Significance of eutrophication in water supply reservoirs

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Key relationships between eutrophication of surface water supplies and the costs and quality of finished water are reviewed, with an emphasis on problems relating to organics. Data from lakes and reservoirs in the United States indicate a positive correlation between total phosphorus and total organic carbon measurements. In view of this correlation and results of controlled laboratory studies reported in the literature, nutrient enrichment is a significant factor contributing to organohalide problems in surface water supplies. Watershed management for control or reduction of phosphorus export is suggested as a potentially significant and cost-effective means of dealing with organics-related problems. Regionally calibrated empirical models can be used in conjunction with appropriate reservoir and watershed monitoring data to assess the extent, significance, and controllability of water quality problems related to phosphorus export and eutrophication.

Reservoir water quality is a complex function of its morphometry and watershed characteristics, including climate, hydrology, geology, morphology, and land uses. Rational planning and operation of water supply systems requires recognition of the cause-effect relationships that influence water quality and, therefore, influence the feasibility and costs of supplying water that meets state and federal standards and criteria. The trend toward increasingly restrictive drinking water standards can be attributed to increased scientific understanding of the relationships between drinking water quality and health and to vast improvements in analytical capabilities, particularly with respect to organics.[1] Given this trend and the current and projected water-supply shortages in many areas of the country, the protection or enhancement of source water quality will become increasingly critical.

Watershed management programs are potentially cost-effective in relation to treatment schemes that may be required to meet finished water quality objectives.[2] For example, the expenses involved in constructing and operating a new filtration plant, which may become necessary as a result of increasing turbidity concentrations in a reservoir, seem likely to exceed the costs of stabilizing certain eroding areas of a watershed. The influence of watershed erosion on suspended solids and turbidity concentrations in a downstream reservoir is a cause-effect relationship that is easily grasped, although factors other than erosion (e.g., algal growth or iron released from anoxic sediments) could also contribute to high turbidity levels. Although source protection is important for all water suppliers, it is especially critical for small systems. Because of the considerable economies of scale associated with water treatment costs,[3] the unit costs of additional treatment, which may be required to offset degrading source quality or to meet new, more restrictive standards, are likely to have larger economic impacts on smaller systems, especially if new capital investments are required.

Management of watersheds for quality protection has been hindered by limited knowledge of the factors and processes involved in nonpoint source pollution and reservoir dynamics. The state of the art in these areas has improved considerably in the past ten years, although these improvements are not reflected widely in current policies and practices. Scientific understanding of eutrophication, which results from the discharge of excessive levels of aquatic plant nutrients into water bodies, has advanced to the point of providing predictive models that have been used widely in managing recreational lakes.[4] This article reviews some of the key effects of eutrophication on water supplies, with a focus on organics.

General effects of eutrophication

There are several direct and indirect relationships between eutrophication and water supply operations, as indicated in Figure 1. These relationships can be outlined in three general categories: (1) impacts on water within the impoundment; (2) impacts on water utility operations; and (3) impacts on water users.

Nutrient enrichment of a reservoir and the resulting increases in algal growth can have the following direct effects on the quality of water within the impoundment:[5]

- Increases in particulate organic substances, such as phytoplankton, zooplankton, bacteria, fungi, and detritus;
- Algal population shifts toward more undesirable types (e.g., blue-greens);
- Increases in dissolved organic compounds that (a) have chelating or complexing properties, (b) impart tastes and odors, (c) increase color, (d) are potential organohalide precursors, (e) provide substrate for bacterial growth in treatment plants and distribution systems, or (f) may contribute to corrosion problems;
- Increases in pH and its daily fluctuations; and
- Depletion of oxygen in the sediment-water contact area, causing incomplete mineralization of organic substances and release of hydrogen sulfide, ammonia, phosphorus, iron, manganese, other metals, methane, and other reduced organic compounds into the water column.

These water quality changes can have direct and indirect effects on water supply operations and treatment costs.

- The effects on flocculation include: hindrance of floc formation by dissolved organics; increased chemical and operation costs for pH control; and breakthrough of algae and other particulates.
- The effects on filtration include: required construction resulting from increased turbidity; increased clogging with algae and other particulates; reduced filter run times; and increased water loss and energy costs in backwashing.
- The effects on disinfection include: increased chlorine demand owing to organic matter and ammonia; decreased effectiveness owing to higher turbidities; and increased formation of chlorinated hydrocarbons, including trihalomethanes, resulting from reaction of chlorine with dissolved organics.
- The effects on distribution include: regrowth of bacteria owing to increased organic content; increased taste-odor problems owing to organic decomposition; and increased iron and manganese deposition.
- The effects on other mitigating measures and costs include: monitoring of reservoir for problem *identification;* monitoring for control of treatment processes; special treatment for iron-manganese removal; special treatment to prevent algal intrusion, for taste-odor

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control, and for trace organics control; reservoir algicide applications; and reservoir aeration.

Finally, potential effects on water users include increases in the following:

- Complaints about taste and odor;
- Risk of exposure to potentially toxic and carcinogenic organic compounds;
- Risk of exposure to potentially pathogenic bacteria;
- Plumbing and clothing replacement costs related to iron-manganese deposition and organics-related corrosion;
- Treatment costs for quality-sensitive industrial users; and
- Fees for use of water, to pay for increased costs incurred by water utility.

Although factors unrelated to eutrophication can influence the frequency and severity of the occurrence of each of these problems, the cause-effect linkages to nutrient loading are extremely important.[5,6] Given these relationships, watershed management for minimization of nutrient export should be considered an essential part of water supply operations.

Organics

The formation of trihalomethanes (THMs) in water supplies has been shown to result from the reaction of chlorine applied in disinfection processes with naturally occurring organic materials in water supplies.[7] Because of the widespread occurrence of natural organics in water supplies and common chlorination practices, it is not uncommon for finished waters to exceed the US Environmental Protection Agency's maximum contaminant level of 100 μg/L of total THMs/L.[3,8] In a recent survey of water supplies in New York state, Schreiber[9] found that THM levels exceeded 100 μg/L in 55 out of 235 supplies sampled at the tap.

At a given pH, temperature, chlorine dose, and reaction time and for a given initial distribution of organic compounds, THM formation has been shown to be a first-order reaction in terms of total organic carbon (TOC).[10] Although humic and fulvic acids have received the most attention as organic precursors to THMs, other substances are also important, including algal biomass and algal extracellular products.[11,12] Humic substances generally result from the decay of plant matter and are partially of algal and aquatic plant origin.[13,14]

At a given chlorine dose, temperature, and TOC level, THM yield has been shown to increase with pH.[15] Under eutrophic conditions, algal activity consumes carbon dioxide present in the water and tends to increase the pH, often to levels exceeding a pH of 9.[13] Water treatment operations may respond to higher algal activity by increasing chlorine doses used to control increased biological growths in the plant and to satisfy increased chlorine demand in disinfection. The above factors suggest that the potential impacts of increased algal growth on THM levels are greater than those indicated by the stoichiometric increases in organic matter or precursor.

Phosphorus as a controlling factor for organics

Many studies have identified significant empirical relationships between phosphorus concentration and various indicators of algal growth in lakes and reservoirs, including chlorophyll-*a*, transparency, and hypolimnetic oxygen depletion rate.[16-20] Smith[21] identified a strong linear relationship between growing season phosphorus concentration and primary productivity in lake photic zones, expressed in grams of carbon per cubic metre per day. Figure 2 shows the relationship between median total phosphorus and median TOC concentrations measured in 38 US lakes and reservoirs, based on data derived from the literature[22,23] and from a database on reservoirs operated by the US Army Corps of Engineers.[24] The regression equation explains 85 percent of the variance in the TOC data on a logarithmic scale.

The relationship between median chlorophyll-*a* and median TOC is shown in Figure 3, based on data for 20 of the 38 lakes and reservoirs. Chlorophyll-*a* data were not available for the remaining 18 water bodies. Although the regression is significant, chlorophyll-*a* explains only 56 percent of the TOC variance. Smith[21] also found that the carbon productivity rate correlated better with total phosphorus (R^2 = 0.94) than with chlorophyll-*a* (R^2 = 0.81). Hoehn et al[11] correlated water supply THM levels with chlorophyll-*a* measurements from one water source, the Occoquan Reservoir. Although a significant relationship was apparent in data from one year, it did not hold in other years. The sources of reservoir organic carbon must be considered in order to interpret these results.

Reservoir TOC levels are derived from a combination of allochthonous supplies (originating in the watershed) and autochthonous supplies (generated as a result of photosynthesis in the reservoir).[13] The former include relatively stable humic materials (color) originating in drainage from organic soils and wetlands,[25] as well as organics that are scoured or eroded from land and impervious surfaces during runoff periods. Autochthonous supplies include live and dead algal cells, dissolved organics released by algae in various phases of growth, higher-level organisms (zooplankton, fish), and dissolved and particulate organics resulting from bacterial decomposition of algae, higher organisms, and their metabolic products. The relative importance of autochthonous carbon sources would be expected to increase with the hydraulic residence time of a lake or reservoir, because longer residence times would permit more opportunities for the decay of allochthonous carbon and for growth of algae and aquatic plants.

The relatively weak correlation between chlorophyll-*a* and TOC or THM measurements is not surprising in view of the fact that algae typically comprise only a small fraction (less than 10 percent) of the TOC pool.[13] Although algae may be an important source of the allochthonous organic carbon in a lake or reservoir, they generally comprise only a small fraction of the standing crop. Both the concentration of algal biomass and the ratio of chlorophyll-*a* to algal biomass vary with season and environmental conditions, whereas the TOC pool is more stable. The accuracies of median chlorophyll-*a* values estimated from limited sampling are also low relative to phosphorus values, because chlorophyll-*a* measurements tend to be more variable in time.[26]

Use of alternative data reduction procedures may shed more light on these relationships. The median values employed here are based on samples taken at various depths and seasons. Epilimnetic, growing season values may only show stronger correlations, although these are not immediately available from existing data summaries. Significant correlations among organic nitrogen, total phosphorus, and chlorophyll-*a* also have been identified for reservoirs operated by the US Army Corps of Engineers.[20]

The strong correlation of TOC levels with phosphorus most likely reflects the importance of autochthonous carbon sources, limitation of algal growth by phosphorus, and distribution of phosphorus among both the algal and the nonalgal TOC pools. Residual errors are attributed to sampling variables, to effects of growth limitation by nitrogen or light in some reservoirs, and to variations in allochthonous carbon levels. In a phosphorus-limited reservoir, autochthonous organic carbon levels are related directly to phosphorus loadings, which depend, in turn, on watershed climate, soils, topography, land use, and management practices.

Although direct measurements of THM precursors are required for precise quantification of the problem, nonpurgeable organic carbon (NPOC) and TOC have been suggested as useful surrogate indicators of potential THM production.[3,27] Additional data and analysis would be required to determine whether a similar correlation exists between phosphorus and direct measurements of THM precursors made under controlled conditions (e.g., pH, temperature, bromide level, chlorine dose, and reaction time). Such a correlation seems likely, however, based on the apparent TOC-phosphorus relationship, the TOC-THM relationships reported in the literature, and controlled laboratory studies indicating that algae can be significant sources of THM precursors.

Control strategies

The linkage between TOC in the raw water supply and THM formation has direct implications for watershed management strategies and their relationships to the costs and quality of finished water. Treatment plants can also be designed or operated to minimize the production of THMs by minimizing the contact of chlorine with organics. Treatment schemes[1,3] include: (1) using a disinfectant other than chlorine; (2) reducing the precursor level prior to chlorination; and (3) reducing THM levels after THM formation.

The feasibility and costs of each of the schemes outlined vary with treatment plant designs, economic factors, and raw water characteristics.

Conservative use of chlorine has been shown to be effective in reducing THM levels but has not always been feasible. For example, eliminating chlorine use prior to coagulation, sedimentation, or filtration can reduce chlorine contact with organic matter and THM formation. Even modest levels of organics in the raw water may promote biological growths on filters, however, and necessitate use of chlorine (or an alternative biocide) prior to filtration.

Typically, more than 80 percent of the organic carbon in a lake or reservoir is in a dissolved form[13,28] and thus is not removed easily by conventional water treatment schemes, which are geared for removal of particulates or turbidity. Coagulation processes can provide some removal of organics, though optimal conditions do not always correspond with optimal conditions for removal of turbidity.[29] Semmens and Field[30] noted that alum doses necessary to achieve optimum organics removal by coagulation are greater than those conventionally used for turbidity removal; doses of 100-200 mg/L may be needed. Davis and Gloor[31] have shown that dissolved organic compounds in the molecular weight range of 500-4000 are adsorbed preferentially by alum floc, that the process is limited by floc surface area (dose) at an alumina concentration of 50 mg/L, and that a significant portion (20-60 percent) of the dissolved organic carbon in lake waters cannot be removed from solution, regardless of alum dose, because the compounds lack the functional groups necessary for formation of strong complexes at the alumina surface. Glaser and Edzwald[32] and Scheuch and Edzwald[27] found that about 40 percent of the THM precursors in relatively low-turbidity (0.68-1.4 ntu) river water could be removed by using cationic polymers and direct filtration and that the optimal polymer dose was roughly proportional to the raw water's organic content. These studies suggest that optimal chemical doses and costs of organics removal via coagulation should be sensitive to raw water quality. Activated carbon is currently the most effective treatment alternative, but it is also relatively expensive.[1,33]

Source controls

Historically, the control of algal growth in reservoirs has received much attention, primarily because of problems relating to taste, odor, and filtration associated with certain algal types.[34] When properly used, algicides can be moderately effective but function more by regulating the dominant algal species than by reducing the total algal biomass. Reduction in watershed nutrient export is the most effective, long-term solution to eutrophication problems.

The feasibility and costs of achieving significant reductions in nutrient loadings through watershed management practice vary with local conditions and need to be assessed on a case-by-case basis. To aid in such assessments, a modeling framework has been designed and tested recently for the New Haven (Conn.) Water Company.[35] The framework consists of a series of regionally calibrated empirical models that relate watershed land use, soil types, and hydrologic and morphometric characteristics to reservoir eutrophication and related water quality conditions, including phosphorus, chlorophyll-*a*, transparency, TOC, and hypolimnetic oxygen depletion. Control pathways are illustrated in Figure 4.

When used in conjunction with appropriate watershed and reservoir monitoring data, the methodology provides perspectives on the sensitivity of water quality conditions to existing or future land use distributions and is particularly useful for evaluating zoning strategies. The potential effectiveness of management practices designed to reduce surface runoff and phosphorus loadings from specific watershed areas can be assessed in relation to the total phosphorus balance of the reservoir. Management practices might include, for example, "traditional" erosion and surface runoff control measures, reductions in phosphorus losses from on-site waste disposal systems, or various urban runoff control strategies.

Future outlook

Current perceptions of water supply problems related to organics may change in the future. As discussed by Dorin,[6] THMs generally constitute only a fraction (typically about 20 percent) of total organohalogens that are formed when chlorine reacts with natural organic compounds. The remaining, generally nonvolatile compounds are still poorly identified and may contain compounds that are more hazardous than THMs. With future refinements in measurement techniques and epidemiologic studies, the organohalogen problem may be found to be considerably more severe than currently perceived. West Germany, for example, already has a THM standard of 25 µg/L, one fourth the current standard in the United States.[6] Protection and enhancement of raw water supply quality may become increasingly important as a potentially effective means of controlling this problem.

In discussing the costs, implications, and intentions of the Safe Drinking Water Act, Clark and Dorsey[1] made the following point:

> Congress intended that the consumer would pay for protection directly. By so doing the consumer may, for the first time, begin to understand what the cost of pollution control is to him or her as an individual. The act may, therefore, in a very real sense "protect" public water supplies by forcing a closer examination of upstream discharges into vulnerable water supply sources.

As monitoring technology and our understanding of the relationships between water supply quality and health improve, standards are likely to become more stringent, and the technologies involved in supplying water that meets standards are likely to change and to increase in real cost. Although they are not "free," closer monitoring and management of watersheds for control of nutrient and other pollutant export are potentially cost-effective, if not essential, elements of a strategy to supply water that meets current and future quality standards and public health objectives.

Conclusions

The author has provided a review of some of the key relationships between eutrophication of surface water supplies and the costs and quality of finished water. Problems with organics are probably the most significant, in view of current and future concerns over organohalides. Data from lakes and reservoirs in the United States indicate a positive correlation between total phosphorus and TOC measurements. This correlation most likely reflects the control of algal and aquatic plant growth by phosphorus. Watershed management for control or reduction of phosphorus export is a potentially significant and cost-effective means of dealing with organics-related problems. Empirical models can be used in conjunction with appropriate reservoir and watershed monitoring data to assess the extent, significance, and controllability of water quality problems related to phosphorus export and eutrophication. Combined with treatment strategy evaluations, watershed assessments provide a means of arriving at local solutions to organics-related problems and of formulating land-use policies as they relate to water quality.

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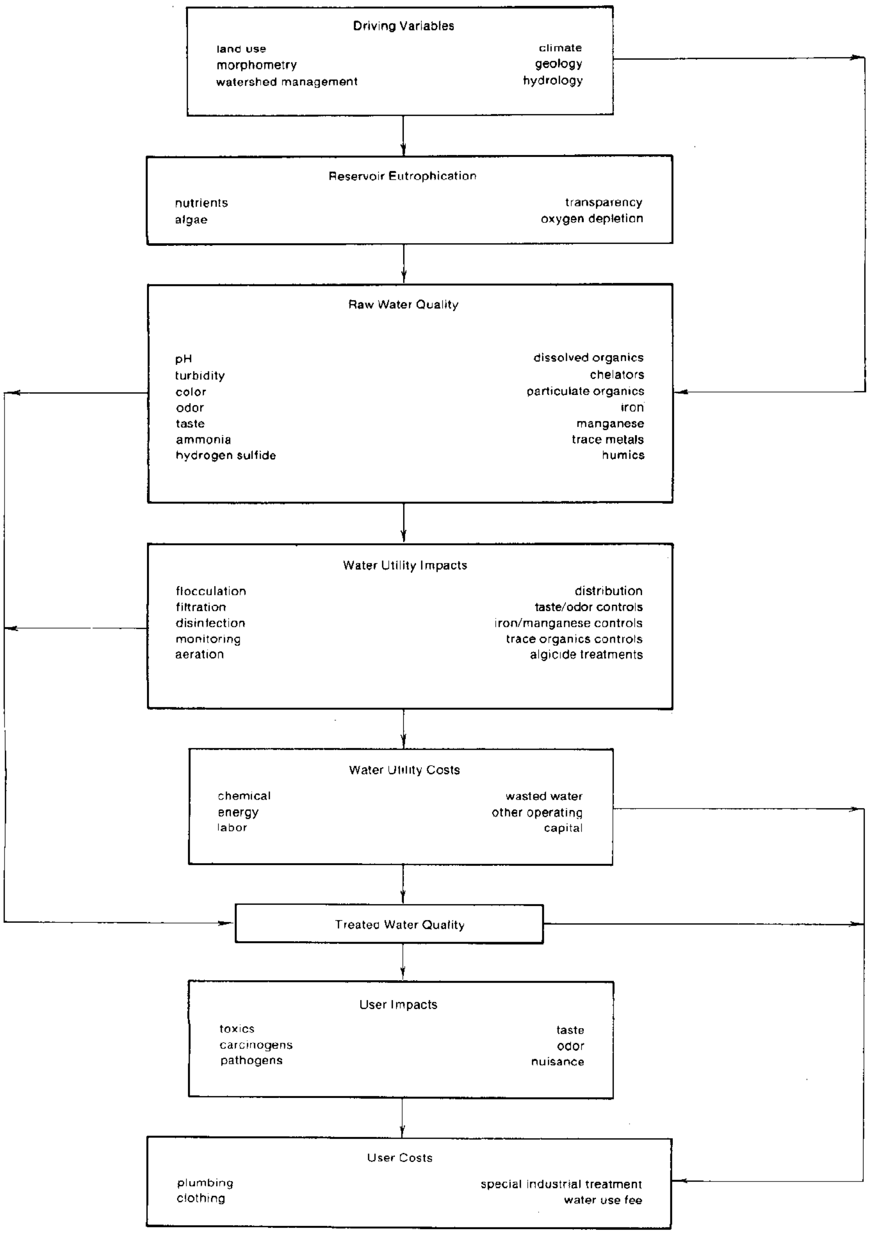

Figure 1. Causal pathways for eutrophication effects on water supplies

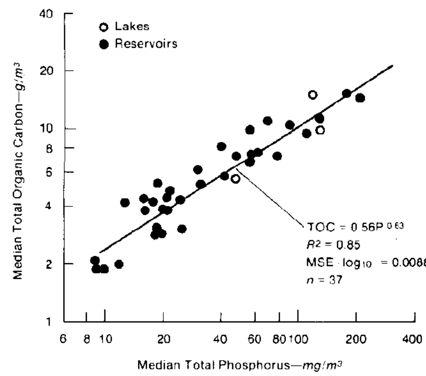

Figure 2. Relationship between total phosphorus and total organic carbon in US lakes and reservoirs

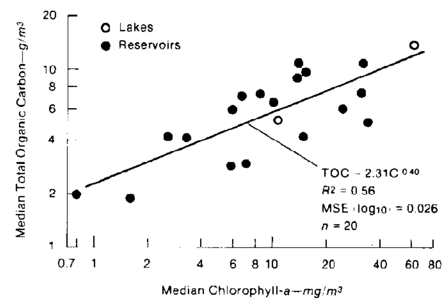

Figure 3. Relationship between chlorophyll-a and total organic carbon in US lakes and reservoirs

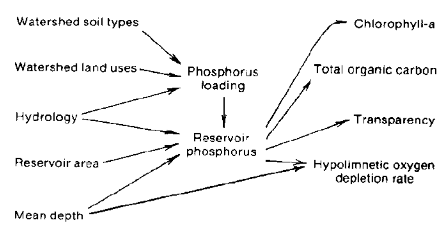

Figure 4. Control pathways in assessment of impoundment eutrophication

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Efficiency of point-of-use treatment devices

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Performances of two devices for point-of-use treatment are reported. One device was a combination of a granular activated carbon bed and a precoat filter; the other was a combination of a reverse osmosis unit, a prefilter, and two granular carbon adsorption units. These devices were studied in order to determine the extent to which they were able to remove various organic, inorganic, microbiologic, and particulate contaminants from potable water.

Most of the previous reports describing the effect of point-of-use treatment devices on the quality of treated water[1-6] have concentrated on bacterial growth in these products during periods of nonuse. No report has reviewed all the changes in water quality that may be attained by using these products. This article presents data about the treatment efficiency of two devices that were challenged with a variety of contaminants.

It is generally recognized that less than 1 percent of the water produced by municipal water treatment facilities is actually used for cooking and drinking and that this small fraction of the treated water must meet much more stringent requirements than the rest of the water. In many small water systems, water quality can be controlled more effectively at the point of use than at the central treatment plant. Indeed, some contaminants present at the household tap, such as taste and odor owing to microbial regrowth, corrosion products from the water mains, by-products of disinfection (not only by-products of chlorination), and influx from main seepage and breakage or flooding, cannot be controlled at the central treatment plant. Thus, point-of-use equipment can supplement centralized water treatment by producing small quantities of specially treated water for specific purposes.

A variety of point-of-use products exists in the marketplace at this time. They range from simple adsorption or particulate filters to high-technology systems based on specialized membranes. Figure 1 shows the basic design of the most common units.

- Of all the units, granular activated carbon (GAC) beds are the most common, the simplest, and the easiest to build. GAC beds remove common tastes and odors, some turbidity, chlorine, and many organic contaminants with varying degrees of efficiency.
- Particulate filters, made of foam or string, can be designed to retain particles of various sizes, from large (30–50 μm) to small (3–5 μm). Rolled paper cartridges also fit in this class of filters. Some of these filters are impregnated with activated carbon, which acts as an adsorbent.
- Membranes similar to those used for coliform analyses in the laboratory can be made into pleated filter cartridges. The membranes may have pore sizes as small as 0.2 μm. Membrane filters provide excellent filtration but are usually protected by a prefilter in order to prevent premature clogging.
- Precoat filters have a finely powdered filter medium, usually activated carbon or diatomaceous earth (sometimes both), applied to the influent side of the barrier portion of the filter. The retentiveness of this precoat efficiently removes particulates that are 1 μm or smaller, depending on the porosity of the filter medium. The layer of filter medium—the filter cake—is usually only a few millimetres thick, but the water flow rate per unit area of filter is sufficiently low so that tastes and odors can be removed. The capacity of precoat filters for removing total organics is usually less than that of granular bed filters of similar size because the amount of activated carbon is smaller. A signif-

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