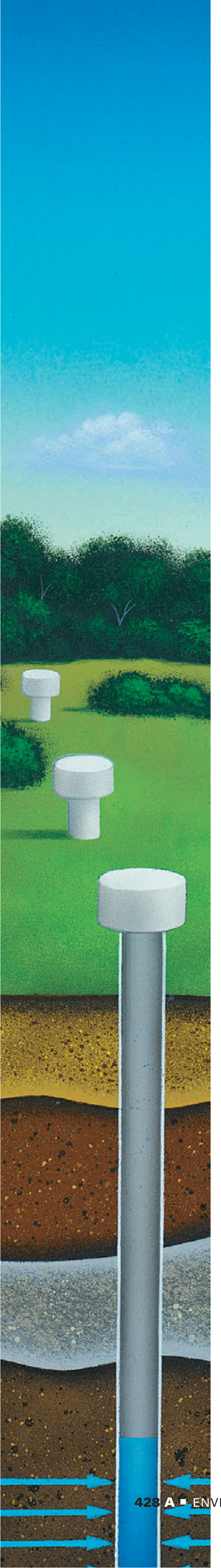
Diurnal or seasonal fluctuations in surface water temperature also contribute to the temporal heterogeneity of alluvial aquifers (*45*). Because the rate of most biogeochemical processes is highly sensitive to temperature, variations in water temperature may lead to decreased microbial activity. Suboptimal temperatures may result in a poorly developed reduced zone, ineffective degradation of NOM and organic contaminants, and a decline in the clogging of sediments by biofilm formation. Changes in water temperature can also affect the rate of infiltration into

TABLE 1

Log removal of microorganisms at three different riverbank filtration sites in the Netherlands

	Rhine River at Remmerden	Meuse River at Zwijndrecht	Meuse River at Roosteren		
Travel distance (m)	30	25	13	25	150
Travel time (days)	15	63	7	18	43
F-specific RNA bacteriophages	6.2	5.7	3.9	6.0	—
Somatic coliphages	—	—	3.8	5.1	7.8
Enteric viruses (Enterovirus and Reovirus)	4.0	4.0	3.7[a]	—	—
Total coliforms	5.0	5.0	—	—	—
Spores of sulfite-reducing clostridia	3.1	3.6	3.3	3.9	5.0
Fecal streptococci	3.2	3.5	—	—	—

Source: Data from References (*41–43*). [a] Reoviruses only.



the alluvial aquifer (*46*). With a rise in temperature, water viscosity decreases, and therefore, hydraulic conductivity increases (*45, 47*). The dynamic nature of conditions and processes at the surface water–groundwater interface suggests that feasibility and performance studies of a riverbank filtration facility should be conducted over extended time periods (*44*).

Future prospects

Despite a century of use in Europe, the mechanisms for removal of dissolved, particulate, and microbial contaminants by bank filtration are still not well understood. A better understanding of contaminant transport and fate is key to efficient design, operation, and optimization of bank filtration schemes in conjunction with subsequent treatment processes.

In addition, because of the varying physical and geochemical settings, interpretation of the limited data on microbe transport in bank filtration is a daunting task. Assessing microbe transport for bank filtration on a case-by-case basis is a discouraging prospect, but we need not accept this. Instead, we should work toward gathering a more detailed understanding of the fundamental processes that govern microbe transport in porous media, especially those related to physically and geochemically heterogeneous porous media. With better understanding, and some relatively simple characterization of hydraulic and geochemical conditions in alluvial valley aquifers, we should be able to make useful predictions for screening alluvial valley aquifers as candidates for bank filtration of pathogenic microbes.

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