FINAL

TECHNICAL MEMORANDUM 1

Desktop Evaluation of Alternatives – GenX and Other PFAS Treatment Options Study

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Executive Summary

Anthropogenic (human-made) organic chemicals known as perfluoroalkyl substances (PFASs) have been detected in water from the Cape Fear River, which supplies the Sweeney Water Treatment Plant (WTP). These compounds include GenX and several others recently identified by a study performed by Dr. Knappe. PFASs are used in a wide variety of manufactured products. Because of their widespread use, most people have been exposed to PFASs. PFASs have been found in many types of waters worldwide.

Neither the Environmental Protection Agency (EPA) nor the North Carolina Department of Environmental Quality (NC DEQ) has set enforceable maximum contaminant levels (MCLs) for GenX or other PFASs. Because of concern over potential health effects associated with these compounds in drinking water, Cape Fear Public Utility Authority (CFPUA) is proactively considering the feasibility and effectiveness of treatment alternatives. CFPUA is one of the first utilities within the United States to pursue enhanced treatment that targets removal of these compounds.

The following list summarizes the main findings of this technical memorandum, which presents a preliminary evaluation of the technical feasibility of water treatment methods:

- Conventional water treatment methods, such as coagulation, clarification, and granular media filtration, are not effective at removing PFASs, including GenX, as shown in a major research study of 15 full-scale WTPs.
- Various studies have shown that granular activated carbon (GAC) media, ion exchange (IX), and reverse osmosis or nanofiltration (RO/NF) are effective at removing PFASs, but the available results are limited, and almost no information specifically addresses GenX.
- For GAC, two options are available: 1A, installing new GAC media in the existing filters, and 1B, locating new GAC contactors, consisting of basins similar to the existing filter boxes, downstream from the existing filters. Both Option 2, installing new anionic IX exchangers, and Option 3, RO/NF, would also be located downstream of the existing filters.
- Option 1A, installing new GAC in the existing filters, would be the lowest initial cost option with the shortest implementation time, however, operating costs would be directly influenced by replacement frequency, which is currently unknown. New GAC media would cost $1 million to $2 million per replacement event.
- To provide an improved basis for decision-making, site-specific testing of these processes (GAC, IX, and RO/NF) is recommended to refine the understanding of design and operational parameters that would affect feasibility and cost.
- Since the lowest initial cost option would be Option 1A, one logical approach would be to conduct GAC media testing on water with Sweeney WTP concentrations to consider the viability of this option before a larger testing program is started.
- As a parallel path activity while testing proceeds, it is recommended that planning-level cost opinions be developed for the lowest and highest cost options, Option 1A and Option 3. The development of the cost opinions would be based on preliminary assumptions that could subsequently be revised when site-specific test results are available.

1.0 Purpose

This document presents a preliminary evaluation of the technical feasibility of several water treatment methods that have been proposed for removal of the anthropogenic (human-made) organic chemical known as GenX and other compounds recently identified. This contaminant, GenX, has only recently been identified as a concern within the field of drinking water treatment, and limited treatment information is available. This evaluation is based on engineering assumptions and extrapolations that could be confirmed by subsequent bench-scale and/or pilot-scale testing before full-scale implementation.

2.0 Introduction

2.1 GENERAL INTRODUCTION

There is a group of organic chemical compounds, collectively referred to as perfluoroalkyl substances (PFASs), also sometimes called perfluorinated compounds (PFCs). The term PFAS is used in this memorandum. Various PFASs have been used in a wide variety of manufactured products, such as firefighting foams, carpets, clothing, cosmetics, food packaging, and cookware. Because of their widespread use, most people have been exposed to PFASs. PFASs have been found in many types of waters worldwide. As shown in the recent literature review by Dickenson and Higgins (2016), this includes the United States, Germany, Canada, South Korea, China, Brazil, United Kingdom, France, Italy, and Spain. As an indication of how widespread these compounds are, a study by Houde et al. (2006) observed the presence of PFASs in the blood of animals in remote areas in the arctic.

Lists of compounds that make up PFASs, as well as information on molecular weight and chemical formula, can be found in various references (including Dickenson and Higgins 2016; Sun et al. 2016; and Water Research Foundation 2016). One specific type of PFAS of special interest to CFPUA, which is known by the trade name GenX, was detected by Sun et al. (2016) in the Cape Fear River at an average concentration of 631 nanogram per liter (ng/L).

GenX is used as a processing aid for the production of fluoropolymer materials. It is the ammonium salt of perfluoro-2-propoxypropanoic acid (PFPrOPrA), according to Heydebreck et al. (2015). PFPrOPrA has the chemical formula $C_6HF_{11}O_3$, a molecular weight of 330 Dalton, and Chemical Abstracts Service (CAS) Registry No. 13252-13-6. According to *The News Journal*, June 27, 2017 (Mordock 2017), Chemours, a company that had been discharging wastewater containing GenX from its Fayetteville, North Carolina, facility to the Cape Fear River about 100 miles upstream from Wilmington, North Carolina, announced that it had temporarily stopped discharging wastewater containing GenX while determining how to address the issue. On June 27, 2017, the North Carolina Department of Environmental Quality (NC DEQ) confirmed that Chemours had stopped discharging GenX wastewater to the Cape Fear River (https://deq.nc.gov/deq-verifies-chemours-has-stopped-discharging-genx-wastewater). Even if the GenX discharge is not restarted, it is anticipated that concentrations of a stable chemical such as GenX may remain in the river for a period of time. It appears that Chemours may be continuing to discharge wastewaters containing other PFAS compounds; information to revise that possibility has not been found.

2.2 REGULATORY HISTORY

Allowable concentrations of PFASs in drinking water is a relatively new topic being considered by the United States Environmental Protection Agency (EPA). The EPA has not issued any regulations regarding PFASs in drinking water, and there are therefore no enforceable maximum contaminant levels (MCLs) for PFASs. However, in 2009, on the basis of the limited health effects information available at that time, the EPA published provisional health advisories for two PFAS compounds: perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS). For reference, the formula for PFOA is $C_7F_{15}COOH$, and it has a molecular weight of 414 Daltons, and PFOS is $C_8F_{17}SO_3H$, and it has a molecular weight of 500 Daltons. In May 2016, the EPA issued revised health advisories for PFOA and PFOS of 70 ng/L, measured either individually or in combination (EPA 2016). The EPA develops health advisories to provide information on contaminants that it believes may cause human health effects and are known or anticipated to occur in drinking water. These health advisories are "non-enforceable and non-regulatory and provide technical information to states agencies and other public health officials" (EPA 2016). There are currently no EPA regulations or health advisories regarding GenX. Although there are no enforceable MCLs for GenX or other PFASs, the Cape Fear Public Utility Authority (CFPUA) is proactively considering the feasibility and effectiveness of treatment alternatives because of concern over potential adverse health effects associated with the presence of these compounds in drinking water.

2.3 TREATMENT METHODS

A major goal of Water Research Foundation Project 4322 (Dickenson and Higgins 2016) was to evaluate removal of PFASs at 15 full-scale water treatment systems throughout the United States, including two potable reuse treatment systems. This study found that conventional water treatment methods, including aeration, chlorination, chloramination, chlorine dioxide, coagulation, flocculation, anthracite media filtration, microfiltration or ultrafiltration, ozonation, permanganate addition, sedimentation, softening (caustic softening followed by solids contact clarification), and ultraviolet (UV) light, were not effective at removing PFASs. In addition, the literature review showed that other researchers have confirmed that these treatment processes provide essentially no removal of PFASs.

Dickenson and Higgins (2016) conducted bench-scale testing of granular activated carbon (GAC) and nanofiltration (NF), as well as observation of a certain type of ion exchange (IX) resin and full-scale reverse osmosis (RO), noting that each of these methods provided varying levels of removal of PFASs. Therefore, these treatment methods (GAC, IX, and RO/NF) are considered in this memorandum.

2.4 TREATMENT AT THE SWEENEY WTP

The existing Sweeney Water Treatment Plant (WTP), which has a rated capacity of 35 million gallons per day (mgd), applies the following processes: ozonation (pre and intermediate), coagulation, flocculation, clarification, biological filtration using GAC media, disinfection including UV, and chlorination. The granular media filtration consists of (from bottom to top) underdrains and gravel, sand, and GAC. The sand layer is 12 inches deep with an effective size of 0.4 to 0.5 millimeters (mm) and a uniformity coefficient of 1.4. The GAC layer is 48 inches deep. The four older filters (1 through 4) initially used Calgon Filtrasorb 300 (coal-based carbon). The GAC in filters 3 and 4 has been in service since 1997; in 2005 the media was replaced in filters 1 and 2 during maintenance work on the underdrains. The other filters use a similar type of coal-based carbon called VGAC 8x30 SNC that has been in service since 2010 (filters 5 to 9) and 2011 (filters 10 to 15). There are 14 filters, as summarized in Table 2-1. On the basis of current demands, typical operating conditions are 25 mgd on higher flow days and 12 mgd on lower flow days (which equate to loading rates of 2.8 gallons per minute per square foot (gpm/ft^2) and 1.4 gpm/ft^2, respectively). These figures indicate a typical loading rate of 2.5 gpm/ft^2 and an empty bed contact time (EBCT) of approximately 12 minutes in the GAC portion of the filter. Water quality of the combined filter effluent is listed in Table 2-2.

Table 2-1 Description of Existing Filters

PARAMETER	UNIT	VALUE
Number of Filters	Number	14
Cells per Filter	Number	1
Area per Filter	ft^2	435
Dimensions, L x W x D	ft	15 x 29 x 15.58
Hydraulic Loading	gpm/ft^2	4
Capacity Rating, each filter	mgd	2.5

Table 2-2 Water Quality of Combined Filter Effluent (2016-2017)

PARAMETER	UNIT	TYPICAL	MINIMUM	MAXIMUM
Temperature	°C	20.9	10.0	31.0
pH	Standard unit	5.7	4.8	6.4
Turbidity	NTU	0.032	0.01	0.68
Alkalinity	mg/L as $CaCO_3$	8	5	14
TOC	mg/L	2.1	1.7	3.1
UV 254	1/cm	0.019	0.008	0.036
Conductivity	µS/cm	176	162	193
NTU = nephelometric turbidity unit cm = centimeter µS/cm = micro-Siemens per centimeter				

3.0 Analytical Measurement of PFAS and GenX

It has been determined that here are two commercial analytical laboratories that offer measurement of PFASs, Eurofins and Test America, based on discussions with researchers in the field, however, only Eurofins is currently providing GenX measurements. Information provided by these laboratories on reporting limits, costs, and sample turn-around time is presented in Table 3-1. Regarding PFASs other than GenX, Eurofins provides measurement for 14 compounds and Test America 17. There are also some non-commercial laboratories that measure PFAS concentrations, including Dr. Knappe's laboratory at North Carolina State University (NCSU), EPA, Colorado School of Mines, and the State of Minnesota. Dr. Knappe has said (personal communication) that NCSU and EPA Region 4 can measure GenX as well as other similar perfluorinated ethers.

Table 3-1 Survey of Analytical Laboratories

PARAMETER	EUROFINS	TEST AMERICA
Provides GenX Measurement?	Yes	No
GenX Method	SPE extraction/preconcentration LC Liquid Chromatography, MS Mass Spect	NA
GenX Reporting Limit, ng/L	10	NA
Price per Sample	$350	NA
Turn-around Time, at cited price	10 Business Days	NA
Sample Holding Time	14 Calendar Days or possibly longer since GenX is quite stable	NA
Provides Measurement of Other PFAS?	Yes	Yes
Number of PFASs in Lab's Standard Package	14	17
Other PFAS Method	Method 537	Method 537
Other PFAS Reporting Limit, ng/L	2.0	2.0
Price per Sample	$325	$250 to $300
Turn-around Time, at cited price	10 Business Days	10 Business Days
Sample Holding Time	14 Calendar Days	14 Calendar Days

4.0 Granular Activated Carbon Treatment Option

4.1 INTRODUCTION

Granular activated carbon (GAC) adsorption is a water treatment process that uses a granular media produced from carbon-based materials such as coal, coconut shells, peat, or wood that have been "activated" by heat and sometimes other manufacturing steps to yield the desired properties. There are many types of GAC media, and selection of an effective carbon for a given situation is frequently based on site-specific testing. Water treatment applications include use as a granular media for filtration to remove particulates and turbidity as well as to remove certain dissolved materials, such as organic constituents that can result in color or the formation of disinfection byproducts (DBPs), taste and odor (T&O) causing compounds, or industrial solvents if present in the water. GAC is also sometimes used to dechlorinate water.

GAC is implemented in water treatment in one of two roles: one, as a filter-adsorber, providing both filtration and adsorption functions or, two, as a post-filter contactor in which adsorption is the primary treatment objective. As the adsorptive capacity of the GAC becomes exhausted, microbial growth on the GAC can be used to convert some of the chemicals in the water to cell mass. This is referred to as biofiltration. The GAC filters at the Sweeney plant operate as biofilters.

When applied as a biologically active filter, microbial activity on the GAC causes the removal of some organics. Adsorption of organic materials on the carbon can also occur. Both of these mechanisms can occur simultaneously when the GAC media is new or recently regenerated. In a typical scenario with new GAC media almost all of the organic material that is chemically attracted to the GAC would be removed. As the adsorption "sites" on the GAC are filled, the adsorptive ability of the carbon becomes exhausted, resulting in a "breakthrough" in which the concentration of organic chemicals being removed increases in the effluent from the GAC filter.

Total Organic Carbon (TOC) is a complex mixture of many organic compounds. Some are adsorbed better by GAC than others, and there is often a small fraction, 5 to 10 percent, that is not adsorbed at all. The nonadsorbable fraction passes to the effluent. Some TOC is removed by biodegradation in the GAC bed after the bed's adsorption capacity has been exhausted. Consequently, a typical TOC breakthrough curve comprises three stages:

1. Immediate breakthrough of the nonadsorbable component of TOC (typically 5 to 10 percent of influent TOC).
2. Removal of TOC by adsorption (decreases with time as the adsorption capacity of the GAC is consumed) and varies by chemical.
3. Continued biological removal of a portion of the TOC.

Each type of GAC exhibits a selectivity or preference for some organic species over others. In addition, when breakthrough occurs, a phenomenon called "chromatographic peaking" may take place. When this happens, the GAC releases some types of organic material that were adsorbed previously while removing other types instead (in a sense trading one that it "prefers" for the other). From a practical standpoint, the outcome of that event is that there can be higher concentrations of some organic chemicals in the effluent than in the influent. A simplified diagram to help explain chromatographic peaking is presented on Figure 3-1. The drawing on the left side of the figure shows new GAC media (or new IX resin which also exhibits chromatographic peaking) that is removing all of the "A" and "B" molecules that are present in the influent water. The drawing on the right shows exhausted GAC media (or IX resin), treating the same influent concentrations of

"A" and "B" while the sites attracted to "A" and "B" are full. On the right side the exhausted media/resin is releasing "A" molecules that have already been captured because there is a preference to attract "B" molecules. On the right side the concentration of "A" in the effluent is greater than in the influent because "A" molecules are being released.

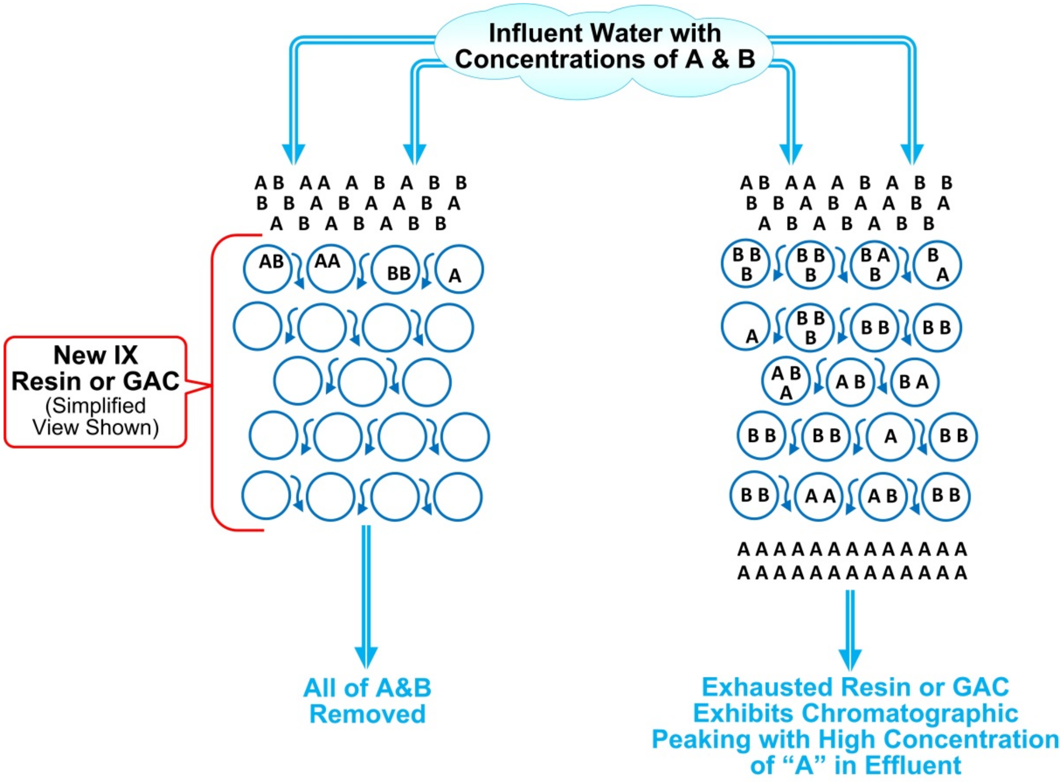

Figure 3-1 **Diagram of Chromatographic Peaking**

Because of the biological removal mechanism, even after the adsorptive capacity of the GAC is exhausted, a portion of the TOC concentration in the water is removed, essentially consumed, by microbes. In many surface water supplies, typically about 10 to 20 percent of the TOC is biodegradable and removed in this way. When the adsorption ability of a GAC bed is exhausted the media needs to be regenerated or replaced to continue to remove organics by adsorption. Preliminary discussions with GAC providers, in regard to the GenX application being considered in this document, indicate that the spent GAC would be shipped off-site for regeneration and replaced with new or regenerated carbon.

Key parameters that affect the design, operation, and costs of applying GAC include loading rate (LR), EBCT, and number of bed volumes (BVs) to breakthrough.

LR is the flow rate per cross-sectional area and, in the United States, that value is typically presented in gpm/ft^2. Even with clean filters, as LR increases, the pressure drop across the filter also increases. When applied to filter/adsorbers, LR is an additionally important variable. In that service, the filter media removes particles from the water. As the filter gets fouled (or plugged) with accumulated particles, the filters are periodically backwashed by the plant staff to remove the captured particles and maintain the pressure drop within a desired range.

EBCT is the amount of time, typically measured in minutes, that the water is in contact with the media with the assumption of an empty bed to facilitate comparison of different media on a common basis. Sufficient EBCT is needed to allow enough time for the chemicals being removed to transfer to the GAC. If EBCT is too short, removal will be inadequate. After LR and EBCT are established, bed height can easily be calculated.

BV is the number of volumes of water that can flow through the GAC before breakthrough occurs. In comparing two different types of GAC, the product that treats the higher number of BVs before breakthrough of the target compound would require less frequent replacement or regeneration. If the number of BVs treated is low, and hence the replacement frequency is high, other treatment methods may be more cost-effective. Each new set of GAC installed in the existing filters would cost $1 million to $2 million, according to discussions with carbon suppliers.

4.2 APPLICATION TO PFAS

Experience with removing PFASs with GAC is summarized in this section.

A key study that included application of GAC to remove PFASs was conducted by Dickenson and Higgins (2016). Their literature review concluded that few studies have been published on the effectiveness of PFAS removal methods, citing Quinones and Snyder (2009); Post et al. (2009); Takagi et al. (2008); Eschauzier et al. (2012). Some batch test studies on PFAS removal by GAC have been published by Deng et al. (2010); Yu et al. (2009); Senevirathan et al. (2010); Lampert et al. (2007) on removal of PFOS and PFOA as well as by Carter et al. (2010) on removal of perfluorobutane sulfonate (PFBS). These studies showed the effectiveness of GAC at removing certain types of PFAS compounds but did not include GenX.

Dickenson and Higgins (2016) evaluated GAC performance for removing PFAS at four full-scale facilities (Utilities 7, 8, 18, and 20). The PFAS concentrations at Utility 8 were too low, so that part of the study was discontinued. Utility 20 applied Calgon F600 (coal-based carbon) in a lead-lag arrangement with about 13 minutes of EBCT in each contactor, which equates to about 10,000 BV every 3 months. The authors reported that Utility 20 operated its lead contactors for approximately 10 months before initial breakthrough of evaluated PFAS. With effluent from the lead contactor feeding the lag contactor, concentrations in the lag effluent for all except one type of PFAS in the study were maintained below detection limits for the 1 year period studied. Utility 18 applied Calgon F300 (coal-based carbon) for surface water treatment. The carbon had already been in service for more than 6 years at the time of the study, and it was observed that effluent concentrations for some PFASs were higher than influent concentrations, so it is possible that leaching and/or chromatographic peaking occurred. Another study (Takagi 2011) was cited as observing a similar case where fresh carbon was initially effective at PFAS removal but was not effective 1 year later. Utility 7 applied Norit GAC300 (coal-based carbon) with EBCT of about 10 minutes and observed removal of many types of PFASs to below detection limits, while three shorter chain PFASs (which were described as perfluorobutanoic acid [PFBA], perfluoropentanoic acid [PFPeA], and perfluorohexanoic acid [PFHxA]) exhibited partial removal at 33 percent, 74 percent, and 91 percent, respectively.

Dickenson and Higgins (2016) conducted a type of bench-scale testing known as rapid small-scale column tests (RSSCTs) on three types of GAC: Calgon F300 (coal-based with Iodine No. 900 I2/g), Calgon F600 (Iodine No. 850 I2/g), and Siemens (now Evoqua) 1240C (coconut-based). RSSCT results for F300 while treating spiked deionized water, exhibited initial breakthrough of some PFASs at about 30,000 BV, while other effluent concentrations did not exceed 2 percent of the influent values after 98,000 to 125,000 BV. There was some indication that smaller chain PFASs had earlier breakthroughs, and a "general chain length dependent pattern was observed, but it did not hold true for all of the PFCAs (PFAS compounds studied)"; therefore, it is difficult to extrapolate the anticipated level of GenX removal at this time. Additional RSSCT results from tests of GAC treating a spiked creek water with a background dissolved organic carbon concentration of 1.7 mg/L yielded lower numbers of BVs to breakthrough. When applied to the creek water, all three GACs had a breakthrough of greater than 20 percent for all PFASs studied within about 11,000 BV, indicating that the presence of the background natural organic matter (NOM) competed for sites on the carbon and shortened the number of BVs. Higher concentrations in the effluent than in the influent were also observed for some of the compounds. In general, F300 provided more BVs, with about 26,000 BVs for PFOA compared to 11,000 BVs for F600 and 1240C.

Dr. Higgins, a professor at the Colorado School of Mines, and a colleague, C. Bellona, are conducting ongoing related work on removal of PFASs by GAC (personal communication). Comparing F400 and F600 from Calgon, N400 from Cabot/Norit, and a coconut-based GAC from Cabot/Norit (GCN 1240) at an LR of 2.5 gpm/ft^2 and an EBCT of approximately 11 minutes, F400 and N400 had the best performance over a 5 month pilot period. Additional testing of F400 and N400 is being planned. In their trials, F400 and N400 have so far provided in excess of 17,000 BVs without breakthrough of the PFASs of interest while treating a groundwater that included about 1.5 mg/L of background TOC. While it would be difficult to directly extrapolate the number of BVs for a surface water case such as Sweeney's, these results indicate that these types of GAC show promise in this application.

Redding (2017) showed about 30,000 and 60,000 BVs to breakthrough for PFOA and PFOS, when treating a groundwater at about 10 minutes of EBCT with influent concentrations of 67 and 49 ng/L, respectively, and 0.3 mg/L of background TOC; better performance (about 40 percent more BVs) was observed with an enhanced coconut-based carbon (1230 CX) than with a coal-based carbon (12 x 40 reagglomerated bituminous).

While none of these studies specifically focused on GenX, they show that GAC is effective at removing PFAS compounds. Studies could be conducted to quantify BV to breakthrough for the more promising GACs, including the effects of having other organics present to compete for adsorption sites, and possibly result in chromatographic peaking, at Sweeney plant conditions.

The literature review of Sun et al. (2016) discusses other studies that have shown that powdered activated carbon (PAC), a more finely powdered version of GAC, is effective at removing various PFASs, but the effectiveness decreases with chain length. However, Sun et al. (2016) indicate, "It is unclear, however, how the presence of ether group(s) [such as occurs in GenX] impacts adsorbability." The comparative testing indicated a lower removal percentage for GenX than for PFOA. For reference, GenX has a molecular weight of 330 Daltons, comprising $C_6HF_{11}O_3$, including one ether group and five perfluorinated carbons. PFOA has a molecular weight of 414 Daltons, comprising $C_8HF_{15}O_2$, including no ether groups and seven perfluorinated carbons. In the authors' view, this is the only published paper to consider removal of GenX or similar PFASs that includes an ether-based backbone by water treatment processes. The authors conclude that carbon provides some removal of GenX and similar PFASs, but that these compounds are difficult to remove. The paper suggests a need for "broader discharge control and contaminant monitoring."

4.3 ADVANTAGES

Advantages of the GAC option are as follows:

1. Essentially no capital costs or additional land (space) would be required if the option proves to be sufficiently effective when installed in existing filter boxes. Pilot-scale testing is being considered to verify that hypothesis.
2. The Sweeney WTP staff is experienced with and understands operation of the GAC filters.
3. This option has the shortest implementation time since new facilities would not be needed.
4. This option has the lowest requirements for additional labor or maintenance.
5. The option would be less energy intensive than RO/NF and would require roughly the same energy usage as for IX.
6. The option does not generate a liquid waste stream on-site. (RO/NF has that as a limitation. GAC and IX do not.)
7. The effectiveness of different types of GAC can be compared on site-specific feedwater in accelerated bench testing, which is being considered. (Accelerated testing is not practical for IX or RO/NF except for measuring RO/NF rejection.)
8. For GAC, there would be no need to increase the capacity rating (i.e., loading rate) of the existing filters or add more filters. (RO/NF has that as a limitation.)
9. All of these options have the advantage of having been applied in a wide range of WTPs, albeit for different applications than GenX removal.

4.4 LIMITATIONS

Limitations of the GAC option are as follows:

1. Performance characteristics on removing GenX and other PFASs at site-specific conditions are unknown. Testing/piloting is advised. (All of the options have this limitation.)
2. The media would require periodic replacement when exhausted. Testing/piloting is being considered to quantify the frequency of media replacement, which could be multiple times a year. (The GAC and IX options have this limitation. RO/NF membrane elements are generally replaced about every 7 years.)
3. This option is potentially susceptible to chromatographic peaking. Testing/piloting is advised to refine understanding. (The GAC and IX options have this limitation.)
4. Selectivity could limit removal of other PFASs even if the option is effective on GenX. (The GAC and IX options have this limitation. RO/NF could also exhibit selectivity but is anticipated to be less selective than GAC or IX [subject to confirmation]).

5.0 Ion Exchange Treatment Option

5.1 INTRODUCTION

Ion exchange (IX) is a water treatment process that applies the use of spherical polymeric particles that are sometimes called ion exchange resin or, less formally, “beads.” IX resins are manufactured for a variety of applications. One of the most widely known examples of IX is in home water softeners. In that application, as water flows through a softener tank containing IX beads, calcium and magnesium ions, which are the source of hardness in the water, are attracted to the resin and exchanged for sodium ions. The resulting effluent has a lower hardness and an increased concentration of sodium. When most of the exchange sites are filled with calcium and magnesium, the water softening resin becomes less effective at removing them, the concentration in the effluent for those ions increases and, similar to the GAC process previously discussed, breakthrough occurs.

In a home water softener, a salt solution, generally a sodium chloride solution, is applied to regenerate the resin by converting the calcium and magnesium-filled sites back to sodium-filled sites, and after regeneration, it is placed back into softening mode. Because the calcium and sodium ions that are exchanged in this process are positively charged ions, which are also called cations, this type of IX is sometimes called cationic IX. There are other types that remove certain negatively charged species, which are called anions, so that type of IX is sometimes called anionic IX (sometimes abbreviated AIX).

Various types of IX are used in water treatment. Some full-scale WTPs use the same type of resin as home water softeners to soften water on a larger scale. Some WTPs employ other types of IX such as for nitrate or arsenic removal. Resin manufacturers offer types of anionic IX to remove certain organic materials, such as PFASs.

It should be noted that the type of resin used in a home water softener is not expected to remove GenX. The types of resins used in softeners are very different from the AIX resins that have been developed to remove PFASs. A basic chemical difference between them is that IX softeners remove certain cations from water, while the resins for PFAS treatment remove certain anions. Another difference between the IX resins used for water softening and the types developed for PFAS removal is regeneration. While softening resin is generally regenerated on-site, for PFASs removal, the resin would be returned to the manufacturer for disposal, probably by thermal destruction according to discussions with the manufacturers.

There are similarities between GAC and IX. Both processes apply media in vessels or tanks to remove certain dissolved materials from water. As previously discussed, GAC is sometimes also used to filter particulates and turbidity from water, but IX is essentially only applied to removing dissolved material. Another difference is that one of the removal mechanisms for GAC is to function as a biologically active filter that removes a portion of the TOC biologically, but IX is not applied with that mechanism. Another similarity is that, for both processes, the adsorption or exchange sites are periodically filled, resulting in breakthrough and requiring replacement or regeneration. In addition, as with GAC, IX does not remove all dissolved material equally, and the phenomenon of chromatographic peaking can result in higher effluent than influent concentrations as breakthrough occurs. For some extensively studied applications such as water softening, an IX system can be designed according to water analysis data without site-specific testing, but less is known about PFAS applications, so testing may be advised.

Another way that IX is similar to GAC is that the major parameters that impact the design, operations, and costs are the same: LR, EBCT, and number of BVs to breakthrough. The values would be different, but the concepts would be similar. A reason to consider IX as an option to GAC in this study is that a preliminary survey of the options indicates that there are IX resins that may remove PFASs to low concentrations with a higher LR and lower EBCT than GAC, which could make the process more compact and possibly more cost-effective.

5.2 APPLICATION TO PFAS

While anionic IX shows promise for removal of PFASs, the available information is quite limited. In their literature review Dickenson and Higgins (2016) summarize five studies that indicate successful removal with various resins in fairly limited testing. It would be difficult and theoretical to extrapolate from these studies to the Cape Fear River water quality. Two manufacturers of IX systems (Calgon and Evoqua applying Dow PSR2 resin) have indicated that, in their experience, the resins remove PFASs with less EBCT than GAC (for example about 2 minutes versus about 10 minutes). If a cost comparison were made between a new GAC system located downstream from the existing filtration versus a new IX system located downstream from the existing filtration, the shorter EBCT for IX would significantly reduce the size and the land area used; in that case, IX would likely result in lower cost. However, it is less clear that the costs for IX would be lower than GAC if it can be shown that installing new GAC media into the existing filter boxes would address the treatment goals. Therefore, it may be advisable to conduct some initial testing of at least one IX resin selected from the more promising types to develop operating parameters (EBCT, BV, etc.) for a comparison of IX and GAC. Unlike for GAC, there is no accepted rapid or accelerated test method for IX. Testing/piloting would be conducted in real time.

5.3 ADVANTAGES

Advantages of the IX option are as follows:

1. IX probably has a higher LR and shorter EBCT than GAC (subject to confirmation). If so, IX may be less costly than GAC if both options were to be located downstream from existing filters.
2. The option is less energy intensive than RO/NF and roughly the same energy usage as GAC.
3. The option does not generate a liquid waste stream on-site. (RO/NF has that as a limitation. GAC and IX do not.)
4. For IX, there would be no need to increase the capacity rating (i.e., loading rate) of the existing filters or add more filters. (RO/NF has that as a limitation.)
5. All of these options have the advantage of having been applied in a wide range of WTPs, albeit for different applications than this.

5.4 LIMITATIONS

Limitations of the IX option are as follows:

1. IX would have higher capital costs and land (space) requirements than installing GAC in existing filter boxes.
2. Accelerated testing is not practical for IX or RO/NF except for measuring RO/NF rejection. (GAC does not have that limitation.)

3. Performance characteristics on removing GenX and other PFASs at site-specific conditions are unknown. Testing/piloting is advised. (All of the options have this limitation.)
4. The media would require periodic replacement when exhausted. Testing/piloting is being considered to quantify the frequency of media replacement, which could be multiple times a year. (The GAC and IX options have this limitation. RO/NF membrane elements are generally replaced about every 7 years.)
5. The option is potentially susceptible to chromatographic peaking. Testing/piloting is advised to refine understanding. (The GAC and IX options have this limitation.)
6. Selectivity could limit removal of other PFASs even if the option is effective on GenX. (The GAC and IX options have this limitation. RO/NF could also exhibit selectivity but is anticipated to be less selective than GAC or IX.)

6.0 Reverse Osmosis or Nanofiltration Treatment Option

6.1 INTRODUCTION

Reverse osmosis (RO) and the associated nanofiltration (NF) process are membrane-based water treatment processes in which a relatively thin (1,000 Angstrom, which is equal to 0.0001 mm) and semi-permeable manufactured barrier removes dissolved materials from water. While the RO/NF process also removes particulate materials from water, it is a misapplication to use it for this purpose because particulates foul the membrane in ways that cause damage, increasing costs and shortening service life, and can result in significant reduction in plant capacity. Therefore, feedwater to RO/NF is pre-filtered including protective cartridge filtration, typically down to about the 5 micron (0.005 mm) level.

RO/NF processes are commonly applied in WTPs with applications ranging from desalination; removal of Total Dissolved Solids (TDS), sodium, chloride, etc.; softening; color removal; organics removal; and specialized applications such as removing nitrate or arsenic. For instance, CFPUA's WTP in New Hanover County applies NF to treat groundwater to remove organic materials that form DBPs when the water is chlorinated as well as softening the water at the same time.

There are some small differences between RO and NF. RO exhibits higher rejection of dissolved materials with less selectivity than NF. For example, RO might tend to provide 98 percent (nominal) rejection of both divalent and monovalent ions (such as sulfate and chloride, respectively), while NF might yield 95 percent rejection of sulfate and only 60 percent rejection of chloride. Since RO provides very high rejections for both types, it is said to exhibit little selectivity. On the other hand, for NF there is sufficient selectivity that it is difficult to generalize regarding the rejection percentages. NF rejection of inorganic solutes varies with ionic strength of the feed solution, the relative concentrations of individual ions, and sometimes as a function of pH.

For this study, the focus is on the removal of PFASs and, more specifically, on GenX. More detailed discussion on experience with RO/NF rejection of PFASs is presented in the following section. Another difference between RO and NF is that NF membrane tends to be productive at lower pressure than RO; however, in the past decade, the difference between operating pressures has been greatly reduced as newer membrane products have become available.

RO/NF membranes, as currently applied in municipal-scale water treatment projects, are manufactured in a flat sheet form that looks like a large roll of shiny white paper but is actually composed of thin layers of specially engineered plastics. The flat sheet membrane is packaged into cylindrically shaped spiral-wound filter elements that for full-scale projects are typically about 8 inches in diameter by 40 inches long. There are also smaller home-sized RO/NF elements that are about 2 inches in diameter by 12 inches long.

Home RO units generally have one element mounted in a single pressure vessel, installed under a sink, and are operated on the available pressure from the community's distribution system. On full-scale systems, multiple elements are mounted inside each pressure vessel, and many pressure vessels are included in each train. Unlike home systems, pumping is used in full-scale facilities to provide the driving pressure, and antiscalant chemicals are added to the feedwater to allow as much water recovery as possible (to minimize the waste discharge flow) without allowing precipitation to occur that could damage the membrane. Periodically, the operators conduct cleaning cycles to maintain capacity at as low an energy consumption as possible.

While many water treatment processes have an influent and an effluent, RO and NF have three process streams flowing while in operation: the influent (which is called the feed) and two effluent streams, the permeate (which is the purified water) and the concentrate (which is the concentrated wastewater). RO/NF are so effective at removing dissolved materials that frequently only a portion of the finished water is made up of permeate, and the rest is bypassed around the RO/NF. However, a preliminary evaluation of the GenX application indicates that 100 percent of the finished water would likely have to be permeate.

Depending on the concentrations and treatment goals, it is even possible that a second pass of RO would be needed to sufficiently remove GenX. In that case, this application of RO/NF would be more like seawater desalination facilities, where at least one 100 percent first pass is applied, and in some cases, a second pass or a partial second pass is also applied. In addition, many seawater RO facilities need and practice post-treatment to add some hardness, alkalinity, and sometimes other constituents back into the permeate water before distribution to make the water noncorrosive; it is highly likely that would also be needed in this case.

Major variables to consider with RO/NF are parameters called rejection, recovery, operating pressure, and flux. Rejection describes the percent of a given component in the feed that is not passed to the permeate. For example, if there is 97 percent rejection of sodium and a concentration of 100 mg/L in the feed, the permeate concentration would be 3 mg/L. Recovery is the percent of feedwater that becomes permeate. The goal is to maximize the recovery to minimize the flow rate of concentrate to waste, but a high value cannot be arbitrarily selected. Recovery is determined after careful calculations considering the site-specific maximum concentration that can be achieved without precipitation occurring inside the RO/NF system. Operating pressure is generally calculated according to the water chemistry and temperature as well as certain aspects of the selected membrane and the system design.

Flux is an important parameter that is determined by past experience with RO/NF, frequently augmented by some site-specific testing, especially for surface water applications such as this one. Flux is the RO/NF equivalent of hydraulic loading rate. With GAC and conventional granular media filters, the loading rate is typically the filtered water flow rate in gpm divided by the cross-sectional area of the filter in ft^2. For RO/NF, the flux is the permeate flow rate in gpd divided by the membrane area in ft^2. The unit of measurement for flux, gpd/ft^2, is typically abbreviated as gfd. As with recovery, the value for flux cannot be arbitrarily selected. If the flux is set too high for a given application, excessive and costly fouling and operational problems will occur at the facility. In the more extreme cases of high flux, the capacity of the facility has to be lowered to yield stable performance.

6.2 APPLICATION TO PFAS

Experience with removing PFASs with RO/NF is summarized in this section.

Steinle-Darling and Reinhard (2008) measured rejection of various PFASs, but not GenX, by four different NF membranes in a small flat sheet test device. Testing was primarily conducted with Dow/FilmTec NF270 with some experiments also performed with Dow/FilmTec 200 or the GE/Osmonics DK or DL membranes. It should be noted that these are piperazine-based polyamide membranes, which are somewhat different from the polyamide type chemistry used in the more widely applied RO and NF membranes. In addition, these tests were conducted on a small flat sheet device, which tends to yield higher rejection values than full-scale two- or three-stage systems with spiral-wound elements that are operated at higher recovery, so the concentration on the feed-concentrate side is higher. Summarizing the results, many PFASs with a molecular weight above

300 Daltons had at least 95 percent rejection. Charge on the solutes and operating pH had an impact for some compounds. For example, one solute with a molecular weight of 499 Daltons that was uncharged at the operating pH, exhibited lower rejection, as low as 42 percent with one of the tested membranes. Sorption of some compounds was also observed on the membrane, and, because this could lead to misleading results, future testing should address that issue. Ionic strength had little impact on rejection of PFASs, which was shown by adding 2,500 mg/L of sodium chloride to the feed solution, and, which resulted in less than a 1 percent change in rejection. Fouling impacted rejection; average rejections for clean membrane were 99 percent but were only 95 percent for fouled membrane.

The literature review by Dickenson and Higgins (2016) described the work by Steinle-Darling and Reinhard (2008), which is discussed above, and Tang et al. (2006) who observed greater than 99 percent removal of PFASs (in that case PFOS) with four different types of RO membrane.

Dickenson and Higgins (2016) also conducted trials with Dow/FilmTec NF270 membrane. They used flat sheet test cells, such as those used by Steinle-Darling and Reinhard (2008), but with modifications to address certain issues. For example, they used a larger feed volume with once-through flow, rather than recycle, and two test cells in series to provide experimental duplication. For all of the PFASs included in this study, rejection exceeded 93 percent and mostly exceeded 95 percent. Dickenson and Higgins compared clean to fouled membrane and did not observe lower rejection with fouled membrane; in some sampling events, the rejection increased with fouling.

Dickenson and Higgins (2016) also evaluated performance at two full-scale potable reuse facilities using RO, one with Hydranautics ESPA2 spiral-wound elements arranged in a three-stage array operated at a flux of 12 gfd and 85 percent recovery and the other with Toray and Hydranautics spiral-wound elements at a flux of 11.6 to 11.9 gfd and 80 percent recovery. All PFASs were below detection in the RO permeate samples. Concentrations in the influent of some PFASs as high as 370 ng/L and RO permeate concentrations of less than 0.5 ng/L were reported in the appendix indicating better than 99 percent rejection.

One of the largest RO/NF membrane manufacturers, Toray (personal communication) reported that testing with a PFAS that is similar to GenX (which they described as being PFHxA with the following formula, $C_6HF_{11}O_2$) resulted in RO rejection normally higher than 94 percent but lower at lower pH values (which were not quantified), and NF with a rejection of about 70 percent.

6.3 ADVANTAGES

Advantages of the RO/NF option are as follows:

1. RO/NF probably (subject to confirmation) removes the widest range of PFAS chemicals with the least selectivity and without chromatographic peaking.
2. CFPUA has experience operating NF at another facility.
3. All of these options have the advantage of having been applied in a wide range of WTPs, albeit for different applications than this.

6.4 LIMITATIONS

Limitations of the RO/NF option are as follows:

1. RO/NF may have (subject to confirmation) the highest capital costs and greatest land (space) requirements of these options.
2. To maintain the existing WTP's rated capacity, using the RO/NF option would require an increase to the regulator-approved loading rate of the existing filters or the addition of more filters.
3. Additional treatment might be needed to sufficiently treat the water to avoid RO/NF fouling; however, the existing WTP's relatively low filtered water turbidity indicates this may not be needed (subject to confirmation).
4. Performance characteristics on removing GenX and other PFASs at site-specific conditions are unknown. Testing/piloting is advised. (All of the options have this limitation.)
5. RO/NF continually generates a liquid waste stream requiring disposal. This could be a major and potentially costly issue if direct discharge is not allowed.
6. RO/NF is energy intensive (would have the highest energy consumption).
7. RO/NF removes such a wide range of solutes from the water that post-treatment of the finished water would be needed to add certain minerals back into the water to prevent corrosion in the distribution system and customers' homes. This step would be necessary to prevent problems such as "red" water or elevated levels of lead and/or copper.
8. Depending on the influent concentrations, effluent goals, and rejection performance, RO/NF may need a second pass or a partial second pass, which would further increase costs.
9. During testing/piloting of RO/NF, it is recommended that measurements include concentrations of targeted organic chemicals (e.g., GenX and other PFASs) in feed and concentrate as well as permeate to allow mass balance calculations to verify that rejection is providing all of the observed removal, not a shorter term adsorption mechanism. Without that information, the projection of long-term performance could be misleading.

7.0 Discussion

The location for each of the options within the Sweeney WTP's process schematic is shown on Figure 7-1. Two locations for suboptions are shown for GAC: (1A) with new GAC media installed in the existing filter-adsorber boxes and (1B) with the GAC installed in new contactors that would treat effluent from the existing filter boxes. Both of the other options (Option 2, IX, and Option 3, RO/NF) would treat effluent from the existing filter boxes. The location shown on the figure (for Options 1B, 2, and 3) is immediately following the existing filters, but the treatment would be just as effective if it were located downstream from the existing UV units. Selection of the location could be made during a subsequent design phase according to plant hydraulic and space issues. The post-filtration options include the assumption that the filters provide sufficient pretreatment, which can be confirmed in site-specific testing.

Schematic diagrams of the options are shown on Figure 7-2.

Of the two GAC options, 1A would be the lower cost option if suitable operating conditions and performance with a sufficient number of BV before change-out can be determined for GAC installed in the existing filters. In some cases, GAC media is more effective when applied to filtered water only as an adsorber. It is possible when used as both a filter and an adsorber that the service life of the media can be shortened by backwashing cycles. The filter-adsorber needs fairly frequent backwashing to remove accumulated solids material; when the GAC is applied as an adsorber only, backwashing is infrequent. Pilot testing could be conducted to determine the difference in performance (BV to breakthrough) in this case.

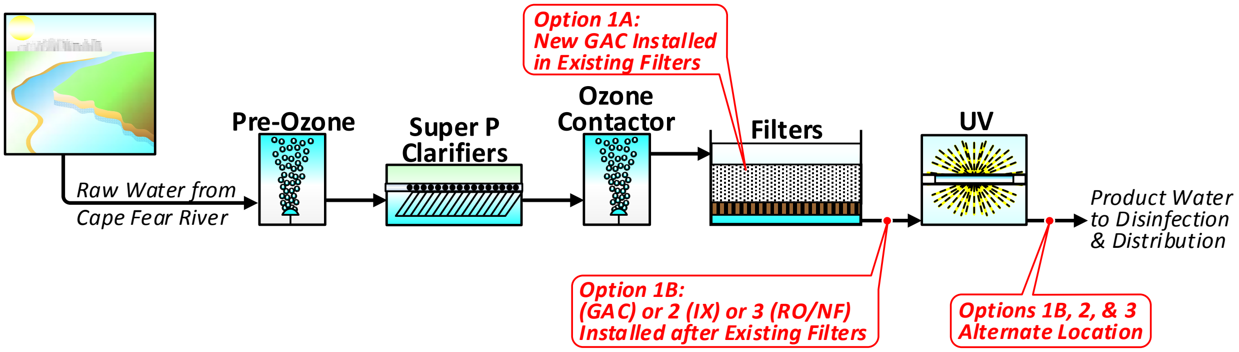

Figure 7-1 **Process Schematic Showing the Potential Locations of New Options at the Existing Sweeney WTP**

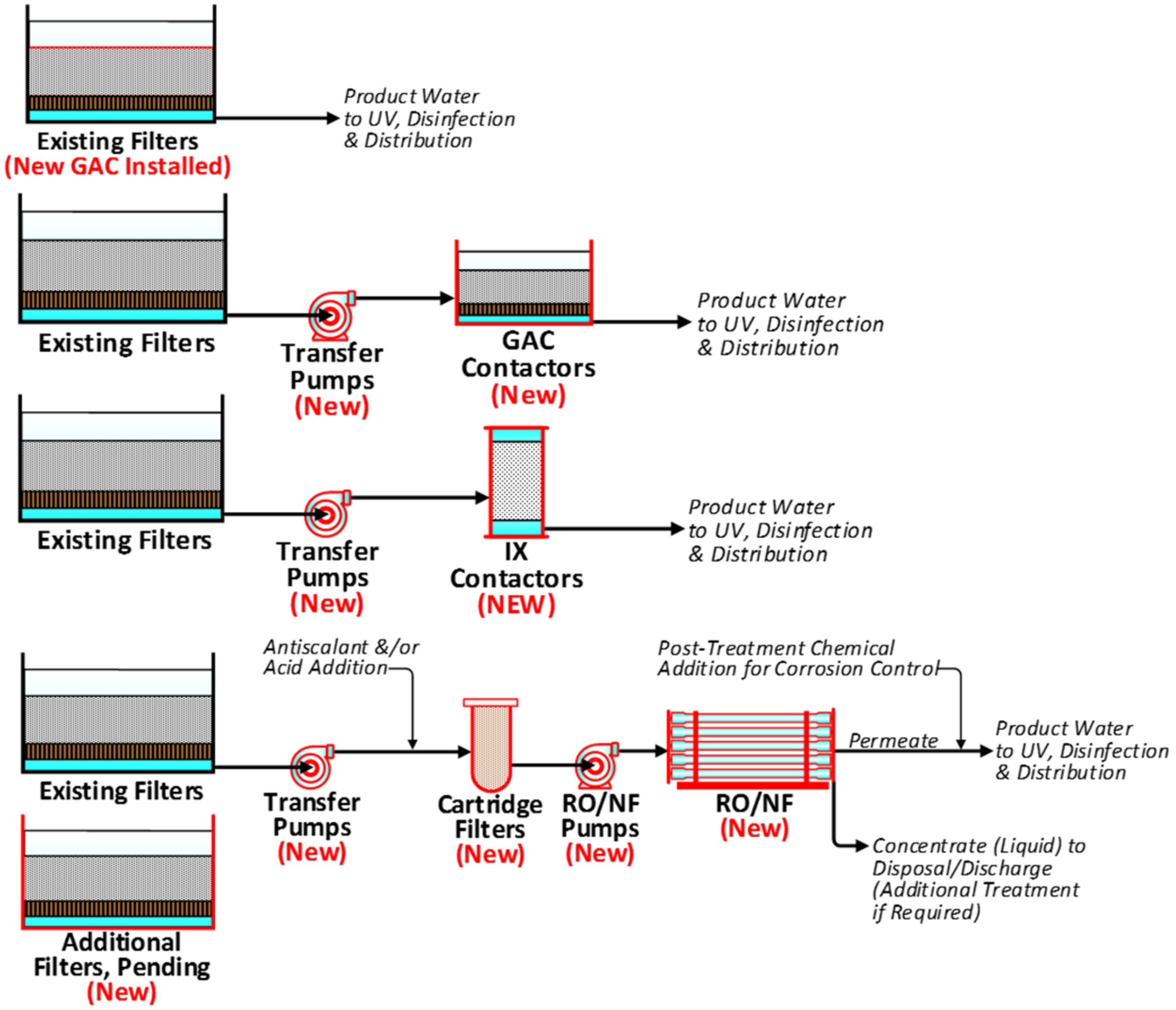

Figure 7-2 **Schematic Diagrams of New Options**

A comparison of the main features of the treatment methods is summarized in Table 7-1. These rankings incorporate engineering assumptions that are based on the currently available information. It is anticipated that additional information would be collected as the project moves forward.

Table 7-1 Comparison of Treatment Methods (5 is Best)

PARAMETER	GAC IN FILTERS	GAC ADSORBER	IX	RO/NF
OPTION NUMBER	**1A**	**1B**	**2**	**3**
Known Performance on GenX and other PFAS	0	0	0	0
Potential on GenX and other PFAS	5	5	5	5
Commonly Used for Water Treatment	5	5	5	5
Capital Cost	5	3	3	1
Implementation Time	5	2	2	1
Liquid Waste	5	5	5	1
Energy Use	5	4	4	1
Labor	5	3	3	1
Rerating Existing Filters	5	5	5	1
Selectivity	1	1	1	5
Chromatographic Peaking	1	1	1	5
Operational Understanding	5	5	2	4
Rapid Test Option	5	5	1	1

Notes related to the table are as follows:

- RATINGS – The ratings are comparative and are expressed on a 0 to 5 scale with 5 being the highest, best rating in each category.
- KNOWN PERFORMANCE ON GENX AND OTHER PFAS– All options were rated the same, a low rating, because there is little information available on water treatment methods to remove GenX.
- POTENTIAL ON GENX AND OTHER PFAS – All options were rated the same, a high rating, because the available information available indicates that any of these methods would be effective at removing GenX.
- COMMONLY USED - All options were rated the same, a high rating, because all of these treatment methods are commonly used in drinking water treatment facilities.
- CAPITAL COST – Option 1A is the best in this category because there would be no new capital cost for installing new GAC in the existing filters. However the life cycle costs could be high if the GAC would require frequent replacement. Regarding the other options, adding GAC adsorbers or IX beds (1B and 2) would qualitatively have lower capital costs than RO/NF (3).

- IMPLEMENTATION TIME – Option 1A (replacing the GAC in the existing filters) could be implemented in the shortest amount of time. Regarding the other options, adding GAC adsorbers or IX beds (1B and 2) would take somewhat less time to build and install than RO/NF (3).

- LIQUID WASTE - Neither GAC nor IX would generate significant additional liquid waste and the spent material would be shipped off-site for regeneration or disposal. RO/NF continuously yields a liquid waste stream, the concentrate. Handling and disposal of this stream can be problematic and sometimes costly.

- ENERGY USE - New GAC in the existing filters (1A) would not increase the WTPs energy usage. New post-filtration GAC or IX systems (1B or 2) would require some additional pressure drop. RO/NF is the highest energy user of these options.

- LABOR - Applying GAC in the existing filter boxes would have minimal impact. New facilities for post-filtration GAC or IX systems (1B or 2) would likely require some additional staff. Experience with RO/NF that option would require more additional staff.

- RERATING EXISTING FILTERS – The RO/NF option would require a higher filtered water flow rate and so would need either an increased loading rate on the existing filters or additional (new) filters. Neither GAC or IX options would require an increase in filtered water capacity.

- SELECTIVITY - While site-specific testing would be needed to fully show this, in general RO/NF removes a wider range of compounds. GAC and IX are more selective.

- CHROMATOGRAPHIC PEAKING - Chromatographic peaking can occur with GAC and IX and that has been indicated in similar applications. If it occurs, then during breakthrough some concentrations are higher in the effluent (the treated water) than in the influent. Since the removal mechanism of RO/NF is rejection, not adsorption, then it would not occur with RO/NF. RO/NF can experience increased passage due to leaks in seals but that is repairable.

- OPERATIONAL UNDERSTANDING - GAC scores best in this category because the existing Sweeney WTP uses GAC. The utility has NF at another location and so their operators also have an understanding of that treatment process, but the Sweeney operators do not have day-to-day experience.

- RAPID TEST OPTION - GAC is the only option with an accepted rapid/accelerated testing method, which is called RSSCT.

8.0 Summary/Recommendations

1. A number of perfluorinated compounds have been observed in the Cape Fear River upstream from the intake of the Sweeney WTP. Researchers measured average GenX concentrations of 631 ng/L. GenX is one of a group of organic chemicals that are referred to as PFASs, which are used in a wide variety of manufactured products.

2. Neither the EPA nor NC DEQ have set enforceable MCLs for GenX or other PFASs. Because of concern over potential adverse health effects associated with the presence of these compounds in drinking water, CFPUA is proactively considering the feasibility and effectiveness of treatment alternatives.

3. Chemours, a company that had been discharging wastewater containing GenX and PFAS into the Cape Fear River announced in late June 2017 that it had stopped discharging wastewater containing GenX while determining how to address the issue. Even if GenX discharge is not restarted, it is anticipated that concentrations of a stable chemical such as GenX may remain in the river for a period of time. It appears that Chemours may be continuing to discharge wastewaters containing PFAS compounds; information to revise that possibility has not been found.

4. A study of full-scale water treatment systems has shown that conventional water treatment methods, including aeration, chlorination, chloramination, chlorine dioxide, coagulation, flocculation, anthracite media filtration, microfiltration or ultrafiltration, ozonation, permanganate addition, sedimentation, softening (caustic softening followed by solids contact clarification), and UV light, were not effective at removing PFASs.

5. Various researchers have found that GAC, IX, and RO/NF are treatment options that have been successful at removing PFASs but that information is limited; almost no information is available on applying water treatment processes specifically to GenX removal.

6. Site-specific testing of these processes is recommended to refine the understanding of design and operational parameters for GAC, IX, and RO/NF.

7. Since the lowest initial cost option would be Option 1A, installing new GAC media into the existing filters, one logical approach would be to conduct testing to verify the viability of that option before staring a larger testing program. A key parameter for Option 1A is replacement frequency, which is directly related to the number of BV that can be achieved by the GAC before breakthrough. For example, even though Option 1A would have no capital cost, it would be too expensive and impractical if the GAC had to be replaced weekly or daily. Another important parameter is the range of PFASs that are removed by each option. For example, the data available from other sites indicate that the highest capital cost option, RO/NF, may provide removal of a longer list of PFAS compounds than GAC or IX. Testing would quantify these and other parameters and provide a basis for decision-making.

8. As a parallel path activity while testing proceeds, it is recommended that preliminary, planning-level, cost opinions be developed for the likely lowest cost and highest cost options to assist the utility with planning. Initially, before testing has been conducted, the development of the cost opinions would be based on preliminary assumptions that could subsequently be revised when test results are available. The low and high cost options would be, respectively, Option 1A (new GAC media installed in the existing filters) and Option 3 (RO/NF).

9.0 List of Abbreviations

AIX	Anionic Ion Exchange
BV	Bed Volume
CAS	Chemical Abstracts Service
CFPUA	Cape Fear Public Utility Authority
cm	Centimeter
DBP	Disinfection Byproducts
EBCT	Empty Bed Contact Time
EPA	United States Environmental Protection Agency
ft^2	Square Foot
GAC	Granular Activated Carbon
gfd	Gal per ft^2 per day = gpd/ft^2
gpm	Gallon per Minute
IX	Ion Exchange
LR	Loading Rate
MCL	Maximum Contaminant Level
mg/L	Milligrams per Liter
mgd	Million Gallons per Day
NC DEQ	North Carolina Department of Environmental Quality
NF	Nanofiltration
ng/L	Nanogram per Liter
NTU	Nephelometric Turbidity Unit
PAC	Powdered Activated Carbon
PFAS	Perfluoroalkyl Substance
PFBA	Perfluorobutanoic Acid
PFBS	Perfluorobutane Sulfonate
PFC	Perfluorinated Compound
PFHxA	Perfluorohexanoic Acid
PFOA	Perfluorooctanoic Acid
PFOS	Perfluorooctane Sulfonate
PFPeA	Perfluoropentanoic Acid
PFPrOPrA	Perfluoro-2-Propoxypropanoic Acid
RO	Reverse Osmosis

RSSCT	Rapid Small-Scale Column Test
TOC	Total Organic Carbon
µS/cm	Micro-Siemens per Centimeter
UV	Ultraviolet
WTP	Water Treatment Plant

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