



and



New Jersey Department of Environmental Protection
Division of Science, Research & Technology



**EVALUATION AND ASSESSMENT
OF
ORGANIC CHEMICAL REMOVAL TECHNOLOGIES
FOR
NEW JERSEY DRINKING WATER
SURFACE WATER REPORT**

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CHAPTER 1 - INTRODUCTION

BACKGROUND

Numerous organic chemicals are used every day in New Jersey (NJ) for industrial, commercial and household purposes. A number of these chemicals have found their way into the State's wastewater treatment facilities, receiving waters, aquifers and drinking water treatment facilities. This situation is not unique to NJ as occurrence studies conducted around the country indicate similar findings. A recent report (dated December 20, 2005) completed by the Environmental Working Group (a nonprofit organization based in Washington, DC) indicated that 141 unregulated organic chemicals were detected in tap waters from 42 states.

The various types of unregulated organic chemicals (UOCs) that have been detected include:

- Pesticides
- Volatile organic chemicals (VOCs)
- Endocrine-disrupting compounds (EDCs)
- Pharmaceuticals and personal care products (PPCPs)
- Petroleum-related compounds
- Other industrial organic chemicals

Also, some naturally-occurring organic chemicals have been detected.

State and Federal agencies, environmental groups and the public are raising concerns regarding these chemicals as emerging contaminants of interest even though many of the chemicals have only been found at trace concentrations and only sparse data are available regarding their health and/or environmental effects. The fact that organic chemicals are being detected in drinking water supplies and that there is a concern regarding their health effects raises a fundamental question – what are the best available treatment technologies for removing these organic chemicals from drinking water supplies? And more specific to NJ, which technologies are most applicable to the State's surface water systems, and to what level should these compounds be removed? As answers to these questions are developed, it should be noted that the ability to detect these compounds is simply a function of the analytical method, and that removal

efficiency is, in reality, a reflection of the detection limits. Verification of complete removal of the compounds is not possible; one can simply document that the concentrations are below the detection limits of the current analytical methods.

The New Jersey Department of Environmental Protection (NJDEP), in conjunction with the Drinking Water Quality Institute (DWQI), is considering potential options for addressing these contaminants in NJ drinking waters, and is seeking information on the effectiveness of various treatment technologies to assist in their evaluations. Treatability data are available for some of the UOCs that have been detected, but very little to no information on removal efficiencies at the low concentrations measured via treatment is available for the vast majority of the chemicals.

PURPOSE AND SCOPE

This project is designed to review and summarize existing information on the effectiveness of various treatment technologies for removing organic chemicals and to identify the best available technologies for removing the organic chemicals found in NJ drinking waters. This report specifically addresses organic chemicals detected in surface waters in the State. For the purpose of this report, the synthetic organic chemicals are referred to as UOCs. It should be noted that the scope of this study does not include disinfection by-products or the “common” volatile organic chemicals that have been detected in drinking waters. An extensive literature review was completed to document existing information on the removal of organic chemicals from drinking water. The available treatment techniques were reviewed and summarized to determine the most applicable technologies for NJ surface water supplies. The most applicable technologies are described relative to performance, reliability, treatment issues, and approximate (or relative) costs. The results of this project will be used by NJDEP to determine the need for and extent of demonstration testing that may be conducted to further evaluate the most feasible technologies as they apply to NJ surface water supplies.

LITERATURE REVIEW

The Project Team conducted a comprehensive literature review to evaluate the state of knowledge of treatment technologies for removing organic chemicals. Much of the information has been assembled from literature searches that Black & Veatch (B&V) and Project Team members have performed for several recent American Water Works Association Research Foundation (AwwaRF) projects and other research projects. Appendix A includes a list of references that have been developed by the Project Team. A significant amount of information on the removal of EDCs and PPCPs during water treatment is now available. The following are examples of AwwaRF studies that have provided important information on the treatment of organic chemicals:

- Project #2897 - Impact of UV and UV - Advanced Oxidation Processes on Toxicity of Endocrine-Disrupting Compounds in Water
- Project #2902 - Evaluation of Triclosan Reactivity in Chlorinated and Monochloraminated Waters
- Project #2758 - Evaluation of Conventional and Advanced Treatment Processes to Remove Endocrine Disruptors and Pharmaceutically Active Compounds
- Pharmaceuticals and Personal Care Products: Occurrence and Fate in Drinking Water Treatment (2004)

B&V and/or the Project Team members have been involved in these projects.

The literature review has focused on two major areas: (1) identification of treatment processes that have been reported to definitively remove specific organic chemicals, and (2) relating the removal of well-studied compounds (*e.g.*, lindane, atrazine, geosmin) by water treatment processes to the physical and chemical properties of lesser studied compounds (*i.e.*, EDCs and PPCPs). It should be noted that EDCs are unique in that there is not a definitive list of EDCs, but rather, they belong to a class of compounds that produce a toxicological effect. While some SOCs and PPCPs can act as EDCs, the US EPA's Endocrine Disruption Screening Program (EDSP) is still at an infancy and it will be several years before a definitive list of EDCs could be produced. This review has included several suspected EDCs and several PPCPs, as well as other micropollutants where more extensive work has been conducted. This review provides a framework for understanding and predicting removal of a broad-range of emerging compounds. These findings have been utilized to identify trends in treatability based upon the physical

structure and chemical behavior of the compounds (i.e., molecular size, polarity, functional groups). The results of the literature review were used to determine which organic chemicals might be removed by the treatment techniques discussed in Chapter 3 - Available Treatment Techniques.

CHAPTER 2 - OCCURRENCE OF UOCs IN NJ SURFACE WATERS

USGS STUDIES

Since 1998, the U.S. Geological Survey (USGS) has been conducting the Toxic Substances Hydrology Program (Toxics Program) to develop information and tools on emerging water quality issues (Kolpin, 2002). This research program includes a combination of laboratory work to develop new analytical techniques and field work on the occurrence, fate and effects of these contaminants. Between 1999 and 2000, the USGS conducted the first US reconnaissance survey of 139 streams across 30 states. Streams were selected based on known or suspected wastewater discharges upstream of the sample points. Four streams in New Jersey were sampled as explained in the following section of this chapter.

Each sample was analyzed for 95 organic chemicals representing a wide range of compounds originating from residential, industrial and agricultural applications. Of the 95 organic chemicals, 82 were found in at least one of the streams. The most frequently occurring compounds were:

- Coprostanol
- Cholesterol
- N,N-diethyltoluamide
- Caffeine
- Tri(2-chloroethyl)phosphate
- 4-nonylphenol
- Triclosan

The types of chemicals that were detected and the detection frequency are listed below:

- Steroids - 89%
- Nonprescription drugs - 81%
- Insect repellent - 74%
- Detergent metabolites - 79%
- Disinfectants - 66%
- Plasticizers - 64%
- Fire retardants - 60%
- Antibiotics - 48%
- Insecticides - 45%
- Polycyclic aromatic hydrocarbons (PAHs) - 44%

- Hormones - 37%
- Other prescription drugs - 32%
- Antioxidants - 29%
- Fragrances - 27%
- Solvents - 24%

Most of the compounds were detected at less than microgram per liter (or parts per billion) levels.

In 2001, a network of 76 drinking water sources (51 surface water and 25 ground water) across 25 states and Puerto Rico was sampled and analyzed. This survey was conducted in collaboration with the U.S. Environmental Protection Agency and with assistance from the American Water Resources Association. The results of this survey are still being reviewed and evaluated.

For the first reconnaissance survey, five separate analytical methods were used. Each method was developed independently in different laboratories for a specific group of chemicals (e.g., hormones and antibiotics). As a result of these differing classes of compounds, varying approaches were used in the development of the five analytical methods. Methods 1-3 used filtered water for solid-phase extraction (SPE) with liquid chromatography/mass spectrometry (LC/MS) analysis. These methods targeted 29 antibiotic compounds and 21 human prescription and nonprescription drugs and certain metabolites. Methods 4 and 5 used whole-water continuous liquid-liquid extraction (CLLE) with capillary gas chromatography/mass spectrometry (GC/MS) analysis. These methods targeted 46 organic wastewater chemicals and 14 steroid compounds. All methods used selected ion monitoring (SIM) for improved sensitivity, thus, only the target compounds were reported with no attempt to identify non-target compounds.

For the purpose of this NJ surface water study, the results from the first survey have been used in accordance with NJDEP's instructions. The results from the NJ surface water sampling sites are presented in the following section.

UOCs DETECTED IN NJ SURFACE WATERS

The USGS stream reconnaissance survey included four sites in NJ:

- Assunpink Creek - Trenton
- Singac Brook - Singac
- Whippany River - Pine Brook
- Ho-ho-kus Brook - Ho-ho-kus

The following numbers of chemicals that were detected in the NJ streams using the each of the previously-described analytical methods are summarized below:

<u>Method</u>	<u>No. of Chemicals</u>
1 - Antibiotics - 21	2
2 - Antibiotics - 8	0
3 - Drugs	9
4 - Wastewater chemicals	15
5 - Steroids	0

Method 1 antibiotics: Carbodox, chlortetracycline, ciprofloxacin, doxycycline, enrofloxacin, erythromycin-H²O, lincomycin, norfloxacin, oxytetracycline, roxithromycin, sarafloxacin, sulfadimethoxine, sulfamerazine, sulfamethazine, sulfamethizole, sulfamethoxazole, sulfathiazole, tetracycline, trimethoprim, tylosin, virginiamycin

Method 2 antibiotics: Chlortetracycline, oxytetracycline, sulfachloropyridazine, sulfadimethoxine, sulfamerazine, sulfamethazine, sulfathiazole, tetracycline

Method 3 drugs: albuterol, cimetidine, codeine, dehydronifedipine, digoxin, dogoxigenin, diltiazem, enalaprilat, fluoxetine, gemfibrozil, metformin, paroxetine metabolite, ranitidine, warfarin, acetaminophen, caffeine, cotinine, 1,7-dimethylxanthine, ibuprofen

Method 4 wastewater chemicals: 1,4-dichlorobenzene, 2,6-di-tert-butylphenol, 2,6-di-tert-butyl-1,4-benzoquinone, 5-methyl-1H-benzotriazole, acetophenone, anthracene, benzo[a]pyrene, 3-tert-butyl-4-hydroxy anisole, butylated hydroxyl toluene, bis(2-ethylhexyl)adipate, bis(2-ethylhexyl) phthalate, bisphenol A, carbaryl, cis-chlordane, chlorpyrifos, diazinon, diethylphthalate, dieldrin, ethanol,2-butoxy-phosphate, fluoranthene, lindane, methyl parathion, 4-methyl phenol, naphthalene, N,N-diethyltoluamide, 4-nonylphenol, 4-nonylphenol monoethoxylate, 4-nonylphenol diethoxylate, 4-octylphenol monoethoxylate, 4-octylphenol diethoxylate, phenanthrene, phenol, phthalic anhydride, pyrene, tetrachloroethylene, triclosan, tri(2-chloroethyl) phosphate, tri(dichlorisopropyl) phosphate, triphenyl phosphate

Method 5 steroids: cis-androsterone, cholesterol, coprostanol, equilenin, equilin, 17a-ethynyl estradiol, 17a-estradiol, 17b-estradiol, estriol, estrone, mestranol, 19-norethisterone, progesterone, testosterone

Of the 95 target compounds that were analyzed for, only 26 were detected in the NJ streams. Five of the compounds were detected in all four streams, while 10 of the compounds were detected in only two streams. The remaining chemicals were detected in only one of the four streams. The number of chemicals found in each stream is summarized below:

Assunpink Creek*	7
Singac Brook	18
Whippany River	17
Ho-ho-kus Brook*	9

Analytical Method 4 was not used for the samples collected from the Assunpink Creek or the Ho-ho-kus Brook which may account for the lower number of chemicals found in these streams compared to the other two streams.

CATEGORIZATION OF DETECTED UOCs

For the purpose of determining appropriate treatment technologies for NJ's surface water supplies, the list of UOCs detected in the four streams was broken down into 3 major classes:

- Aliphatics
- Cyclics which are defined as saturated ring compounds without aromatic characteristics
- Aromatics which are ring compounds that are unsaturated, thus more reactive than cyclic compounds

Within each class, the UOCs were further broken down into several categories as follows:

- Pharmaceuticals
- Polycyclic Aromatic Hydrocarbons (PAHs)
- Insecticides
- Consumer Products
- Other Industrial Chemicals – compounds that are manufacturing intermediates for a variety of end products but do not fit into the other categories; for example, corrosion inhibitors for metals

The number of UOCs that fell into the three classes and various categories are shown in Table 2-1. Most of the compounds fall into the categories of pharmaceuticals or other industrial chemicals.

The specific compounds in the three classes (aliphatics, cyclics, and aromatics) and various categories are presented in Appendix B. When available, the Chemical Abstracts Service number (CAS#), class, molecular weight, and uses of the compound, if known, are included in the tables. Classification and categorization of the organic chemicals also were used to determine plausible treatment techniques (see Chapter 3).

Table 2-1
Classes and Categories of UOCs Detected

Class - Categories	<u>Aliphatics</u>	<u>Cyclics</u>	<u>Aromatics</u>	<u>Totals</u>
Pharmaceuticals	1	1	6	8
Insecticides	0	0	2	2
Consumer Products	1	2	3	6
Other Industrial Chemicals	1	0	5	6
PAHs	0	0	4	4
TOTALS	3	3	20	26

CHAPTER 3 - AVAILABLE TREATMENT TECHNIQUES

INTRODUCTION

Various treatment techniques have been evaluated, tested, and applied to remove UOCs from surface water supplies. These techniques generally are categorized as follows:

- Conventional processes
- Adsorption processes
- Oxidation processes
- Air stripping processes
- Membrane processes
- Biological processes

Each of these categories of processes is discussed in the following sections of this chapter with respect to general process description, factors affecting process efficiency and applicability to UOC removal.

Information on the removal of UOCs from drinking water varies largely on the molecular structure of the chemicals. For instance, much work has been done on the removal of pesticides from surface water supplies, while much less is known about the removal of non-regulated, emerging contaminants (e.g., EDCs and PPCPs). Information on the removal of unregulated chemicals is somewhat limited because the analytical procedures associated with these compounds are complex and generally not available to commercial/utility laboratories. Therefore, occurrence data for these compounds are relatively rare. Even when detected, concentrations are often close to the analytical method detection limits and can fluctuate greatly. Most of the knowledge regarding the removal of these emerging contaminants is derived from laboratory or bench-scale studies. When treatment data are not available, removal predictions can be made based on research using contaminants with similar chemical structure and behavior.

For some of the more frequently occurring chemicals, bench, pilot and even full-scale data are available which may be used to directly evaluate the efficiency of certain treatment techniques.

Of the 26 UOCs that have been detected in NJ surface waters, treatability data are available for all but seven of the compounds.

It should be noted that much of the information on the removal of the UOCs from drinking water was obtained from previous research work performed by either Dr. Shane Snyder of the Southern Nevada Water Authority or Dr. Karl Linden of Duke University. References to their work are indicated throughout the text and are shown in the various documents listed in Appendix A.

CONVENTIONAL PROCESSES

General Process Description

Conventional surface water treatment plants typically utilize the following processes: chemical addition, rapid mixing, coagulation/flocculation, clarification, filtration, and disinfection. Coagulation is accomplished using alum or iron salts and/or synthetic polymers. Clarification can be achieved using settling or flotation processes. At some plants, powdered activated carbon (PAC) is added prior to the clarification step to enhance the removal of organic chemicals, especially taste and odor producing chemicals. Filtration generally occurs through sand or anthracite/sand media. Disinfection is commonly accomplished using chlorine for primary disinfection and chlorine or chloramines for secondary disinfection. Some water treatment plants have added advanced processes such as ozonation and/or post-filtration carbon adsorption. For purposes of this report, these advanced processes are not considered as part of a conventional treatment plant.

In most plants, most particulate removal occurs through treatment prior to filtration. A coagulant is added to destabilize suspended particles in the raw water and to agglomerate to form new particles. Dissolved organic or inorganic material may be precipitated as a result of coagulant addition, but this is the exception rather than the norm. Flocculation acts to aggregate the particles so that they will more readily be removed via clarification. Additional particle removal is achieved through filtration.

Factors Affecting Process Efficiency

Information on the efficiency of conventional treatment processes for the removal of emerging contaminants at trace levels found in surface waters is quite limited because utilities rarely analyze for these compounds. Also, when they are detected (usually through research projects), the concentrations are often near or below method detection limits. There is much information on chlorination and activated carbon. However, information on the removal of organic chemicals through coagulation and filtration is limited.

The removal of organic chemicals through coagulation and filtration has been found to be modest at best. Organic chemicals that are in the particulate state may be removed via settling in conjunction with the settling of other particles in the raw water. Better removals have been shown when powdered activated carbon (PAC) is used in conjunction with coagulation/settling. Chlorination has been found to provide the vast majority of removal of the emerging organic contaminants through conventional treatment processes. Factors that can affect the removal of organic chemicals with conventional processes include the use of preoxidants such as potassium permanganate, ozone, chlorine, or chlorine dioxide and the use of PAC as indicated above.

Organic chemicals may adsorb to particles in the water and metal hydroxides formed during coagulation. Chemical precipitation can remove moderately hydrophobic organic chemicals that have a strong affinity for natural organic matter (Snyder). One mechanism of removal of organic chemicals is hydrophobic partitioning. For conditions typically found in drinking water treatment plants, mostly hydrophobic, nonpolar compounds can be removed. In addition to hydrophobic partitioning, organic compounds can be adsorbed to particles by interactions of polar functional groups with charged particles and mineral surfaces by complexation or ion exchange (Snyder, 2003). Since most strongly hydrophobic compounds bind readily to particles, they are not seen in filtered samples at all. However, in the USGS method using CLLE, cited in Chapter 2, the hydrophobics will be extracted from the particles. In work by Snyder where they spiked a water treatment plant, the hydrophobic compounds did bind quickly to the particles. However, in a regular, non-spiked situation, the strongly hydrophobic compounds would be expected to already be bound to particles before they enter the plant. Essentially, if the contaminant is already bound

to a particle, conventional coagulation/flocculation/filtration has a high probability of removing it. The analytical method has a bearing on this, as filtered methods (like the USGS SPE) will have already removed the particulate with the sorbed contaminant, whereas non-filtering methods (like USGS CLLE) will give results as a total, since sorbed particles can, and will often, be released in CLLE.

Applicability to UOC Removal

Despite these predictions, available data from pilot and full-scale treatment plants indicate that removal of most UOCs via conventional treatment processes is modest at best (Snyder, 2005). Several studies of coagulation/flocculation/sedimentation have indicated poor removals of several pharmaceuticals and steroids (e.g., trimethoprim and carbamazepine). Snyder concluded that EDCs and PPCPs not associated with colloidal or particulate matter will most likely be poorly removed during coagulation.

In a study conducted by the USGS and the Centers for Disease Control and Prevention, samples were collected from a conventional treatment plant to determine the removal of targeted organic chemicals (Stackelberg, 2004). The samples were analyzed for 25 antibiotic compounds, 22 human prescription and non-prescription drugs, and 63 other organic contaminants of wastewater origin. Many of the compounds that have been detected in the four NJ streams were detected in the raw water from this study. Stackelberg reported the following conclusions regarding the removal of target compounds through the treatment process evaluated:

- Several compounds that were frequently detected in stream and raw water samples were also frequently detected in finished water samples indicating very poor to no removal through the treatment processes. These compounds included tri (2-chloroethyl) phosphate.
- Other compounds like caffeine and cotinine exhibited either the same or lower concentrations in the finished water compared to the raw water. However, they also were in the blanks.
- Still other compounds including trimethoprim, 1,7-dimethylxanthine, erythromycin – H₂O, triclosan, phenol, 4-nonylphenol, and acetaminophen were frequently detected in the raw water but not detected in the finished water.

Overall, for the organic chemicals that have been found in NJ streams, it would appear that up to 50 per cent removal might be achieved for some of the compounds through conventional treatment processes. The use of PAC would provide higher removals of certain compounds.

ADSORPTION PROCESSES

General Process Description

Adsorption is the collection and condensation of a substance or substances from the water phase to the solid surface of an adsorbent. Both granular activated carbon (GAC) and powdered activated carbon (PAC) adsorption have been used in drinking water treatment for surface water sources. Activated carbon has a large surface area (important because adsorption is a surface phenomenon), different pore sizes that can physically help remove various sizes of molecules, and surface chemistry that varies from non-polar to very oxidized and polar (McGuire and Suffet, 1978). Water is passed through a bed of GAC in a manner similar to passing water through a filter. Adsorbed compounds adhere to the carbon, competing for bonding sites; therefore, the adsorptive capacity of the carbon will become exhausted and it must be regenerated or replaced to continue removal of the desired compounds from the water.

GAC beds may be open to the atmosphere and operate much like multi-media filters or the carbon may be placed in closed vessels and operate in a pressurized system. Surface water applications are typically designed like multi-media filters. PAC has been used in conjunction with settling processes in conventional treatment where the PAC is added before settling. Contact times of 1 to 3 hours is provided for the PAC in the settling basins, after which the PAC settles out in the basins and is disposed with other water treatment plant residuals.

Factors Affecting Process Efficiency

The principle mechanisms that affect the transfer of contaminants from the aqueous phase to the GAC or PAC adsorbent are transport across the hydrodynamic layer around each activated carbon particle, intra-particle transport through the activated carbon bed, and chemical equilibrium. Typically, contaminants that are water soluble are not well adsorbed by activated

carbon. Mixtures of compounds reduce the capacity of the activated carbon to remove any one compound because of competition for bonding sites. In addition to the mix of organics, the efficiency of activated carbon adsorption is affected by:

- The properties of the activated carbon itself
- The contact time of the water with the activated carbon (in the GAC bed or in the settling basin for PAC). PAC should be added at the head of the treatment plant to maximize the contact time ahead of any chemical addition.
- PAC dosage
- Water temperature
- pH
- The concentration of inorganic substances in the water
- The concentration of natural organic matter in the water which competes for adsorption sites, thereby reducing the adsorption capacity for the target organic chemicals to be removed
- The presence or absence of chlorine in the water

Activated carbon reacts with chlorine (or other oxidants) in a reduction-oxidation reaction, which may change the surface characteristics of the activated carbon. Therefore, PAC should not be used in conjunction with the use of oxidants as they may render the PAC ineffective. Also, the loss of chlorine through GAC may result in additional costs for re-chlorination post-GAC. Over time, GAC could become colonized by bacteria that metabolize adsorbed compounds, enhancing the capacity of the activated carbon and prolonging its life, although this phenomenon has not been observed for the emerging contaminants.

There are different types of GAC and PAC that have been developed from source compounds as diverse as bituminous coal and coconut shells. The different types of GAC and PAC can exhibit greater affinities for some contaminants; therefore the selection of an optimal activated carbon can significantly improve the efficiency of the process for a specific water and particular contaminant. Isotherm tests are conducted to determine if an activated carbon can remove a contaminant or mixture of contaminants from a water source.

Applicability to UOC Removal

GAC adsorption already has widespread use in the drinking water industry for removal of regulated organic chemicals as well as taste and odor compounds. GAC has been found to be capable of removing a broad range of organic chemicals. Tests conducted by USEPA have indicated that 38 of the organic chemicals on the Candidate Contaminant List (CCL) published in 1998 can be removed using GAC. An important factor in determining the applicability of GAC for organic chemical removal is the carbon usage rate – the rate at which the GAC will become exhausted and must be replaced. Organic chemicals exhibiting high carbon usage rates may not be amenable to treatment using GAC. This is discussed further in Chapter 4.

Since the discovery of halogenated disinfection by-products in the early 1970s, a number of studies have been conducted to determine the relative amenability of different organic compounds and classes of compounds to activated carbon adsorption. Some of the readily adsorbed classes of organic compounds are:

- Aromatic solvents and fuels (e.g, benzene, toluene, xylene, gasoline, kerosene)
- Polycyclic aromatic hydrocarbons (PAHs) such as phenanthrene and fluoranthene
- Aliphatic hydrocarbons with more than six carbons, because the smaller hydrocarbons are volatile. Some of the larger hydrocarbons are hexane, octane, nonane, decane.
- Non-polar, halogenated organic compounds, aliphatic and aromatic, ranging from carbon tetrachloride and dichloroacetonitrile to the pesticide chlordane and polychlorinated biphenyls (PCBs)

There has also been some experience with adsorption of aromatic alcohols (phenols), humic substances, dyes, surfactants (such as long chain fatty acids and fatty acid esters as the long chain is non-polar), and organic compounds containing nitrogen (EPA, 2000). Work by Snyder indicated that GAC was very effective for removal of 31 specific EDCs and pharmaceuticals; however, more water soluble compounds had relatively fast break-through, requiring frequent carbon regeneration. PAC was also found to be effective, although natural organic matter (NOM) had a negative impact on contaminant removal.

Polar, water soluble, compounds are not well adsorbed by GAC, which results in rapid breaching of the GAC. These include:

- Short-chain alcohols
- Low molecular weight aldehydes and ketones
- Low molecular weight carboxylic acids
- Carbohydrates – both sugars and starches

Very large, high molecular weight, organics (such as tannins) are not well adsorbed by activated carbon and must be removed by other processes.

Work completed by Snyder indicated the following regarding the removal of organic chemicals using PAC in conjunction with coagulation/flocculation/settling processes:

- Laboratory studies conducted with EDCs suggest that PAC will be effective in removing between approximately 60 and 80 percent of nonphenyl depending on the PAC dose.
- PAC experiments conducted by Snyder indicated similar removals of triclosan. Laboratory studies using 5 mg/L of PAC and a contact time of 4 hours indicated > 90 percent removal of triclosan and < 50 percent removal of trimethoprim.

OXIDATION PROCESSES

General Process Description

Oxidation processes have been used in drinking water treatment to accomplish several objectives: disinfection, iron/manganese oxidation, oxidation of organic compounds (particularly taste and odor compounds), and color removal. The mechanism for removal of organic chemicals by oxidation is either the conversion of the chemical into an intermediate reaction product or into carbon dioxide and water (mineralization). Complete destruction is rarely achieved, as intermediates formed can be resistant to further oxidation.

Several oxidation processes are available for removing organic chemicals from drinking water:

- Ozone
- Chlorine

- Chlorine dioxide
- Ultraviolet (UV) light
- Chloramine

Each of these is discussed briefly below.

Ozone - Ozone is the most powerful oxidant available for water treatment and therefore has a greater capacity to oxidize organic chemicals as compared to other oxidants. Ozone can react in aqueous solutions by two mechanisms: direct reaction of the ozone molecule and indirect reaction through decomposition of the ozone to hydroxyl free radicals (OH) that in turn react directly with the organic chemicals. The actual oxidation of organic chemicals in an ozone treatment process occurs by a combination of direct and indirect reactions.

The direct molecular ozone reaction pathway is relatively fast as compared to chlorine or chloramines, with most reactions completed within a few seconds to a few minutes. The ozone molecule is a rather selective oxidizing agent, seeking electron-rich centers for oxidative attack. When used alone, the ozone process generally involves an ozone contact basin to provide sufficient time for oxidation to occur. Typically, where ozone is used in drinking water treatment, the theoretical contact time can range from several minutes to greater than 20 minutes. Ozone dosages often range from 1 to 5 milligrams per liter (mg/L), depending upon the ozone demand and water temperature. Ozone doses for contaminant removal will depend on the organic chemical and the amount of NOM in the water. Since the NOM typically is at much higher concentrations than contaminants of concern, NOM levels will tend to drive the ozone dosage. Ozone is generated on-site from oxygen gas, thus oxygen must be supplied to the treatment plant, or generated on site. Where bromide is found in the raw water, the by-product, bromate, is formed through oxidation with ozone

In contrast to the direct reaction pathway, the indirect reaction pathway (via the OH radical) is faster, occurring on the order of microseconds. The OH radical is a more powerful oxidant (oxidation potential of 2.8 V) than ozone itself (oxidation potential of 2.07 V). The OH radical is less selective with respect to oxidation of micropollutants. Oxidation processes that utilize the highly reactive OH radical are called advanced oxidation processes (AOPs). Advanced oxidation can be accomplished in several ways including:

- Ozonation at high pH
- Ozonation with addition of hydrogen peroxide
- Ozonation followed by ultraviolet (UV) light
- UV light followed by ozone
- Ozone with titanium oxide catalysts
- UV with titanium catalysts

The UV processes are described later in this chapter. By utilizing the OH radical, contact times required for effective organic chemical removal can be reduced, or higher removals can be achieved at equivalent design conditions of dosage and contact time compared to ozone alone. Unfortunately, drinking water treatment plants do not receive disinfection credit for ozone/AOP, since ozone residuals in the presence of peroxide are not possible. Furthermore, hydroxyl radicals are a weaker disinfectant as compared to molecular ozone.

Chlorine - Chlorine is commonly used for disinfection of drinking water and also has been evaluated for oxidation of organic chemicals. Chlorine is a less powerful oxidant compared to ozone and chlorine dioxide. Therefore, higher chlorine dosages and contact times, compared to ozone oxidation, are needed to achieve effective removal of organic chemicals. High dosages of chlorine could result in unacceptable levels of disinfection by-products. The typical design parameters (contact time and residual) for chlorine disinfection may provide good removal of certain organic chemicals. Higher residuals and contact times may be needed for other compounds and for removals greater than 50 per cent.

Chlorine Dioxide - Chlorine dioxide is a strong oxidant – stronger than chlorine but not as strong as ozone. At typical chlorine dioxide dosages (1 to 1.5 mg/L) and contact times (10 minutes) used in drinking water treatment, removal of certain organic chemicals have been reported to be less than 50 percent. Higher dosages may not be practical because of the concern for producing the by-products chlorite and chlorate. Higher contact times also may not be practical.

UV Light - UV light has become a rather attractive treatment technology for disinfection of drinking water to achieve high inactivation of *Giardia* and *Cryptosporidium*. Typical dosages that are used for disinfection range from 30-60 millijoules per square centimeter (mJ/cm²). At

these dosages, direct photolysis of organic contaminants is poor, if at all. Studies have shown that dosages as high as 1,000 mJ/cm² are needed to achieve reasonable removals of organic chemicals that are oxidizable. Removal efficiencies can be improved by combining high-energy UV with hydrogen peroxide or ozone, as indicated previously. Both of these advanced oxidation processes can achieve more reasonable removal efficiencies compared to UV alone; however, UV doses of several hundred mJ/cm² and excess hydrogen peroxide are required.

Factors Affecting Process Efficiency

Important factors that affect contaminant removal efficiencies achieved with oxidation or advanced oxidation processes include:

- Characteristics of the organic chemical – discussed further below
- pH of the water - at pH ranges below 7.0, molecular ozone predominates over the OH radical; above pH 8.0, the ozone molecule decomposes very rapidly to form OH radicals. Lower pH also has been found to provide higher removals with chlorine (due to hypochlorous acid).
- Alkalinity of the water - the presence of bicarbonate and carbonate ions may slow down the decomposition of ozone to OH radicals.
- Presence of humic substances in the water - humic substances may function as an initiator or promoter of the decomposition of ozone to the OH radical.
- Contact time - the longer the contact time, the more time for oxidation to occur provided an oxidant is present.
- Oxidant dosage - the higher the oxidant dosage, the greater the removals. Lower dosages generally can be used with advanced oxidation processes.
- Oxidant demand of the water - sufficient oxidant must be added to the water to overcome the demand exerted by such things as natural organic matter or iron and manganese that may be present in the water.

Applicability to UOC Removal

Based on various bench, pilot and full-scale studies on the removal of organic chemicals through oxidation or advanced oxidation processes, the following results have been observed:

General Observations

- Dissociated acidic compounds are more reactive than protonated forms (i.e., reactivity increases with pH), but non-dissociated bases are more reactive when not protonated.

- General order of reactivity from highest to lowest for aromatic or aliphatic compounds - thiols > amines > hydroxyl > carboxyl.
- Aromatic compounds are more reactive than aliphatic compounds.

Ozone

- Ozone is rather selective and reacts with amines, phenols and double bonds in aliphatic compounds. Under conditions found in water treatment systems, only those compounds with ozone rate constants greater than $50 \text{ M}^{-1}\text{s}^{-1}$ will be removed to an appreciable degree (>50 percent) through direct reactions with ozone.
- Greater removals can be achieved by promoting OH radical formation through the use of advanced oxidation.
- Work conducted by Linden indicated that most of the CCL (1998) compounds are not very reactive with ozone.
- Work by Snyder indicated that a 0.1 to 0.3 mg/L ozone residual at 5 minutes contact time provided greater than 70 percent removal of many EDCs and pharmaceuticals, including erythromycin-H₂O, triclosan, trimethoprim, acetaminophen, and caffeine which all have been detected in the four NJ streams.
- Snyder also found that the addition of hydrogen peroxide does not significantly increase removal and concluded that hydrogen peroxide is rarely, if ever, needed in addition to ozone for removal of most organic chemicals.

Chlorine

- Free chlorine reacts rapidly with phenolic compounds.
- The transformation of several amine-containing antibiotics, diclofenac, and caffeine was observed in laboratory studies.
- Snyder reported that tests with free chlorine at a residual dosage of 0.5 mg/L after 24 hours yielded varying results. Of the 31 pharmaceuticals and EDCs tested, about half (including caffeine) were removed by less than 30 percent and another half (including erythromycin-H₂O, triclosan, trimethoprim, and acetaminophen) were removed by over 70 percent. Reducing the pH to 5.5 provided somewhat better removals.

Chlorine Dioxide

- Chlorine dioxide can oxidize herbicides, pesticides, and PAHs, but removal efficiencies have been reported to be below 50 percent and contact times can be very long – hours. It is anticipated that compounds containing phenolic amino and thiol functional groups will react with chlorine dioxide.

UV Light

- Extremely high doses of UV light are required to oxidize most organic contaminants. The use of high-energy UV in combination with ozone or hydrogen peroxide will provide greater removals.

- Work conducted by Snyder indicated that UV doses of 40 mJ/cm² (typical of disinfection) provided little removal of the 31 EDCs and PPCPs evaluated. At a UV dose of 1,000 mJ/cm², removals of some compounds increased to over 80 percent, but removal of many compounds still was less than 20 percent. At 1,000 mJ/cm², erythromycin, caffeine, and trimethoprim exhibited low removal (< 20 percent). At 40 mJ/cm² acetaminophen was removed by almost 40 percent and triclosan by almost 70 percent, while at 1,000 mJ/cm² removal increased to approximately 100 percent for both compounds.
- Snyder also reported that with the addition of 4 and 8 mg/L of hydrogen peroxide and a UV dose of 1,000 mJ/cm², removals of many compounds increased to greater than 80 percent, including erythromycin, caffeine, trimethoprim, acetaminophen, and triclosan.

Overall, for the oxidation processes, it would appear that the use of chlorine dioxide is not feasible for treating NJ surface waters as the dosages and/or contact times required for efficient UOC removal are unreasonably high. Removal by existing chlorine processes used for disinfection will remove several of the compounds detected in raw waters. The use of ozone or high energy UV alone may provide reasonable removal efficiencies for a number of the UOCs found in NJ surface waters. However, an AOP would provide greater removal efficiencies for a wide range of UOCs by promoting the indirect reaction with OH radical.

AIR STRIPPING PROCESSES

General Process Description

Air stripping is a treatment technique in which air is brought into contact with water in a controlled manner to permit the transport of volatile contaminants from the water into the air. The goal is to transfer the contaminant from the water to the air at the gas-liquid interface as efficiently as possible (Montgomery, 1985). Air stripping has been used in water treatment to reduce the concentrations of taste and odor producing compounds, carbon dioxide, hydrogen sulfide and volatile organic chemicals. This process also has been used to oxidize iron and manganese by adding air to the water – referred to as aeration or gas absorption. Air stripping processes that have been used most frequently in water treatment include:

- Diffused bubble aerators where a blower adds fine bubbles of air to a chamber of flowing water,

- Packed towers where the water is pumped to the top of a chamber filled with materials that separate the water flow so that introduced air can contact thin films of water,
- Shallow tray aeration where water is introduced to a top layer of stacked trays filled with coal or a similar medium that facilitates air and water contact.

Each of these techniques has been used extensively in treating ground water supplies. There is one surface water supply in NJ that uses packed tower air stripping for volatile organic chemical removal.

Factors Affecting Process Efficiency

The driving force for mass transfer is the difference between the existing and equilibrium concentrations of the waterborne contaminant in air and water (Montgomery, 1985). The equilibrium concentration of a solute or contaminant in air is directly proportional to the concentration of the solute in water at a given temperature, according to Henry's Law which states that the amount of gas that dissolves in a given quantity of liquid, at constant temperature and total pressure, is directly proportional to the partial pressure of the gas above the solution. Therefore, the Henry's Law Coefficient describes the tendency of a given compound to separate between a gas and a liquid. The Henry's Law Coefficient can be used to give a preliminary indication of how well an organic chemical can be removed from water, as discussed further below.

Factors that affect this transfer include:

- The temperature of both water and air
- The physical chemistry of the contaminant (i.e., volatility)
- Concentration of the contaminant
- The ratio of air to water in the process
- Contact time
- Available area for mass transfer
- The pressure of the system

The latter four factors can be controlled in the design of the air stripping system, while the first two factors are a function of the specific ground water supply and the nature of the organic chemicals in that supply.

Applicability to UOC Removal

The contaminants that can be removed by aeration are those that are gases or that become vapors at ambient temperatures and pressures. Aliphatic compounds of 4 carbons or less are gases and aliphatic compounds with 5 to 6 carbons are volatile. Many of the smaller cyclic and aromatic compounds are also volatile. Figure 3-1 illustrates the types of UOCs that may be volatile and removed using air stripping techniques based on polarity and molecular weight.

	Volatile	Semivolatile	Nonvolatile
Polar	Alcohols	Alcohols	Polyelectrolytes
	Ketones	Ketones	Carbohydrates
	Carboxylic Acids	Carboxylic Acids	Fulvic Acids
		Phenols	
Semipolar	Ethers	Ethers	Proteins
	Esters	Esters	Carbohydrates
	Aldehydes	Aldehydes	Humic Acids
		Epoxides	
		Heterocyclics	
Nonpolar	Aliphatic hydrocarbons	Aliphatics	Non-ionic polymers
	Aromatic hydrocarbons	Aromatics	Lignins
		Alicyclics	Hymatomelanic acid
		Arenes	
	Low Molecular Weight	Medium Molecular Weight	High Molecular Weight

Figure 3-1 Volatility of Classes of Organic Chemicals

The Henry's Law Coefficient of a compound indicates how well a compound can be removed from water via air stripping. A higher Henry's Law Coefficient indicates good removal from the water phase to the air phase. Figure 3-2 presents Henry's Law Coefficients for selected organic chemicals. Generally, the more water soluble the gas, the lower the value of the Henry's Law Coefficient. The polarity and molecular weight of a gas strongly affect its water solubility – with more polar and higher molecular-weight gases being more water soluble. This information can be used to provide a preliminary indication of the applicability of air stripping to remove the organic chemicals that have been detected in NJ surface waters.

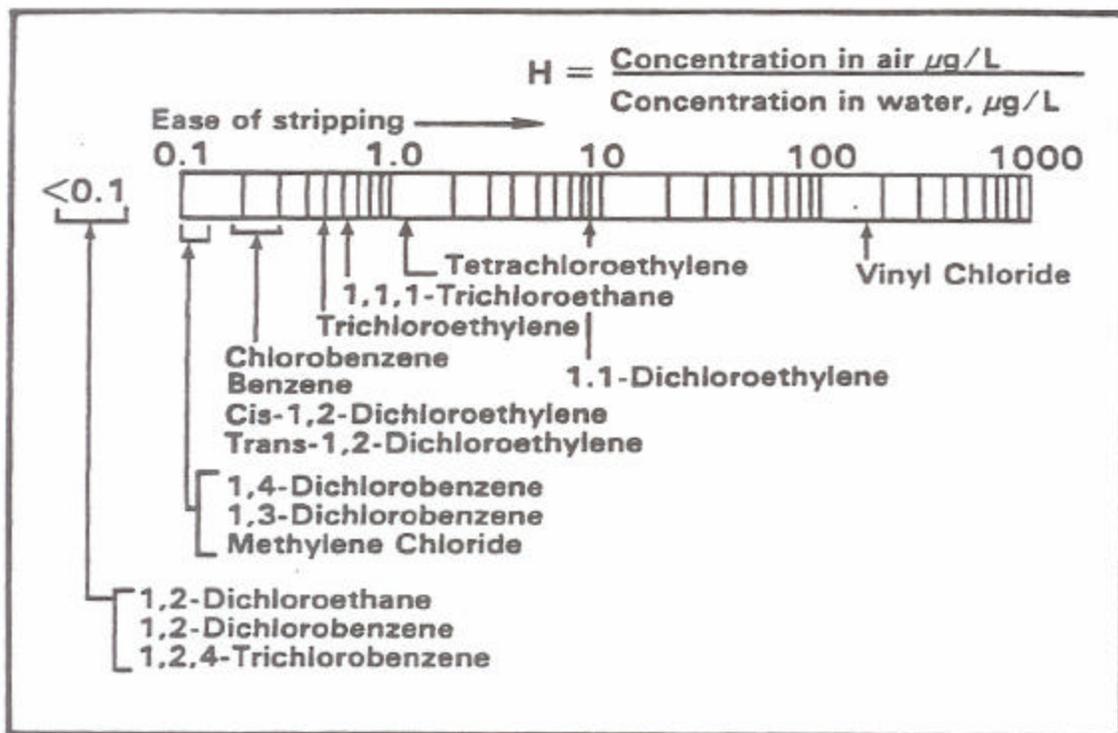


Figure 3-2 Henry's Law Coefficients for Various Organic Chemicals

MEMBRANE PROCESSES

General Process Description

Increasingly, utilities are using membrane technology for a wide array of water treatment applications, including the following:

- Surface water treatment with microfiltration or ultrafiltration.

- Water reclamation with microfiltration or ultrafiltration followed by reverse osmosis or ozone.
- Desalination with reverse osmosis.
- Softening with reverse osmosis or nanofiltration.
- Removal of nitrate (and other ions) with reverse osmosis.
- Removal of color, total organic carbon (TOC), and DBP precursors with reverse osmosis or nanofiltration and ultrafiltration with coagulation.
- Treatment and recovery of filter backwash water with ultrafiltration or nanofiltration.
- Industrial processing for ultrapure water and reuse with reverse osmosis.

Membranes used in water treatment may be defined as a thin film barrier that selectively removes some of the constituents in the water. The constituents removed include particles, colloidal species, and dissolved organic and inorganic compounds. The major membrane types used in water treatment and discussed in this report include:

- microfiltration (MF),
- ultrafiltration (UF),
- nanofiltration (NF),
- reverse osmosis (RO)

These membranes differ from each other in several aspects including driving force, materials, configurations, removal mechanism and rejection ability as listed in Table 3-1.

MF, UF, NF and RO membrane processes use pressure to induce transport of water across the membrane (or vacuum (negative pressure) in submerged membrane applications). Pressure is applied on the feed side of the membrane to separate the feed stream into a permeate (or filtrate) stream that passes through the membrane, and a reject or concentrate stream that does not pass through the membrane and contains the rejected constituents in the feed water. For submerged MF and UF membranes, suction is used instead of pressure to move the water through the membrane.

Table 3-1
General Description of Membrane Systems Commonly Used
in Water Treatment

Membrane type	Driving force	Mechanism of separation	Membrane structure
Microfiltration (MF)	Pressure or suction	Physical sieving	Macropores
Ultrafiltration (UF)	Pressure or suction	Physical sieving	Macropores
Nanofiltration (NF)	Pressure	Physical sieving + diffusion + exclusion	Dense membrane phase & nanopores
Reverse Osmosis (RO)	Pressure	Physical sieving + diffusion + exclusion	Dense membrane phase

MF and UF membranes are porous in nature and the removal mechanism is primarily one of sieving. Under applied pressure or vacuum (negative pressure), water is transported across the membrane, while all contaminants larger than the size of the membrane pores are retained. RO and NF membranes are semipermeable membranes allowing transport of water across the *membrane phase* through diffusion, and limiting the diffusive transport of solutes. The transport of water across the membrane occurs by convection under the applied pressure gradient.

Factors Affecting Process Efficiency

The ability of membrane processes to reject various contaminants in water is highly dependent on the removal mechanism and membrane structure. Based on that, the membrane processes listed above could be grouped into two categories:

- MF and UF membranes: Pressure or suction driven process; removal through sieving
- NF and RO membranes: Pressure driven process; removal through diffusion and sieving
- All - removal by electrostatic repulsion based on zeta potential and contaminant charge (both dependent on pH)

MF and UF membranes

The surfaces of these membranes consist of macropores which allows passage of water, while retaining all constituents larger than the pore size. The main difference between MF and UF membranes is the nominal pore size. The commercially available MF and UF membranes are characterized by nominal pore sizes of approximately 0.1 μm and 0.01 μm , respectively. Due to their pore sizes, these membranes effectively remove all contaminants larger than their pore size. Of particular interest to the water treatment industry is their ability to reject pathogens such as *Cryptosporidium* oocysts and *Giardia lamblia*. UF membranes, depending on their pore size, could achieve significant removal of viruses. The molecular weight cut off for UF membranes is generally around 10,000, which is much higher than any of the organic chemicals.

NF and RO membranes

NF and RO membranes are not characterized by pores. Rather they are considered as dense membrane phase. The primary separation mechanism is selective diffusion of water through the membrane phase. However, some investigators have reported some pore structure in NF membranes with pore sizes in the range of nanometers. Due to the lack of discrete pore structure, the rejection capability of these membranes is characterized by nominal molecular weight cut off (MWCO). It is defined as the size of a macromolecule (such as some proteins or sugars) for which the membrane achieves certain rejection (typically 90%). It is typically assumed that for macromolecules larger than the MWCO, efficient rejection is possible and for macromolecules smaller than MWCO, rejection would be lower. However, the rejection of a given contaminant is dependent on molecular weight as well as degree of dissociation of the species, polarity, molecular structure, membrane chemistry and chemistry of the feed water.

The main distinction between RO and NF membranes is their ability to reject salts. Typically RO membranes achieve high rejection of many dissolved substances including monovalent ions (e.g., chloride). The salt rejection of nanofiltration membranes is lower, particularly for the monovalent ions. NF systems are sometimes referred to as 'loose' RO membranes, as their pressure requirement as well as rejection ability is lower.

Applicability to UOC Removal

Based on bench and pilot scale testing of membranes for removal of organic chemicals, the following results have been reported:

- Typically, compounds associated with particles or colloidal matter in the water would be removed by microfiltration or ultrafiltration.
- Both RO and tight nanofiltration systems are effective in removing most organic chemicals.
- Polar compounds and charged compounds that interact with membrane surfaces will be better removed than less polar or neutral compounds.
- Overall, membrane separation provides an excellent barrier for most EDCs and PPCPs, except lower molecular weight uncharged compounds.
- Work by Linden indicated that the CCL (1998) compounds could be removed by as much as 80 percent and higher with the use of RO.

In general, MF and UF membrane systems would not be expected to remove the vast number of organic contaminants, while NF and RO membrane systems can achieve as high as 100 percent removal.

BIOLOGICAL PROCESSES

General Process Description

Biological processes have been used in water treatment for removal of iron, manganese, ammonia, and biodegradable NOM (or assimilable organic carbon (AOC)). Also, biological treatment has been used in conventional surface water treatment plants to provide a greater barrier for microbiological control. Typically, biological treatment is accomplished in combination with a filtration process using sand, anthracite or GAC media. Biologically-active filtration (BAF) is often preceded by ozonation, as ozone forms AOC that can form significant biofilms in the distribution system. Additionally, ozone saturates the water with oxygen, which increases biological activity on down-stream bio-filters.

Generally, an initial start-up period is required for the process to establish the biomass in the filter or adsorber. This can be significant depending on the nature of the compounds to be removed. Once the system is operating, it is better to run it continuously to avoid a reduction in the biomass and a resultant reduction in removal efficiency. Depending on the nature of the

water, a nutrient may need to be added before biological filtration to provide sufficient food for the microorganisms to grow. In BAF systems, backwashing often requires de-chlorinated water in order to minimize disruption of the biofilm.

Factors Affecting Process Efficiency

The key factors that would impact the removal efficiency of a biological process for organic chemical removal are:

- Biodegradability of the compound to be removed
- Amount and nature of nutrients in the raw water.
- pH of the water
- Operating scenario - continuous vs. intermittent
- Contact time
- Presence and concentration of dissolved oxygen in the water

Applicability to UOC Removal

Very little work has been done to determine the removal efficiency of biological processes on organic chemicals in drinking water. More work has been done on wastewater treatment; however, the nature of the water is obviously much different especially regarding the food supply for microorganisms. Also the temperature of the wastewater is generally warmer than that found in surface waters, promoting greater biological growth. If GAC were used for organic chemical removal from a surface water supply, it is likely that some biological growth would occur. This may be especially true for GAC adsorbers preceded by ozone as oxygen tends to be added to the water enhancing microbiological growth. The organic chemical removal that would take place in a GAC adsorber would depend on the nature of the water and the biodegradability of the organic chemicals.

FULL-SCALE TREATMENT STUDIES

There have been a few completed studies conducted to evaluate the effectiveness of full-scale treatment processes for UOC removal (Fischer, 2005 and Snyder, 2005). Other studies currently

are underway. The work by Fischer was done in conjunction with the NJDEP and USGS and Passaic Valley Water Commission (PVWC). Samples were collected in 2003 and 2004 after each process in the PVWC Little Falls Water Treatment Plant. The Little Falls WTP takes raw water from the Passaic River and at the time of sample collection included the following processes: coagulation, settling, disinfection with either chlorine or ozone, filtration with sand and GAC, and secondary disinfection with chlorine. The detection and concentration of the more frequently found UOCs are shown in Figure 3-3.

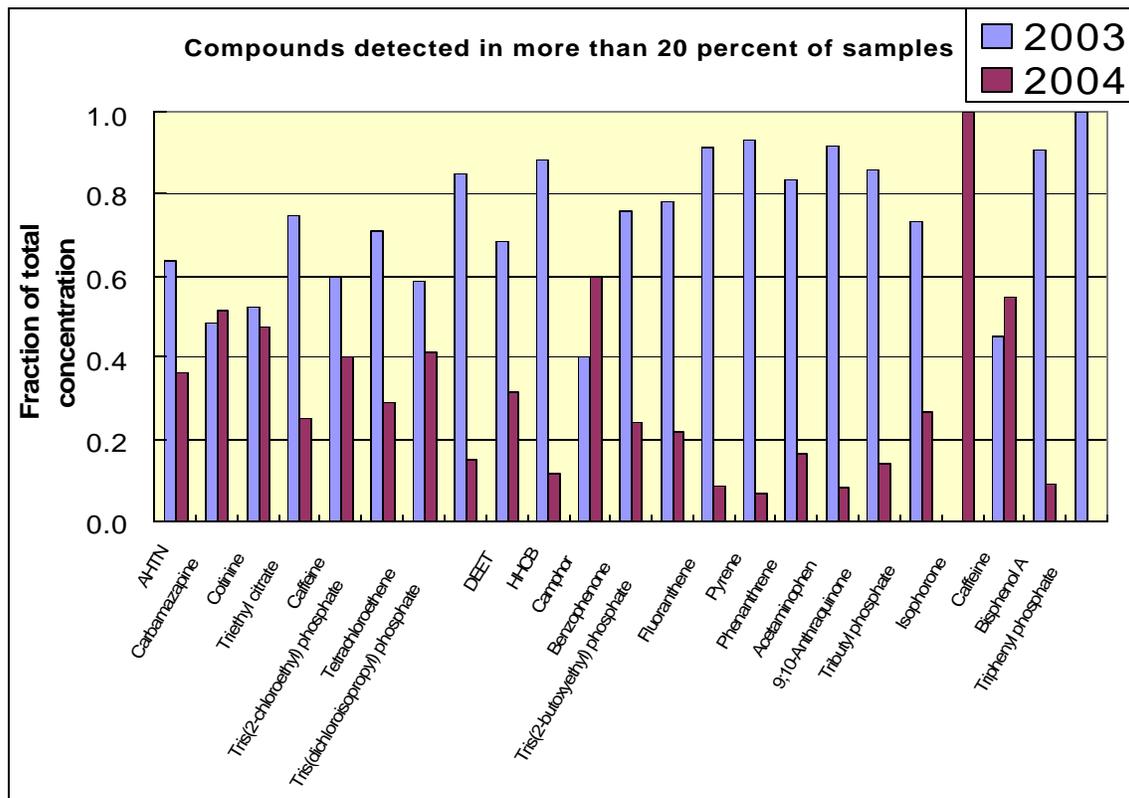


Figure 3-3 UOCs Detected in PVWC Little Falls WTP Raw Water

(Source: Fischer, 2005)

The per cent reduction in the concentration of a number of the UOCs through the treatment processes is shown on Figure 3-4.

The major findings of the study were reported as:

- Approximately 150 of 220 UOCs were detected in the raw water

- Treatment processes were effective at removing over 80 percent of detected UOCs through:
 - Removal with solids
 - Reactions with free chlorine or ozone
 - Sorption on activated carbon
- A few persist to finished water at low concentrations (<0.05ug/L)
- 29 compounds were detected in finished water, half of these were detected less than 20% of the time. 5 compounds were detected 40% to 100% of time.

Regarding the effectiveness of the treatment processes, the study reported the following:

- Ozone was more effective than chlorination at removing compounds and reducing concentrations
- Activated carbon filters removed many compounds ozone and chlorine missed
- Similar numbers and types of compounds were detected in finished water treated with ozone or chlorine
- Concentrations in finished water were low (<0.05ug/L), and treatment processes reduced concentrations from 30% to 100%

The work conducted by Snyder was part of an AwwaRF project that investigated the occurrence and treatment of endocrine disruptors and pharmaceuticals. As part of the project, 18 full-scale water treatment plants from a variety of locations around the US were sampled – both raw and finished water. At some locations, samples were collected between treatment processes as well. A summary of the results for some of the more frequently detected UOCs is shown below:

UOC	Average Raw Water Concentration (ng/L)	Average Finished Water Concentration (ng/L)	Average Removal Efficiency (%)
N,N-diethyl- meta-toluamide (DEET)	10.8	10.9	0
Caffeine	26.6	27.7	0
TCEP	21.9	9.9	55
Dilantin	4.1	3.3	20
Carbamazepine	5.7	4.1	28
Sulfamethoxazole	17.8	2.1	88
Ibuprofen	7.3	10.4	0
Atrazine	153.8	117.8	24
Meprobamate	6.8	5.7	16
Iopromide	13.8	9.0	35
Naproxen	5.6	1.0	82
Triclosan	1.7	0	100
Trimethoprim	2.3	0	100
Acetaminophen	3.8	1.1	71

The study concluded that ozone and GAC were found to be the most effective processes employed in existing treatment facilities for removing UOCs.

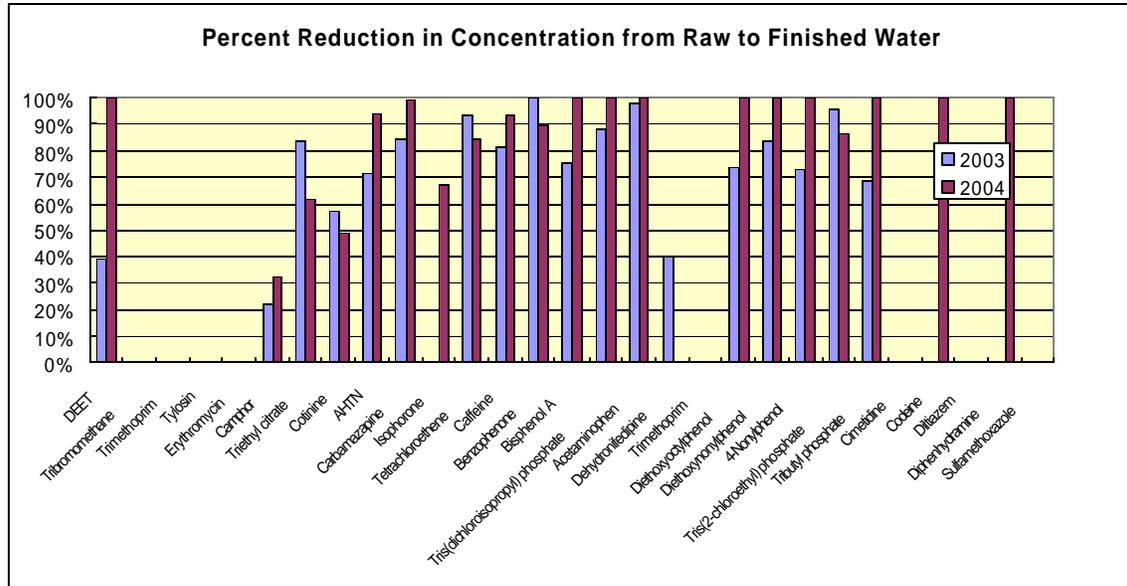


Figure 3-4 Removal of UOCs Through PVWC Little Falls WTP

(Source: Fischer, 2005)

SUMMARY OF AVAILABLE TREATMENT TECHNIQUES

The review of available treatment data indicates that data exist for many of the individual compounds that have been detected in the NJ surface water systems as summarized in Chapter 2. As a result, the applicability of specific treatment techniques for NJ surface waters was estimated based on published treatability data and from compounds of similar characteristics. An example is shown in Table 3-2 which presents a summary of information developed by Snyder on the treatability of various groups and classes of organic chemicals found in water.

Based on the available information, the potential for treatment of the specific organic chemicals by the various treatment techniques is presented in Appendix C. Summaries of this information by contaminant class and category are also presented in Tables 3-3 (cyclics), 3-4 (aliphatics), and 3-5 (aromatics). The information contained in the previous tables regarding the potential for removal of the 26 UOCs by the treatment techniques evaluated are summarized below:

	<u>Cyclics</u>	<u>Aliphatics</u>	<u>Aromatics</u>	<u>Totals</u>
Conventional Treatment	2	1	8	11
Oxidation	1	0	14	15
Adsorption	3	0	11	14
Air Stripping	0	1	4	5
Biological Treatment	3	2	7	12

It is estimated that membranes, particularly RO, could be applicable for removal of almost all the UOCs. However, because of cost and waste disposal issues, RO is not considered a practical alternative at this time.

From the above information, the available treatment techniques have been divided into the following general categories:

Most Applicable Technologies - Adsorption with GAC or PAC and AOP

Other Possible Technologies - Oxidation/Biological Treatment and Conventional Treatment

Additional Technologies - Oxidation (alone) and Membranes

Oxidation and adsorption processes appear to be the most applicable technologies because of their ability to remove a wide range of compounds. The type of compound and treatment conditions applied will ultimately dictate whether or not a particular compound can be reduced to below the detection limit of modern analytical instrumentation. For instance, GAC must be replaced regularly in order to maintain adsorption capacity. Likewise, PAC contact time and dose will affect contaminant removal efficiency. Advanced oxidation processes involving ozone or high-energy UV also are considered most applicable to NJ surface waters. It should be noted that conventional treatment is listed as “Other Possible Technology”, because most surface water

treatment plants in NJ include this technology. Removal efficiencies using conventional treatment (coagulation/filtration) are not expected to be highly-efficient for many UOCs. Chlorine may be applicable depending on the required residual and contact time. Oxidation using ozone followed by biological filters is considered a possible technology considering the potential removals and the fact that several surface water treatment plants in NJ include these processes. Membranes are not considered as applicable at this time because they are more costly when compared to the other techniques, especially in the case of RO.

It should be noted that based on the various studies that have been completed to date on the fate of organic chemicals in water treatment processes, no single treatment technique can remove all of the UOCs that have been detected in NJ surface waters. In addition, it is unlikely that all of the UOCs from a given location could be removed to zero levels even using a combination of processes, since modern analytical methodology permits sub-ng/L detection limits. By-products of oxidation and biological activity are likely to be generated, with unknown toxicological impacts as is reported in Chapter 4.

Table 3-2 Unit Processes and Operations Used for EDCs and PPCPs Removal

Group	Class	AC	BAC	O ₃ /AOP	UV	Cl ₂ /ClO ₂	Coagulation/ Flocculation	NF	RO	Degradation {B/P/AS} ^a
EDCs	Pesticides	E	E	L-E	E	P-E	P	G	E	E {P}
	Industrial Chemicals	E	E	F-G	E	P	P-L	E	E	G-E {B}
	Steroids	E	E	E	E	E	P	G	E	L-E {B}
	Metals	G	G	P	P	P	F-G	G	E	P{B},E{AS}
	Inorganics	P-L	F	P	P	P	P	G	E	P-L
	Organo- metallics	G-E	G-E	L-E	F-G	P-F	P-L	G-E	E	L-E
PhACs	Antibiotics	F-G	E	L-E	F-G	P-G	P-L	E	E	E {B}
	Anti- depressants	G-E	G-E	L-E	F-G	P-F	P-L	G-E	E	G-E
	Anti- inflammator y	E	G-E	E	E	P-F	P	G-E	E	E {B}
	Lipid regulators	E	E	E	F-G	P-F	P	G-E	E	P {B}
	X-ray contrast media	G-E	G-E	L-E	F-G	P-F	P-L	G-E	E	E {B and P}
	Psychiatric control	G-E	G-E	L-E	F-G	P-F	P-L	G-E	E	G-E
PCPs	Synthetic musks	G-E	G-E	L-E	E	P-F	P-L	G-E	E	E {B}
	Sunscreens	G-E	G-E	L-E	F-G	P-F	P-L	G-E	E	G-E
	Anti- microbials	G-E	G-E	L-E	F-G	P-F	P-L	G-E	E	L-E {B}
	Surfactants/ detergents	E	E	F-G	F-G	P	P-L	E	E	L-E {B}

^aB, biodegradation; P, photodegradation (solar); AS, activated sludge; E, excellent (>90% removal); G, good (70–90% removal); F, fair (40–70% removal); L, low (20–40% removal); P, poor (<20% removal).

Table 3-3

Treatability of Cyclics

<u>Category</u>	<u>Convent. Treatment Yes/Partial</u>	Air Stripping		Adsorption		Oxidation		Biological	
		<u>Yes</u>	<u>Possible</u>	<u>Yes</u>	<u>Possible</u>	<u>Yes</u>	<u>Possible</u>	<u>Yes</u>	<u>Possible</u>
Pharmaceuticals 1	-	-	-	-	1	-	-	-	1
Consumer Products – 2	2	-	-	2	-	1	-	2	-
TOTALS – 3	2	-	-	2	1	1	-	2	1

Table 3-4

Treatability of Aliphatics

<u>Category</u>	<u>Convent. Treatment Yes/Partial</u>	Air Stripping		Adsorption		Oxidation		Biological	
		<u>Yes</u>	<u>Possible</u>	<u>Yes</u>	<u>Possible</u>	<u>Yes</u>	<u>Possible</u>	<u>Yes</u>	<u>Possible</u>
Consumer Products – 1	-	-	-	-	-	-	-	1	-
Pharmaceuticals 1	-	-	-	-	-	-	-	-	1
Industrial Chemicals-1	1	-	1	-	-	-	-	-	-
TOTALS - 3	1	0	1	0	0	0	0	1	1

Table 3-5

Treatability of Aromatics

<u>Category</u>	<u>Convent. Treatment Yes/Partial</u>	<u>Air Stripping</u>		<u>Adsorption</u>		<u>Oxidation</u>		<u>Biological</u>	
		<u>Yes</u>	<u>Possible</u>	<u>Yes</u>	<u>Possible</u>	<u>Yes</u>	<u>Possible</u>	<u>Yes</u>	<u>Possible</u>
Pharmaceuticals 6	2	-	-	2	-	-	-	-	-
Consumer Products 3	2	-	1	2	-	3	-	-	1
Industrial Chemicals – 5	2	1	-	4	-	5	-	1	-
PAHs – 4	2	1	1	1	-	4	-	-	3
Insecticides - 2	-	-	-	-	2	1	1	2	-
TOTALS – 20	8	2	2	9	2	13	1	3	4

CHAPTER 4 - APPLICABLE TECHNOLOGIES FOR NJ

INTRODUCTION

A variety of treatment techniques were reviewed and evaluated in the previous chapter for removing the UOCs that have been detected in NJ surface water supplies. As indicated in Chapter 3, the techniques that appear to be applicable to NJ surface waters based on available information are:

- Activated Carbon Adsorption
- Oxidation and Advanced Oxidation
- Oxidation/Biological Treatment
- Conventional Treatment

Applicable technologies are those technologies that have been demonstrated to remove the UOCs detected in NJ surface waters, or are expected to remove them based on their characteristics. Each of these treatment techniques is discussed in more detail in the following sections of this chapter with respect to general description, process description, and operational/regulatory considerations. In addition, capital and operating cost estimates are presented for each technology for three system sizes: 10, 50, and 100 mgd.

ACTIVATED CARBON ADSORPTION

General

Adsorption of synthetic organic chemicals from water using activated carbon is recognized as the best available technology for removal of many regulated organic contaminants. Early studies by the water industry looked at removal of disinfection by-products and removal of naturally occurring taste and odor compounds. Research expanded to include removal of pesticides and herbicides and a number of synthetic industrial chemicals by activated carbon. It is expected that many of the tentatively identified compounds found in NJ surface waters will be amenable to activated carbon adsorption.

Activated carbon adsorption might be accomplished at a surface water treatment plant using either granular activated carbon (GAC) or powdered activated carbon (PAC). Both processes currently are used at surface water plants in NJ. There are at least seven surface water plants in NJ that employ GAC to remove either taste and odor compounds or natural organic chemicals that contribute to disinfection by-product formation. There are also several surface water plants in NJ that use PAC, mostly for taste and odor control during the summer months.

GAC Process Description

In GAC treatment, water is passed through a bed of GAC in much the same way that settled water is introduced to sand or multimedia filter beds for final polishing. The adsorbable organic compounds transfer from the bulk water to the surfaces of the activated carbon. The key process design parameters for a GAC system include:

- Contactor Configuration
- Empty Bed Contact Time
- Loading Rate
- Pretreatment
- GAC Regeneration

Each of these parameters is discussed in the following paragraphs.

Contactor Configuration – Contactors can be configured in a variety of ways for different applications. Upflow contactors have been used more often in wastewater applications where there is the potential to blind the GAC with suspended solids while downflow systems, which are easier to operate, are most often used for drinking water. Downflow contactors can be further categorized into gravity flow contactors and pressure contactors. In addition, GAC contactors can be designed and operated as filter-adsorbers or post-filter adsorbers. When operating as filter-adsorbers, the GAC contactor removes both turbidity and organic chemicals in the same bed. This mode of operation requires frequent backwashing which has a tendency to disrupt the adsorption profile through the GAC bed resulting in “leakage” of the target compound(s). When operated as post-filter adsorbers, the GAC contactor is placed after the filters and is used solely for organic chemical removal. Occasional “fluffing” (light backwash) of the media is necessary, but the disruption to the adsorption profile is insignificant.

The reason for using gravity contactors in surface waters plants is to reduce the construction cost and the footprint required to install GAC. Also, the use of pressure contactors would require an extra pumping step (which may not be required in every instance for gravity contactors) that would increase construction and operating costs. Filter-adsorbers tend to be used over post-filter adsorbers to reduce both construction and operating costs.

The larger surface water systems in NJ that use GAC utilize gravity contactors as filter-adsorbers. Two of the surface water GAC facilities in NJ use pressure contactors in a post-filter adsorber mode of operation. Both of these plants are small to medium size: 5 – 10 mgd. The use of pressure vs. gravity and filter-adsorber vs. post-filter adsorber for UOC removal at surface water plants in NJ probably will depend primarily on the size of the treatment plant and other factors, such as the depth of media that can be placed in existing filters, etc.

Empty Bed Contact Time (EBCT) – The adsorption of dissolved organic compounds from the water phase to the solid granular activated carbon surface requires time for the transport and attachment of the compound to the surface of the activated carbon. Determination of an optimal contact time of the water to the activated carbon bed is a critical design parameter as contact time has a major impact on carbon usage (EPA, 1991). Researchers have found that a minimum EBCT of 7.5 minutes is needed to achieve any appreciable organic chemical removal. Typically, EBCTs of 10 to 30 minutes have been used in evaluating GAC for synthetic organic chemical removal. In the GAC systems that have been installed in NJ, the EBCT varies depending on the contactor configuration. Those used in a filter-adsorber mode generally provide between 3 and 10 minutes of EBCT. Those used in a post-filter adsorber mode generally provide additional EBCT – 10 to 20 minutes. Because of the uncertainty of the adsorbability of many of the organic chemicals found in NJ surface waters, an EBCT of 15 minutes at the average plant flow should be provided. For systems treating less than 10 mgd, this contact time probably would be accomplished using pressure contactors in a post-filter adsorber mode of operation. For larger plant flows, gravity contactors operating in a filter-adsorber configuration may be more reasonable from a cost standpoint, although existing filters may not be sized adequately to provide the necessary EBCT. For example, achieving an EBCT of 15 minutes in a filter-

adsorber requires 6 feet of media with a surface loading rate of 3 gpm/ft² of filter area. Bed depths of greater than 6 feet are typically not used in filter-adsorbers because of the need to clean the media of filtered solids during backwash.

Loading Rate – Once the EBCT is established, a combination of hydraulic loading rate and carbon bed depth can be determined. Hydraulic loading rates used in practice have ranged from 2 to 10 gallons per minute per square foot (gpm/ft²). Moderate hydraulic loading rates of about 3 gpm/ft² for filter-adsorbers and about 5 gpm/ft² for post-filter adsorbers (both at maximum plant flow) were selected for the design basis and for determining cost estimates that are presented later in this section.

Pretreatment - All surface water systems have undesirable levels of suspended solids or turbidity that can blind the pores of the activated carbon and create premature headloss. Therefore surface waters require at least particle removal pretreatment to extend the life of the carbon contactors; consequently, the GAC contactors must be located after sedimentation. The carbon contactors should also have backwash capability to reduce headloss and keep the activated carbon clean during operation. As a minimum, the carbon must be backwashed after initial installation to remove the carbon fines. Backwash capability is included in the cost estimates for the activated carbon adsorption contactors.

Pretreatment also might be provided in conjunction with GAC to reduce organic chemical levels in the water applied to the GAC. This would lessen the organic loading to the GAC contactors and extend the carbon life. Five of the surface water treatment systems in NJ that use GAC also use ozone ahead of GAC. Such combined treatments are discussed further under Combinations of Processes.

GAC Regeneration – Over time, all of the available sites on the carbon become filled with adsorbates resulting in breakthrough of contaminants. At that point, the contactor must be taken off line and the GAC must be replaced. The spent carbon can be regenerated off-site or on-site, or disposed of and replaced with virgin GAC. The USEPA estimated that carbon usage in the range of 500 to 2,000 lbs per day is most compatible with off-site regeneration. A 50 MGD GAC

facility (15 minute EBCT) that replaces its GAC every 3 years uses about 2000 lbs per day. At higher usage rates than 2000 lbs per day, on-site regeneration may be cost effective. On-site regeneration requires carbon transport and storage facilities in addition to a regeneration furnace which is used to “burn” the organic chemicals off the carbon. None of the GAC systems in NJ use on-site regeneration.

Often, the carbon supplier will remove and regenerate the spent carbon and provide new or regenerated carbon as part of an operations contract. For the purpose of this study, off-site GAC regeneration is assumed.

PAC Process Design

PAC is used in a surface water treatment plant in conjunction with the settling process. PAC typically is added ahead of the settling process, and the PAC becomes enmeshed in the floc which settles out in the settling basin. Organic chemicals are adsorbed to the PAC and removed along with the PAC and the residuals that accumulate in the settling basin. The important process design parameters for PAC treatment are:

- Dosage - typical dosages used in surface water treatment range from 5 to 100 mg/L.
- Contact Time - the time provided for contact between the PAC and the water is important as the higher the contact time, the greater the removal efficiency. Typically, a settling basin will provide 2 – 4 hours of contact time.
- Type of PAC - There are different types of PAC. A lighter PAC will travel further along in the settling basin before settling out, and provide more contact time. Other important factors include pore structure and capacity. Pore structure can have a great influence on the time necessary for adsorption to occur and capacity for a specific compound will determine how much of a substance can be removed.

Operational/Regulatory Considerations

There are three operational and regulatory issues that must be considered relative to activated carbon adsorption processes:

- Impacts on Carbon Usage Rate
- Spent Carbon Disposal
- PAC Handling

Carbon Usage Rate - Carbon usage rate for a single contaminant is typically derived by performing isotherms to determine the capacity of the specific activated carbon for the contaminant. For complex mixtures of contaminants, it is more difficult to determine the carbon usage rate for several reasons:

- Various organic compounds with different adsorptive characteristics - some contaminants will adsorb more strongly than others.
- Competition among the various organic compounds for adsorption sites.
- Desorption (displacement) of compounds as more strongly adsorbed compounds take up sites - there may be displacement reactions as the compounds that adsorb more strongly replace less strongly adsorbed contaminants.
- Changing organic chemical concentrations, especially with very low concentrations.
- Type of GAC - activated carbon can be made from source materials such as bituminous coal, lignite, peat, wood, and coconut shells. Bituminous coal based activated carbons are the most commonly used in water treatment.
- Biological activity on the GAC - discussed further under Oxidation/Biological Treatment.

The concentrations of tentatively identified chemicals from the surface waters tested in NJ were typically quite low – microgram to nanogram per liter levels. The variability in surface water concentrations of these UOCs has not been established but would affect the carbon usage rate of the carbon. If levels remain low, the life of the carbon should be quite long, particularly if some of the compounds are biologically degraded once they are adsorbed to the activated carbon. If concentrations vary, carbon life will be shorter and some of the less adsorbable compounds may be driven back into the water, displaced by higher levels of more strongly adsorbed organic compounds.

For the reasons stated above, it is very difficult to accurately estimate the carbon usage rate for any given surface water supply in NJ. Based on the very low levels of UOCs in NJ surface waters and the limited information on treatability, it would appear that the carbon should last from 6-12 months before it must be replaced. Bench scale tests could be conducted rather easily

and quickly as part of a preliminary design to more accurately determine the carbon usage rate and life.

Spent Carbon Disposal - In all GAC installations treating NJ surface waters, the method of GAC regeneration is off-site by the carbon supplier. As a result, there are no disposal issues. Off-site carbon regeneration is assumed for purpose of this study.

PAC Handling - PAC is a rather difficult chemical to store, handle and feed. Special design considerations are needed to protect plant staff from any harmful effects of exposure to PAC, especially through inhalation of the powder. Also, PAC feed systems often are plagued with clogged lines requiring frequent maintenance.

Cost Estimates

Capital and operating cost estimates were developed for the installation of GAC contactors and PAC storage and feed systems to remove the UOCs that have been detected in NJ surface waters. The equipment and facility assumptions that were used to generate these costs and the costs are presented in the following subsections.

Equipment and Facility Assumptions - Although the design of a GAC system will vary depending on the local conditions (types and levels of organic chemicals present in the water and the location of the facility), the major components of any GAC treatment system are:

- Carbon Contactors
- Carbon Charge
- Backwash Capabilities
- GAC Contactor Building: It is necessary to house the GAC contactors to protect them from freezing.
- Repumping: Additional head will be introduced with the installation of the GAC contactors and intermediate pumping may be needed to compensate for the additional head.

For the GAC contactors, the following design criteria have been used for the purpose of developing cost estimates based on the process description presented previously:

- EBCT - 15 minutes at the design flow
- Contactor configuration
 - < 10 mgd - pressure, downflow contactors, used in post-filter adsorber mode of operation
 - > 10 mgd - gravity, downflow contactors, used in a filter-adsorber mode of operation
- Liquid loading rate - 5 gpm/ft² for post-filter adsorbers and 3 gpm/ft² for filter-adsorbers
- Backwash - taken from finished water
- Regeneration - off-site
- Pretreatment - existing coagulation/sedimentation process

PAC is stored as a dry powder but is wetted into slurry form for application to the raw water. Gravimetric or volumetric dry feed systems are used to store and feed the PAC. The storage facilities consist of one or more pneumatically filled storage silos with associated dust control, fill piping, and level sensors. The storage bin has a conical bottom with vibrator to facilitate the exit flow of the activated carbon to a wetting tank where the PAC is made into slurry form. Transfer pumps move the slurry from the wetting tank to the point of application.

Activated carbon dust can explode if exposed to sparks. Therefore, it must be in a room separate from all other chemicals and protected with fire proof construction, explosion proof wiring, and a sprinkler system. Dust control and proper ventilation are also critical.

Costs - Capital and operating costs were developed for three system sizes for the GAC contactors and for three sizes of PAC feed systems: 10, 50 and 100 mgd. Based on the facility and design assumptions presented above, it is estimated that the capital costs (including all facility costs and engineering) would be in the range presented in Table 4-1 for the GAC contactors and Table 4-2 for the PAC feed systems.

Operating costs will include:

- Carbon replacement
- Labor
- Power
- Maintenance

The majority of the cost will be for replacement of the carbon. Considering the number and variety of UOCs that may be in a given surface water supply, it is very difficult to estimate the carbon replacement frequency in the contactors or the doses required for the PAC feed system. For purposes of this report, it is estimated that the replacement frequency may be 6-12 months.

Table 4-1
Estimate of Capital and O&M Costs of GAC Contactors
 In US Dollars

	10 mgd	50 mgd	100 mgd
Capital	\$5,000,000 – 5,500,000	\$22,000,000 – 25,000,000	\$40,000,000 – 44,000,000
O&M	\$350,000 - 550,000	\$1,100,000 - 2,100,000	\$2,200,000 - 4,200,000

Table 4-2
Estimate of Capital and O&M Costs of a PAC Feed System
 In US Dollars

	10 mgd	50 mgd	100 mgd
Capital	\$490,000 – 500,000	\$1,200,000 – 1,400,000	\$2,500,000 – 2,700,000
O&M	\$250,000 - 400,000	\$1,200,000 - 2,100,000	\$2,500,000 - 4,000,000

The above costs for GAC are for complete contactors and carbon. A utility might be able to simply replace their filter media with GAC to convert their filters to filter-adsorbers. If that is possible, it is estimated that the cost for media replacement will be about \$0.5 million for a 10 mgd plant, \$2 million for a 50 mgd plant, and \$4.2 million for a 100 mgd plant.

OXIDATION PROCESSES

General

Advanced oxidation processes have less history in water treatment than adsorption. Ozonation is well known as a disinfectant and a means to reduce taste and odor compounds but also can oxidize many organic chemicals. Ultraviolet (UV) light at high irradiance levels also can oxidize certain organic chemicals. When either ozone or UV is supplemented by hydrogen peroxide addition (advanced oxidation), it has been shown in some research that these processes are able to oxidize even more organic contaminants or achieve higher removal efficiencies. These processes have not been explored to the full extent of their potential capabilities, but look very promising for removal of organic compounds. Another oxidant that may prove feasible for surface waters in NJ is chlorine which is already used at most surface water plants in NJ. Each of these processes is discussed below.

Process Description

Ozone and UV both have been demonstrated to achieve varying degrees of removal of some of the types of organic chemicals that have been detected in NJ surface water supplies. In addition, both oxidation processes have been able to achieve higher removal efficiencies in many cases with the use of hydrogen peroxide. Both ozone and UV with the addition of hydrogen peroxide act to generate hydroxyl radicals that enhance the oxidative degradation of organic materials. The hydroxyl radicals are non-selective, though some compounds are oxidized more easily than others. Many compounds are partially oxidized to degradation products that may be as toxic or undesirable as their parent compound; very few react to carbon dioxide and water. Ultraviolet light energy can also be absorbed directly by some organics, depending on the output of the ultraviolet source, the absorbance characteristics of the water and the absorbance characteristics of the organic chemical. Chlorine is used most frequently for disinfection and may also provide adequate removal of some UOCs.

Ozone - There are a number of parameters that must be taken into account in the design of an ozone process including:

- Ozone demand of the water
- Ozone dosage
- Contact or reaction time
- Method of application
- Ozone source
- Hydrogen peroxide dosage (when used for advanced oxidation)

The ozone demand of the water itself must be taken into account during design. Natural organic material present in the raw water and measured as Total Organic Carbon (TOC) will exert a demand and must be compensated for when determining an ozone dose. Typically, surface waters in NJ exhibit moderate TOC levels, and so there will be an ozone demand in the raw water. Other oxidizable species (As (III), reduced forms of iron, manganese, etc.) exert oxidant demand, especially if they are more easily oxidizable than the target organics. Bromide, if present in sufficient concentrations, can be converted to bromate (which has a Maximum Contaminant Level) by ozone.

Bench and pilot tests of ozonation to oxidize organic chemicals have indicated dosages of between 2 – 5 mg/L are required to achieve good removals. Contact time between the water and the ozone also is important for reaction of the ozone with the organic chemicals to occur. Contact times of 5 – 10 minutes have been used to achieve good removals of organic chemicals.

Ozone can be added either before coagulation and sedimentation as a preoxidation step or after coagulation and sedimentation as an intermediate oxidation step. It is more beneficial to add it as an intermediate step to minimize the ozone demand of the water, and thereby reduce the amount of ozone needed for oxidation.

Although the application of ozone has not changed substantially in the past 7 years, the technology of the generation and application of ozonation has changed. In the past, ozone has been generated from air using drying, cooling and compressor equipment. Ozone system suppliers now are using high purity feed gases (such as liquid oxygen) and more efficient generators with advanced contacting systems to make ozonation a more affordable option. The

application of ozone in a pipeline has become more convenient with the use of specially designed injectors (side-stream injectors), nozzles, and static mixers.

Although ozone alone has been found to provide good removal of the types of UOCs found in NJ surface waters, hydrogen peroxide has been used to generate hydroxyl radicals to achieve even higher removal efficiencies and of more compounds. The hydrogen peroxide is added ahead of the ozone process, and a dosage of 5 to 10 mg/L has been shown to provide as high as 90% removal of some of the organic chemicals.

UV - The parameters that are important in the design of a UV process for organic chemical removal are:

- UV transmittance of the water
- Type of UV reactor (low pressure vs. medium pressure)
- UV dosage or intensity

The influent water quality has a direct impact on a system's efficiency to remove organic contaminants. Oxidation is a non-selective process. Therefore, other compounds in the water can react besides the contaminants of concern. This increases the oxidant demand, thus increasing costs. The other reactions may also prevent complete oxidation, resulting in by-products other than carbon dioxide and water. Examples of how water quality can affect the AOP process are the following:

- Alkalinity scavenges hydroxyl free radicals and may require pH reduction to minimize the scavenging effect.
- Nitrate absorbs UV light and is converted to nitrite, which exerts an oxidant demand.
- Turbidity lowers transmittance of UV light.

Because of these water quality impacts, it is desirable to locate the UV process at the end of a conventional treatment plant.

Both medium and low pressure UV devices have been tested for organic chemical removal efficiency. The medium pressure units have exhibited slightly better removals compared to low pressure units.

UV intensities of 40 mJ/cm² to over 1,000 mJ/cm² have been tested for organic chemical removal. The lower intensity is typically used for microbial inactivation, but has been found to provide very low organic chemical removal - less than 30 % for many compounds. A dosage of several hundred mJ/cm² can improve removal efficiencies to about 50 %. To achieve high removal efficiencies such 90 %, an intensity of 1,000 mJ/cm² and higher is required. The use of hydrogen peroxide has been shown to increase organic chemical removals using UV because of the generation of hydroxyl radicals. The application of 5 to 10 mg/L of hydrogen peroxide in conjunction with UV at an intensity of several hundred mJ/cm² can boost removals to 80 % and higher for some compounds.

Chlorine - Although chlorine has been shown to provide good removals of some organic chemicals, it also has been shown to provide poor removals of other organic chemicals. Chlorine alone probably would not be sufficient for the variety and levels of UOCs found in NJ surface waters. However, because of the use of chlorine at most surface water treatment plants, the degree of removal that is achieved through the disinfection process should be taken into consideration in the overall removal of UOCs through the plant.

Operational/Regulatory Considerations

The use of ozone or chlorine for UOC removal must take into account the potential by-products that might be formed. For ozone, the presence of bromate in the raw water will result in the formation of bromoform. The use of high dosages of chlorine also will result in the formation of disinfection by-products.

The use of hydrogen peroxide does have some operational considerations. Hydrogen peroxide is a liquid chemical. It is generally used as an oxidizing agent, though can be a reducer in some reactions. Concentrated solutions can decompose spontaneously to form water and oxygen and

release heat. Hydrogen peroxide vapor can detonate above 70°C (158 °F), so it is best to keep solutions cool. The typical hydrogen peroxide solution is provided at 35% and is compatible with stainless steel or polyethylene.

Cost Estimates

Capital and operating cost estimates were developed for the installation of an oxidation facility to remove UOCs that have been detected in NJ surface waters. The equipment and facility assumptions that were used to generate these costs and the costs are presented in the following subsections. No costs were prepared for chlorine oxidation as it is assumed that the existing chlorination system would not be modified.

Equipment and Facility Assumptions - The equipment required for typical ozone and UV installations consists of the following:

Ozone

- Contactor: Concrete basins would be used to provide the necessary contact time.
- Injection System: A side-stream injector would be used to apply the ozone to the water. Ozone would be added in a sidestream injection loop that will use an eductor to add the ozone, a small reaction vessel, and a gas separation column to remove the offgas prior to the sidestream being pumped back to the main flow in a pipeline contactor.
- Ozone Generation: A liquid oxygen (LOX) system would be used to generate ozone.
- Building: A building will be needed to house the equipment listed above.
- Piping: Piping modifications will be needed to re-route the water to and from the ozone contactor.
- Additional pumping may have to be provided to account for the additional headloss through the ozone contactor.
- For AOP, a hydrogen peroxide storage and feed system will be needed.

For the ozone system, the following design criteria have been used for the purpose of developing cost estimates based on the process description presented previously:

- Ozone dosage: 2-5 mg/L
- Contact time: 10 minutes
- Hydrogen peroxide dosage: 5-10 mg/L

It should be noted that the actual design criteria and equipment/facility requirements will be dictated by local conditions - types and levels of UOCs present in the water and the location of the facility.

UV

- Reactor: A medium pressure UV device would be used.
- Building: A building will be needed to house the equipment listed above.
- Piping: Piping modifications will be needed to re-route the water to and from the UV reactor.
- Additional pumping may have to be provided to account for the additional headloss through the UV reactor.
- For AOP, a hydrogen peroxide storage and feed system will be needed.

For the UV system, the following design criteria have been used for the purpose of developing cost estimates based on the process description presented previously:

- UV transmittance: 90%
- UV intensity: 1,000 mJ/cm²
- No. of Reactors: at least 2
- Hydrogen peroxide dosage: 5-10 mg/L

It should be noted that the actual design criteria and equipment/facility requirements will be dictated by local conditions - types and levels of UOCs present in the water and the location of the facility.

Costs - Based on the facility and design assumptions presented above, construction and operating costs were developed for both an ozone system and a UV system for water plant sizes of 10, 50, and 100 mgd as shown in Tables 4-3 and 4-4, respectively. These costs include the cost for a hydrogen peroxide storage and feed system and all facility costs and engineering. Operating costs for either system will include:

- Labor
- Power
- LOX (for ozone only)
- Hydrogen peroxide
- Maintenance

Power will be a major part of the operating cost, especially for the UV system.

Table 4-3
Estimate of Capital and O&M Costs of Ozone/H₂O₂
 In US Dollars

	10 mgd	50 mgd	100 mgd
Capital	\$4,600,000 – 5,000,000	\$8,850,000 – 12,200,000	\$14,100,000 – 17,100,000
O&M	\$240,000 - 320,000	\$1,050,000 - 1,300,000	\$1,900,000 - 2,400,000

Table 4-4
Estimate of Capital and O&M Costs of UV/H₂O₂
 In US Dollars

	10 mgd	50 mgd	100 mgd
Capital	\$2,300,000 – 3,300,000	\$9,400,000 – 11,500,000	\$17,300,000 – 21,000,000
O&M	\$475,000 - 500,000	\$ 2,000,000 - 2,200,000	\$3,800,000 - 4,200,000

OXIDATION/BIOLOGICAL TREATMENT

General

Oxidation/biological treatment typically is accomplished using ozone followed by GAC. It was noted previously that most of the GAC treatment facilities on NJ surface waters use ozone ahead of the GAC. In most of these instances, ozone/GAC was installed to promote biological reactivity on the GAC.

Process Description

The ozone/GAC process essentially is the combination of the ozone and GAC processes described previously. Ozone is used ahead of the GAC to oxidize organic chemicals and break them down into more biodegradable compounds. Activated carbon can support microbial growth by fixing biodegradable organic compounds on surfaces accessible to the bacteria and by reducing disinfectants such as chlorine. The microbial growth removes some of the adsorbed organic matter, potentially extending the life of the activated carbon. The treated water must be disinfected after activated carbon contact to kill bacteria in the water.

Similar process design parameters would be used for each process. To minimize costs, the GAC would be used in a filter-adsorber mode of operation, which is how the ozone/GAC facilities are used in the NJ treatment facilities.

Cost Estimates

No additional costs were developed for the ozone and GAC processes as the processes described above would be used in series.

CONVENTIONAL TREATMENT

Although conventional treatment has not been shown to achieve high removals of UOCs, the fact that this treatment is part of practically every surface water treatment plant in NJ warrants consideration of the capabilities of conventional treatment in the overall organic chemical treatment process train. It has been reported that most of the removal of UOCs through a conventional process is achieved through oxidation via chlorination, and very little if any is achieved through coagulation/sedimentation. However, it may be that in some raw waters, some of the organic chemicals are sorbed onto colloidal matter. If adsorbed on colloids, the organic chemicals might be removed in the coagulation/sedimentation process. Also, as discussed previously under adsorption, PAC might be used in conjunction with the coagulation/sedimentation process to remove organic chemicals.

Another option associated with conventional treatment is the optimized removal of natural organic compounds that are typically found in surface waters. Natural organic matter will compete with the other organic chemicals for adsorption sites on activated carbon, thus reducing the efficiency of the carbon for removal of the organic chemicals of concern. Therefore, it would be very beneficial to optimize the coagulation/sedimentation process for natural organic matter removal when using GAC for UOC removal.

One issue that might be raised regarding the use of conventional treatment is the accumulation of the UOCs in the treatment plant residuals and the disposal of these residuals. This issue must be evaluated further.

COMBINATIONS OF PROCESSES

The application of any of the above treatment processes for removing UOCs from a surface water supply in NJ would be accomplished in conjunction with the existing conventional treatment process. The existing conventional treatment process should be considered as the baseline process and should be evaluated for optimization to achieve whatever organic chemical removal that is technically and cost-effectively feasible. Once the capabilities of the conventional

process are determined, consideration can be given to adding other processes to accomplish the desired UOC removal efficiencies.

The first step would be to determine if the conventional processes can be enhanced to provide additional UOC removals. The following processes might be combined with the conventional processes:

- Enhanced coagulation - to achieve additional natural organic matter removal through the coagulation/sedimentation processes to reduce the demand on ozonation or to reduce the loading on GAC.
- PAC - to achieve some organic chemical removal prior to adding ozone, UV or GAC to reduce the load on these processes.
- Additional chlorination - to achieve as much UOC removal using chlorine oxidation without compromising finished water quality in terms of raising disinfection by-product levels.

If the addition of these processes does not provide sufficient UOC removal, the following processes would be evaluated for possible implementation:

- GAC - either as a filter-adsorber or a post-filter adsorber
- Ozone - ahead of the filtration and/or GAC process
- UV - after filtration and/or GAC

Because the surface water sites that were sampled in the USGS survey detected a mixture of organic compounds, the use of GAC would be the most appropriate technology. One of the key considerations in the application and operation of a GAC system is the frequency at which the carbon must be replaced. It is very difficult to estimate with any certainty what the carbon replacement frequency will be if GAC were installed at any one of the surface water supplies in NJ because of the variety and number of UOCs that may be in the water. A carbon replacement frequency of once every month or even up to once every three months would be cost prohibitive, as it would be hundreds of thousands of dollars per carbon change. To reduce the cost for carbon replacement (which represents the majority of the operating cost for a GAC system) or if GAC, ozone, or UV alone do not provide sufficient removals, the following combinations could be evaluated:

- Ozone and GAC - ozone would be used ahead of the GAC to oxidize some of the UOCs, thereby reducing the load on the carbon. Because complete removal would not be needed through the ozone system, it could be designed for lower removal efficiencies. For example, ozone might be designed for a lower dosage (1-2 mg/L) and a smaller contact time (2-5 minutes). This would reduce the size of the ozone contactor and the generator. AOP might not be needed so a hydrogen peroxide system would not be included.
- GAC and UV - UV would be used after the GAC to oxidize some of the UOCs, thereby permitting use of the carbon for a longer time period before replacement. Because complete removal would not be needed through the UV system, it could be designed for lower removal efficiencies. A lower UV intensity might be used - 100-300 mJ/cm². AOP might not be needed so a hydrogen peroxide system would not be included.

It should be noted that with the use of ozone, the use of GAC following this process is important to remove any by-products that might be formed by the incomplete oxidation of the UOCs in the raw water. The use of GAC would remove any by-products that could be more undesirable than the original UOCs.

Another concept that is worth considering is the potential for biological growth to occur on the GAC and the resultant UOC removal through bio-degradation. The point of chlorine application must be moved to after the GAC in any process combination because GAC will adsorb the chlorine, thus using adsorption sites and reducing the capacity of the carbon for adsorbing organic compounds. Moving the chlorination point will allow for the growth of microorganisms on the GAC that could use the organic chemicals as a food supply. This phenomenon could help to extend the life of the carbon and provide additional UOC removal.

SUMMARY OF APPLICABLE TREATMENT TECHNIQUES

The applicable treatment techniques and their estimated costs are summarized in Tables 4-5, 4-6, and 4-7 for 10 mgd, 50 mgd, and 100 mgd plants, respectively. If ozone or UV were combined with GAC, the cost for either the ozone or the UV system would be reduced because the hydrogen peroxide storage and feed system would not necessarily be needed.

Table 4-5

Cost Summary for 10 MGD Surface Water Plant

<u>Technique</u>	<u>Capital Cost</u>	<u>Annual Operating Cost</u>
PAC	\$490,000 - 500,000	\$250,000 - 400,000
GAC	\$5,000,000 - 5,500,000	\$350,000 - 550,000
Ozone/Hydrogen Peroxide	\$4,600,000 - 5,000,000	\$240,000 - 320,000
UV/Hydrogen Peroxide	\$2,300,000 - 3,300,000	\$475,000 - 500,000
Ozone/GAC	\$8,600,000 - 9,600,000	\$425,000 - 680,000
GAC/UV	\$7,000,000 - 7,500,000	\$670,000 - 870,000

Table 4-6

Cost Summary for 50 MGD Surface Water Plant

<u>Technique</u>	<u>Capital Cost</u>	<u>Annual Operating Cost</u>
PAC	\$1,200,000 - 1,400,000	\$1,200,000 - 2,100,000
GAC	\$22,000,000 - 25,000,000	\$1,100,000 - 2,100,000
Ozone/Hydrogen Peroxide	\$8,900,000 - 12,200,000	\$1,000,000 - 1,300,000
UV/Hydrogen Peroxide	\$9,400,000 - 11,500,000	\$2,000,000 - 2,200,000
Ozone/GAC	\$30,000,000 - 35,000,000	\$1,400,000 - 2,700,000
GAC/UV	\$30,000,000 - 36,000,000	\$2,400,000 - 3,400,000

Table 4-7

Cost Summary for 100 MGD Surface Water Plant

<u>Technique</u>	<u>Capital Cost</u>	<u>Annual Operating Cost</u>
PAC	\$2,500,000 – 2,700,000	\$2,500,000 - 4,000,000
GAC	\$40,000,000 - 44,000,000	\$2,200,000 - 4,200,000
Ozone/Hydrogen Peroxide	\$14,100,000 - 17,100,000	\$1,900,000 - 2,400,000
UV/Hydrogen Peroxide	\$17,300,000 - 21,000,000	\$3,800,000 - 4,200,000
Ozone/GAC	\$53,000,000 - 60,000,000	\$2,800,000 - 5,200,000
GAC/UV	\$55,000,000 - 65,000,000	\$4,700,000 - 6,700,000

CHAPTER 5 - SUMMARY OF FINDINGS AND CONCLUSIONS

BACKGROUND

Numerous organic chemicals are used every day in NJ for industrial, commercial and household purposes. A number of these chemicals have been found in the State's wastewater treatment facility discharges and in surface waters around the State. The various types of organic chemicals that have been detected include:

- Pesticides
- Volatile organic chemicals (VOCs)
- Endocrine-disrupting compounds (EDCs)
- Pharmaceuticals and personal care products (PPCPs)
- Petroleum-related compounds
- Other industrial organic chemicals

Also, some naturally-occurring organic chemicals have been detected.

The fact that unregulated organic chemicals (UOCs) are being detected in drinking water supplies and that there is a concern regarding their health effects raises a fundamental question – what are the best available treatment technologies for removing these UOCs from drinking water supplies? And more specific to NJ, which technologies are most applicable to the State's surface water systems, and to what level should these compounds be removed? As answers to these questions are developed, it should be noted that the ability to detect these compounds is simply a function of the analytical method, and that removal efficiency is, in reality, a reflection of the detection limits. Verification of complete removal of the compounds is not possible; one can simply document that concentrations are below the detection limits of the current analytical methods.

The New Jersey Department of Environmental Protection (NJDEP), in conjunction with the Drinking Water Quality Institute (DWQI), is considering potential options for addressing these contaminants in NJ surface waters, and is seeking information on the effectiveness of various treatment technologies to assist in their evaluations. This report reviews and summarizes existing information on the effectiveness of various treatment technologies for removing UOCs and

identifies the best available technologies for removing these chemicals found in NJ surface water supplies.

Since 1998, the U.S. Geological Survey (USGS) has been conducting the Toxic Substances Hydrology Program (Toxics Program) to develop information and tools on emerging water quality issues. This research program includes a combination of laboratory work to develop new analytical techniques and field work on the occurrence, fate and effects of these contaminants. Between 1999 and 2000, the USGS conducted the first US reconnaissance survey of 139 streams across 30 states. Streams were selected based on known or suspected wastewater discharges upstream of the sample points. Four streams in New Jersey were sampled: Assunpink Creek - Trenton; Singac Brook - Singac; Whippany River - Pine Brook; Ho-ho-kus Brook - Ho-ho-kus. Each sample was analyzed for 95 organic chemicals representing a wide range of compounds originating from residential, industrial and agricultural applications. Of the 95 organic chemicals, 82 were found in at least one of the streams. The most frequently occurring compounds were:

- Coprostanol
- Cholesterol
- N,N-diethyltoluamide
- Caffeine
- Tri(2-chloroethyl)phosphate
- 4-nonylphenol
- Triclosan

The following numbers of UOCs that were detected in the NJ streams are summarized below:

<u>Types of UOCs</u>	<u>No. of UOCs</u>
Antibiotics (Method 1) - 21	2
Antibiotics (Method 2) - 8	0
Drugs	9
Wastewater chemicals	15
Steroids	0

Method 1 antibiotics: Carbodox, chlortetracycline, ciprofloxacin, doxycycline, enrofloxacin, erythromycin-H²O, lincomycin, norfloxacin, oxytetracycline, roxithromycin, sarafloxacin, sulfadimethoxine, sulfamerazine, sulfamethazine, sulfamethizole, sulfamethoxazole, sulfathiazole, tetracycline, trimethoprim, tylosin, virginiamycin

Method 2 antibiotics: Chlortetracycline, oxytetracycline, sulfachloropyridazine, sulfadimethoxine, sulfamerazine, sulfamethazine, sulfathiazole, tetracycline

FINDINGS

Based on the USGS survey, the total list of UOCs was broken down into 3 major classes of compounds:

- Aliphatics
- Cyclics which are defined as saturated ring compounds without aromatic characteristics
- Aromatics which are ring compounds that are unsaturated, and thus more reactive than cyclic compounds

Within each class, the UOCs were further broken down into several categories as follows:

- Pharmaceuticals
- Polycyclic Aromatic Hydrocarbons (PAHs)
- Insecticides
- Consumer Products
- Other Industrial Chemicals – compounds that are manufacturing intermediates for a variety of end products but do not fit into the other categories; for example, corrosion inhibitors for metals

Various treatment techniques have been evaluated, tested, and applied to remove organic chemicals from surface water supplies. These techniques generally may be categorized as follows:

- Conventional processes
- Adsorption processes
- Oxidation processes
- Air stripping processes
- Membrane processes
- Biological processes

For some of the more frequently occurring chemicals, bench, pilot and even full-scale data are available to determine the efficiency of certain treatment techniques. However, for the vast

majority of the organic chemicals that have been detected in NJ surface waters, no treatability data are available, and estimates of removal efficiencies were made based on previous research with organic chemicals exhibiting similar chemical characteristics or in similar classes or categories.

CONCLUSIONS

Based on the available information, the potential for treatment of the specific UOCs by the various treatment techniques is presented below:

	<u>Cyclics</u>	<u>Aliphatics</u>	<u>Aromatics</u>	<u>Totals</u>
Conventional Treatment	2	1	8	11
Oxidation	1	0	14	15
Adsorption	3	0	11	14
Air Stripping	0	1	4	5
Biological Treatment	3	2	7	12

From the above information, the available treatment techniques have been divided into the following general categories:

Most Applicable Technologies - Adsorption with GAC or PAC and AOP

Other Possible Technologies - Oxidation/Biological Treatment and Conventional Treatment

Additional Technologies - Oxidation (alone) and Membranes

The estimated capital and operating costs for these techniques are summarized below for a 50 mgd plant:

Cost Summary for 50 MGD Surface Water Plant

<u>Technique</u>	<u>Capital Cost</u>	<u>Annual Operating Cost</u>
PAC	\$1,200,000 – 1,400,000	\$1,200,000 - 2,100,000
GAC	\$22,000,000 - 25,000,000	\$1,100,000 - 2,100,000
Ozone/Hydrogen Peroxide	\$8,900,000 - 12,200,000	\$1,000,000 - 1,300,000
UV/Hydrogen Peroxide	\$9,400,000 - 11,500,000	\$2,000,000 - 2,200,000
Ozone/GAC	\$30,000,000 - 35,000,000	\$1,400,000 - 2,700,000
GAC/UV	\$30,000,000 - 36,000,000	\$2,400,000 - 3,400,000

These costs must be refined based on the design information that is obtained through the demonstration project.

It should be noted that based on the various studies that have been completed to date on the fate of organic chemicals in water treatment processes, no one treatment technique can remove all of the UOCs that have been detected in NJ surface waters. In addition, it is unlikely that all of the UOCs could be removed from a given location even using a combination of processes. Third, by-products of oxidation and biological activity are likely to be generated creating other organic chemicals while the original organic chemicals in the surface water are removed to a certain extent.

Although GAC may be the most applicable technology, oxidation might be used in conjunction with GAC to reduce the frequency at which the carbon must be replaced. Also, there may be incidental biological treatment on the GAC because of natural microbial growth on the carbon.

FURTHER RESEARCH

The variety and number of UOCs that have been found in NJ surface waters makes it difficult to establish process design criteria for any of the applicable processes with any degree of certainty. The vast majority of the UOCs have not been tested for treatability. Therefore, additional testing

is needed to determine the removal efficiencies of the applicable technologies and to develop more certain design criteria.

It is understood that NJDEP plans to conduct demonstration testing at surface water facilities in NJ. It is recommended that GAC be tested because it appears to be the most applicable technology. In addition to testing GAC, it is recommended that the other technologies be tested, even if at a lower flowrate. For example, side streams of the main treatment train could be treated to evaluate oxidation and advanced oxidation processes. Testing of the various applicable processes will provide valuable information regarding:

- The amount of organic chemicals that can be removed by existing conventional processes and modifications such as PAC, enhanced coagulation, or additional chlorination. It should be noted that PAC should be added at the head of a conventional plant and should not be added in conjunction with other chemicals that could adsorb to the PAC and render it ineffective.
- The effectiveness of GAC alone to remove the organic chemicals and the projected life of the carbon.
- The effects of biological degradation on GAC removal efficiency and carbon life.
- The effectiveness of both ozone and UV to remove the organic chemicals.
- The need for advanced oxidation using hydrogen peroxide in conjunction with either ozone or UV.
- The effect of using ozone ahead of GAC to reduce the organic load onto the GAC and to prolong the life of the carbon.

This information will not only provide more accurate data for the applicability and design of these processes, but will provide for more accurate cost estimates for these processes.

POTENTIAL FUNDING

NJDEP plans to fund the demonstration testing of the applicable processes. In addition to state funds, NJDEP might consider obtaining funds from:

- USEPA research group in Cincinnati
- AwwaRF tailored collaboration program

It is believed that both of these organizations would be interested in participating in the demonstration project by contributing towards the cost.

APPENDIX A
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APPENDIX B
COMPOUNDS FOUND IN NJ SURFACE WATER

Appendix B				
Compounds found in NJ Surface Water				
Compound	CAS #	Class	Mol. Weight	Information
Pharmaceuticals				
Metformin (ali)	657-24-9	alkyl amide	130	anti-diabetic
Acetaminophen (arom)	103-90-2	Amino phenol	151	antipyretic
Cimetidine (arom)	51481-61-9	heteroaromatic w/ alkyl,N	252	antacid
Trimethoprim (arom)	738-70-5	heteroaromatic	290	antibiotic
Codeine (arom)	76-57-3	Fused heteroaromatic	299	analgesic derived from opium
Dehydronifedipine (arom)	67035-22-7	heteroaromatic acid	346	anti-anginal
Diltiazim (arom)	42399-41-7	fused aromatic	414.5	anti - hypertensive
erythromycin - H ₂ O (cyc)	114-07-8	fused cyclic	734	antibiotic metabolite
Insecticides				
Carbaryl (arom)	63-25-2	fused aromatic w acid/ amine	201	insecticide, Vp < 4x 10 ⁻⁵ mm Hg
Diazinon (arom)	333-41-5	heteroaromatic w thiophosphate	304	organophosphate insecticide, Vp 1.8 x 10 ⁻⁴ mbar, hydrolysis at pH<2
Consumer Products				
Cotinine (arom)	486-56-6	heteroaromatic	176	nicotine metabolite, found in cigarette smoke
N,N diethyltoluamide (arom)	134-62-3	Aromatic amide	191	insect repellent
Caffeine (cyc)	58-08-2	Fused heterocyclic	194	alkaloid stimulant, naturally occurring in many plants
1,7 dimethylxanthine (cyc)	611-59-6	fused heterocyclic	180	caffeine metabolite
Triclosan (arom)	3380-34-5	diphenyl ether	289	antimicrobial disinfectant
2 butoxyethanol phosphate (ali)	78-51-3	alkyl phosphate	398	high volume chemical used in paints, plasticizer

Compound	CAS#	Class	Mol. Weight	Information
Industrial chemicals				
Phenol (arom)	108-95-2	aromatic	94	coal tar, used as intermediate in industry, disinfectant, Vp 0.35 mm Hg
5 methyl 1H benzotriazole (arom)	136-85-6	fused heteroaromatic	133	anti-corrosive, photographic reagents, Vp 0.03 mHg
4 nonyl phenol (arom)	25154-52-3	alkylphenol	220	non-ionic detergent
4 octylphenol monoethoxylate (arom)		alkylphenol	220	non-ionic detergent metabolite
4 nonyl phenol monoethoxylate (arom)		alkylphenol	237	non-ionic detergent, surfactant, used in PCP
tris(2 chloroethyl) phosphate (ali)	115-96-8	halogenated alkylphosphate	285	fire retardant plasticizer, Vp 0.5 mm Hg
Polycyclic Aromatic Hydrocarbons				
Naphthalene (arom)	91-20-3	PAH	128	coal tar, incomplete combustion products, used as moth repellent, chemical intermediate, fungicide, lubricant, textiles
Anthracene (arom)	120-12-7	PAH	178	coal tar, incomplete combustion products, also manufactured for dyes, organic semiconductor, Vp 1.96×10^{-4} mm Hg
Fluoranthene (arom)	206-44-0	PAH	202	coal tar, incomplete combustion products, Vp 0.1 mm Hg
Pyrene (arom)	129-00-0	PAH	202	coal tar, incomplete combustion products, used to make benzopyrenes, Vp 6.85×10^{-7} mm Hg
(ali = aliphatic)				
(arom = aromatic)				
(cyc = cyclic)				

APPENDIX C
COMPOUNDS FOUND IN NJ SURFACE WATERS

APPENDIX C					
Compounds found in NJ Surface Waters					
Compound	Treatment Techniques				
	Convent. Treatment	Air Stripping	GAC	Oxidation	Bio-degradation
Pharmaceuticals					
Metformin (ali)		No			?
Acetaminophen (arom)	Yes	No	Yes		
Cimetidine (arom)		No			
Trimethoprim (arom)	Yes	No	Yes		
Dehydronifedipine (arom)		No			
Diltiazim (arom)		No			
erythromycin - H ₂ O (cyc)		No	Yes		?
Codeine (arom)		No			
Insecticides					
Carbaryl (arom)		No	Yes?	Yes	Yes, slow
Diazinon (arom)		No	Yes?	Yes ?	Yes, slow
Consumer Products					
Cotinine (arom)	Yes	Partial?		Yes	
N,N diethyltoluamide (arom)			Yes	Yes	
Caffeine (cyc)	Yes	No	Yes	Yes	Yes
1,7 dimethylxanthine (cyc)	Yes		Yes		Yes
Triclosan (arom)	Yes		Yes	Yes	Slow
2 butoxyethanol phosphate (ali)					Yes
Industrial Chemicals					
Phenol (arom)	Yes	Yes	Yes	Yes	Slow
5 methyl 1H benzotriazole (arom)				Yes	
4 nonyl phenol (arom)	Yes		Yes	Yes	
4 octylphenol monoethoxylate (arom)			Yes	Yes	
tris(2 chloroethyl) phosphate (ali)	Yes	Partial?			

4 nonyl phenol monoethoxylate (arom)			Yes	Yes	
Polycyclic Aromatic Hydrocarbons					
naphthalene		Yes	Yes	H2O2 with Fe 2+	
anthracene		No		H2O2 with Fe 2+	Very slow
fluoranthene	Yes	Partial		H2O2 with Fe 2+	Very slow
pyrene	Yes	No		H2O2 with Fe 2+	Slow

Notes: (ali) denotes aliphatic compound

(arom) denotes aromatic compound

(cyc) denotes cyclic compound

For both Carbaryl and Diazinon - alkaline degradation, pH>9

Yes - denotes that removal is probable based on existing information

Yes? – denotes removal appears to be probable but may not be

No – denotes that removal is not probable based on existing information

? – denotes that removal may or may not be possible based on existing information

Partial – denotes that removal is probable but only to a limited extent based on existing information