VIRGINIA WATER RESOURCES RESEARCH CENTER

THE FEASIBILITY OF USING DESALINATION TO SUPPLEMENT DRINKING WATER SUPPLIES IN EASTERN VIRGINIA

Virginia Tech

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
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FINAL REPORT

The Feasibility of Using Desalination to Supplement Drinking Water Supplies in Eastern Virginia

Submitted to

The State Water Commission
and
Virginia Department of Health

by

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Executive Summary

The 2003 Virginia General Assembly Session passed the Senate Joint Resolution No. 381 that requested the Virginia Water Resources Research Center at Virginia Polytechnic Institute and State University to study desalination issues as part of a strategy to meet the Commonwealth's future drinking water needs.

The major goal of this report was to investigate the feasibility of implementing desalination technologies in Virginia to supplement drinking water supplies. For the purposes of this report, desalination (or desalinization) is defined as removing salts from brackish water and/or seawater to produce potable water. Issues critical to implementing desalination technologies are: type of desalination technology, environmental concerns and regulations, energy availability and cost, availability of water source for desalination, and cost to the customer. This report provides an overview of those issues in six chapters. The synopsis for each chapter, the rationale for implementing desalination technologies in eastern Virginia, and the report's recommendations are provided below.

Chapter 1 is an introductory chapter. It describes several options for meeting future water demand, defines salinity and desalination, and provides a synopsis of chapters that follow.

The objective of Chapter 2 is to introduce the available desalination technologies. The chapter presents an overview of current and futuristic desalination technologies to treat brackish and saltwater to produce potable water. It also discusses the applicability and the limitations of the technologies.

The objective of Chapter 3 is to provide an overview of environmental issues related to desalination. Environmental concerns are a major factor in the design and implementation of cost-effective desalination technologies. Major environmental concerns include issues related to brackish groundwater withdrawal, surface water intake, disposal of brine and other water treatment residuals (called concentrate), and ecosystem effects.

Desalination is energy-intensive, because energy is needed in various stages of desalination. Energy consumption directly affects the cost-effectiveness of using desalination technologies. Chapter 4 presents energy types, use, methods of conservation, and the potential use of renewable energy resources for desalination. Some of the information provided in this chapter may not be applicable to today's Virginia energy issues. However, the chapter provides a comparison between costs associated with various energy sources as applied to desalination worldwide, and can be used as a reference for future energy development and use in Virginia.

Chapter 5 focuses on issues that relate to the feasibility of implementing desalination in eastern Virginia. A major assumption of this study is that the greatest potential for implementing desalination exists in the counties and cities in eastern Virginia within close proximity of the Chesapeake Bay and the Atlantic Ocean. Many localities in eastern Virginia project significant population growth that will affect future water demand. Estimates from this study show that projected population increases (using 2000 population data as a reference) will translate to an additional drinking water demand of approximately 20 MGD (2010), 50 MGD (2020), and 75MGD (2030) in eastern Virginia. Chapter 5 discusses feasibility issues including potential water resources for desalination, environmental effects of desalination, required permits and regulations, availability of energy resources, and potential costs. The chapter also presents a description of existing desalination plants in eastern Virginia and the rationale for future desalination plants.

Chapter 6 contains major conclusions and recommendations of the report. A comprehensive database of water resource inventory for eastern Virginia is not available. Based on available information, a significant need exists for using desalination in eastern Virginia:

1. The Hampton Roads area is the home of one of the largest port facilities in the country and hosts a major military complex. As a result, the area has experienced rapid population growth that has strained local water supplies. Because of the population growth and the difficulty in developing new water sources locally, water shortages in the region have become commonplace over the last two decades. Water restrictions resulting from water shortages have occurred in every dry period since 1976.
2. Because of withdrawals from Coastal Plain aquifers, groundwater levels have declined in the region as deep as 160 feet below the sea level near major pumping centers. Groundwater levels in the interior portions of the Middle Potomac (Southampton County), in the Yorktown-Eastover aquifer (Southampton County), and Chickahominy-Piney Point (King William, Caroline, King and Queen counties) are approaching critical condition.
3. Because of withdrawals from Coastal Plain aquifers, groundwater levels have declined in the region as deep as 160 feet below the sea level near major pumping centers. Groundwater levels in the interior portions of the Middle Potomac (Southampton County), in the Yorktown-Eastover aquifer (Southampton County), and Chickahominy-Piney Point (King William, Caroline, King and Queen counties) are approaching critical condition.

4. Major cities in eastern Virginia (Chesapeake, Virginia Beach, Norfolk, Newport News, Portsmouth and Suffolk) are within the Groundwater Management Area. From a regulatory standpoint, the stress on the aquifer system is such that the DEQ may have to start denying permit issuance in some areas of the Ground Water Management Area.
5. Virginia Beach, the largest city in the area has very little fresh groundwater available to meet current or future needs. Virginia Beach relies on interbasin transfer from the Lake Gaston pipeline. If the pipeline is disrupted for any reason, it will have major consequences for Virginia Beach and the region.
6. The Virginia Department of Health has advised the City of Newport News (Newport News Water Works) and James City County for the need to develop additional sources of supply, as the current demands have exceeded the "trigger level" contained in the *Commonwealth of Virginia Waterworks Regulations* for such action. To meet future demand, brackish groundwater or other saline waters will be the only available local resources.
7. Portsmouth and Norfolk, the older cities in the area, developed the limited surface water supplies before the newer cities of Chesapeake, Suffolk, and Virginia Beach came into existence. Portsmouth and Norfolk have sufficient water supplies to meet their current needs and supply their surplus water to Virginia Beach and Chesapeake. However, the surplus is not adequate to meet the needs of these cities where much of the population growth is occurring.
8. The proposed King William Reservoir project will supply only up to 60% of the lower Peninsula's future water needs. Desalination of brackish groundwater is considered as potential way to supplement a portion of the additional demand.
9. Construction of additional reservoirs in eastern Virginia is less likely because of environmental concerns, high cost, and difficulty in purchasing the needed land.
10. Parts of New Kent, Charles City, Hanover, Henrico, and Petersburg are situated within the Eastern Virginia Ground Water Management Area. These localities will compete with Hampton Roads area and Middle Peninsula for available water resources in the region.
11. Accomack and Northampton counties rely solely on groundwater to meet drinking water needs. Future economic growth in the area depends of availability of alternative source of water.

Recommendations

Desalination cannot be considered as a stand-alone measure to meet increased water demand for public water supplies. Desalination should be considered as a viable component of an overall water supply management that includes all available sources of water (fresh and impure) and all uses of water (public water supplies, agricultural, industrial, etc.). Technologies are available for desalination of brackish and seawater. These technologies are implemented worldwide, and further research and development of more cost-effective desalination technologies are underway. Advanced brackish water desalination technologies are already implemented in the Hampton Roads area with acceptable cost to the public. Therefore, technology is not a factor in implementing desalination in eastern Virginia. However, there are issues related to availability of water sources, institutional needs, and ecosystem impacts that need to be addressed.

Water Resource Inventory Need

At present, a comprehensive and reliable database of surface and groundwater resources in eastern Virginia is not available. It is important to understand that brackish and saline groundwater resources are not disconnected from fresh surface and groundwater resources. Extraction of brackish water will have effects on adjacent fresh groundwater reservoirs, and ultimately surface water resources as well. A better inventory of surface and groundwater resources is needed for optimal site selection of desalination plants.

Recommendation. *Legislative guidance and state government leadership is needed to develop a comprehensive database of available water resources in eastern Virginia to be followed by a viable regional water supply and allocation plan based on the scientific evaluation of existing water resources and the potential for developing impure water sources such as saline water.*

Institutional Needs

There is a significant need for regional collaboration for successful implementation of desalination and to meet future water demand.

Recommendation. *Legislative guidance and state government leadership is needed to form a regional utility task force that will coordinate activities of numerous utilities in the region and to develop a strategic plan for future use of large-scale desalination technologies in eastern Virginia. The task force should determine where the needs are and identify potential sites to locate desalination facilities.*

Recommendation. *Legislative guidance is needed to form an inter-governmental task force that will coordinate and expedite permit reviews between various federal and state agencies for the implementation of future desalination plants.*

Recommendation. *Energy costs are a major factor in the production cost for desalination plants, particularly when using high salinity waters such as tidal and seawater. There is a need to develop a mechanism for enhanced cooperation between water utilities and power companies to make existing and future desalination plants more cost-competitive.*

Research Needs for Ecosystem Management

Less is known about various effects of desalination plants on receiving waters and coastal ecosystems. Research is needed to provide science-based information that can facilitate science-based permitting and developing regulatory guidelines.

Recommendation. *Legislative action is needed to provide funds that can support research for developing environmentally sound desalination practices. Research is needed to address ecosystem impacts such as effects of water withdrawal, water intake structure and brine disposal; and cost effectiveness of various brine disposal and management technologies, such as Zero Liquid Discharge and brine reuse potential.*

1. Introduction

From 1999 to 2002, many localities in Virginia experienced a severe drought condition. However, periodic droughts in Virginia are not unusual. The impact of the recent drought was significant because of the increased water demand and declining groundwater levels in many regions of the state. Normally, groundwater resources have served as a backup resource during critical water shortages. There is a high probability that Virginia, specifically in populated coastal areas and northern Virginia, faces a severe water shortage in coming decades because of increased water demand and periodic natural droughts.

1.1. Meeting Future Water Demand in Virginia

There are several measures, or a combination of measures, that Virginia can implement to meet future water demand. However, some of the conventional methods to meet future water demands may not be considered practical or economical any longer. For example, building dams and reservoirs, one of the popular water storage and supply measures, may not be viable solutions because of the high cost of acquiring land, and meeting environmental and regulatory requirements. During past decades, inter-watershed water transfer has supplied water to some regions of the state. However, long-term economic, environmental, regulatory, and societal implications of future water transfer projects remains uncertain.

To meet long-term water supply demands, decision-makers can consider the following options, or combinations of these options, to supplement existing water resources: water conservation, water reuse, groundwater recharge, and desalination.

Water conservation is an effective method where saved water can compensate for additional demand. Generally speaking, “each gallon of water that is conserved by one user essentially ‘creates’ a gallon of water for another user.” In Virginia, citizens practice water conservation mostly during drought conditions. Ensuring water conservation during normal years requires public education programs. However, conservation by itself is unlikely to meet increased water demand.

Water reuse is another option. Currently, reclaimed water is reused in industry and agriculture in the U.S. and other countries. Similar to water conservation, each gallon of reused water substitutes for a gallon of water that from natural sources. An example of a successful water reuse strategy is the Occoquan reservoir system in northern Virginia. The Upper Occoquan Sewage Authority (UOSA) Water Reclamation Facility is one of the nation’s largest and most successful projects for the indirect reuse of reclaimed water to supplement a public surface water supply. Implementation of reuse strategies in other Virginia localities is a matter of public perception and public policy.

Preservation and restoration of groundwater aquifers is another water conservation option. Elements of long-term water supply planning should include protecting aquifer recharge zones, and increasing subsurface infiltration and groundwater recharge by implementing low-impact development techniques such as forestation and bioretention in urban and suburban areas. Underground storage of excess water in half-empty aquifers during wet periods and artificial recharge of highly treated wastewater are options to be studied for their potential to meet future water demand.

1.2. Introduction to Desalination

A broad definition of desalination includes treatment of all impaired waters. A definition of impaired water is waters contaminated by salts, metals, radionuclides, biologic organisms, organic chemicals, fertilizers, pesticides, and a host of other substances that must be removed prior to water being suitable for potable use. The U.S. Department of Interior, Bureau of Reclamation in collaboration with the Sandia National Laboratories has created the Desalination and Water Purification Technology Roadmap to meet future water demand in the United States [1]. As an example, future desalination technologies can treat excess runoff and wastewater for possible reuse or underground storage.

The 2003 Virginia General Assembly Session passed Senate Joint Resolution No. 381 "Requesting the Virginia Water Resources Research Center at Virginia Polytechnic Institute and State University to study desalinization as part of a strategy to meet the Commonwealth's drinking water needs" [2]. For the purposes of this report, the definition of desalination is limited to removing salts from brackish water and seawater to produce potable water.

The concentration of total dissolved solids (TDS) in the water describes the amount of salts in the water. TDS refers to the sum of all minerals, salts, metals, cations, and anions dissolved in water. Water that contains significant concentrations of dissolved salts is called saline water. In this case, the concentration is the amount (by weight) of TDS in water, as expressed in mg/L. There are more than seventy elements dissolved in seawater but only six make up greater than 99 percent (by the weight) of all dissolved salts. These major elements occur as electrically charged ions. Table 1.1 shows the approximate composition of typical seawater by weight and concentration. Seawater is a solution of salts of nearly constant composition. Brackish water contains less TDS than seawater but more than freshwater. Most brackish water environments are dynamic and TDS levels in these environments are fluctuating spatially and temporally.

The salinity of brackish surface water near the coast can vary depending on the tide, the amount of freshwater entering the system as rain or river flows, and the rate of evaporation. Brackish water also occurs in coastal aquifers. Some deep groundwater aquifers contain brackish water under natural conditions. In coastal aquifers, excessive groundwater withdrawals may cause the seawater to move into freshwater aquifers (a phenomenon known as saltwater intrusion) and create brackish water in the aquifer. Because of many influencing factors, the range of TDS concentrations in brackish water and seawater can range between 500 mg/L to 50,000 mg/L, with brackish water TDS concentrations in the lower range and seawater TDS concentrations on the upper end of the range. The U.S. Environmental Protection Agency has set the Secondary Maximum Contaminant Level (SMCL) or aesthetic standard for TDS in potable water as <500 mg/L [3][1]. A TDS concentration of less than 200 mg/L in drinking water is desirable. High TDS content in potable water is a nuisance that may cause scaling in pipes, staining bathroom fixtures, corrosion of piping and fixtures, reducing soap lathering, and objectionable tastes.

Table 1.1. Composition of Seawater

Element	**% Weight/Gram of Water**	**Concentration (mg/L)**
Chloride (Cl)	55.04	19,400
Sulfate (SO_4)	7.68	904
Calcium (Ca)	1.16	411
Sodium (Na)	30.61	10,800
Magnesium (Mg)	3.69	1290
Potassium (K)	1.10	392

Conventional water treatment plants that use coagulation, sedimentation, and filtration technologies cannot remove dissolved salts from brackish or seawater. Desalination technologies are being developed and used worldwide to convert brackish water and seawater to water that meets drinking water standards or other intended uses. Currently there are 12,500 desalination plants in the world totaling to a water production capacity of approximately 6 billion gallons/day (22.8 x 10^6 m^3/d) [4]. At present, major large-scale desalination facilities in the United States are being developed or planned in Florida and California [5]. Chapter 5 of this report describes existing desalination plants in Virginia and North Carolina.

1.3. The Objective and Contents of this Report

The goal of this report is to investigate the feasibility of using desalination technologies in Virginia to supplement drinking water supplies. Issues critical to implementing desalination technologies are: type of technology; energy availability, consumption and cost; environmental effects and associated costs; and permits and regulatory issues. Chapters 2 through 6 of this report discuss these topics and the feasibility of implementing desalination in Virginia. The synopsis for each chapter follows here.

The objective of Chapter 2 is to present an overview of current and futuristic technologies applied to desalination of brackish water and seawater to produce freshwater. Water purification technologies that are used for desalination can be categorized into synthetic membrane, ion exchange, and thermal

[1] The Virginia Department of Health has an enforceable Secondary Maximum Contaminant Level (SMCL) for TDS, set at 500 mg/L (*Commonwealth of Virginia Waterworks Regulations*).

technologies. Some water purification plants use a combination of technologies. At present, thermal technologies are not common in the United States, due in large part to the energy costs and a lack of centralized water and power planning that would result in less expensive, thermally-desalinated water. However, for comparative purposes Chapter 2 includes a brief overview of thermal technologies. The chapter also includes a summary of new technologies under research and development for possible applications to desalination.

The objective of Chapter 3 is to discuss environmental issues related to desalination. An acceptable desalination plant is expected to meet environmental regulations and be cost-effective in terms of construction, operation and management, and costs associated with monitoring and permit fees. Major environmental concerns include issues related to desalination plant location and water intake, concentrate (waste generated from desalination plant) management and disposal, and environmental effects of energy consumption. Chapter 3 provides an overview of the above issues and discusses steps for the design and construction of environmentally sound desalination plants.

The objective of Chapter 4 is to discuss energy needs and consumption in desalination. Energy needs and consumption directly affect the cost-effectiveness and feasibility of using desalination technologies for drinking water production. Energy types, use, conservation, and renewable energy approaches and their potential for application to desalination are presented in this chapter. Although some of the information provided in Chapter 4 may not be applicable to conditions in Virginia today, the information provides a comparison between costs associated with various energy sources as applied to desalination, and can be used as a reference for future energy development and use in Virginia.

A major assumption of the study was that the greatest potential for implementing desalination technologies exists in the counties and cities in eastern Virginia within close proximity of the Chesapeake Bay and the Atlantic Ocean. Chapter 5 provides data on projected population growth and future water demand, available surface and groundwater resources, the rationale for implementing desalination technologies, a description of the existing desalination plants in eastern Virginia, and a discussion of feasibility of using desalination technologies in eastern Virginia. Feasibility issues include potential water resources for desalination; environmental effects of desalination; required permits and regulations; availability of energy resources; and potential costs. The chapter is concluded with a set of recommendations for actions that could facilitate the implementation of future desalination technologies in eastern Virginia.

Chapter 6 contains major conclusions and recommendations of this report.

2. Overview of Water Treatment Technologies Applied to Desalination

Chapter Synopsis

The objective of this chapter is to present an overview of current and futuristic technologies applied to the desalination of brackish and saltwater to produce freshwater for supplementing drinking water supplies. The goal of this chapter is to introduce the application of available desalination technologies for producing drinking water. Discussion of detailed design concepts and processes of desalination is beyond the scope of this chapter. Also, some technologies are applicable to the purification of wastewater and other polluted waters. Discussion of those applications is not the goal of this chapter. Where appropriate, references for further reading are introduced.

Water purification technologies that are used for desalination can be categorized into synthetic membrane technologies, ion exchange technologies, and thermal technologies. Some water purification plants use a combination of technologies. At present, thermal technologies are not widely used in the United States, due in large part to the energy costs and a lack of centralized water and power planning that would result in less-expensive, thermally-desalinated water. However, for comparative purposes this chapter includes a brief overview of thermal technologies. The chapter also includes a summary of new technologies under research and development for possible applications to desalination.

2.1. Membrane Technologies

A membrane is a thin film of porous material that allows molecules of certain sizes such as water to pass through, but simultaneously serves as a barrier preventing the passage of larger and undesirable molecules such as viruses, bacteria, metals, and salts [1]. Membranes are made from a wide variety of materials such as polymeric materials, including cellulose, acetate, and nylon and non-polymeric materials such as ceramics, metals and composites. Synthetic membranes are the most widely used technology for desalination and their use is growing at a rate of 5-10% annually [2].

Membrane processes use pressure-driven or electrical-driven technologies. There are four types of pressure-driven membrane processes: reverse osmosis (RO), nanofiltration (NF), ultrafiltration, and microfiltration (Table 2.1). Reverse osmosis (RO) is a diffusion-controlled process that can remove total dissolved solids. Nanofiltration (NF), a process similar to RO, has some ability to remove salinity [36]. Electrodialysis (ED) and electrodialysis reversal (EDR) are electrical-driven membrane technologies that are effective with TDS removal.

Table 2.1. Characteristics of Applications of Pressure -Driven Membrane Processes [3]

Membrane Process	**Applied Pressure psi (kPa)**	**Minimum Particle Size Removed**	**Application (type, average removal efficiency %)**
Microfiltration	4-70 (30-500)	0.1-3 μm	Particle/turbidity removal (>99%) Bacteria/protozoa removal (>99.99 %)
Ultrafiltration	4-70 (30-500)	0.01-0.1 μm	Particle/turbidity removal (>99 %) Bacteria/protozoa removal (>99.999 %) TOC removal (<20%) Virus removal/(partial credit only)
Nanofiltration	70-140 (500-1000)	200-400 daltons	Turbidity removal (>99%) Color removal (>98%) TOC removal (DBP control) (>95%) Hardness removal (softening) (>90%) Synthetic organic contaminant (SOC) removal (500 daltons and up) (0-100%) Sulfate removal (>97%) Virus removal (>95%)
Hyperfiltration (Reverse Osmosis)	140-700 (1000-5000)	50-200 daltons	Salinity removal (desalination) (>99%) Color and DOC removal (>97%) Radionuclide removal (not including radon) (>97%) Nitrate removal (85 to 95%) As, Cd, Cr, Pb, F removal (40 to >98%) Pesticide/SOC removal (0 to 100%) Virus removal (>95%)

In 2003, the U.S. EPA issued the Membrane Filtration Guidance Manual [4]. Chapter 2 of the EPA report documents an extensive overview of membrane filtration design and configuration. Membrane configuration refers to the arrangement of individual elements (cartridges) in a membrane treatment process. The AWWA Manual M46 documents detailed information about applications of synthetic membranes to desalination [5].

2.1.1. Reverse Osmosis

Reverse Osmosis (RO) is a physical process based on the osmosis phenomenon, i.e., the osmotic pressure difference between the saltwater and the pure water. In a RO process, a pressure greater than the osmotic pressure is applied on saltwater (feedwater). The process enables only pure water (freshwater) to pass through the synthetic membrane pores and be separated from the salt (Figure 2.1). A concentrated salt solution is retained for disposal. The RO process is effective for removing total dissolved solids (TDS) concentrations of up to 45,000 mg/L and can be applied to desalinate both brackish water and seawater.

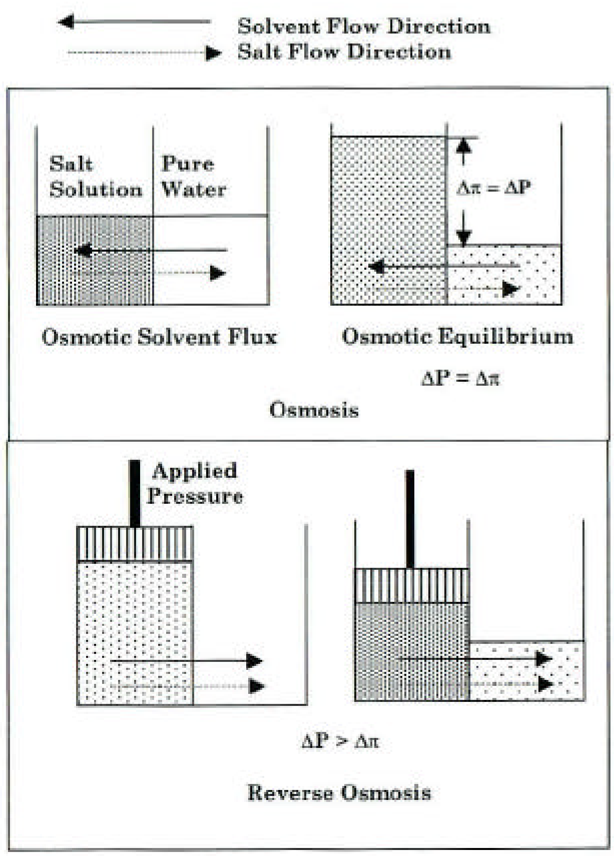

Figure 2.1 Reverse Osmosis vs. Osmosis [2]

Reverse osmosis needs energy to operate the pumps that raise the pressure applied to feedwater. The amount of pressure required directly relates to the TDS of the feedwater. For brackish water reverse osmosis, the pump pressure requirement is between 140 and 400 psi. For seawater reverse osmosis systems, pumps may need to generate up to 1200 psi. Therefore, the TDS concentration of the feedwater has a substantial effect on the energy use and the cost of the product water.

Two types of membranes are being used in RO desalination. Cellulose Acetate (CA) membrane developed in the 1960s is the first membrane incorporated in the RO process and is currently used in modified and improved blends. The term cellulosic describes the materials composed in a CA membrane. The CA membrane has a relatively smooth surface that facilitates resistance to fouling. It is theorized that material that may cause fouling cannot deposit in the crevices if the membrane is rather smooth [6].

Noncellulosic (Non-CA) membranes, typically called “thin-film composite membranes”, are the second type of membrane used in the RO desalination process. These include aromatic polyamide (PA) membranes and other common organic membrane materials such as polysulfone. These composite membranes have a higher flux (volume of freshwater per membrane surface area) and allow lower salts passage than the CA membrane. PA membranes are more stable over a broader pH range than the CA membranes but are susceptible to degradation by chlorine [7].

Feedwater to RO systems should be free of organic matter, bacteria, large particles, and oil and grease. Pre-treatment of feedwater is essential in order to protect the RO membrane, reduce energy costs, and increase salt retention. Typical pre-treatment involves filtration (multimedia filters, cartridge filters, sand filters, etc.) to remove larger particles, organics and other materials; and adding chemical additives to prevent the formation of precipitates and scaling of the membrane. Often pH adjustment is also needed. Certain membrane materials are sensitive to oxidants such as chlorine; therefore, additional chemicals may be needed in order to remove the oxidants from the feedwater prior to membrane treatment. Depending on the purpose for the product water (drinking water, industrial water, other), post-treatment of RO discharge may be needed as well. For example, carbon dioxide and soda ash may be added to increase alkalinity of the treated water. The other major reason to add carbon dioxide or soda ash is to reduce corrosiveness of the RO permeate.

Recovery rate is a major parameter for evaluating membrane effectiveness and is defined as the volume of freshwater produced as a percentage of the volume of feedwater processed. Typical recovery rates for RO systems can be 30% to 80% depending on the quality of feedwater, pressure applied, and other factors.

Designers have developed reverse osmosis membranes that operate at low pressures, but maintain high recovery rates. Typically, these ultra low-pressure reverse osmosis membranes (ULPRO) are made of thin film composites of polymers, with an active surface layer that is negatively charged with improved fouling resistance properties [8]. Current literature offers information about low-pressure membrane configurations [9].

2.1.2. Nanofiltration

A nanofiltration (NF) membrane works similar to reverse osmosis except that with NF less pressure is needed (70 and 140 psi) because of larger membrane pore size (0.05 µm to 0.005 µm).

Nanofiltration can remove some total dissolved solids but is often used to partially soften water and is successful at removing solids, and dissolved organic carbon. For low TDS brackish waters, NF may be used as a stand-alone treatment for removing salts.

2.1.3. Ultrafiltration

Ultrafiltration (UF) technology uses a pressure-driven membrane with larger pore sizes (ranging from 0.15 µm to 0.05 µm). UF has shown potential to reduce total organic carbon, colloidal organic material, suspended solids, bacteria, and some viruses. UF requires operating pressures between 4 and 70 psi. Therefore, UF requires less energy than NF and RO because less pressure is needed to pass water through the UF. UF membranes are not effective for TDS removal. However, a combined UF/RO plant can be effective for desalination. For example, a desalination plant with capacity of 13 mgd in the Netherlands is currently using UF membranes for pretreatment before the RO treatment [10].

2.1.4. Microfiltration

Microfiltration (MF) pores range from 0.1 µm to 1 µm, and work the same as the other pressure-driven membranes described above. Microfiltration membranes are made using a wide variety of membrane materials and processes [11]. Microfiltration requires low pressure (between 4 and 70 psi). MF membranes are successful at removing coliform bacteria, *Cryptosporidium oocysts, Giardia cysts,* and suspended solids from water but are not effective for TDS removal.

2.1.5. Electrodialysis and Electrodialysis Reversal

Electrodialysis (ED) is a treatment process that utilizes electromotive force applied to electrodes adjacent to both sides of a membrane to separate dissolved minerals in water. The separation of minerals occurs in individual membrane units called cell pairs, which consist of an anion transfer membrane, a cation transfer membrane, and two spacers. The complete assembly of cell pairs and electrodes is called the membrane stack. Figure 2.2 shows a typical electrodialysis stack. The number of cells within a stack varies depending on the system. The spacer material is important for distributing the water flow evenly across the membrane surface.

The process is effective with salt removal because the cathode attracts the sodium ions and the anode attracts the chloride ions in feedwater. Required pressure is between 70 and 90 psi [12]. In general, ED has a high recovery rate and can remove 75% to 98% of total dissolved solids from feedwater.

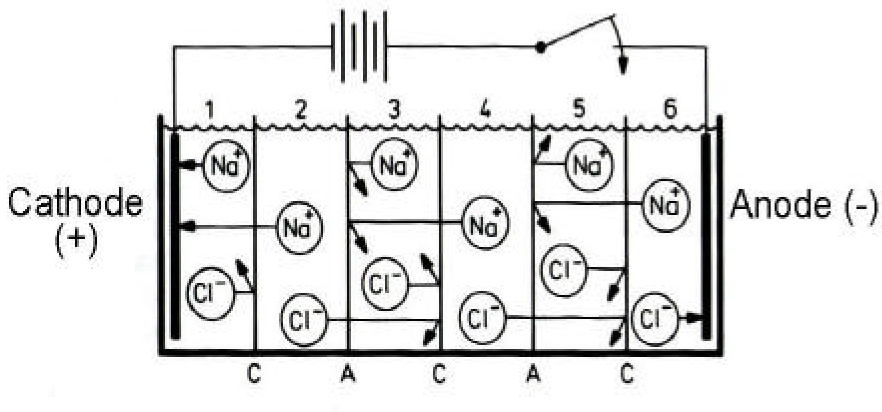

Figure 2.2 – Electrodialysis Stack [13]

Electrodialysis reversal (EDR) is a similar process except that the cation and anion reverse to routinely alternate current flow. In design applications, the polarity is reversed 4 times per hour. This creates a cleaning mechanism, which decreases the scaling and fouling potential of the membrane. EDR has a higher recovery rate (up to 94%) because of the feedwater circulation within the system and alternating polarity.

ED and EDR can remove or reduce a host of contaminants from feedwater and is not as sensitive to pH or hardness levels in feedwater. The EDR process is adaptable to various operation parameters, requires little labor, and the maintenance costs are generally low [14]. However, when using ED and EDR technologies for desalination, treatment cost is directly related to the TDS concentration in feedwater. These technologies are best applicable to treating brackish water with TDS up to 4000 mg/L and are not economical for higher TDS concentrations [15]. The City of Washington, Iowa is currently operating a 1.1 mgd ED plant that successfully removes 50% of the TDS in the water [16]. The first ED desalination plant in Florida was installed in 1968 but the system was not effective for reducing TDS adequately and the plant operation was discontinued [17].

2.2. Ion Exchange Technologies

Ion exchange is a well-known phenomenon that occurs in natural soils. The application of the ion exchange principle to water treatment is an old technology and often used for softening water among other applications. The ion exchange technologies are well-developed; detailed information can be found in the current literature [18]. Briefly, the ion-exchange system can best be described as the interchange of ions between a solid phase and a liquid surrounding the solid. Chemical resins (solid phase) are designed to exchange their ions with feedwater (liquid phase) ions; therefore, purifying the water. Resins can be made using naturally-occurring inorganic materials such as zeolites or synthetic materials.

Modern ion-exchange materials are prepared from synthetic polymers tailored for different applications. These resins are solid, porous beads with considerable external and pore surface where ions can attach. Resins that exchange positive ions are called cation exchangers, and resins that exchange negative ions are called anion exchangers. In the desalination process, saltwater is washed over resin beads and the salt ions from the water take the place of other ions on the resin. The process removes Na^+ and Cl^- ions from water, thus producing potable water. Ion-exchange technologies applied to desalination are rather complex. For details, readers can explore available publications [19].

When an ion-exchange system is used for water treatment at a certain time the resin beads become saturated with ions. Under saturated circumstances, ion exchange does not take place and therefore the system does not remove ions from the feedwater and regeneration of the system, such as backwashing or chemical use, will be needed. Modern ion-exchange systems usually employ columns with well-defined water distribution systems that can operate in either a cocurrent or countercurrent fashion. The cocurrent column employs downflow for both feedwater and regeneration. The countercurrent system employs a flow opposite to feedwater flow (usually upflow) for regeneration. Cocurrent type is cheaper in initial costs, but is less efficient with chemical use for regeneration. The initial cost for a countercurrent system is higher, but the system is more efficient with chemical use for regeneration [20]. The costs of the regeneration using chemicals can be high, amounting to 70% of the total operation cost.

Ion exchange is best suitable for treating waters with less than 125 mg/L of solubility expressed as $CaCO_3$. With this range of solubility, ion exchange can completely de-mineralize water and is economical [21]. Ion exchange can be used in combination with reverse osmosis processes such as blending water treated by ion exchange with RO product water to increase water production.

2.3. Summary of Existing Technologies

The use of membrane technologies for desalination has become a necessary process where there is a degradation of coastal freshwater aquifers by saltwater intrusion or where there is a need for developing brackish groundwater when freshwater supplies are not meeting demand.

Advantages of membrane technologies were discussed in the previous section. Problems associated with using membranes (depending on membrane type) may include short design life; the need for backwashing and chemical treatment for cleaning purposes; high membrane replacement costs; low resistance to chlorine and lack of resistance to fouling. A primary factor affecting water productivity is fouling. Fouling occurs when the membrane pores become blocked because of residual buildup. Pretreatment can prevent membrane fouling. The method of pretreatment to be used depends on the feedwater quality and the type of membrane used. The four primary mechanisms of fouling are scaling, plugging, adsorption and biological growth. Methods of fouling control are described below [22]:

Scaling control is required for all RO/NF membrane systems in either surface or groundwater and is achieved by acid and/or antiscalent addition.

- Plugging control is required for all RO/NF membrane systems in either surface or groundwater and is achieved by feedwater turbidities and silt density indexes (SDI's) less than 0.2 NTU and 2, respectively.

- Bio-fouling is most often controlled by feeding free chlorine (either gas chlorine or hypochlorite solution) at the front of the plant. Depending on the type of membrane, this may be followed by adding a de-chlorinating agent to protect against oxidation damage to the membrane. Bio-fouling can also be achieved by adding monochloramine (NH_2Cl) or other bactericidal agents.

- Organic fouling can occur in surface water systems with TOC > 3-6 mg/L and is typically reduced by coagulation, sedimentation and filtration or advanced pretreatment.

The quality of feedwater is certainly the determining factor for deciding the type of membrane processes to use. River water supplies represent the most variable water quality, particularly in terms of particle loadings and turbidity. Water treatment processes in the future may more readily employ integrated membrane processes that can effectively treat fresh, brackish and seawater sources. Consequently, control of membrane fouling for surface water systems can be significant. In addition, risk assessments relative to security and supply vulnerability may also influence the selection of membrane processes [23].

Current research is focusing on developing high-pressure membranes with high recovery rates. Researchers have determined that high-pressure membrane systems are capable of improving energy consumption and cost performance because the freshwater water recovery ratio is increased. A recent study showed that a high-pressure membrane system in series after a conventional reverse osmosis system increased water recovery by 20% as opposed to a conventional reverse osmosis system [24]. Other studies focus on developing fouling-resistant membranes. Fouling-resistant membranes will extend membrane life and reduce cleaning and energy costs [25]. Table 2.2 shows a summary of available membrane technologies and their applicability to desalination.

Table 2.2. Summary of processes used for desalination and/or pretreatment

Technology	Brief Description – advantages & disadvantages	Typical Feed Source
Reverse Osmosis (RO)	Reverse osmosis is a physical process based on osmosis phenomenon, i.e., osmotic pressure difference between the concentrate (salt water) and the solvent (water). In RO process, a pressure greater than the osmotic pressure is applied on concentrate (salt water) that enables solvent (water) to pass through synthetic membrane pores and be separated from the solute (salt). The salt is retained for disposal. Experience in industry, can purify high salinity and highly contaminated water, less energy than MSF and MEE / SW: require high energy amounts, high salinity brine produced. BW & SW: scaling and fouling of membranes, use of chemicals	SW*/BW**
Electrodialysis (ED) Electrodialysis Reversal (EDR)	Electrodialysis (ED) is a membrane separation process that utilizes electric current. The separation of minerals in water occurs in individual membrane units called cell pairs, which consists of an anion transfer membrane, a cation transfer membrane, and two spacers. The process is effective with saltwater because the cathode attracts the sodium ion and the anode attracts the chloride ion. EDR is same as electrodialysis except that the flow of the electric current alternates regularly. Cost comparable with RO at low salinities, can handle more harsh water than RO membranes, less chemical use /not cost-effective for higher salinities, does not remove organics	BW
Nanofiltration (NF)	A process similar to RO. Very effective for removing hardness from the water but very limited success with removing salts. Reduces pretreatment chemical use for RO, able to remove some salts / membranes expensive and susceptible to fouling and scaling.	BW/Pretreatment for any
Ultrafiltration (UF)	Water is pushed through membrane pores removing some organics and other impurities but not salts. Reduces pretreatment chemical use for RO / membranes expensive and susceptible to fouling and scaling.	Pretreatment for any
Microfiltration (MF)	Water is pushed through membrane pores and particulates in water are removed. Reduces pretreatment chemical use for RO / membranes expensive and susceptible to fouling and scaling.	Pretreatment for any
Ion Exchange (IX)	Saltwater is washed over resin beads and the salt ions from the water take the place of other ions on resin. Na^+ and Cl^- ions are removed from water, thus producing potable water. Only potable water use is for softening. Low energy amounts, low costs, can be used to remove other impurities / high chemical use	BW

* Seawater ** Brackish water

2.4. Thermal Technologies

Thermal technologies (evaporation/distillation), one of the oldest technologies, use thermal energy to separate salt from water. Modern thermal-based technologies around the world are developed as dual-purpose power and water desalination systems. At present, thermal technologies are not popular in the U.S. because of the need for high amounts of energy that make the systems less cost-effective. Table 2.3 provides a brief overview of thermal technologies.

Table 2.3. Summary of processes of typical thermal technologies

Technology	Brief Description – advantages & disadvantages	Feedwater
Solar Distillation (SD)	A pond of saltwater with a clear lid takes advantage of solar heat. The saltwater evaporates and condenses on the lid. The brine stays in the pool and condensation forms potable water [26]. Low energy costs, low material and equipment costs / requires large amounts of land and direct sunlight, low productivities	SW/BW
Multistage-Flash Evaporation (MSF)	Combination of many flashing stages. One flashing stage: Saltwater traveling through tubes is cooler than the vapor surrounding the tubes. Heat exchange preheats the saltwater. The saltwater is emptied to the brine pool where it evaporates and fills the vapor space that preheats the incoming saltwater. The vapor is condensed to form potable water, and the brine becomes the feed water for the next stage [27]. Proven reliable for years, can operate from waste thermal energy, can handle large capacities / requires highest amount of energy of all technologies	SW
Multiple Effect Evaporation (MEE)	Combination of many effects. One effect: Saltwater is sprayed overtop of hot tubes. It evaporates and the vapor is collected to run through the tubes in the next effect. As the cool saltwater is sprayed over the vapor filled tubes, the vapor condenses and is collected as potable water. The resulting brine collects in the bottom of each effect, and is either circulated to next effect or exited from system [28]. Requires less energy than MSF, can operate from waste thermal energy, can handle large capacities / high amounts of energy, scaling on tubing	SW
Thermal Vapor Compression (TVC)	Works as first effect of multiple effect evaporation. The steam jet ejector is used to compress the vapor for the tubes in the first effect. A condenser is responsible for condensing the vapor to the final product [29]. Increases MEE performance ratio when combined with MEE.	SW
Mechanical Vapor Compression (MVC)	Works the same as thermal vapor compression except that mechanical compressors are used instead of steam jet ejectors [30]. Meet needs in remote areas, transportable.	SW/BW
Adsorption Vapor Compression Absorption Vapor Compression	Pressure differences occur between two tanks as a fluid mixture is transferred between them. This drives the heat exchange for evaporation and condensation of saltwater to form potable water [31]. Heat is released from an exothermic reaction between blending of feed water with a solution such as LiBr, which preheats the feed water that is sent to the evaporator [32].	SW/BW

2.5. Developing and Futuristic Technologies

Several new technologies are researched with potential for future applications to desalination. For example, electrodeionization (EDI) is a combination of ion exchange and electrodialysis. Other new technologies include combinations of membrane/distillation technologies, and freezing. Table 2.4 shows a brief summary of developing technologies.

Table 2.4 – Summary of processes of desalination technologies under research and development

Methods under Research and Development	Brief Description – advantages & disadvantages	Typical Feed Source
Electrodeionization (EDI)	EDI is a combination of ion exchange and electrodialysis. Electric charge is applied to plates outside of membranes with resin beads between them. Saltwater passes between membranes. Saltwater ions take place of ions on resin then are pulled out through membranes in front of electrically charged plates. Water passes through resin and is free from ions, thus producing purified water [33]. Can produce ultra-pure water	BW
Membrane Distillation (MD)	A temperature difference occurs on opposing sides of the membrane. Differences in vapor pressure drive the system and only vapor passes through the membrane. Salt is not vaporized so cannot pass through pores [34]. Requires high amounts of energy / not fully developed	Researched using 15,000-300,000 mg/L TDS
Freeze Separation (FS)	Freezing of saltwater forms pure water ice crystals which have to be separated from brine and then melted to get potable water [35]. Less energy required than evaporation techniques / not fully developed	SW
Capacitive Deionization (CDI)	Salt water passes through plates coated with carbon aerogel material. Carbon aerogel absorbs ions, thus producing potable water [36]. Applicable to special needs / not fully developed.	BW
Rapid Spray Evaporation (RSE)	Saltwater is sprayed through nozzles at high velocity. As it exits it is vaporized and salt is not, thus producing potable water [37]. Potential to process brine and high salinities, can use waste energy, high recovery / not used for large applications	Brine/SW/BW
Freezing With Hydrates (FH)	A saltwater vapor/gas mixture is cooled. Hydrates are formed and separated from the brine. Hydrates are decomposed to form potable water and the hydrate former gas [38]. Potential for future use because of research of hydrates developing / still being researched and not developed	SW
Vacuum Distillation (VD)	By subjecting saltwater to vacuum, the boiling temperature is reduced. Saltwater is vaporized at lower temperatures and is condensed to form potable water [39]. Low amounts of energy, ability to run off of waste energy, no scaling because of low temperatures / being researched and not developed	Researched using 32,100 mg/L TDS

3. Environmental Issues of Desalination

Chapter Synopsis

Environmental issues related to desalination are a major factor in the design and implementation of desalination technologies. An acceptable desalination plant is expected to meet environmental regulations; be cost-effective in terms of construction, operation and management, and costs associated with monitoring and permit fees. Major environmental concerns include issues related to desalination plant location and water intake structure, and concentrate management and disposal. This chapter provides an overview of the environmental issues related to desalination.

3.1. Desalination Plant Location

The first step in planning a desalination plant is to select a site where the plant will be located. Planners consider many factors in this process such as available energy sources, and costs and risks associated with transporting the feedwater to the plant and the location of concentrate discharge. The proximity of a desalination plant to population centers and environmentally protected and sensitive areas are also critical factors.

3.1.1. Proximity of Population Centers

A major issue to consider is land use in the proximity of a proposed desalination plant site [1]. If planners place a desalination plant in the middle of population areas, it can definitely impact the residential environment. Some desalination plants generate noise and gas emissions. For example, reverse osmosis plants generate noise because of the use of high-pressure pumps. If located near population centers or other public facilities, plans should include steps to mitigate the noise pollution such as using canopies or acoustical planning [2].

Desalination is often energy-intensive. Desalination plants can have an indirect impact on the environment because many plants receive energy from the local grid instead of producing their own. With the burning of fossil fuels and increased energy consumption comes more air pollution and gas emissions. Gaseous emissions from desalination stacks include carbon monoxide (CO), nitric oxide (NO), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2). These air pollutants can have a harmful impact on public health [3]. There is also concern regarding the large amounts of chemicals stored at the plants. Chemical spill risks require storing chemicals away from residential areas.

3.1.2. Possible Environmental Effects

The construction process can be time-consuming, inconvenient, loud, and disruptive to the environment. It is ideal to have as little construction as necessary. If the fuel resources, electricity connection, and water connections are near the proposed plant site, then the construction lessens. A near already built and running infrastructure decreases the construction impact even more. After construction begins, planners need to develop an environmental monitoring plan to track issues identified in the earlier stages. This plan will help monitor the project's success toward meeting the established guidelines. Management plans are also necessary during the plant's operation to ensure consistent environmental acceptability [4].

Construction of water intake structures and pipelines to carry feedwater and concentrate discharge may cause disturbances to environmentally-sensitive areas. Concentrates are high in salinity and may contain low concentrations of chemicals as well as elevated temperatures. These properties of concentrate can pose problems for the marine habitats and receiving water environments. A later section of this report discusses concentrate management issues in detail. Environmental impact studies are necessary to protect environmentally-sensitive areas.

Potential contamination of groundwater aquifers in the proximity of desalination plants can be an environmental concern. There is a risk of polluting the groundwater from the drilling process when installing feedwater pumps. Leakage from pipes that carry feedwater into the desalination plant and highly concentrated brine out of the plant may percolate underground and cause damage to groundwater aquifers. To prevent this, plants should include sensors and monitoring devices and workers should notify plant operators if leaks develop in the pipes.

Desalination projects require an environmental impact assessment study (EIAS) to determine the impact the project can have on the environment. The EIAS considers all environmental parameters and criteria. It evaluates the potential impacts to air, land, and marine environments. It also proposes mitigation measures to reduce environmental impacts. The EIAS report discusses the chosen desalination process, the emissions the process will generate, the implications the facility will have on the environment, the considerations to be made about the energy supply, the benefits the facility will have on the community, and the proposed mitigation measures to reduce problems associated with the facility [5].

3.2. Concentrate Management

Desalination plants generate two products (clean water) and concentrate (reject or residual stream). Proponents recognize that that cost-effective and environmentally-sensitive concentrate management as the most significant obstacle to the widespread use of desalination technologies. Proper concentrate disposal and construction methods incorporated in the plant's design can mitigate the concentrate's impact on the receiving water environments and groundwater aquifers. The following section describes concentrate characteristics and concentrate management options.

3.2.1. Concentrate Characteristics

Concentrate is the byproduct from desalination. Concentrates are generally liquid substances that may contain up to 20% of the treated water. Brine is a concentrate stream that contains a TDS concentration greater than 36,000 mg/L. Critical concentrate parameters are TDS, temperature, and specific weight (density). The concentrate may also contain low amounts of certain chemicals used during pretreatment and post-treatment (cleaning) processes. Characteristics of the generated concentrate depend on the type of desalination technology used. Table 3.1 shows characteristics of concentrates from various types of desalination plants [6].

The amount of concentrate produced from a desalination plant is a factor of the desalination process' recovery rate (product water/feedwater). Generally, membrane plants have a higher recovery rate than distillation plants, resulting in a higher salt amount in the concentrate. As shown in Table 3.1, concentrate produced from seawater reverse osmosis (SWRO) plants can have up to two times more salt concentration than the receiving water while the concentrate produced from a distillation process may have only a 10% higher salt concentration than the receiving water. In distillation processes, the system mixes the concentrate with once-through cooling water to dilute the salt concentration. Table 4.1 also shows that concentrate from distillation processes is typically warmer, 10-15°F above the ambient water temperature. Concentrate temperature from the reverse osmosis process remains at the ambient water temperature.

Specific weight (or density) is another critical concentrate parameter. Compared to freshwater, concentrate has a higher density due to the increased salt concentration. When concentrate with a higher density is disposed into waters of lower salinity (lower density), the concentrate tends to sink. In comparison, typical discharge from wastewater treatment plants will float, because its density is less than the receiving water. The tendency of the concentrate to sink when interacting with the receiving water introduces problems for the marine environments. In some cases, plants reduce the concentrate density by diluting it before being discharging it into a receiving water. The concentrate disposal section discusses this in more detail.

Pretreatment can include processes such as chlorination, clarification, coagulation, acidification, and degasification used on the feedwater to minimize algae growth, scaling, and corrosion. The pretreatment chemical agents are important to consider because they remain in the concentrate before disposal. The following list notes some possible pretreatment chemicals:

- NaOCl or free chlorine - prevents biological growth
- $FeCl_3$ or $AlCl_3$ - flocculation and removal of suspended matter from water
- H_2SO_4 or HCl - pH adjustment
- $NaHSO_3$ – neutralizes chlorine remains in feedwater
- Various scale inhibitors – prevents scale formation on the pipes and membranes

Table 3.1. Concentrate Characteristics for Various Desalination Technologies [1]

Process	BRO	SWRO	MSF/MED
Feedwater	Brackish	Seawater	Seawater
Recovery	60-85%	30-50%	15-50%
Temperature	Ambient	Ambient	10-15 °F Above Ambient
Concentrate blending	Possible, not typical	Possible, not typical	Typical, with cooling water
Final concentration factor	2.5-6.7	1.25-2.0	<1.15
Pretreatment			
Somewhat similar schemes may be used in all processes			
Chlorination where biological growth may be present (more for surface waters)			
Polymer additives used for scale control			
Acid sometimes used in addition to additives (particularly for RO)			
Corrosion inhibitors used in thermal processes			
Dechlorination for some membrane processes where chlorination is used			
Post-treatment			
Degasification for CO_2, H_2S (BRO) aeration for adding O_2 (BRO)			
pH adjustment for corrosion protection (RO)			

BRO = brackish water reverse osmosis
SWRO = seawater reverse osmosis
MSF = multistage flash evaporation
MED = multiple effect distillation

If a membrane becomes fouled or scaled, the fouling or scaling material has to be removed by chemical cleaning. Therefore, concentrate from membrane processes often contains cleaning chemicals. The type of chemicals used for cleaning depends on the type of membrane. For RO and NF systems, chemical cleaning agents fall into the following categories [7]:

- Enzymes to break down bacterial slimes
- Detergents and surfactants to resuspend particulate material and dissolve organic material
- Biocides to kill bacteria
- Chelators to remove scale
- Acids to dissolve inorganics

- Caustics to dissolve organic substances and silica

The National Pollutant Discharge Elimination System (NPDES) program regulates the concentrate discharge to surface waters. The NPDES requires Whole Effluent Toxicity (WET) testing of concentrate to determine potential impacts on aquatic species. Several utilities in Florida that use membrane technologies have failed WET tests for unknown reasons necessitating research to determine failure causes [8]. The follow-up research investigated concentrate characteristics from nine utilities in Florida. The research results pointed to the existence of excessive ions in the concentrate as cause of WET test failure. Excessive calcium and fluoride levels in concentrate were major contributors to ion toxicity of concentrate [9]. Furthermore, research showed that the chemical properties of natural groundwater (used as feedwater) caused the occurrence of major ion toxicity, not the membrane treatment process.

In coastal areas, due to the dynamic nature of freshwater and saltwater interaction, the composition of brackish groundwater is not uniform or chemically balanced. In these waters, calcium carbonate and calcium sulfate concentrations are dominant over sodium chloride. Groundwater may also contain low levels of dissolved oxygen and high levels of other gases such as carbon dioxide and hydrogen sulfide that contribute to the toxicity of concentrate [10]. This fact somewhat validates the hypothesis that groundwater characteristics may influence the ion toxicity of concentrate from desalination plants.

3.2.2. Concentrate Disposal Methods

At present, about 48% of desalination facilities in the U.S. dispose of their concentrate to surface waters [11]. Other concentrate disposal options include deep well injection, land application, evaporation ponds, brine concentrators, and zero liquid discharge (ZLD) technologies. Table 3.2 shows the distribution of current concentrate disposal techniques in the U.S.

Table 3.2. Distribution of Concentrate Disposal Methods in the U.S. [4]

Means	FL	CA	Rest of U.S.	Average
Surface	39	6	21	66
	46%	50%	51%	48%
POTW	12	5	15	32
	14%	42%	37%	23%
Land	17	0	0	17
	20%	0%	0%	12%
Deep Well	18	1	0	14
	21%	8%	0%	10%
Evaporation Ponds	3	0	5	8
	4%	0%	12%	6%
Total	84	12	41	137
	100%	100%	100%	100%

Planners consider a variety of factors to choose the best disposal option. Decision factors include volume or quantity of the concentrate, the quality of the concentrate, the location of the desalination plant, and environmental regulations. Other factors include public acceptance, capital and operating costs, and the ability for future plant expansion. The next section describes various concentrate disposal methods.

3.2.2.1. Surface Disposal

Surface disposal methods include surface water disposal and submerged disposal.

Surface water disposal

Disposing of concentrate in surface water is the most common method of concentrate disposal. Surface water disposal includes disposal into freshwater, tidal rivers and streams; coastal waters such as oceans, estuaries, and bays; and freshwater lakes or ponds. As concentrate enters the receiving water, it creates a high salinity plume in the receiving water. Depending on the density of the concentrate in comparison to the seawater, this plume sinks, floats, or stabilizes in the water. The radius of the plume impact varies. The type of dispersion and natural dilution of the concentrate plume that may occur depends on the discharge pipe's location. Waves, tides, bathymetry, currents, water depth and the presence of waves are all important factors that determine natural dilution and the amount of mixing that may occur at the concentrate disposal point [12].

Without proper dilution, the plume may extend for hundreds of meters, beyond the mixing zone, harming the ecosystem along the way. Mixing zones are quantified limits within the receiving waters where the law allows surface water to exceed water quality standards because of the existence of point source disposal. State governments determine these limits and utilities monitor them. For example, Florida's mixing zone limitations are 2,625 ft for canals, rivers, and streams; 31 acres for lakes, estuaries, bays, lagoons, and bayous; and 124 acres for oceans [13].

Table 3.3 displays the main concerns with surface water disposal, as well as mitigation methods to reduce those concerns. If the concentrate does not pass the WET test and natural dilution is not enough to properly diffuse the concentrate, then plants use artificial dilution methods. The concentrate can be diluted through efficient blending, diffusers, or within mixing zones prior to surface disposal. Blending is simply mixing the concentrate with cooling water, feedwater, or other low TDS waters before disposal. Diffusers are jets that dilute the concentrate at the concentrate disposal outlet for maximum mixing. Factors to consider for jet dilution are the difference in densities between the concentrate and the receiving water, and the momentum and velocity of the water at the outlet.

Pretreatment prior to disposal consists of aeration by adding oxygen to the concentrate, and degasification to remove hydrogen sulfide from the concentrate [14]. Using non-toxic additives and dechlorination techniques limits the toxic chemical concentrations that enter the environment. The need for these techniques is site-specific depending on the maximum concentrations of the additives and chlorine allowed in the discharge, set by regulatory agencies. Using materials in the desalination process that are less likely to corrode can limit the occurrence of corrosion products in the water.

Table 3.3. Surface Water Disposal Problems and Mitigation [1]

Environmental Concem	**Process**	**Mitigation Method**
from raw water…		
Contaminants present in raw water	Brackish-RO (others)	Limit degree of concentration, blending, mixing zones, post-treatment
Imbalance in essential ions (some groundwater)	Brackish-RO	Diffusers, blending, mixing zones
Low dissolved oxygen, high H_2S, etc. (some groundwater)	Brackish-RO	Aearate, degasify, or otherwise treat prior to discharge
from pretreatment…		
Toxicity of additives	All	Use non-toxic additives
Low pH (due to acid addition)	RO	Raise pH prior to discharge
from the concentrate salinity….		
Different salinity than receiving water	RO more than thermal	Diffusers, blending, mixing zones, ZLD

Submerged disposal

Submerged disposal is disposing of concentrate underwater, rather than just on the surface that could occur in brackish tidal waters or estuarine environments. Sometime submerged disposal is practiced via long pipes that stretch far into the ocean, in contrast with surface disposal that happens immediately at the coastline. Usually, regulatory agencies establish mixing zones around the outlet of the surface or submerged disposal pipe in order to control the salinity of the receiving water. Regulations can define the zones as "'allocated impact zones' within which the numeric water quality limits may be exceeded for the non-toxic category pollutants" [15]. Typically, with surface water disposal the concentrate sinks to the ocean bottom and a quantitative boundary is established where the salinity regulations allow it to exceed normal limits. With submerged disposal, an initial dilution zone is established where the mixing zone definition is the distance the plume travels before it contacts the ocean bottom [16]. Most at risk is the benthic marine organisms living at the sea bottom. The increase in salt concentration disrupts the ecosystem, leading to dehydration, decrease of turgor pressure, and death. The species' tolerances to the increase in salinity vary. Studies show that long abdomen invertebrates are more sensitive to high salinities than short abdomen invertebrates [17].

Discharge at the coastline may be appropriate, depending on the surroundings and the properties of the receiving water. If the area is highly populated, coastline disposal may be a problem, because of the interference of the mixing zone to the recreation on the beach. This is especially noticeable on days when the sea is calm and little to no natural dilution occurs.

Small-scale plants studied in Florida, which dispose directly into the sea, or use a short discharge pipe showed no environmental impact on the animal and plant life near the outlet pipes [18].

The EPA developed two different codes to study the dispersion of buoyant discharges. The B-CORMIX code from the EPA Environmental Research Laboratory in Athens, Georgia, and the PLUMES code from the EPA Pacific Ecosystems Branch in Newport, Oregon use different computer codes. The B-CORMIX code was used to study dispersion from a large seawater reverse osmosis plant that used submerged, offshore surface water discharge. These computer programs are helpful in predicting different dispersion rates [19].

3.2.2.2. Disposal to Front of Wastewater Treatment Plant

The option to dispose the concentrate to the front or headworks of a wastewater treatment plant or publicly owned treatment works (POTWs) is the second most common practice after surface water disposal [20]. The major concern with this disposal method is that if the volume of brine flow is too high, the level of TDS in the influent can have a significant impact on the biological treatment process, possibly to the point of disrupting treatment performance. Another concern with this disposal method is the increase in the total dissolved solids (TDS) of the water processed through the wastewater treatment plant and the probable loss of plant treatment capacity. Conventional wastewater treatment plants do not remove TDS, and therefore it remains in the discharge water from the treatment plant. The high TDS content of treated wastewater poses an environmental concern if the plant returns the treated water into surface water systems. Some reuse options such as land application, as described later, may be considered.

3.2.2.3. Disposal to End of Wastewater Treatment Plant

Because of the disadvantages of disposing of the concentrate at the front of the wastewater treatment plant, some plants are moving to the option of disposing the concentrate to the end of the treatment process by mixing the concentrate with the treated water. Because the concentrate is free of viruses and large amounts of contaminants, it is not necessary to process the concentrate through the wastewater treatment. Mixing the low TDS effluent from the POTW with the high TDS concentrate dilutes the brine and reduces the load put on the POTW [21]. The major drawback of this method is that bringing the brine stream to wastewater treatment plant requires constructing a separate pipeline to carry the brine stream. Because water treatment plants and wastewater treatment plants are generally located as far apart as possible, that means a long, large diameter pipeline (most often with pumping facilities), which means an additional cost factor.

3.2.2.4. Land Application

This method of concentrate disposal includes using spray irrigation, infiltration trenches, and percolation ponds. Land application of concentrate provides an opportunity for a beneficial use of concentrate as well. Concentrate can be used to irrigate salt-tolerant crops and grasses such as those used on golf courses. The feasibility of land application depends on the local climate, vegetation tolerance to salinity, the availability of land, and the location of the groundwater table. According to a survey of concentrate disposal methods in the U.S., Florida is the only state that currently uses land application for concentrate disposal [22].

3.2.2.5. Deep Well Injection

Deep well injection is the practice of injection concentrate into aquifers not used for drinking water. Injection wells range in depths from 0.2 miles to 1.6 miles below the earth's surface [23]. In many locations, deep well injection is not feasible because of geologic conditions or regulatory constraints. Florida is a state where the geologic condition is considered suitable for deep well injection [24]. In Florida, there are at least 70 deep injection well systems used mostly for wastewater disposal but some serve for concentrate disposal as well. An underground layer known as the 'Boulder Zone' where wells are formed from masses of fractured rock isolated by impermeable dolomite and limestone from the surrounding aquifers provide a suitable environment for deep well injection.

Injection wells must be separate from drinking water aquifers to prevent contamination. Planners should include monitoring wells along with injection wells and operators should check monitoring wells regularly to detect any changes to groundwater quality. Deep injection wells also should be subjected to tests for strength under pressure and checked for leaks that could contaminate adjacent aquifers [25]. The above constraints add substantially to the overall cost of deep well injection for concentrate disposal.

3.2.2.6. Evaporation Ponds

Evaporation ponds are constructed ponds where water from concentrate is allowed to evaporate while the remaining salts accumulate in the base of the pond. These ponds have historically been used for salt production, but now prove to be an effective method for concentrate disposal as well. Evaporation ponds are used in areas that have warm climates and high evaporation rates. The size of an evaporation pond depends on the evaporation rates in the region and the surge capacity, freeboard, and storage capacity. The evaporation rates determine the surface area required, while the other factors determine the depth of the pond. It is important for these ponds to have liners in order to prevent saline water from percolating into the groundwater aquifer. The pond water should be maintained at a significant depth to prevent liners from drying and cracking [26]. Evaporation ponds are a cost-effective option for inland plants to dispose of concentrate. However, they are modestly land-intensive and also cause significant loss of the basic water resource through evaporation.

3.2.2.7. Zero Liquid Discharge

Zero liquid discharge (ZLD) technique uses some type of mechanism (evaporator) to convert the liquid concentrate into dry solid. Therefore, instead of concentrate disposal this option deals with solid waste disposal. ZLD is the only disposal option for areas where surface water, sewer, and deep well injection are either not feasible or prohibited. The solid waste generated from the ZLD process can be put in a landfill, but it may create problems with chemical leaching into the groundwater if the landfill is not designed appropriately (no liners). The ZLD process is a high-energy cost technique. ZLD warrants further research and development to reduce the cost and to recover or capture water that is lost through the evaporation process.

3.2.2.8. Brine Concentrators

Typical concentrate flow is about 25% of the feedwater flow. The brine concentrators can reduce the concentrate flow to about to 2% of the feedwater flow. [27] Brine concentrators can reduce the amount of concentrate discharged from a desalination plant. An ionic RRC website describes the brine concentrator process as follows [28]: wastewater enters a feed tank, where the pH is adjusted between 5.5 and 6.0. The acidified wastewater is pumped through a heat exchanger that raises its temperature to the boiling point. Wastewater passes through a deaerator which removes non-condensable gases. Hot feed combines with the brine slurry in the sump. The brine slurry is constantly circulated from the sump to a floodbox at the top of a bundle of heat transfer tubes. Some of the brine evaporates as it flows in a falling film down through the heat transfer tubes and back into the sump. The vapor travels down the tubes with the brine and is drawn up into mist eliminators on its way to the vapor compressor. Compressed vapor flows to the outside of the heat transfer tubes. Heat from the compressed vapor is transferred to the cooler brine falling inside. The vapor condenses as it gives up latent heat. This condensate, or distillate, is pumped to the heat exchanger, where it gives up heat to the incoming wastewater. A small amount of waste brine is blown down from the sump to control density. With a brine concentrator, 95% of wastewater can be recovered as high purity distillate with less than 10 mg/L of TDS concentration.

The remaining 5%, concentrated slurry, may be reduced to dry solids in a crystallizer or spray dryer. A crystallizer can reduce that last 5% to dry solid cake, which is easy to handle for disposal. The spray dryer is another method for dewatering the concentrated slurry left over from the brine concentrator. The spray dryer transforms the slurry into a fine powder of mixed salts for disposal. The spray dryer atomizes the wastewater slurry inside a hot chamber, instantly vaporizing the water droplets and leaving only dry salts behind.

The concentrated brine can also be further processed by the ZLD technique, or added to lime settling ponds where the solids will form sludge. It could also be transported to a salt manufacturing company.

3.2.2.9. Recent Concentrate Disposal Techniques

In California, a new technology is under study to dispose of an inland plant's concentrate to a saline vegetative marsh [29]. The state of Florida has developed the "hothouse evaporation shed" method for brine disposal. Here the concentrate flows to a container, and a system of fans and sprinklers disperses the concentrate through the high humidity air encouraging evaporation to occur. One engineering firm suggests using an oil field injection method for a brackish water reverse osmosis plant in California [30]. The San Diego County Sweetwater Authority suggests using coastal wetlands for the concentrate disposal. Though this option may be more costly, it can mitigate the project's environmental impact [31].

3.2.3. Summary of Concentrate Disposal Techniques

Table 3.4 shows summary disposal techniques and mitigation methods.

Table 3.4. Summary of Concentrate Disposal Techniques [1]

Disposal Option	Environmental Concern	Mitigation Method
Surface Water	Contamination of receiving water	See Table 3.3
Sewer System Blending	Contamination of eventual receiving water	Reduce recovery; membrane type selection
Land Application	Contamination of underlying groundwater, and of soil	Reduce recovery; blending membrane type selection
Deep Well Injection	Contamination of overlying drinking water aquifers due to well leakage	Move disposal location or change means of disposal
Evaporation Ponds	Contamination of underlying higher quality aquifers due to pond leakage	Double lining with leachate collection system
Zero Liquid Discharge	Contamination of underlying higher quality aquifers due to landfill leakage	Double lining with leachate collection system

3.2.4. Concentrate Management Case Studies

The Suffolk, Virginia plant uses electrodialysis reversal technology. The plant originally disposed of the concentrate in a nearby stream. That disposal method, however, did not properly disperse the concentrate and the high fluoride content of the concentrate was determined to be toxic to the aquatic environment. The plant managers patiently worked for five years to develop the best method of disposal and to attain a discharge permit. The new method of concentrate disposal incorporates diffusers to dispose of the concentrate in the Nansemond River. The plant is required to renew the permit every 5 years and submit on a quarterly basis acute toxicity tests, all of which the Virginia Department of Environmental Quality regulates.

The Sweetwater Authority in San Diego County is actively developing a program of brackish groundwater and urban runoff demineralization using desalination technologies. The authority is evaluating several concentrate disposal options. Options included discharge to the San Diego Bay, coastal wetlands, existing sewer networks, to the South Bay outfall or using deep well injection. Discharge to the bay should meet requirements of the San Diego Regional Water Quality Control Board because of the potential impact on the marine environment. The sewer system is not a feasible choice without additional construction that could handle the concentrate transport. The bay discharge is an option but the authority would need to construct 5-miles of transport pipes to carry the concentrate to the outfall. The deep well injection option requires environmental impact assessment to demonstrate that the concentrate will not negatively affect the groundwater. The most affordable option for the authority was surface water disposal to the San Diego Bay. However, the authority is considering concentrate disposal to brackish water coastal wetlands–the best option to minimize environmental impacts [32].

Other countries have studied the impact of high salinity brine on marine life. In Dhkelia, Cyprus, where an 820-foot discharge pipe is used, the range of the concentrate's impact is between 330 ft. and 660 ft. from the pipe outlet. There was an impact to the plants and wildlife in this region, and many species disappeared. In Larnaca, Cyprus, they use a discharge pipe of 4,922 ft. located 82 ft. below the surface. The plant is new and seems to have good dilution conditions. A study performed at the Canary Islands researched the impact of concentrate disposal. Here the disposal pipe was 984 ft. long and 25 ft. below the surface. The dilution appeared satisfactory at the water surface, but the study showed that farther down, there was a dense solution. The salt concentration was more than 60% (of concentrate) at a distance of 330 ft. from the outlet. The researchers noticed impacts on the plant life near the outlet [33].

3.3. Cost of Concentrate Disposal

Concentrate disposal costs can be anywhere between 5-33% of the produced water cost [34]. It is difficult to compare the costs for different concentrate disposal options because it depends on site characteristics for the desalination plant. In many instances the options of concentrate disposal methods are limited due to the geology of the land, soil conditions, or public approval.

In general, surface water disposal and wastewater treatment plant disposal options are the two most affordable options when costs associated with concentrate transport, post-treatment, and outfall structures are considered. Disposal costs for inland desalination plants are generally higher than disposal costs of coastal plants, because inland plants cannot dispose to surface water.

Costs associated with land application techniques (evaporation ponds, spray irrigation, and percolation) are dependent on the characteristics of the site. If land availability, climate, and soil conditions are favorable for using one or more of the land application techniques, then land application may be the most cost-effective. If all of the conditions of the land and the transport costs are identical, then the percolation technique is the least expensive, followed by spray irrigation, and evaporation ponds. It should be understood that soil conditions do not always allow for percolation and/or spray irrigation, because of the vegetation's sensitivity to high salinities, or the already-high saline groundwater and soil. If this is true, evaporation ponds are sometimes the most cost-effective.

The cost of deep well injection depends on the volume of the concentrate to be disposed. It is most expensive at very small volumes and maximizes at a point below 1 MGD of discharge. A typical municipal effluent disposal well in Florida, including monitoring costs and construction costs, can be as high as $3 million according to experts in the field [35].

The ZLD method is another expensive option due to the high amounts of energy it uses, where as the other techniques do not have costs associated with energy [36].

Table 3.5 shows design parameters and capital cost factors for various disposal options. This table can be used to compare available options and to determine the most appropriate method of disposal for a selected desalination plant.

Table 3.5. Design Variables and Capital Cost Items for Different Disposal Methods [1]

	Methods of Disposal						
	Surface Water Disposal	**Sewage Treatment Plant**	**Deep Well Injection**	**Percolation**	**Spray Irrigation**	**Evaporation Pond**	**Zero Discharge**
Design Variable							
Distance	Y*	Y	Y	Y	Y	Y	Y
Volume	Y	Y	Y	Y	Y	Y	Y
Depth	---	---	Y	---	---	---	---
Evaporation rate/hydraulic loading	---	---	---	Y	Y	Y	---
Land availability, type, cost	---	---	---	Y	Y	Y	---
Storage time	---	---	---	Y	Y	---	---
Sprinkling spacing	---	---	---	---	Y	---	---
Reject flow	---	---	---	---	---	---	Y
Energy cost	---	---	---	---	---	---	Y
Capital Cost Item							
Transport system (pipe, pump)	Y	Y	Y	Y	Y	Y	Y
Treatment system (includes blending)	Y	Y	---	(Y)	(Y)	---	---
Outfall structure	Y	---	---	---	---	---	---
Injection well (depth, pump, materials)	---	---	Y	---	---	---	---
Monitoring wells	---	---	Y	Y	Y	Y	---
Land, land preparation	---	---	---	Y	Y	Y	---
Distribution system (pipe, pump)	---	---	---	Y	Y	---	---
Wet weather storage	---	---	---	Y	Y	---	---
Alternate disposal system	---	---	Y	---	---	---	---
Subsurface drainage system	---	---	---	(Y)	Y	---	---
Disposal fee	---	Y	---	---	---	---	---
Skid mounted system	---	---	---	---	---	---	Y

* Methods with ‘Y’ must consider the design variable or cost item when used for concentrate disposal

4. Energy Needs, Consumption, and Sources

Chapter Synopsis

Energy is needed in various stages of desalination. Energy consumption directly affects the cost-effectiveness and feasibility of using desalination technologies for drinking water production. This chapter presents energy types, use, methods of conservation, and the potential use of renewable energy resources for desalination. Some of the information provided in this chapter may not be applicable to today's Virginia energy issues. However, the information provides a comparison between costs associated with various energy sources as applied to desalination worldwide, and can be used as a reference for future energy development and use in Virginia.

4.1. Energy Needs and Consumption

Energy is needed in various stages of desalination. Desalination technologies use pumps in various stages of desalination, i.e., feedwater intake, treatment process, and discharge of product water and concentrate. Pumps consume a significant amount of energy. RO plants use pumps to pressurize feedwater passing through the membranes. Ion exchange plants use pumps to pass the feedwater over the resin, and use backwash pumps to clean and recharge resin beads. In electrodialysis, pumps pressurize feedwater to generate flow across the surface of the membranes. The amount of energy pumps consume depends on the type of process, the TDS concentration in the feedwater, the capacity of the treatment plant, the temperature of the feedwater, and the location of the plant with respect to the location of the intake water and concentrate disposal site.

Each desalination technology is unique in design and mode of operation and it is rather difficult to compare energy consumption for different types of desalination technologies. Table 4.1 is a generalization of typical energy consumption for various technologies.

The energy consumption for reverse osmosis plants depends on the salinity of the feedwater and the recovery rate. Seawater reverse osmosis plants require higher amounts of energy due to the higher osmotic pressure of seawater compared to brackish water reverse osmosis plants that require less energy because of lower osmotic pressure. The osmotic pressure is related to the TDS concentration of the feedwater.

Electrodialysis plants use electric energy to desalt the water. For electrodialysis, the energy required is directly related to the TDS concentration in the water. Electrodialysis is economical only for brackish waters (TDS < 4000 mg/L).

Table 4.1 – Energy Consumption for Various Desalination Technologies

Technology	Type of Energy	Work Consumed, Btu/Gal (kWh/m^3)	Reference	Type of Feedwater
RO	Mechanical Energy	0.0827 (6.4)	1	BW & SW*
		0.1034 (8.0)	2	
		0.1293 (10.0)		
		0.1138 (8.8)	3	
		0.0543 (4.2)	4	
	With Cogeneration	0.0750 (5.8)	5	SW
	& Steam	0.0297 (2.3)		
ED	Electric Energy	0.0220 (1.7)	6	BW
MSF	Thermal Energy	0.2431 (18.8)	7	SW
	+ Mechanical Energy	0.3000 (23.2)		
	With Cogeneration	0.0608 (4.7)	5	
LT- MEE	Thermal & mechanical energy	0.0647 (5.0)	8	SW
	With Cogeneration	0.0272 (2.1)	5	
		0.0595 (4.6)		
MEE-TVC	Thermal and mechanical energy	0.1164 (9.0)	9	SW
		0.2198 (17.0)		
MVC	Mechanical Energy	0.0776 (6.0)	10	SW
		0.1293 (10.0)	2	
		0.2392 (18.5)		
Hybrid RO/ME	Thermal & Mechanical energy	1.35-1.6	5	SW
** RO can be used for BW or SW. Higher energy consumption is equated with SW.*				
LT--Low temperature top Brine <194 °F				
BW--Brackish water				
SW--Seawater				

4.2. Energy Conservation and Recovery

A system's ability to conserve or recover energy is critical for implementing an economical desalination technology. The section below describes various energy conservation and recovery techniques.

4.2.1. Methods of Energy Conservation

Pelton impulse turbines (PIT) and hydraulic turbochargers (HTC) are the most widely used devices for energy conservation in desalination plants [11]. Reverse running pumps may be found in older facilities but these pumps are least effective for energy conservation.

Figure 4.1 shows the integration of a PIT with a reverse osmosis plant. Normally, the motor uses electric energy to drive the feed pump. For energy conservation purposes, a shaft is used to connect the PIT to the motor. The feed pump is run at a constant speed and the pressure energy in the brine is used to rotate the PIT. As the turbine rotates, it converts the brine pressure energy to mechanical energy. The mechanical energy from the PIT is then directed to the motor shaft that, in turn, drives the feed pump. Therefore, the motor requires less energy from the electricity grid to drive the feed pump than it would without the PIT.

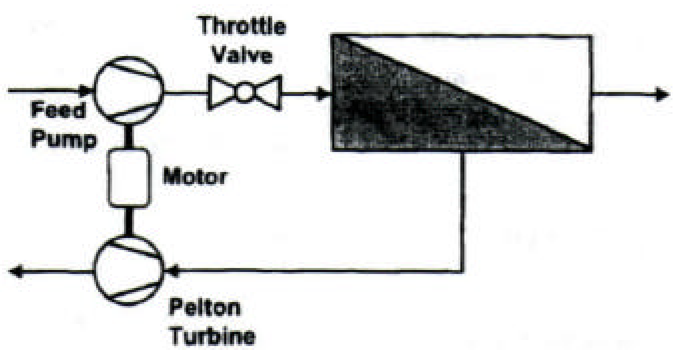

Figure 4.1. – Integration of RO with PIT [11]

Figure 4.2 shows the integration of the hydraulic turbocharger (HTC) system into a reverse osmosis plant. The HTC serves as a feed pump and energy recovery turbine. The HTC directs any remaining pressure energy in the brine to feed pressure. Thus, it boosts the pressure of the feedwater and reduces the energy used by the first feed pump. The brine bypass valve is the control device for this system. It allows the amount of recovered energy to be managed so that the energy used by the first feed pump and the added energy to the HTC to equal the appropriate pressure energy to push feedwater through the membrane.

Different combinations of turbines, pumps, and control devices can be used to minimize specific energy consumption. One proven combination called PROP incorporates a variable frequency drive (VFD)- pump and a Pelton turbine. The advantage of using a VFD-pump is a significant energy savings realized from the reduced pump horsepower requirement. With this arrangement, the turbine recovers as much energy as possible and the VFD pump compensates for a marginal energy need. The size of the VFD pump is decreased significantly making it much more affordable [11].

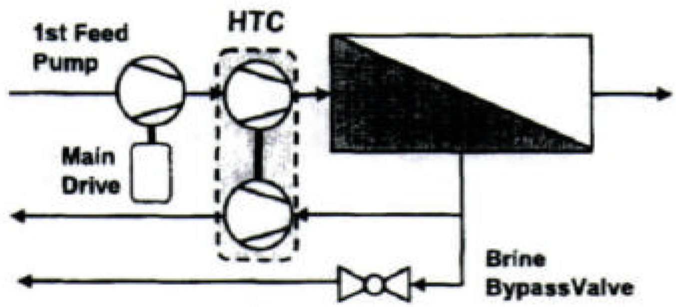

Figure 4.2. – Integration of RO with HTC [11]

4.2.2. Control Mechanisms

Membrane systems operate best under continuous, constant conditions. However, the characteristics of the natural environment may not be constant; in fact, they are usually variable. Salinity and temperature of the feedwater can vary according to weather and seasonal changes. Thus, it is necessary to incorporate some type of control to maintain constant conditions. Control methods are of two types, energy dissipation and energy control.

Energy dissipation techniques work by consistently applying extra energy to membrane pumps. If the salinity increases, this extra energy is used to increase the pressure of the feedwater to keep the flows constant through the membrane. All excess energy in the system is dissipated in order to keep the pressure constant. This method requires that more energy than is necessary is consistently applied to the system, which assures that there is never a lack of energy for the pumps. Obviously, this theory to dissipate excess energy is wasteful. Though it is capable of keeping the plant operations constant, it is not effective for conserving energy [11]. The brine bypass valve is an example of an energy dissipation technique (Figure 4.2).

The energy control method uses variable frequency drive (VFD) pumps. These pumps use only as much energy as needed, making it much less wasteful than the dissipation of energy technique. The use of VFD pumps is most desirable in facilities that have highly variable operating conditions. Their disadvantage is their high investment costs. These pumps are used in reverse osmosis and electrodialysis plants [11].

4.2.3. Cogeneration Plants

It is becoming a common practice to combine power plants with desalination plants in order to reduce energy consumption. Combined power and desalting plants are called cogeneration plants. The typical power plant produces steam at high pressure and high temperature. This steam is expanded, and the pressure difference from the expansion drives the turbine to form mechanical energy, and then electrical energy (combustion turbine power generation cycle). The expanded steam is typically rejected from the plant as waste. A cogeneration plant, however, uses this low-grade steam for desalination.

Cogeneration has both advantages and disadvantages. One advantage is that it is beneficial to both the power plant and the desalination plant. The power plant gains extra income by selling the waste steam to the desalination plant. The desalination plant does not have to pay for the construction and operation of its own boilers, thus also saving money. The desalination plant will use low-grade steam and thus saves fossil fuel costs. A disadvantage is that the energy demand varies. The power plant's power generation is not constant. This may have an impact on the desalination plant unless mitigation methods are applied to limit this impact. Researchers report that cogeneration can achieve cost savings [7,12].

4.2.4. Collocated Plants

In this process, a seawater reverse osmosis (SWRO) plant is collocated with a power plant. In general, coastal power plants draw large volumes of cooling water directly from the ocean. A collocated SWRO plant draws heated seawater from the power plant's cooling water loop as feedwater for RO and then discharges the concentrate stream into the power plant's cooling water outflow [13]. Because the SWRO facility "piggybacks" on the existing cooling water loop it can substantially reduce construction and operating costs. Also, it provides a method for diluting the SWRO brine stream before it is discharged into the ocean. A collocated SWRO plant has the advantages of a cogeneration plant. Also, with collocated plants, because of higher water temperature, less energy is needed. The disadvantage of the collocated plant is that it entirely depends on the power plant for its existence.

4.2.5. Hybrid Plants

Hybrid plants use a combination of treatment technologies—such as using RO and thermal technologies simultaneously—to take advantage of benefits of different treatment technologies. This enables the system to reuse energy, reduce energy costs, and achieve optimized performance [14, 15]. The necessity for a hybrid facility can be considered on a case-by-case basis.

4.2.6. Case Studies of Energy Conservation

The following case studies describe how turbines, cogeneration and hybrid plants reduce energy consumption in desalination plants.

Cape Hatteras, North Carolina has had a hybrid RO/Ion exchange plant running since 2000. This desalination plant withdraws water from separate wells with different water properties. The high salinity water from well 1 is processed by the RO and the water with high organic material from well 2 is processed by Ion Exchange. The treated water from the RO and Ion exchange processes are blended for the final product water. This plant has incorporated an energy recovery turbine (Turbo supplied by Pump Engineering) into the RO treatment process. The expected payback at the power rate of $0.04/1000 Btu ($0.12/kWh) is 4.5 years [16].

Studies in Kuwait compared two gas turbines with different combinations of heat recovery [7]. For a simple gas turbine power plant operating in cogeneration with reverse osmosis, the fuel energy consumption is 39.9 Btu/lb (92.78 kJ/kg). If a heat recovery steam generator is added to each gas turbine, supplying MSF units with recovered steam, the energy consumption is lowered to 37.4 Btu/lb (86.88 kJ/kg). If a condensing steam turbine and a heat recovery steam generator are added to each gas turbine, the energy consumption is further decreased to 27.4 Btu/lb (63.6 kJ/kg). This study shows how different combinations of turbines and technologies affect energy consumption.

Another study, conducted in some Middle Eastern cities, investigated different plant arrangements operating from the waste heat of a gas turbine power plant [17]. In this study, LiBr-H_20, low-temperature thermal vapor compression (LT-TVC) heat pumps were used to boost the gas turbine performance, because of their ability to recover energy in the form of heat. Table 4.2 compares RO (no hybrid used) energy consumption with four different hybrid combinations [17]. All four options proved to be better, economically, than SWRO alone. Option 4 (MVC/MES) proved to be the most energy saving combination, in which the thermal efficiency increased 55.9% when compared with SWRO. This option included mechanical vapor compression with multiple-effect distillation and low-temperature thermal vapor compression. In option 3, the thermal efficiency increased 55.9% when compared with SWRO. It was the only process that did not incorporate the vapor compression heat recovery in its design.

A study of an existing RO plant in Egypt that uses turbines for energy recovery analyzed the plant's performance after the plant was running for six years [3]. The energy consumption in this plant amounted to 35-60% of the total production costs but the recovered mechanical energy reduced the required pump energy. It therefore saved in the overall costs [3].

Table 4.2 – Comparison of different hybrid facilities [17]

Hybrid Process	Capacity MGD	TDS mg/L	Energy Btu/Gal (kWh/m^3)	Diesel Fuel Savings tons/yr	Hybrid Options
SWRO/MES (LT-TVC)	3.78	395	124 (9.58)	4,937	1
SWRO/BPT/MES (LT-TVC)	3.92	468	119 (9.23)	5,319	2
SWRO/BPT/SWRO	3.88	500	121 (9.34)	4,162	3
MVC/MES (LT-TVC)	5	50	94 (7.27)	11,094	4
SWRO	2.9	500	162 (12.5)		
	SWRO	Seawater reverse osmosis			
	MES	Multiple-effect evaporation			
	BPT	Back pressure turbine			
	MVC	Mechanical vapor compression			
	LT-TVC	Low temperature - Thermal vapor compression			

4.3. Renewable Energy Sources for Desalination

The most common renewable energy sources are solar, wind, geothermal, and ocean. At present, uses of renewable energy sources for desalination are very limited. The world's share of total renewable energy sources used for desalination is only about 0.02% of the total energy used [18]. However, renewable energies have potential for powering future desalination plants. Tables 4.3-4.5 list desalination plants in various countries that use renewable energies (solar, photovoltaic, and wind) found in existing literature. Desalination powered by renewable energies can be an ideal solution for some small communities where an affordable fossil fuel supply for desalination is not available.

4.3.3. Solar Energy

Solar energy is a promising renewable energy source to power desalination plants. Solar energy can be used directly for simple distillation or indirectly through the use of collectors.

4.3.3.1. Direct Solar Energy

Solar stills take advantage of direct solar energy via the greenhouse effect. The process is as follows. A black-painted basin, sealed tightly with a transparent cover, stores the saline water. As the sun heats the water, the basin water evaporates and vapors comes into contact with the cool glass ceiling where it condenses to form pure water [19]. The water is drained from the solar still for potable use. The maximum efficiency of solar stills is 35% (35% of energy entering the still is utilized to evaporate the water) [20]. This technology is optimized when running at capacities of near 200 gal/d. Using heat recovery devices and hybrid systems may make solar stills more cost-competitive [21]. Research indicates that multiple-effect stills increase water production by 40-55% when stacked in a vertical arrangement [20, 22]. Solar stills require large amounts of land and can only handle small quantities of water. They are not a viable option for most areas in the U.S. [19].

4.3.3.2. Indirect Solar Energy

MSF and MEE technologies use solar collectors as an indirect means of solar energy to develop the thermal energy needed to drive the desalination process. Other applicable technologies using indirect solar energy are RO, vapor compression, and freeze desalination. Solar collectors are used successfully in Saudi Arabia for freeze separation technologies. The steam created from the solar collectors drives a steam turbine that provides power to a vapor compression system. Energy in the exhaust steam from the turbine provides refrigeration for the freezing [21].

Photovoltaic

Currently, the most promising solar energy technology is photovoltaic (PV) arrays. Photovoltaic arrays convert solar energy into electricity through the transfer of electrons. The arrays are made of silicon chips. Silicon is the best material for generating the transfer of electrons. When sun rays shine on the silicon chips the electrons jump to another orbit. This movement creates a voltage that can be used to power pumps for desalination, mostly for membrane technologies [18].

Hundreds of small photovoltaic power plants have been developed. Reverse osmosis systems connected to photovoltaic plants are already commercialized and considered the most promising combination of solar energy with desalination [23]. Also, some pilot plants have been developed to study electrodialysis with PV cells [18]. Disadvantages of PV systems include low efficiency (typically ranging from 10-15%), high manufacturing costs, the requirement of large arrays for RO systems, and the general use of lead-acid batteries [18, 23].

Solar Energy Concentrators and Collectors

Using flat mirrors with a heliostat is a technique used to concentrate light. The mirrors are arranged in a curved configuration. The heliostat attracts the rays of sun and maintains the focus of the reflection on the mirrors to a focal point. It alters itself according to the position of the mirrors to the sun, since this position changes throughout the day. Concentrated light is directed to pipes filled with air or water in order to create steam or heated air that can be used for power [21]. An alternative technique is using flat plates to collect low-intensity radiation. Flat plates collectors are well adapted to absorb diffused radiation as opposed to concentrated radiation. Flat plates can produce low-grade thermal energy. The main disadvantage of a flat plate collector is its requirement for large amounts of space [21].

Parabolic trough radiation collectors are another option. These collectors are able to withstand high temperatures without degradation of the collector efficiency and for this reason are preferred for solar steam generation [24]. Solar ponds can also be used as radiation collectors. Research shows that a solar pond is able to preheat the intake water [25]. Some researchers consider solar pond-powered desalination one of the most cost-effective methods [18].

Recent Methods

Table 4.3. Desalination Plants Incorporating Solar Energy

Location	Type of Solar Energy	Type of Desalination	Capacity (gal/d)	Reference
El Paso, TX	Solar Pond	MSF	4,227	[27]
La Paz, Mexico	Flat Plate & Concentrating Collectors	MSF	2,642	
Yanbu, Saudi Arabia	Dish Collectors	FS	52830	
Gillen Bore, Central Australia	Solar Panels	BWRO	317	
La Desired Island, French Caribbean	Solar-Evacuated tube	ME	10,570	[18]
Abu Dhabi, UAE	Solar-Evacuated tube	ME	31,700	
Kuwait	Solar Electricity Generation System	MSF+ RO	6,604 + 11,890	
Arabian Gulf	Solar-Parabolic Trough	ME	1,585,000	
Al-Ain, UAE	Solar-Parabolic Trough	ME, MSF	132,100	
Takami Island, Japan	Solar-Parabolic Trough	ME	4,227	
PSA, Almeria, Spain	Solar-Parabolic Trough	ME-Heat Pump	19,020	
Margarita de Savoya, Italy	Solar Pond	MSF	13,210-15,850	
Islands of Cape Verde	Solar Pond	Atlantis "AutoFlash"	79,250	
University of Ancona, Italy	Solar Pond	ME-VC	7,385	
Near Dead Sea	Solar Pond	MED	792,500	
Lampedusa Island, Italy	Solar-Low Concentration	MSF	19020 + 12680	
Gran Canaria, Spain	Solar-Low Concentration	MSF	2,642	
Area of Hzag, Tunisia	Solar Collector	Distillation	26-92	
Safat, Kuwait	Solar Collector	MSF	2,642	

One recent design takes advantage of the heat storage capacity of air. Solar heat is used to heat air. This air becomes humidified when cooling water is injected into it. When the humid air is cooled, the water is separated from the salts. This process has not been developed commercially and is still being researched

[26]. Other research focuses on optimizing systems so that solar panels are sized appropriately and battery storage is not needed [23], as well as using solar energy to power smaller system heat pumps such as absorption vapor compression [18].

Table 4.4. Desalination Plants Incorporating Photovoltaic Energy

Location	**Power Generated 10^3 Btu/hr (kW)**	**Type of Desalination**	**Capacity gal/d**	**Reference**
Perth, Western Australia	4.1 (1.2)	RO	634-3170	[21]
Jeddah, Saudi Arabia	27 (8.0)	SWRO	845	
Concepcion del Oro, Mexico	8.5 (2.5)	BWRO	396	
North of Jawa, Indonesia	87 (25.5)	BWRO	3,170	
Vancouver, Canada*	16 (4.8)	SWRO	264	
Red Sea, Egypt	68 (19.84) + 2.2 (0.64)	BWRO	13210	[18]
Hassi-Khebi, Argelie	8.8 (2.59)	BWRO	6,023	
Cituis West, Jawa, Indonesia	85 (25)	BWRO	9,510	
Doha, Qatar	38(11.2)	SWRO	1,506	
Thar Desert, India	1.5 (0.45)	BWRO	264	
North west of Sicily, Italy	33 (9.8) + 102 (30) diesel	SWRO	---	
St. Lucie Inlet State Park, FL, USA	9.2 (2.7)+ diesel	SWRO	159	
Lipari Island, Italy	215 (63)	SWRO	12,680	
Lampedusa Island, Italy	341(100)	SWRO	19,020 + 12,680	
University of Almeria, Spain	80 (23.5)	BWRO	15,850	
Borj-Cedria, Tunisia	14 (4) + Wind	Distillation/RO/BWED	26/1,585	
Spencer Valley, NM*		ED	740	
Thar Desert, India*		ED	264	
Oshima Island, Nagasaki, Japan*		SWED	2,642	
Fukue City, Nagasaki, Japan*	222 (65)	BWED	52,813	
* Pilot or Demonstration Plants				

4.3.4. Wind Energy

Wind energy rotates windmills creating mechanical energy that can be converted to electrical energy. Windmills come in both vertical axis arrangements, and multiple axis, horizontal arrangements. Turbines utilizing wind energy for low power (34 –341 10^3 Btu/hr or 10-100 kW), medium power (341 – 1707 10^3 Btu/hr or 100 kW-0.5 MW), and high power (> 1707 10^3 Btu/hr or 0.5 MW) are mature technologies [18].

In the United States, wind currents are strongest in the central states and along the coasts of Alaska and New England, as well as parts of California where wind farms are responsible for producing 76% of the world's total wind energy. The global trend shows stronger currents in coastal areas [28, 29].

Wind energy can be converted to shaft power that directly goes toward powering the desalination, or sent to the local grid or batteries and stored until needed [18]. Electrodialysis and MVC systems are well suited to operate using direct wind energy [18]. Using direct wind energy to power RO systems is limited because RO systems do not operate well under non-continuous conditions. Table 4.5 shows a list of desalination plants around the world that are powered by wind energy.

Table 4.5. Desalination Plants Incorporating Wind Energy

Location	**Power Generated 10^3 Btu/hr (kW)**	**Type of Desalination**	**Capacity gal/d**	**Reference**
Shark Bay, Western Australia	109 (32)	BWRO	44,380 & 34,340	[27]
Island in North Sea	20 (6)	SWRO	1,600	
Borj-Cedria, Tunisia		RO + ED		[18]
Island of St. Nicolas, West France		RO		
Fuerteventura Island, Spain		RO	14,794	
Middle East		RO	6604	
Drepanon, Achaia		RO		
Ile du Planier, France Pacific Islands		RO	3,170	
Helgoland, Germany		RO	6,086000	
Island of Drenec, France	34 (10)	RO		
Borkum Island, North Sea		MVC	1,902-12,680	
Ruegen Island, Germany	683 (200)	MVC	31,700-79,250	
Gran Canaria, Spain		RO	52,830	

Some researchers have studied the potential of hybrid wind/diesel and hybrid solar/wind plants. In the wind/diesel case, the wind power is transferred to the shaft of the diesel generator, thus reducing the fuel needed for the generator to work at a constant load. These systems can maintain a constant load, a solution for the intermittent nature of wind energy. For the solar/wind case, distillation devices can be used to desalt water; the solar energy can provide needed thermal energy and the wind turbines can provide needed mechanical energy. Hybrid renewable energy systems have been researched at the University of Massachusetts and the Center for Renewable Energy Systems in Greece [21].

4.3.5. Geothermal Energy

Heat energy exists at depths of hundreds and even thousands of feet below the surface of the earth. In the inner core of the earth, temperature ranges from 6,700 °F to 11,000 °F. Geothermal energy resources exist in three forms: thermal, hydraulic, and methane gas. Geothermal energy can be harnessed and applied to produce electricity that is sent to local grids, or to directly power thermal desalination plants. Today, the world's power capacity from geothermal energy is 20.5×10^9 Btu/hr (6000 MW) used for electricity and 51.2×10^9 Btu/hr (15,000 MW) used for space heating [29]. Geothermal power plants exist in New Zealand, Mexico, Japan, Iceland and the United States. Reykjavik, the capital of Iceland, uses geothermal energy to provide 99% of its heating energy needs [18]. The U.S. retrieves 0.2% of its power through this method. Figure 4.4 shows geothermal basins in the United States.

At present, 99% of geothermal energy in the U.S. is produced in three sites in California: Geysers north of San Francisco, the China Lake in Los Angeles, and the Imperial Valley north of Los Angeles [30]. There is great potential for developing geothermal energy sources in other parts of the United States. According to the U.S. Geological Survey, power amounts ranging from 79×10^9 Btu/hr to 819×10^9 Btu/hr (23,000 MWe to 240,000 MWe) can be attained from geothermal resources in areas around the Gulf of Mexico for the next 30 years. Application of geothermal resources to desalination has not been practiced as yet. Greece is planning a desalination plant to use geothermal energy [18].

Figure 4.4. Geopressured Basins in the United States [31]

4.3.6. Ocean Energy

The category of ocean energy can be divided into tidal energy, wave energy, and ocean thermal energy conversion (OTEC) methods. Tidal power is the most-developed technology in this category.

4.3.6.1. Tidal Power

Tidal energy takes advantage of the hydraulic head difference between low tide and high tide. Typically, elevation differences from low to high tide are between 4 ft. and 6 ft. In certain areas of the world, elevation differences are much greater. In these certain areas, power plants have been or can be installed to take advantage of the large differences in hydraulic head that occur there. Table 4.6 shows a few examples of tidal power plants [29].

Table 4.6. High Tidal Differences and Power Generated

Location	**Elevation Difference**	**Power produced 10^6 Btu/hr (MW)**
La Rance, France	37 ft	819 (240)
Severn, Great Britain	37 ft	1,263 (370)
Bay of Fundy, Canada	36 ft	61 (18)
Chaussey, France	40 ft	------------
Passamaquoddy, Maine	24 ft	------------

Because tidal movements occur only at certain periods throughout the day, the energy is not constant. Therefore, when attaining energy from tidal changes the energy must be stored on some sort of community power grid so that it can be accessed as needed. Tidal energy plants have an approximate efficiency of 20%. This means that only 20% of the tidal energy is available as usable energy. Tidal power plants are three times as expensive as coal power plants.

4.3.6.2. Wave Energy

Waves develop because of wind interacting with water. The energy held in waves can be converted to useful energy. Monthly average wave power is a function of the height of the waves. It can be measured by using the average height of the highest 1/3 of all waves. In Santa Cruz, California the average wave height is 7.9 ft, which gives them total wave energy potential equal to 88,764 Btu/hr per foot of coastline (26 kW per meter of coastline) [32]. In the best locations, wave energy can provide as much as 238,980 Btu/hr per foot of coastline (70 kW per meter of coastline) [33].

There are different devices for recovering energy from the waves. These devices can be categorized into heaving, heaving and pitching, pitching, oscillating water columns, and surging. A pilot desalination plant in Coffin Island, Puerto Rico incorporates heaving technology using a hose and a buoy.

The movement of the buoy with the waves drives the pump. This mechanism is able to convert wave energy to mechanical energy that is then used to drive the 350 gal/d reverse osmosis plant [32]. A seawater desalination study tested a vapor compression technology combined with a pitching device able to harness wave energy [33]. The waves put a device called a "duck" in motion. This drives a large fluid piston at wave frequencies of (0.1-0.2 Hz). Higher-pressure vapor is condensed in a falling film evaporator/condenser. A portion of the seawater vaporizes as a result of this heat exchange. The vapor spaces alternate between compression and expansion according to the up and down "nods" of the "duck." The research showed that using this method that the wave energy could desalinate 0.255 MGD of water [33].

4.3.6.3. Ocean Thermal Energy Conversion

The ocean thermal energy conversion (OTEC) technique uses the temperature difference between the warmer surface water of the ocean and the cooler deep ocean water. The temperature difference is used to alternately condense and evaporate a working fluid, thus generating water volume and pressure changes that can rotate turbines and produce electricity [34].

The main problem with ocean thermal energy is the relatively small temperature differences found between surface water and deep ocean water. Another problem is the depths at which cooler water is found and this requires large volumes of water to be pumped. These facilities need to either have long, large seawater pipes, or a floating platform. Ocean thermal energy has a maximum efficiency of 7% and is generally around 2%. It is also about three times more expensive than coal energy [30].

The tropics are potential areas under consideration for developing and using this type of energy. In the tropics, ocean temperatures can reach anywhere from 40° F to 75° F [30]. Nauru, an independent island nation, used OTEC to produce 102,420 Btu/hr (30 kW) net power for the island, until the power plant was damaged in a storm. Now the project is continuing with designs for 3.4 x 10^6 Btu/hr (1 MW) and 341 x 10^6 Btu/hr (10 MW) facilities [34]. Also, a 170,700 Btu/hr (50 kW) power demonstration plant in the Hawaiian Islands is studying the harnessing of thermal ocean gradients. Other research and development is occurring in the UK, France, the Netherlands, and Japan. In the U.S., the Solar Energy Research Institute, National Renewable Energy Laboratory, U.S. Department of Energy is researching OTEC design.

The combination of OTEC with desalination has been considered [34]. This facility would be an open-cycle configuration that uses seawater as the working fluid. Some of the seawater is flashed into vapor at low pressure. This removes the salts from the seawater, producing potable water. Also, another option is a hybrid process using seawater and another fluid such as ammonia. In this process, seawater is flashed into steam and condensed to form potable water. The other fluid is incorporated into the evaporation and condensation process in such a way that the phase change of the seawater/ammonia mixture is able to drive a low-pressure turbine [34].

4.4. Summary of Renewable Energy Sources

Table 4.7 provides a summary of various energy sources and their potential applicability in Virginia.

Table 4.7. Renewable Energy Summary

Energy	Advantages	Disadvantages	Cost	Applicability in Virginia
Solar Stills	Affordable and easy to maintain, good efficiency	Require large land area and sunlight	Low	Not applicable as a significant energy source in Virginia - applicable for remote areas with lots of sunlight
Photovoltaic & Collectors	Good energy collectors	Low efficiency, high manufacturing costs, requires large arrays, may need lead-acid batteries	Medium	Has potential for use as a power supplement but Virginia will never be able to depend on this energy source completely, because we do not receive enough sunlight
Wind	High energy in coastal areas, using wind energy for power is a mature technology, can generate large amounts of energy	Wind is intermittent	?	Applicable but may not have enough winds to be cost-effective in Virginia coastal areas
Geothermal	Large amounts of resources available in some areas	Technology is undeveloped for application to desalination	?	Not applicable as a significant energy source in Virginia - there are not enough geothermal reserves
Tidal	Tides occur at every coastline, fairly efficient	Energy is intermittent	High	Applicable but may not have enough difference in elevation between tides to be cost-effective
Wave	Cost-effective for large plants, less expensive than diesel or hydropower	Wave heights vary	Medium	Applicable for Virginia!
Thermal	Is being researched	Few areas where ocean has significant temperature variations with depth, expensive, low efficiency	High	Applicable for Virginia, not practical until technology is further improved and costs are decreased.

4.5. Energy Storage and Control Options

A major disadvantage of renewable energies is the lack of continuity and consistency in the supply. To compensate, some sort of control system or energy storage unit is required, especially if no backup energy is available.

Batteries are one option of storing energy, but they are not preferred because of their short lifetimes and because a large number of batteries will be needed to store the required energy and could be very costly. Another method of storing energy is connecting renewable energy sources to diesel generators or electricity grids that power the desalination plant. With this method, fuel consumption can be reduced, but generally more maintenance will be required and problems will develop if there is a fuel shortage [35]. For intermittent wind energy supply, turbine de-rating mechanisms can be used to control the rotation angle of the turbine blades. Turbine de-rating mechanisms maneuver the pitch of the blades according to the power being supplied and the current water demand. The rotation angle of the blades determines the amount of mechanical energy produced which is often a very expensive option [35].

4.6. Nuclear Energy

Using nuclear energy to power desalination plants is a developing technology. Currently, research is being conducted to determine the feasibility of developing dual-purpose power and desalination plants.

Nuclear power plants generate power using the concept of fission, i.e., energy is released when a larger atom splits into smaller atoms. The released energy is controlled and contained to heat a coolant material and ultimately generates steam that drives turbines, which rotate a coil in a magnetic field to produce electricity. The main components of a nuclear power plant are the fuel rods which hold the fissionable material, the moderator material which controls the speed of the neutrons, the control rods which absorb the neutrons to control the rate of the reaction, and the coolant which absorbs the heat that is passed onto the turbines [30].

Combining nuclear power plants with desalination plants is economical because 2/3 of thermal power generated is waste heat [36]. Typically this waste heat is sent to surrounding waters or air. Researchers have found that it is economical to send this heat to desalination plants instead. Also power plants are able to provide immediate electricity to the desalination plant.

The International Atomic Energy Agency has developed a team of researchers to study seawater desalination combined with nuclear reactors. One research project incorporated nine countries in its efforts to optimize the coupling of nuclear reactor and desalination systems in 1998. They determined that the costs are in the same range as fossil fuel costs. New plants are envisioned for South Korea, Russia, and India. Countries looking into nuclear/desalination plants are Indonesia, Tunisia, Pakistan, and Iran. The technical industry leaders in this field are South Korea, Russian Federation, Argentina, Canada, France, and China. Also Morocco and Egypt are conducting studies. A desalination plant in southeast India that began operating in 1998 produced 10 MGD of freshwater in 2003. It is a hybrid

MSF-RO demonstration plant coupled to a pressurized water reactor at Madras Atomic Power Station in Kalpakkam [37].

A project called EURODESAL incorporated researchers from different countries and backgrounds to study nuclear powered desalination as compared with fossil fuel powered desalination facilities. It also compared reverse osmosis technologies with distillation technologies. The results from this study showed that even under the most unfavorable circumstances the nuclear power plant/desalination plant proved more economical than the fossil fuel power plant/desalination plant. It also determined that using preheated water with the reverse osmosis technology was the cheapest technology to use, independent of the power plant it is connected with. They noted that the cost decreased as the capacity of the plant increased [36].

There are many factors to weigh when considering nuclear energy. It creates no air pollution; therefore, it does not contribute to greenhouse effect concerns. However, it operates at low efficiency, and generates nuclear waste. Storing nuclear waste is a problem because of its extremely long decay time. At present, nuclear energy power plants are not cost-effective in the United States because of the strict regulations imposed by the federal government after the Chernobyl accident. The last order for construction of a nuclear power plant was in 1978 [30]. Other countries are much more accepting of nuclear power. In France there are 58 PWR plants making up 76.6% of the countries total electricity supply [36].

5. Feasibility of Using Desalination in Eastern Virginia

Chapter Synopsis

A major assumption of the study was that the greatest potential for implementing desalination technologies exists in the counties and cities in eastern Virginia within close proximity of the Chesapeake Bay and the Atlantic Ocean. This chapter provides data on projected population growth and future water demand, available surface and groundwater resources, the rationale for implementing desalination technologies, a description of the existing desalination plants in eastern Virginia, and a discussion of the feasibility of using desalination technologies in eastern Virginia. Feasibility issues include potential water resources for desalination; environmental effects of desalination; required permits and regulations; availability of energy resources; and potential costs. The chapter concludes with a set of recommendations for actions that could facilitate the implementation of future desalination technologies in eastern Virginia.

5.1. Eastern Virginia Localities

Geographic regions in eastern Virginia where using desalination can be a high priority are Hampton Roads and the Accomack/Northampton Peninsula (Eastern Shore). The Hampton Roads area is within the Eastern Virginia Ground Water Management Area.[2] Hampton Roads includes the cities of Chesapeake, Franklin, Hampton, Newport News, Norfolk, Poquoson, Portsmouth, Suffolk, Virginia Beach, and Williamsburg; and the counties of Gloucester, Isle of Wight, James City, Southampton, Surry, and York. Four desalination plants already operate in the Hampton Roads area.

The Accomack/Northampton counties make up the Virginia part of the Delmarva Peninsula (Delaware, Maryland, and Virginia) and are within the Eastern Shore Ground Water Management area. This area has no freshwater resources and very limited available groundwater. The populations in these counties are low and most of the population is concentrated around the Town of Cape Charles at the southern tip of the Peninsula.

The third geographic area that includes five counties (Essex, King & Queen, King William, Mathews, and Middlesex) is situated within the Middle Peninsula and is mostly rural. King William County is situated within the Eastern Ground Water Management Area. At present, the area has adequate freshwater resources to meet its needs. In the future, it is likely that this area will compete for the available resources with neighboring counties and cities.

[2] The Virginia Ground Water Act allows the state to declare Ground Water Management Areas where the groundwater supply is being depleted or polluted. Currently, there are two groundwater management areas in Virginia: the Eastern Virginia Ground Water Management Area and the Eastern Shore Ground Water Management Area. For details see Section 5.3.

The fourth geographic area includes the cities of Richmond and Petersburg, and the counties of Charles City, Chesterfield, Hanover, Henrico, New Kent, Prince George, and Sussex. Parts of this area (New Kent, Charles City, Hanover, Henrico, Sussex, and Petersburg) are situated within the Eastern Virginia Ground Water Management Area. These localities will compete for available water resources in the region and may consider desalination to supplement their water supplies in the future.

5.2. Projected Population Growth and Water Demand in Eastern Virginia

Future water demand closely relates to future population growth and economic productivity. The 2000 census recorded Virginia's population as 7,293,542 people. Of this, 2,601,185 people, or about 36% of Virginia's population, live in eastern Virginia. Population projection information is usually available from planning districts and utilities in eastern Virginia. However, to be consistent with projection date and method of projection, in this study, population projection data from the Virginia Employment Commission database was used [1]. Tables 5.1a to 5.1d show population projection for 2010, 2020 and 2030 in the four geographic areas identified above.

Table 5.1a. Population Projection in Hampton Roads Area [1]

Locality	2000 Population	2010 Population	2020 Population	2030 Population
Chesapeake	199,184	230,000	255,000	280,000
Franklin	8,346	9,700	8,400	8,400
Hampton	146,437	149,600	152,600	155,600
Newport News	180,150	184,100	187,100	190,100
Norfolk	234,403	215,003	228,300	228,300
Poquoson	11,566	12,608	12,300	12,600
Portsmouth	100,565	97,400	95,900	94,400
Suffolk	63,677	74,999	87,800	97,800
Virginia Beach	425,257	444,800	460,900	477,000
Williamsburg	11,998	13,402	13,500	13,900
Gloucester	34,780	41,495	42,700	46,200
Isle of Wight	29,728	34,098	37,500	41,500
James City	48,102	60,001	77,500	92,000
Southampton	17,482	16,997	18,900	19,900
Surry	6,829	7095	7,400	7,700
York	56,297	78,002	80,000	91,000
Total Population	**1,574801**	**1,669300**	**1,765800**	**1,856400**

Table 5.1b. Population Projection in Accomack/Northhampton Peninsula [1]

Locality	2000 Population	2010 Population	2020 Population	2030 Population
Accomack	34,007	39,408	44,500	46,500
Northampton	12,929	14,868	12,200	12,000
Total Population	**46,936**	**54,276**	**56,700**	**58,500**

Table 5.1c. Population Projection in Middle Peninsula [1]

Locality	2000 Population	2010 Population	2020 Population	2030 Population
King William	6,630	16,003	17,400	19,400
Mathews	9,207	10,689	10,600	11,200
Middlesex	9,932	11,498	10,700	11,100
King & Queen	6,630	7,000	7,400	7,800
Essex	9,989	10,400	11,300	11,900
Total Population	**42,388**	**55,590**	**57,400**	**61,400**

Note: Gloucester is included in Hampton Roads region (Table 5.1a)

Table 5.1d. Population Projection in Richmond, Petersburg and Nearby Counties [1]

Locality	2000 Population	2010 Population	2020 Population	2030 Population
Richmond City	197,456	186,008	189,600	189,600
Petersburg	33,115	31,502	29,400	28,900
Charles City	7,239	7900	7,800	8,300
Chesterfield	271,142	317,004	366,000	412,000
Hanover	92,050	93,491	122,800	139,200
Henrico	268,270	277,003	335,000	365,000
New Kent	14,157	16,497	18,800	21,400
Prince George	34,135	34,504	39,000	41,800
Sussex	12,221	11,494	11,800	11,800
Total Population	**92,9785**	**97,5403**	**112,0200**	**121,8000**

Many localities in eastern Virginia project significant population growth that will affect future water demand. The average per capita use of water can vary from 80 gallons/day to 200 gallons/day. The *Commonwealth of Virginia Waterworks Regulations* are based on a use of 100-gallons/day/capita. For planning purposes, consideration should be given to water losses from the treatment plant to delivery point, which is estimated at about 30%. Also, a margin of safety will compensate for uncertainty in population projection. For example, the Hampton Roads Planning District Commission (HRPDC) has projected the area population for the year 2026 as 1,923,600 people, which is higher than what is shown for the year 2030 in Table 5.1a. Therefore, for this study an estimate of water demand per capita of 125-gallons/day was used to compensate for uncertainty in per capita water use and population increase. Using 125-gallons/day/person (this amount does not include industrial, agricultural and other uses), the projected population increases in 2010, 2020, and 2030 (using 2000 population data as a reference) will translate to an additional water demand of approximately 20 MGD (2010), 51 MGD (2020), and 75MGD (2030) in eastern Virginia (Table 5.2). Significant population growth (by the year 2030) in Chesterfield, Hanover, and Henrico counties will result in intense competition for available water resources in the region.

Table 5.2. Projected Additional Water Demand in Eastern Virginia (MGD)

Region/Year	2010 (MGD)	2020 (MGD)	2030 (MGD)
Hampton Roads Area	11.80	23.87	35.2
Accomack/Northhampton Peninsula	0.92	1.22	1.44
Middle Peninsula	1.65	1.88	2.38
Richmond, Petersburg, Nearby Counties	5.7	23.8	36.03
Total Additional Drinking Water Demand	**20.07**	**50.77**	**75.05**

5.3. Status of Water Use in Eastern Virginia

In March 2004, the U.S. Geological Survey published the status of water use in the United States [2]. Table 5.3 and Table 5.4 show summary data (year 2000) for categories of surface and groundwater use in Virginia and eastern Virginia extracted from the USGS database. Significant water uses in eastern Virginia include public and domestic water supplies, industrial, agricultural, and thermoelectric uses. The USGS database is based on water use reports for each county/city. It should be noted that several counties/cities in eastern Virginia withdraw brackish groundwater for their desalination plants but the USGS database does not differentiate between freshwater and brackish water.

Table 5.3a Surface Water Use Categories in Eastern Virginia [2]

Water Use Category	Surface Water Use All Virginia (MGD)		Surface Water Use Eastern Virginia (MGD)	
	Freshwater	Saline Water	Freshwater	Saline Water
Public Water Supplies	650	0	294.97 (23%)	0
Domestic (Self-Supplied)	0	0	0	0
Industrial	365	53	64.46	53.26
Irrigation	23	0	10.34	0
Thermoelectric	3,850	3,580	928.23 (72%)	3,341.26
Total Use (MGD)	4,888	3,633	1,298	3,394

Surface freshwater withdrawals (1,298 MGD) in eastern Virginia correspond to 26.6% of total surface freshwater withdrawals (4,880 MGD) in Virginia. Saline water withdrawals (3,394 MGD) in eastern Virginia correspond to 93.2% of total saline water withdrawals (3,640 MGD) in Virginia. About 77% (995 MGD) of fresh surface water withdrawal in eastern Virginia takes place in Chesterfield County, mostly used by thermoelectric power plants. Saline surface water withdrawals are concentrated in Surry

County (1966 MGD), York County (905 MGD), and Chesapeake (524 MGD), mostly by thermoelectric power plants.

Table 5.3b Groundwater Use Categories in Eastern Virginia [2]

Water Use Category	Groundwater Use All Virginia (MGD)	Groundwater Use Eastern Virginia (MGD)
Public Water Supplies	71	29.75
Domestic (Self-Supplied)	133	31.33
Industrial	104	62.6
Irrigation	4	2.29
Thermoelectric	1.5	1.45
Total Use (MGD)	**314**	**127**

The groundwater withdrawals (127.42 MGD) in eastern Virginia correspond to 40.6 % of total groundwater withdrawals (314 MGD) in Virginia. From total groundwater withdrawals in eastern Virginia, 23.3% is used for public water supplies, 24.6% for domestic (self-supplied) use, 49.1% for industrial use, and 1.8% for crop production.

Table 5.4 Approximate Water Withdrawals in Eastern Virginia [2]

	Year 2000 Water withdrawals (MGD) by Source and Type								
	Groundwater			**Surface water**			**Total**		
County/City	Fresh	Saline	Total	Fresh	Saline	Total	Fresh	Saline	Total
Accomack	6.26	0.00	6.26	2.61	0.00	2.61	8.87	0.00	8.87
Charles City	0.57	0.00	0.57	0.22	0.00	0.22	0.79	0.00	0.79
Chesterfield	2.57	0.00	2.57	994.85	0.00	994.85	997.42	0.00	997.42
Gloucester	1.88	0.00	1.88	1.17	0.00	1.17	3.05	0.00	3.05
Hanover	3.35	0.00	3.35	3.62	0.00	3.62	6.97	0.00	6.97
Henrico	4.44	0.00	4.44	0.28	0.00	0.28	4.72	0.00	4.72
Isle of Wight	36.21	0.00	36.21	2.86	0.00	2.86	39.07	0.00	39.07
James City	10.97	0.00	10.97	0.91	0.00	0.91	11.88	0.00	11.88
King William	20.70	0.00	20.70	0.61	0.00	0.61	21.31	0.00	21.31
Lancaster	0.82	0.00	0.82	0.05	0.00	0.05	0.87	0.00	0.87
Mathews	0.66	0.00	0.66	0.00	0.00	0.00	0.66	0.00	0.66
Middlesex	0.71	0.00	0.71	0.14	0.00	0.14	0.85	0.00	0.85
New Kent	0.89	0.00	0.89	27.91	0.00	27.91	28.80	0.00	28.80
Northampton	1.52	0.00	1.52	1.71	0.00	1.71	3.23	0.00	3.23
Northumberland	0.75	0.00	0.75	0.00	0.00	0.00	0.75	0.00	0.75
Prince George	1.19	0.00	1.19	16.75	0.00	16.75	17.94	0.00	17.94
Southampton	6.14	0.00	6.14	1.66	0.00	1.66	7.80	0.00	7.80
Surry	1.00	0.00	1.00	0.26	1,965.91	1,966.17	1.26	1,965.91	1,967.17
Sussex	0.80	0.00	0.80	0.66	0.00	0.66	1.46	0.00	1.46
York	3.44	0.00	3.44	29.71	904.62	934.33	33.15	904.62	937.77
Chesapeake*	7.22	0.00	7.22	7.61	523.99	531.60	14.83	523.99	538.82
Franklin	1.11	0.00	1.11	0.00	0.00	0.00	1.11	0.00	1.11
Hampton	0.03	0.00	0.03	1.14	0.00	1.14	1.17	0.00	1.17
Newport News*	2.35	0.00	2.35	37.15	0.00	37.15**	39.50	0.00	39.50
Norfolk	0.25	0.00	0.25	2.39	0.00	2.39	2.64	0.00	2.64
Petersburg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Poquoson	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Portsmouth	1.60	0.00	1.60	0.03	0.00	0.03	1.63	0.00	1.63
Richmond	0.08	0.00	0.08	89.08	0.00	89.08	89.16	0.00	89.16
Suffolk*	6.67	0.00	6.67	74.18	0.00	74.18	80.85	0.00	80.85
Virginia Beach	3.23	0.00	3.23	0.37	0.00	0.37	3.60	0.00	3.60
Williamsburg	0.01	0.00	0.01	0.07	0.00	0.07	0.08	0.00	0.08
Total (MGD)	**127.42**	**0.00**	**127.42**	**1,298.00**	**3,394.52**	**4,692.52**	**1,425.42**	**3,394.52**	**4,819.94**

* The USGS database does not differentiate between freshwater and brackish water withdrawals. The 2.35 MGD withdrawal in Newport News and a portion of withdrawal in Chesapeake and Suffolk are, in fact, brackish groundwater. See Section 5.7, Existing Desalination Plants in Eastern Virginia.

** Total surface withdrawal (year 2000) in Newport News was 52.05 MGD, which includes withdrawals from terminal reservoirs.

5.4. Groundwater Resources of Eastern Virginia

Eastern Virginia depends on the following coastal plain aquifers for its water demand: Potomac (Upper, Middle, and Lower), Aquia, Yorktown-Eastover, Columbia, Chickahominy-Piney Point, and Virginia Beach. Coastal Plain aquifers comprise a complex and interconnected hydrologic system, consisting of confined and unconfined aquifers. The aquifer depth (below sea level) ranges from 700 ft. to 3,000 ft. for the Potomac Aquifer, 250 ft. to 700 ft. for the Aquia Aquifer, and 50 ft. to 250 ft. for the Yorktown-Eastover Aquifer. The Columbia Aquifer in the Accomack/Northampton Peninsula is an unconfined aquifer (about 50 ft. depth). It is estimated that significant amounts of recharge water that enters into the Columbia aquifer exits into the Chesapeake Bay and the Atlantic Ocean but some water from the Columbia aquifer is a source of recharge to the Yorktown-Eastover aquifer [3]. The U.S. EPA has designated the Accomack/Northampton Peninsula's aquifer system as a sole source multi-aquifer system. Factors that describe sole source aquifer designation include: the service area relies on the aquifer for more than 50% of its drinking water needs; the aquifers are highly vulnerable to contamination; and there is no alternative to groundwater to meet drinking water needs [3]. Details of aquifer geohydrologic characteristics are available from the USGS publications [4, 5].

Determining the productivity of the coastal plain aquifers is a complex task and can only be approximated. At present, the Virginia Coastal Plain model (VCPM) is used to estimate water withdrawal and availability in coastal plain aquifers [6]. The VCPM, originally developed by the USGS, consists of a computer program and related data sets that can simulate the effects of current withdrawals as well as possible future withdrawals. The Virginia Department of Environmental Quality (DEQ), the agency responsible for groundwater management, is using the VCPM to evaluate withdrawal effects and make groundwater management decisions. The VCPM uses data from the Virginia Water Use Data System (VWUDS). Records for regulated wells are added or updated as new information becomes available during the permitting process. Table 5.5 shows estimates of total, annual groundwater withdrawals from coastal plain aquifers for all uses in 2001 and 2002 using the VCPM [6]. The VCPM does not explicitly define fresh or brackish withdrawals. The current model considers only flow between aquifers in the coastal plain system and does not model transport or a fresh/salt water interface.

In 2002, a total use of 110.29 MGD in the Virginia Coastal Plain was reported to the regional offices as permit compliance reports to the VWUDS. The model simulation (Table 5.5) approximated 107.04 MGD. Of the 3.25 MGD that could not be allocated, 1.13 MGD was assigned to unknown wells and 2.12 MGD was assigned to wells determined to be outside the simulated area. The USGS withdrawal data (Table 5.4) reports 127.42 MGD of freshwater groundwater withdrawals in eastern Virginia. Table 5.4 includes data for localities outside the coastal plain aquifers.

Table 5.5 Total Estimated Groundwater Withdrawals (All Uses) [6]

Aquifer Name	2001Withdrawals (MGD)	2002 Withdrawals (MGD)
Lower Potomac	15.64	16.30
Middle Potomac	55.18	59.70
Upper Potomac	17.34	19.33
Aquia	0.26	0.19
Chickahominy-Piney Point	4.89	5.10
Yorktown-Eastover	5.93	5.96
Columbia	0.39	0.40
Virginia Beach	0.04	0.06
Total Withdrawal	**99.67**	**107.04**

At present, the current version of the Coastal Plain Model is the best available tool for groundwater management in eastern Virginia. Model modifications that could improve model performance are underway. It is important to understand that brackish and saline groundwater resources are not disconnected from other surface and groundwater resources. Extraction of brackish water will have effects on adjacent fresh groundwater reservoirs, and ultimately surface water resources as well. Although it is recognized that additional groundwater level drawdown will occur, the magnitude of the consequent aquifer-system compaction and potential land subsidence is largely unknown. In the low-elevation coastal areas where brackish- or saline-water resources will likely be developed, a small quantity of incremental land subsidence may induce a disproportionately large, yet largely unrecognized, additional risk of flooding with consequent economic losses. It is also important to characterize the time scale of different effects of the groundwater extractions.

The Virginia Ground Water Act allows the state to declare Ground Water Management Areas where the groundwater supply is being depleted or polluted. Currently, there are two groundwater management areas in Virginia; the Eastern Virginia Ground Water Management Area and the Eastern Shore Ground Water Management Area. Groundwater withdrawal permits are required in the Ground Water Management Areas. Permits are required for those entities that withdraw or plan to withdraw, on average, 300,000 gallons (or more) of groundwater per month. The Virginia Water Withdrawal Reporting Regulation (9 VAC 25-200-10 et seq.) requires that individuals or facilities that withdraw water at volumes greater than 10,000 gallons per day (one million gallons per month for crop irrigators) must measure and report annually to DEQ the monthly volume of water withdrawn. A withdrawal renewal permit is required every ten years.

One of the several criteria that must be met in permit application is what is referred to as the "80 percent criterion."[3] This criterion is in the permit application: "the proposed withdrawal in conjunction with all existing lawful withdrawals, will not lower the water levels in any confined aquifer that the withdrawal impacts below a point that represents 80-percent of the distance between the historical prepumping water levels in the aquifer and the top of the aquifer at the points that are halfway between the proposed withdrawal site and the predicted one-foot drawdown contour based on the predicted stabilized effects of the proposed withdrawal."[4] In other words, the 80-percent criterion is a regulatory definition and indicator of available water resources. If, for any given withdrawal application, the 80-percent criterion is exceeded, the DEQ will not issue a permit. The 80 percent criterion applies to both fresh and brackish groundwater. The Hampton Roads Planning District Commission (HRPDC) and the DEQ have recognized that in some coastal plain aquifers there are some areas for which a proposed withdrawal may result in exceeding the 80-percent criterion. For example, the 2002 total permitted model simulation shows that the water level in a portion of the Yorktown-Eastover aquifer in the Eastern Groundwater Management Area is below the 80% drawdown criterion. From a regulatory standpoint, the stress on the aquifer system is such that the DEQ may have to start denying permit issuance in some areas. However, so far, no permits that have been requested in the Eastern Virginia Ground Water Management Area have been denied by DEQ based on the 80-percent criterion.

Groundwater Quality

The groundwater quality in coastal aquifers is influenced by the aquifer's recharge zone, and its proximity to the Fall Line and the Atlantic coast. The Fall line is the primary recharge zone for the confined coastal aquifers. The recharge areas for shallow unconfined and semi-confined aquifers are mostly local. Figure 5.1 illustrates the transition of the chemical composition of groundwater between the coast and the Fall Line. The sodium and chloride content of groundwater tends to be higher near the ocean, while carbonate content of groundwater is higher further west.

The USGS scientists have investigated chlorides distribution in the Coastal Plain aquifers [7]. Studies show that salinity concentrations in the groundwater increases with aquifer depth below ground surface and increases as a function of the aquifer proximity to the ocean. Table 5.6 shows concentration of chloride and of several other elements in the coastal aquifers.

[3] The regulation directs that 20% head must be maintained above top of aquifer after pumping has stabilized in relation to historical water levels (9 VAC 25-610-110 D.3.h.) [34].

[4] The one-foot drawdown contour is estimated using the Virginia Coastal Plain Model.

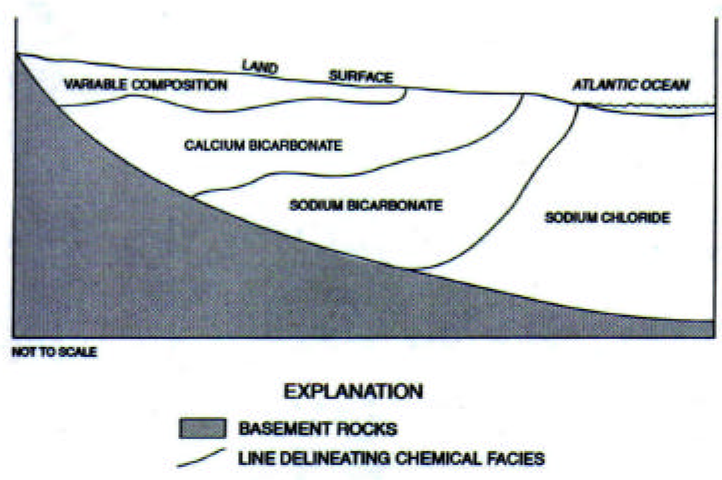

Figure 5.1– Chemical composition of water in Coastal Plain aquifers [8]

There is significant variance between the minimum and maximum sodium and chloride concentrations in each aquifer. Generally, the Lower Potomac aquifer has the highest sodium and chloride concentrations. Because of correlation between chloride and total dissolved solids (TDS) concentrations, it can be assumed that high chloride concentrations are indicative of high TDS concentrations. Highest chloride concentrations (19,000 mg/L to 23,000 mg/L) in the Potomac aquifer were observed in the areas that border Norfolk and Virginia Beach, and in Matthews County and Northampton County. The chloride concentrations in the Potomac Aquifer in Chesapeake City area, Gloucester County area, and York County area are 1,000 mg/L to 5,000 mg/L. Chloride concentrations in the Piney Point and the Aquia aquifers are also 1,000 mg/L to 5,000 mg/L.

Table 5.6. Water Quality of Main Virginia Coastal Aquifers [8]

	Yorktown-Eastover			**Chickahominy-Piney Point**			**Upper Potomac**			**Middle Potomac**			**Lower Potomac**		
	Min	Median	Max	Min	Median	Max	Min	Median	Max	Min	Median	Max	Min	Median	Max
Hardness, total, mg/L as $CaCO_3$	62	170	812	14	53	700	2	12	450	<1	10	570	2	31.0	3345
Calcium, mg/L	9	58	260	1	13	100	<0.1	3	1100	0	3	120	0.4	9.0	960
Alkalinity, total mg/L as CaCO3	76	230	630	76	160	770	89	360	850	24	190	676	42	160.0	557
Sodium, mg/L	5	28	561	3	61	2900	5	210	3000	4	94	3000	13	73.0	8100
Chloride, mg/L	3	18	1200	1	6	4800	1	20	4400	1	3	5000	2	12.0	17000

5.5. Surface Water Resources of Eastern Virginia

Potential surface water resources in eastern Virginia fall into three categories: rivers and reservoirs, the Chesapeake Bay, and the Atlantic Ocean.

5.5.1. Rivers of Eastern Virginia

The James, York, and Rappahannock are large rivers that form the peninsulas of eastern Virginia [9, 10]. Chowan River is another important river in southeastern Virginia. These rivers and their tributaries are major sources of surface water supplies in eastern and coastal Virginia.

Five major tributaries of the James River in coastal Virginia are the Appomattox River, Chickahominy River, Pagan River, Nasemond River, and Elizabeth River.

- The Appomattox River is 137 miles long, flows east through Lake Chesdin, past Petersburg, and drains to the James River in Hopewell.
- The Chickahominy River is 90 miles long, flows southeast past Mechanicsville and Roxbury and drains to the James River 10 miles west of Williamsburg. The Chickahominy River is an important water source for the Newport News Waterworks.
- The Pagan River is 10 miles long, flows through Isle of Wight County and drains to the James River past Smithfield. The Nansemond River is 25 miles long, flows north through Suffolk to the James River estuary and empties in Hampton Roads harbor.
- The Elizabeth River flows in southeast Virginia south of the Hampton Roads harbor and James River estuary. The Elizabeth River has three branches: Western Branch, Southern Branch and Eastern Branch, each 20, 40 and 25 miles long, respectively.

Two major tributaries of the York River are the Pamunkey River and the Mattaponi River.

- The Pamunkey River is 90 miles long and is formed in the confluence of the North and South Anna rivers 20 miles north of Richmond. The Pamunkey flows southeast past Hanover and merges to the Mattaponi River at Westpoint and drains to the York River. The Little River, the other major tributary of Pamunkey, is 40 miles long and flows southeast to the North Anna River.
- Mattaponi River is 120 miles long, is formed in Caroline County at the confluence of the Matta and Poni Rivers. Mattaponi flows southeast, past Bowling Green, and joins the Pamunkey River at Westpoint.

The major tributary of the Rappahannock River in coastal Virginia is the Rapidan River. This 90 mile long river rises in the Blue Ridge on the Madison-Greene county border. Rapidan River flows past the Town of Rapidan and drains to the Rappahannock 8 miles northwest of Fredericksburg. Robinson River merges with the Rapidan River 3 miles west of the Town of Rapidan.

Major tributaries of the Chowan River are the Meherrin River, the Nottoway River and the Blackwater River. Nottoway and Blackwater rivers are a source water used to maintain the Western Reservoir System water levels.

- The Meherrin River is 126 miles long and is formed by headstreams on the border of Lunenburg and Mecklenburg Counties in Virginia. Meherrin flows past Emporia into North Carolina where it drains to the Chowan River.
- The Nottoway River is 170 miles long and rises in Prince Edward County, flows southeast past Courtland and merges to the Blackwater River 9 miles south of Franklin at the North Carolina state line.
- The Blackwater River is 80 miles long and rises in Central Prince George County, flows southeast and south past Franklin and merges to the Nottoway River at the North Carolina state line to form the Chowan River.

Other important rivers in the eastern Virginia include the Northwest River, North Landing, Lynnhaven, Warwick, and Hampton Creek. The Northwest River flows through the City of Chesapeake and supplies a major portion of the Chesapeake's overall water needs.

River Water Salinity

Because of tidal effects and proximity to the Chesapeake Bay, salinity in most eastern rivers increases gradually downstream. The salinity for the James, Rappahannock and York rivers at the mouth of the rivers ranges from 20,000 mg/L to 30,000 mg/L.

5.5.2. Lakes and Reservoirs of Eastern Virginia

More than 30 lakes and reservoirs are located along eastern rivers and some of these are major sources of water supplies in the region [11]. For example, the Western Reservoir System[5] serves as the primary source for drinking water for the City of Norfolk. The Lone Star Lakes are a series of 12 excavated lakes (some interconnected) and serve as the major source of water for the City of Suffolk. Portsmouth water treatment plant receives water from lakes Cohoon, Meade, Kilby and Speights.

[5] The Western Reservoir System also called "western reservoirs" consists of Lake Prince, Lake Burnt Mills, and the Western Branch Reservoir. The system is owned and operated by the City of Norfolk.

Table 5.7. Lakes and Reservoirs of Eastern Virginia [11]

Lake/ Reservoir	County/City
Beaverdam Reservoir	Gloucester
Big Bethel Reservoir	York County, Hampton City
Chickahominy Lake	Charles City, New Kent
Crumps Mill Pond	Suffolk
Diascund Reservoir	James City, New Kent County
Falling Creek Reservoir	Chesterfield
Game Refuge Lake	Sussex
Godwins Mill Pond	Suffolk City
Harrison Lake	Charles City
Harwoods Mill Reservoir	York
Lake Burnt Mills	Isle of Wight, Suffolk City
Lake Cohoon	Suffolk City
Lake Kilby	Suffolk City
Lake Lawson	Virginia Beach City
Lake Maury	Newport News City
Lake Meade	Suffolk City
Lake Powell	James City
Lake Prince	Suffolk City
Lake Smith	Virginia Beach City
Lake Taylor	Norfolk City
Lake Wright	Norfolk City
Lakeview Reservoir	Colonial Heights City
Lee Hall Reservoir	Newport News City
Little Creek Reservoir	James City County, Norfolk City
Lone Star Lakes	Suffolk City
Skiffes Creek Reservoir	Newport News, James City County
Speights Run Lake	Suffolk City
Swift Creek Lake	Chesterfield
Swift Creek Reservoir	Chesterfield
Third Branch Lake	Chesterfield
Waller Mill Reservoir	York

5.5.3. The Chesapeake Bay

The Chesapeake Bay with its 11,684 miles of shoreline is the largest estuary in the United States. The Bay is 190 miles long and its width ranges from 4 to 30 miles with an average width of 15 miles [12]. The Bay is relatively shallow with an average depth in the main stem of less than 30 feet. The Bay holds approximately 18 trillion gallons of water. From a salinity perspective, starting from the headwaters going to the lower Bay, the Bay can be divided into four zones where the salinity is ranging from 500 mg/L to 35,000 mg/L. At the head of the Bay and at the head of each Bay tributary stream there is some tidal influence but no significant amount of ocean-derived salt is present in the Bay water. Moving downstream from the Bay headwaters the water gradually changes to brackish, moderately salty, and salty. Salinity of the Bay is also changing from the surface to the bottom. In general, the salinity of deeper waters is 2,000-3,000 mg/L higher than the salinity of surface water. Parts of the Bay exhibit a seasonal variation in salinity as well. During spring, when freshwater flow rates are higher, that salinity can be 2,000 mg/L below average but during autumn, under the low flow conditions, salinity can be 2,000 to 6,000 mg/L above average.

5.5.4. The Atlantic Ocean

Water from Atlantic Ocean can be a future source for desalination. The salinity of the ocean water is 35,000 to 45,000 mg/L or higher.

5.6. Current Status of Water Supplies in Eastern Virginia

High priority geographic areas for desalination include Hampton Roads Metropolitan Statistical Area, Accomack/Northampton Peninsula, and parts of the Middle Peninsula.

5.6.1. Hampton Roads Area

Hampton Roads is recognized as the 31st largest Metropolitan Statistical Area (MSA) in the United States. Major water users and suppliers in the Hampton Roads area are the cities of Chesapeake, Newport News, Norfolk, Portsmouth, Suffolk, Virginia Beach, and the counties of James City, York, and Gloucester. At present, Hampton Roads uses a total of 169 MGD for public water supplies (143 MGD fresh surface water withdrawals, 24 MGD groundwater withdrawal). To supplement its needs, the Southside Hampton Roads area receives water transferred from Lake Gaston.[6]

Water transported from Lake Gaston is the major intrabasin transfer water source for Virginia Beach. The Lake Gaston pipeline and pumping station, put into service on January 1, 1998, is owned and operated by Virginia Beach. The pipeline stretches 76 miles from a tributary of the lake in Brunswick County to its discharge point in Isle of Wight County. The Lake Gaston pipeline is permitted to carry up

[6] Lake Gaston, located approximately 65 miles south of Richmond, is an artificial impoundment of more than 20,000 surface acres along the Roanoke River. The lake begins at the upstream Kerr Dam in Virginia, and flows more than 34 miles over the Lake Gaston Dam into the Roanoke Rapids Lake in North Carolina. The artificial lake was constructed in 1963 for the purpose of generating hydroelectric power. The lake is managed by two Federal Agencies - the U.S. Corps of Engineers and the Federal Energy Regulatory Commission (FERC). The U.S. Coast Guard and the Wildlife Commissions of both North Carolina and Virginia monitor the lake. According to a recent agreement between Virginia and North Carolina, the project will supply water to Norfolk and Virginia Beach until year 2050.

to 60 MGD of water but typically carries less than 60 MGD. The contract between Virginia Beach and Norfolk calls for Virginia Beach to pump up to 50 MGD of raw water via the pipeline to Norfolk's Western Reservoir System. The Western Reservoir System is the primary source of drinking water for Norfolk. The City of Norfolk, under contractual agreement, treats the water and delivers up to 45 MGD of finished water to Virginia Beach. One-sixth (10 MGD) of the Lake Gaston pipeline capacity is the property of the City of Chesapeake.

Chesapeake withdraws about 10 MGD from the Northwest River and 4.5 MGD from deep wells. In addition, Chesapeake purchases finished water from both Norfolk (3.75 MGD) and Portsmouth (up to 5 MGD) and has a contract with Norfolk to purchase an additional 7 MGD of raw water. Chesapeake is currently constructing the pipeline and treatment plant to utilize its 10 MGD share from Lake Gaston. The schedule calls for construction to be completed by December 2005. The available contracted water resources that the facility expansion is expected to provide Chesapeake enough water to meet growth and increased demand until year 2040 [15].

The Newport News Waterworks is situated in the York-James Peninsula and supplies drinking water to more than 350,000 people. The York-James Peninsula service area includes the following localities: Hampton, Williamsburg, Newport News, Poquoson, and parts of James City and York counties. The Newport News Waterworks uses mostly surface water (Chickahominy River is a major source). The Virginia Department of Health has advised the Newport News Waterworks and James City County for the need to develop additional sources of supply, as the current demands have exceeded the "trigger level" contained in the *Commonwealth of Virginia Waterworks Regulations* for such action. The Regional Raw Water Study Group, working through Newport News Water Works, is attempting to construct the King William Reservoir to meet future water demand.[7] According to the area water managers, with the development of the proposed King William Reservoir water needs in the area should be met until 2040 [13, 14]. The Hampton Roads Area has already realized the need for desalination to supplement its water supplies. Four desalination plants are currently operating in the region and a few more are under consideration. The construction of a 5 MGD desalination plant in James City County is

[7] The proposed King William Reservoir Project on Mattaponi River with a capacity of 12.2 billion-gallons will be located in eastern King William County on Cohoke Creek, 10 miles west of the town of West Point. The reservoir is expected to meet future water needs in parts of the Hampton Roads (Hampton, Newport News, Poquoson, York County, James City County, and Williamsburg, and portions of New Kent and King William Counties. For details see website: http://www.kwreservoir.com/index.shtml.)

approximately 50 % complete. The existing desalination plants in eastern Virginia are described in Section 5.7 of this report.

The Suffolk water treatment plant uses water from Lone Star Lakes. The Crumps Mill Pond is another source for Suffolk's conventional water treatment plant. The city operates a conventional water treatment system (3 MGD), a groundwater desalination (EDR) plant currently permitted at 2.82 MGD (maximum output 3.75 MGD), and a fluoride well (0.8 MGD). There is a design plan for the modifications to the conventional plant and a concurrent expansion of the EDR plant, which will result in an additional 3.75 MGD of desalinated water.

Portsmouth operates its own water treatment plant and water distribution system using the water from lakes Cohoon, Meade, Kilby, and Speights. A newly installed pipeline between Norfolk's Western Reservoir System and Portsmouth's lakes will provide Portsmouth with additional water in drought situations.

Beaver Dam Reservoir, built in 1990, is a major water source in Gloucester County. This reservoir provides 800,000 gallons/day of water to a total of 3,450 customers in Gloucester Court House and Gloucester Point areas of the county. According to the Gloucester County Comprehensive Plan (Middle Peninsula), this system can handle an expansion of up to 4 MGD [16]. Gloucester also operates a brackish groundwater RO desalination plant.

The Middle Peninsula

King William County is the only county in this region designated as a groundwater management area (Gloucester was discussed under Hampton Roads area). There is a significant groundwater level decline in the county with a 29-mile radius cone of depression. In 2002, the region had a total industrial withdrawal of 20.66 MGD, mostly attributed to industrial water withdrawals by Smurfit Stone one of the major water users in the area [16].

The Beaver Dam Reservoir in Gloucester County is a major source of public water supplies in this region. According to the Gloucester County Comprehensive Plan, this source can handle an expansion of up to 4 MGD [16]. There are three other public water supplies in this region: Tappahannock, 124,897 GPD; Urban, 125,000 GPD; and West Point, 450,000 GPD. The total public water supplies, from groundwater and surface water sources amounts to 2.14 MGD.

The proposed King William Reservoir is considered as a potential source of water for the Middle Peninsula localities. The agreement stipulates that for King William County's service to construct the reservoir in the county, the county would receive 3 MGD of water from the reservoir.

Accomack/Northampton Peninsula

Currently, Accomack and Northampton rely solely on groundwater to meet drinking water needs. There are no appropriate fresh surface water sources, lakes or rivers in either county. Groundwater from the upper part of the Lower Yorktown-Eastover aquifer and the Columbia aquifer is withdrawn for all uses. About 31% of households in Accomack County and 12% of households in Northampton County depend on the public water system for their drinking water. A large number of households rely on private wells for their drinking water. The total estimated groundwater withdrawal in the area is approximately 5 MGD. Public water supplies use about 1.1 MGD, private wells about 2.1 MGD, and irrigation use is about 1.6 MGD [17].

5.7. Summary of Status of Water Needs in Eastern Virginia

Although a comprehensive database of water resources for eastern Virginia is not available, based on the existing state of knowledge, a significant need for desalination can be projected:

- The Hampton Roads area is the home of one of the largest port facilities in the country and hosts a major military complex. As a result, the area has experienced rapid population growth that has strained local water supplies. Because of the population growth and the difficulty in developing new water sources locally, water shortages in the region have become commonplace over the last two decades. Water restrictions resulting from water shortages have occurred in every dry period since 1976.
- Because of withdrawals from Coastal Plain aquifers, groundwater levels have declined in the region as deep as 160 feet below the sea level near major pumping centers. Groundwater levels in the interior portions of the Middle Potomac (Southampton County), in the Yorktown-Eastover aquifer (Southampton County), and Chickahominy-Piney Point (King William, Caroline, King and Queen counties) are approaching critical condition.
- Major cities in eastern Virginia (Chesapeake, Virginia Beach, Norfolk, Newport News, Portsmouth and Suffolk) are within the Groundwater Management Area. From a regulatory standpoint, the stress on the aquifer system is such that the DEQ may have to start denying permit issuance in some areas of the Ground Water Management Area.
- Virginia Beach, the largest city in the area has very little fresh groundwater available to meet current or future needs. Virginia Beach relies on interbasin transfer from the Lake Gaston pipeline. If the pipeline is disrupted for any reason, it will have major consequences for Virginia Beach and the region.
- The Virginia Department of Health has advised the City of Newport News (Newport News Water Works) and James City County for the need to develop additional sources of supply, as the current demands have exceeded the "trigger level" contained in the *Commonwealth of Virginia Waterworks Regulations* for such action. To meet future demand, brackish groundwater or other saline waters will be the only available local resources.

- Portsmouth and Norfolk, the older cities in the area, developed the limited surface water supplies before the newer cities of Chesapeake, Suffolk, and Virginia Beach came into existence. Portsmouth and Norfolk have sufficient water supplies to meet their current needs and supply their surplus water to Virginia Beach and Chesapeake. However, the surplus is not adequate to meet the needs of these cities where much of the population growth is occurring.
- The proposed King William Reservoir project will supply only up to 60% of the lower Peninsula's future water needs. Desalination of brackish groundwater along with enhanced water conservation are considered as potential ways to supplement additional 40% demand.
- Construction of additional reservoirs in eastern Virginia is less likely because of environmental concerns, high cost, and difficulty in purchasing the needed land.
- Parts of New Kent, Charles City, Hanover, Henrico, and Petersburg are situated within the Eastern Virginia Ground Water Management Area. These localities will compete with Hampton Roads area and Middle Peninsula for available water resources in the region.
- Accomack and Northampton counties rely solely on groundwater to meet drinking water needs. Future economic growth in the area depends of availability of alternative source of water.

5.8. Existing Desalination Plants in Eastern Virginia

Currently, four brackish water desalination plants are operating in eastern Virginia: Lee Hall Reverse Osmosis Plant in Newport News, the Electrodialysis Reversal Plant in Suffolk, the Northwest River Water Treatment Plant in Chesapeake, and the Gloucester Desalination Plant in Gloucester County. A desalination plant to be operated by the James City Service Authority is under construction. Major features of the existing desalination plants in eastern Virginia are described below.

5.8.1. Lee Hall Reverse Osmosis Plant – Newport News

The Lee Hall plant was built in 1998 to meet water demand during drought periods in the Newport News Waterworks Service Area that include the cities of Newport News, Poquoson, and Hampton, and parts of York, and James City counties. The overall capacity of the Newport News Waterworks is 45 MGD. The reverse osmosis (RO) plant (finished water capacity 5.7 MGD) supplements the total water supplies by 10% in the service area.

The plant pumps brackish groundwater (TDS concentration approximately 2,300 mg/L TDS) from the upper and middle Potomac Aquifers and blends the treated RO product (TDS concentration 101 mg/L) with conventionally treated water for distribution to customers. The Newport News Waterworks maintains an agreement with Virginia Power for using electricity. The concentrate (TDS concentration 11,346 mg/L same as the James River) is disposed of into the James River using a 24-inch pipe. Lee Hall has its own incorporated power generators. During down times the plant can generate its own power and can sell the power back to Virginia Power. Table 5.8 shows a summary of technical and cost information for the Lee Hall OR plant [13, 14].

Table 5.8. Technical and Economic Features of the Lee Hall Reverse Osmosis Plant

Technology	
Type	Brackish water reverse osmosis
Membrane Provider	CPA 3 by Hydanautics
Pretreatment Chemicals	Anti-scalant
Posttreatment Chemicals	Remove CO_2, raise pH
Capacity (MGD)	5.7
Recovery	81%
Product Use	Drinking water
Year built	1998
Energy	
Source	Virginia Power
Costs	$444,615.65 (Fiscal Year '03)
Amount Consumed	1010.49 MW
Environment	
Brine TDS (mg/L)	11,346 mg/L, same as receiving water
Posttreatment of Brine	Add Oxygen
Feedwater TDS (mg/L)	2277 mg/L
Product TDS (mg/L)	101 mg/L
Disposal Method	Surface water -James River
Population Size Served	-----
Cost to the Public ($/$10^3$ gal)	$3.40
Total 0&M Costs	Approximately $664,000/yr
Notes	
*Mixes RO product with conventionally treated water for final product to customers.	
* 2 stage RO process.	
* Pumps brackish water from Upper and Middle Potomac Aquifers.	
* Uses 5-micron filters for pretreatment.	
* Pump pressure run between 200 and 300 psi.	
* Construction and development costs $18.5 million.	
* Use VFD pumps to control energy that pumps water through membranes.	

5.8.2. Suffolk Electrodialysis Reversal (EDR) Plant

This facility began operation in 1990 to meet water needs in the area. The plant is using brackish groundwater from the Middle Potomac Aquifer (TDS concentration 470 mg/L). The plant is capable of producing a maximum of 3.75 MGD of potable water utilizing the EDR stacks, and has the ability to produce an additional 3 MGD from a conventional treatment plant (sedimentation, filtration, disinfection) that receives water from a nearby lake system.

This facility uses 10-micron cartridge filters for EDR pretreatment. Ionics, Incorporated provided the membranes for this facility. According to the water production manager for the City of Suffolk these membranes have been very successful, lasting much longer than their life expectancy [18]. Using a pilot study, the EDR system of treatment was chosen primarily due to higher observed recovery levels (94%) versus those of reverse osmosis (85-89%). An additional factor influencing the decision to go with EDR was the fact that no chemical feeds were needed during operation. The EDR membranes are cleaned quarterly using an acid (hydrochloric) cleaning in place (CIP) system for scale removal and a salt (sodium chloride) CIP for removal of organics. Soda ash (sodium carbonate) is used to raise the pH quickly to an acceptable level after an acid CIP. These are the only chemicals this facility uses. The reduced use of hazardous chemicals is considered a great benefit of the EDR system. Table 5.9 shows technical and economical features of the Suffolk Electrodialysis Reversal Plant [18, 19].

The concentrate disposal from the plant was a challenge. It was initially a single point discharge into a nearby narrow estuarine river (Cedar Creek). Subsequent toxicity testing results revealed that the high levels of fluoride, along with a reduced mixing zone at the point of discharge, contributed to high levels of fluoride negatively impacting the discharge site. The test results showed elevated levels of fluoride existing in the creek at the discharge site with the possibility of it impacting organisms in that area. Extending the discharge line approximately a mile and a half to a much larger estuarine body of water (Nansemond River), along with the addition of an underwater diffuser, corrected the situation. Suffolk monitors this outlet and performs acute toxicity testing quarterly. An engineering firm out of Maryland, EA Engineering, performs the actual analysis.

Table 5.9. Technical and Economical Features of the Suffolk Electrodialysis Reversal Plant

Technology	
Type	Electrodialysis reversal.- Aquamite 120's (3)
Membrane Provider	Ionics [**]
Pretreatment Chemicals	None (10 micron cartridge filters)
Post treatment Chemicals	Chlorine
Capacity (MGD)	3.75 MGD
Recovery	94%
Product Use	Drinking Water
Year built	1990
Energy	
Source	Virginia Power
Costs	$0.05 / kWh
Amount Consumed	$0.18 / 1000 gal
Environment	
Brine TDS (mg/L)	3250
Post treatment of Brine	None
Feed water Source	Middle Potomac (550 ft -1000 ft depth below ground)
Feed water TDS (mg/L)	460-500
Product water TDS (mg/L)	160
Disposal Method	Surface water-Nansemond River (uses diffusers)
Population Size Served	49,000
Cost to Public ($/1000gal)	$3.55
[**]AR204SXZR412 (anion) and CCR65AZR412 (cation) membranes	
Notes	
* Plant currently in design phase for three additional EDR units	
* Water quality issue is of high fluoride	
* Life cycle of membranes and electrodes has been longer than expected.	
* Acid (HCl) CIP one unit/mo, salt CIP one unit/mo for organics, add soda ash to raise pH post acid CIP.	
* Production well – 400 h.p. (VFD drive)	

5.8.3. Northwest River Water Treatment Plant - Chesapeake

The Northwest River Water Treatment plant was built in the late 1970s and placed in operation as a conventional water treatment plant in March 1980. A large-scale upgrade was undertaken from 1996-1999 to add both surface and brackish groundwater RO capability. Brackish groundwater is obtained from four deep wells in the Middle Potomac Aquifer (TDS concentration - 5,000 mg/L) and the surface water supply comes from the Northwest River in southern Chesapeake. Total plant capacity is 10 MGD.

The plant originally used thin-film composite membrane elements for the groundwater RO and a cellulose-acetate blend (CAB) for the surface water RO, both supplied by Hydronautics. After approximately 4 years of service, the original surface water elements were replaced with spiral-wound low pressure composite membranes from the Tri-Sep Corporation. Energy recovery is not used at this facility. However, during the cold season the plant does utilize heat exchangers in which groundwater permeate is used to raise the temperature of surface RO feedwater. The increased water temperature results in lower feed pressures and thus lower energy costs.

The groundwater is pH-adjusted and filtered through 5-micron cartridge filters upstream of the RO units. Disinfection occurs downstream of the RO process in a dedicated pipeline designed to achieve the required free chlorine contact time followed by chloramination as the final means of disinfection. Surface water is first conventionally treated using coagulation, flocculation, sedimentation and filtration. The raw water TOC and chloride concentrations dictate the percentage of surface water that is also treated with RO membranes. The portion of raw water that is not treated with RO passes through dedicated manganese contactors (in addition to the conventional media filters) for removal of iron and manganese. These metals cannot be removed with chemical precipitation on the media filters due to the chlorine intolerant nature of the RO membranes.

RO-treated surface water (permeate) flows into the same disinfection pipeline as the RO-treated groundwater. Surface water treated with the manganese contactors has a dedicated disinfection pipeline separate from that used to treat ground and surface water RO permeate. Ultimately, both sources are combined into one flow stream which is treated with zinc orthophosphate, fluoride and caustic prior to on-site storage and final pumping to the distribution system. Concentrate from the RO units (approximately 3 MGD at full capacity) is disposed of via a 15-mile pipeline into the Southern Branch of the Elizabeth River. Table 5.10 shows major technical and economical features of the plant.

The City of Chesapeake is constructing a second water treatment facility, the first in eastern Virginia to use ultrafiltration membranes. The City's Aquifer Storage and Recovery (ASR) System is being incorporated into the plant as an additional water resource. ASR is a means of storing (injecting) surplus treated water underground into a confined aquifer and withdrawing it (recovery) during periods of high demand. Engineering studies estimate the total ASR storage capacity to be approximately

500 million gallons. This unique combination of treatment methodologies is being closely watched by nearby municipalities.

Table 5.10. Technical and Economical Features of the Northwest Reverse Osmosis Plant [15]

Technology	
Type	Surface Water, conventional and/or RO Brackish Groundwater, RO
Membrane Provider	Groundwater -Hydronautics Surface Water - Hydronautics (originally), TriSep (currently)
Pretreatment Chemicals	Scale inhibitor
Posttreatment Chemicals	Hypochlorite, Ammonia, Zinc Orthophosphate, Fluoride, Caustic
Capacity (MGD)	10 MGD
Recovery	75%
Product Use	Drinking water
Year built	Original plant 1980; RO upgrade 1999
Energy	
Source	Virginia Power
Costs	average of $69,526/month[1]
Amount Consumed	20,000 Btu/10^3 gal
Environment	
Brine TDS (mg/L)	20,000
Posttreatment of Brine	Add oxygen, control pH between 6 and 9, no chlorine residual, monitor P, N, TSS
Feedwater Source	Northwest River and Middle Potomac Aquifer
Feedwater TDS (mg/L)	5,000 mg/L from Middle Potomac
Disposal Method	Southern Branch of Elizabeth River
Population Size Served	91,228
Cost to Public	$3.83/1000 gal
1. This includes energy consumed by main building, membranes, and pumps for groundwater and Northwest River	
Notes	
* Different RO membranes to treat the surface water and the groundwater. The products from these treatments are blended to form potable final product. * River often has high organics or is tidal - sometimes river water must be fed through RO membranes to purify it. * Iron and manganese contactors precipitate out iron and manganese using sodium hypochlorite. * Feedwater from river is passed through heat exchangers to improve flow through membranes. This saves on energy costs. * Use VFD pumps to control energy that pumps water through membranes, and use SCADA as overall monitoring system.	

5.8.4. Gloucester Desalination Plant

The Gloucester Desalination Plant started operation on March 2003. This plant was originally a surface water treatment plant but a reverse osmosis unit for desalination was added to the conventional water treatment plant to increase the capacity by 2 MGD. The desalination plant uses brackish groundwater from two wells (TDS concentrations 2,248 mg/L and 4,272 mg/L). Table 5.11 shows some technical features of the Gloucester plant [20].

Table 5.11. Technical Features of the Gloucester Reverse Osmosis Plant

Technology	
Type	MS CPA3 and MS ESPA2
Membrane Provider	Membrane Systems
Pretreatment	Antiscalent and Socket Filters
Posttreatment Chemicals	pH adjustment and Cl for disinfection
Capacity (MGD)	2 MGD
Recovery	75-80%
Product Use	Drinking Water
Year built	Mar-03
Energy	
Source	Dominion Electric Power
Energy Reduction	Use 2-stage RO because more efficient
	Use VFD pumps
Costs	See notes
Amount Consumed	See notes
Environment	
Brine TDS (mg/L)	11,300
Posttreatment of Brine	Sent to nearby surface water, no adverse affects seen
Feedwater TDS (mg/L)	2248 from well 1, and 4272 from well 2 (Middle Potomac Aquifer)
Product TDS (mg/L)	Very low
Disposal Method	Surface water disposal
Population Size Served	Approximately 10,000
Cost of to the public ($/1000gal)	$6.63
Total 0&M Costs	Unknown at this time
Notes	
* RO product blended with treated surface water for final product	
Energy costs can be determined only by the increase in energy costs since the reverse osmosis plant was added. For January 2003 (w/o RO) energy costs were $3,051.18, and for January 2004 (w/RO) they were $9,480.50. For February 2003 (w/o RO) energy costs were $2,681.34 and for February 2004 (w/RO) they were $7,466.60. High cost to the public ($6.63/1,000 gal) is due to the high amount of debt. Eliminating debt, the cost would be $1.75/1,000 gallons.	

5.8.5. James City Service Authority Desalination Plant

James City County has used its permitted groundwater withdrawal capacity due to population growth and increased water demand. Therefore, the authority is building a 5 MGD reverse osmosis desalination plant to meet the projected water demand. The new plant is scheduled to come online January 2005 with an initial capacity of 2.5 MGD to be increased to 5 MGD by the year 2010. The plant will use brackish groundwater from the Lower and Middle Potomac aquifers (TDS concentration 1,000 to 2,500 mg/L). Table 5.12 shows major features of the proposed plant [21].

Table 5.12. Technical Features of the James City Service Authority Desalination Plant

Technology	
Type	Brackish water reverse osmosis
Membrane Provider	----
Pretreatment	Cartridge Filters
Posttreatment Chemicals	Caustic, calcium chloride
Capacity (MGD)	2.5 to upgrade to 5
Recovery	80%
Product Use	Drinking water
Year built	First phase 2005, Expansion 2010
Energy	
Source	----
Costs	----
Amount Consumed	36 10^3 Btu/hr per day
Energy Reduction?	All major pumps driven by VFD's
Environment	
Feedwater Source	Middle and Lower Potomac Aquifers
Brine TDS (mg/L)	13,000
Posttreatment of Brine	Aeration to meet DO requirements
Feedwater TDS (mg/L)	Middle Potomac: 1,000-1,100 mg/L
	Lower Potomac: 2,000-2,500 mg/L
Product TDS (mg/L)	< 350 mg/L
Disposal Method	James River
Population Size Served	----
Cost of Product ($/gal)	----
Total 0&M Costs	----
Notes	
This information is based on a study performed by Buchart Horn, Inc. For the James City Service Authority, prepared on June 2002	

5.8.6. Desalination Plants in North Carolina. For reference purposes, technical features for several desalination plants in North Carolina are provided in Appendix 5A.

5.9. Feasibility of Using Desalination Technologies in Eastern Virginia

For studying the feasibility of desalination in eastern Virginia, the following issues will be considered: availability of source water for desalination, environmental concerns and permit issues, available energy sources, and cost issues. A discussion of these topics is provided below.

5.9.1. Potential Water Sources for Desalination

Potential available water sources for desalination in eastern Virginia include brackish groundwater, tidal river waters, the Chesapeake Bay, and the Atlantic Ocean. Table 5.13a, 5.13b and 5.13c show potential water sources and corresponding water salinity for those sources in the Hampton Roads area, Accomack/Northampton Peninsula, and Middle Peninsula, respectively.

Table 5.13a. Surface and Groundwater Availability for Desalination in Hampton Roads

Water Source	Typical TDS (mg/L)		Availability
Groundwater			
Columbia Aquifer	0-500		Low
Yorktown-Eastover Aquifer	>500		Low
Chickahominy-Piney Point Aquifer	>500		Low
Aquia Aquifer	>1,000		Low
Upper Potomac	Virginia Beach Area	Gloucester Area	High
	>19,000	>1,000	High
Middle Potomac	>19,000	>1,000	High
Lower Potomac	>19,000	>1,000	High
Surface Water			
James River	20,000-30,000		High
York River	25,000-30,000		High
Chesapeake Bay	30,000-35,000		High
Atlantic Ocean	35,000-45,000		Very High

In the Hampton Roads area only the Potomac aquifers may have adequate amounts of brackish water available. The 80% drawdown criterion discussed earlier applies to withdrawals from brackish aquifers as well. If permits can be attained, pumping from the Potomac aquifers can be a potential source for desalination. In terms of quantity, surface water sources in the area are more reliable than groundwater. Tidal waters, the Chesapeake Bay, and the Atlantic Ocean can be major sources of water for desalination. However, to use these sources, significant levels of pretreatment will be required due to the large amounts of solids in the water and the tidal nature of the system which will require innovative treatment design. In addition, because of industrial and military activities in the waterways around Norfolk the selection of the most appropriate location of the water intakes should be studied very carefully. At present, pumping from the Chesapeake Bay is a less likely alternative because of the strict regulations applied to the Bay. To use water from the Atlantic Ocean, the ideal location for a desalination plant would be somewhere on the Virginia Beach coast. The feasibility of this option should be studied in conjunction with the Virginia Beach water distribution system, currently supplied from Norfolk in the west.

In the Accomack/Northampton Peninsula, the surface water supplies are limited to the Chesapeake Bay and the Atlantic Ocean. The hydrologic and environmental conditions in the peninsula are similar to the coast of North Carolina (Appendix 5A) where desalination plants are operating. Experiences in North Carolina can be useful to desalination issues in Accomack/Northampton Peninsula. However, it should be noted that the economic conditions in the Accomack/Northhampton Peninsula are much different than the North Carolina coast. The Peninsula is mostly rural and is supported by agricultural industry while the North Carolina coast is supported mainly by tourism.

Table 5.13b. Surface and Groundwater Availability in Accomack/Northampton Peninsula

Water Source	**Typical TDS (mg/L)**	**Availability**
Groundwater		
Columbia Aquifer	0-500	Fairly low
Yorktown-Eastover Aquifer	0-500	
Chickahominy-Piney Point Aquifer	>500	
Aquia Aquifer	>500	Fairly low
Upper Potomac	>1,000	High
Middle Potomac		High
Lower Potomac		High
Surface Water		
Atlantic Ocean	35,000-45,000	Very High
Chesapeake Bay	30,000-35,000	High

In the Middle Peninsula, less is known about the capacities of freshwater aquifers in the area. Also, there is a lack of data on aquifer salinity. Salinity appears to be high in aquifers in the vicinity of the town of West Point. The Potomac aquifer in the Gloucester area has high chloride levels. Surface water withdrawal from three rivers; York, Rappahannock and Mattaponi is an option of the Peninsula to meet future water demand. Table 5.13c shows the estimated salinities of surface water and groundwater sources.

Table 5.13c. Surface and Groundwater Availability in Middle Peninsula

Water Source	Typical TDS (mg/L)	Availability
Groundwater		
Columbia Aquifer	0-500	32-57 MGD is estimated total for the region
Yorktown-Eastover Aquifer	Increases closer to coast	
Chickahominy-Piney Point Aquifer		
Aquia Aquifer		
Upper Potomac	>1,000 in Gloucester	
Middle Potomac		
Lower Potomac		
Surface Water		
York River	25,000-35,000 at mouth, decreases moving inland	High
Rappahannock River	20,000-30,000 at river mouth	High
Chesapeake Bay	30,000-35,000	High

5.9.2. Environmental Concerns for Implementing Desalination in Eastern Virginia

The two major environmental concerns are the effects of concentrate (reject salt solution or residual stream) disposal and surface water withdrawal on the ecosystem. The third concern relates to effects, caused by energy consumption, on the environment. Chapter 3 of this report provides a detailed discussion of the environmental impacts of desalination.

The concentrate contains mostly salts and small amounts of pretreatment and cleaning chemicals. It has elevated temperatures that could adversely impact plants and animals of receiving waters in the vicinity of discharge outfall. Selecting an effective concentrate disposal technique depends on parameters such as water treatment, plant capacity, concentrate characteristics, and quality of receiving water. Specific measures can be taken on a case-by-case basis to minimize the environmental effects, such as using diffusers or diluting the concentrate. If the receiving water salinity is low, significant dilution or other measures will be required.

The concentrate can be disposed of using a variety of techniques. The most common disposal method in eastern Virginia is surface water disposal. Other applicable methods are zero-liquid discharge (ZLD) that further treats the brine. Transferring the concentrate to a wastewater treatment plant for further treatment is also an option. However, wastewater treatment plants are not always able to handle the added load of salts because it can be harmful to the biological treatment process. Although surface water disposal requires many permits and extensive monitoring (see Section 5.8.3 of this report), it is considered the most appropriate disposal option in eastern Virginia. Studies are needed on the cost-effectiveness and practicality of using other concentrate disposal technologies in eastern Virginia.

Withdrawal of the feedwater from surface water sources will have environmental consequences. Withdrawal can cause impingement and entrainment issues. Impingement occurs when animals collide with the screen at the intake pipe. Entrainment occurs when animals are pulled into the pipe and are killed during the processing of the water. Certain precautions need to be taken when constructing intake pipes to prevent such occurrences. Technologies exist that use appropriately sized screens to prevent or limit such environmental concerns. Structures such as onshore intake wells and infiltration galleries have proven effective to prevent impingement and entrainment.

The desalination process is often energy-intensive and desalination plants, therefore, can have an indirect impact on the environment. With the burning of fossil fuels and increased energy use comes increased air pollution and gas emissions. Gaseous emissions from a desalination plant complex include carbon monoxide (CO), nitric oxide (NO), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2) that can be harmful to public health. There is also concern regarding large amounts of chemicals being stored at the plants near population centers. The risk of a chemical spill requires that chemicals be kept away from residential areas. Noise can be another public concern.

5.9.3. Permits and Regulatory Requirements for Desalination Plants

There are two major regulatory and permitting issues that relate to planning and implementing desalination plants. Issue 1 relates to developing and using a brackish or saline water source for desalination. Issue 2 relates to discharge and disposal of concentrate (brine) and other byproducts of the desalination plants. An overview of permit requirements is provided below.

5.9.3.1. Developing Groundwater Sources

Developing the brackish groundwater follows the established permitting regulations for developing aquifers in Virginia. These regulations are defined in Section 62.1–256 of the Ground Water Management Act of 1992 (Chapter 25, Title 62.1 of the Code of Virginia) and the Ground Water Withdrawal Regulation (9 VAC 25-610-10 et seq). The DEQ staff reviews the permit applications for the proposed withdrawals in groundwater management areas. The DEQ has adapted the Virginia Coastal Plain Model (VCPM) to assist its staff in groundwater management decisions. For details, see Section 5.3.1 of this report. The State Water Control Board authorizes or declines the permit to withdraw water and use the groundwater.

The permit includes information on groundwater withdrawal points (aquifer and its location), maximum pump settings for each target aquifer, water level and water quality monitoring wells. The permit may also include a Water Conservation and Management Plan and a Mitigation Plan. The purpose of the Mitigation Plan is to provide a dispute resolution mechanism that existing and grandfathered groundwater users can use to resolve claims that may arise due to groundwater withdrawals from the wells owned and operated by the permitee.

5.9.3.2. Developing Surface Water Sources

For surface water development the current Local-State-Federal Joint Permit Application (JPA) process is used to review proposed intake structures. The JPA process allows for review by the Army Corps of Engineers (401 Certification), the Virginia Marine Resources Commission (VMRC), the Virginia Department of Environmental Quality (VWP Permit), and local Wetlands Boards. In addition to the regulatory agencies listed above, the JPA is sent to other agencies for comment. Depending on the nature and location of a project, VMRC generally requests comments from the Virginia Institute of Marine Science, the Department of Health, the Department of Game and Inland Fisheries, the Department of Conservation and Recreation, the Chesapeake Bay Local Assistance Department, the Department of Historic Resources and others prior to issuing a construction permit. The JPA is used by the Corps to coordinate review and comment by other federal agencies such as the EPA, the U.S. Fish and Wildlife Service, and the National Marine Fishery Service.

Permits would be required from the Marine Resources Commission for placement and operation of any intake structures on or over State-owned submerged lands pursuant to Section 28.2-1204 and 28.2-1205 of the Code of Virginia. Section 28.2-1205 requires that, in addition to other factors, consideration shall be given to the public and private benefits of the encroachments over State-owned submerged lands and the effect of any structures on other reasonable and permissible uses of State waters and State-owned bottom lands; marine and fisheries resources of the Commonwealth; tidal wetlands; adjacent or nearby properties; water quality; and submerged aquatic vegetation. This code section also specifies that the Commission when determining to grant or deny any permit shall be guided by the provisions of Article XI, Section I of the Constitution of Virginia and shall exercise its authority consistent with the public trust doctrine. It should be noted that VMRC does not authorize withdrawal limits, but would respond to a request for comments by the DEQ as part of its review for withdrawal authorization. Intake structures would need to be sited and operated so as to avoid or minimize the effects to those resources identified in Section 28.2-1205 and to avoid conflicts with other uses. Such uses could include but may not be limited to commercial and recreational fishing, navigation, recreational boating, as well as shellfish harvest and aquaculture.

Developing a surface water source will require permit review from the Army Corps of Engineers [22]. The legislative origins of the program are the Rivers and Harbors Acts of 1890 (superseded) and 1899 (33 U.S.C. 401, et seq.). The geographic jurisdiction of the Rivers and Harbors Act of 1899 includes all navigable waters of the United States which are defined (33 CFR Part 329) as, "those waters that are subject to the ebb and flow of the tide and/or are presently used, or have been used in the past, or may be susceptible to use to transport interstate or foreign commerce." This jurisdiction extends seaward to include all ocean waters within a zone three nautical miles from the coastline (the "territorial seas").

Limited authorities extend across the outer continental shelf for artificial islands, installations and other devices (see 43 U.S.C. 333 (e)).

Activities requiring Section 10 permits include structures (e.g., piers, wharfs, breakwaters, bulkheads, jetties, weirs, transmission lines) and work such as dredging or disposal of dredged material, or excavation, filling, or other modifications to the navigable waters of the United States. In 1972, amendments to the Federal Water Pollution Control Act added what is commonly called Section 404 authority (33 U.S.C. 1344) to the program. The Secretary of the Army, acting through the Chief of Engineers, is authorized to issue permits, after notice and opportunity for public hearings, for the discharge of dredged or fill material into waters of the United States at specified disposal sites. Selection of such sites must be in accordance with guidelines developed by the Environmental Protection Agency (EPA) in conjunction with the Secretary of the Army; these guidelines are known as the 404(b)(1) Guidelines. The discharge of all other pollutants into waters of the U. S. is regulated under Section 402 of the Act, which supersedes the Section 13 permitting authority mentioned above.

5.9.3.3. Concentrate Discharge and Disposal

In Virginia, the discharge from desalination plants is regulated and permitted as industrial discharge for manufacturing operation (SIC Code 4941). The manufacturing operation consists of the owner operating a potable water treatment plant. The authorization to discharge concentrate is issued under the Virginia Pollutant Discharge Elimination System and the Virginia State Water Control Law in compliance with the provisions of the Clean Water Act as amended. The owner of the desalination plant can be authorized to discharge the concentrate in accordance with the effluent limitations, monitoring requirements, and other conditions set forth in the permit.

Effluent limitation and monitoring requirements include eight effluent characteristics: Flow (MGD), pH (S.U.), Dissolved Oxygen (mg/L), Total Suspended Solids (mg/L), Total Phosphorus (mg/L), Total Nitrogen (mg/L), Total Dissolved Solids (mg/L), and Total Residual Chlorine (µg/L). No limit is set for total dissolved solids (TDS) concentration in the effluent, although monthly monitoring and reporting is required. Disposal of concentrate (brine) should be managed, limited or sited so as to avoid impacts to marine fishery resources and their habitats. The permit may include requirements for special conditions such as discharge into nutrient enriched waters, compliance with the toxic management program[8] (biological monitoring of receiving waters), and a toxicity reduction evaluation plan. Effluent limitations are based on state water quality standards and best professional judgment.

[8] Virginia follows the national goals set out by National Pollutant Discharge Elimination System (NPDES) that regulates water quality. It requires Whole Effluent Toxicity (WET) tests to be performed by persons responsible for discharging pollutant that may be considered toxic to organisms in the receiving water. The authority to use WET tests for regulating discharge is found under 9VAC 25-31-220 D.1. a.-d. Brine disposal and discharge from water treatment plants fall under this category [23, 24].

The Virginia Department of Health conducts reviews and comments on discharge permits. VMRC would only comment on the review of discharge permit limits as requested by the Virginia Department of Environmental Quality. Ocean disposal of concentrate is practiced in other states and remains a future option in Virginia. Commonwealth ownership of submerged lands extends offshore to the 3-mile limit and includes all the beds of the Chesapeake Bay and tributaries. All Virginia laws for water use and concentrate disposal apply to this 3-mile limit.

5.9.4. Potential Energy Providers for Desalination

One of the largest costs of desalination is the cost of energy required to run a plant. The amount of energy required to desalinate water varies with the water quality, type of technology, and a variety of other factors such as the temperature of feedwater and if energy recovery devices are being incorporated. Cogeneration plants where power plants and desalination plants can share resources are ideal for implementing cost-effective desalination. See Chapter 4 of this report about details related to energy issues. Table 5.14 shows existing and proposed major power plants in eastern Virginia. These power plants vary in size, and the type of fuel used.

Table 5.14 Power Plants in Eastern Virginia

Existing Plants		Energy Produced 10^9 Btu/hr (MW)	Fuel Type
Accomack Co.	Commonwealth Chesapeake Power Station	1.2 (350)	Natural Gas
	http://www.tecopowerservices.com/PSChesapeake.html		
Chesapeake	Chesapeake Energy Center	2.6 (760)	Coal/Petroleum
	http://www.dom.com/about/stations/fossil/chesapeake.jsp		
Yorktown	Yorktown Power Station	3.9 (1150)	Coal
	http://www.dom.com/about/stations/fossil/yorktown.jsp		
Hopewell	Hopewell Cogeneration Plant	0.4 (120)	Coal
	http://www.cogentrix.com/plants/hopewell.html		
Portsmouth	Portsmouth Cogeneration Plant	0.4 (120)	Coal
	http://www.cogentrix.com/plants/portsmouth.html		
Hanover Co.	Doswell Limited Partnership	2.9 (836)	Unknown
Sussex Co.	LS Power Development	Unknown	Unknown
Surry Co.	Surry Power Plant	5.5 (1602)	Nuclear
	http://www.dom.com/about/stations/nuclear/index.jsp		
Louisa Co.	Lake Anna Power Plant	Unknown	Nuclear
Proposed Plants			
Isle of Wight Co.	Duke Energy	2.4 (700)	Coal
Charles City Co.	Chickahominy Power	2.5 (728)	Natural Gas
James City Co.	James City Energy	2.0 (580)	Natural Gas

5.9.5. Costs of Implementing Desalination Technologies

This section describes an overview of cost issues related to desalination. The section provides a preliminary analysis of water production costs using an existing desalination economic model. Economic analyses for a given desalination are site-specific and usually cannot be generalized for applications to other situations. Information provided in this section aims to introduce basic economic concepts and can be used only as a reference.

5.9.5.1. Factors Affecting Product Cost

In general, unit product cost is affected by several site-specific design and operational variables as described below:

Quality of feedwater. Low feedwater TDS concentration allows for higher conversion rates to freshwater for a given quantity of power usage. As a result, the plant can operate with lower power consumption and dosing of antiscalant chemicals. Down time related to chemical scaling is also considerably reduced. In general, compared to brackish groundwater, surface waters will need a higher level of pretreatment because of higher level of impurity, therefore higher production cost.

Plant capacity. Plants with larger capacity require a higher initial capital investment, but the unit production cost is lower than those plants with lower capacity due to economies of scale.

Energy cost. Since energy cost is one of the main costs in production, the availability of a cheap electricity (or other) power source will considerably reduce the production cost.

Site conditions. If there is an existing water treatment plant, the installation of new units as an expansion of existing sites may eliminate the costs associated with facilities for feedwater intake, brine disposal, and feedwater pretreatment.

Qualified labor. Qualified labor will increase productivity, such as shorter downtimes.

5.9.5.2. The Production Costs

The per unit product cost is a factor of the plant capacity, the type of technology, and the process design features. The plant capacity determines the size of various treatment equipment, pumping units, and water storage and distribution units. The type of technology determines requirements for pretreatment and post-treatment equipment and chemical consumption. The process design features affect the consumption of electric power.

The production cost consists of starting costs and operation and maintenance (O&M) costs. These costs are usually considered after site condition and type of desalination technology have been specified. Starting costs and O&M costs are described below.

Starting costs

The starting costs are the costs incurred in the initial construction stages. Starting costs can be further divided into direct capital cost and indirect capital cost. Direct capital costs usually include the purchase cost of major equipment, auxiliary equipment, land, and construction. The indirect capital costs are usually estimated as percentages of the total direct capital cost.

Direct costs

Land. The cost of land may vary considerably, from zero to a sum that depends on site characteristics.

Production wells. The construction cost of production wells depends on capacity requirement.

Water intake structure. The construction cost of the surface water intake structure depends on the capacity requirement and the need to meet environmental regulations.

Process equipment. These costs cover processing equipment, instrumentation and controls, pipes and valves, electric wiring, pumps, process cleaning systems, pretreatment and post-treatment equipment. This category is one of the main costs in the initial stages. It depends on the specification for the type of desalination technologies and the production capacity.

Auxiliary equipment. Auxiliary equipment includes open intakes or wells, transmission piping, storage tanks, generators and transformers, pumps, pipes and valves.

Building construction. Building costs cover the construction of such buildings as control rooms, laboratories, offices and workshops. It is site-specific and depends on the building type.

Membranes. The cost of membrane modules depends on the plant capacity.

Brine disposal. The construction costs for brine disposal depends on the type of desalination technology, the plant capacity, the discharge location, and the applicable environmental regulations. It should be calculated on a case-by-case basis.

Other costs

Freight and insurance. This cost is typically equal to 5% of the total direct capital cost.

Construction overhead. Construction overhead costs include fringe benefits, labor burden, field supervision, temporary facilities, construction equipment, small tools, contractor's profit and miscellaneous expenses. They are about 15% of direct material and labor costs (depends on the plant size).

Owner's costs. These include engineering and legal fees, and are approximately 10% of direct materials and labor costs.

Contingency costs. These are costs for additional services. It is generally estimated at 10% of the total direct costs.

5.9.5.3. Operating and Maintenance (O&M) Costs

The operating and maintenance costs can be divided into two categories: fixed costs and variable costs.

Fixed costs. Fixed costs include insurance and amortization. Usually, the insurance cost is 0.5% of the total capital cost. Amortization covers the annual interest payments for direct and indirect costs and depends on the interest rate and the lifetime of the plant.

Variable costs. The main variable costs are labor, energy, chemicals, maintenance, and miscellaneous items. Labor, energy and chemical costs are site-specific and depend on the availability of labor, the energy supply, and the chemicals supply. The local market prices can be used to calculate the variable costs.

The estimated cost for membrane replacement depends on the quality of the feedwater. For low-salinity brackish water, the membrane replacement rate is about 5% per year. For high-salinity seawater the membrane replacement could be as high as 20%. The cost for maintenance and spare parts is typically less than 2% of the total capital cost on an annual basis.

5.9.5.4. Estimating Water Production Cost

In this report, the Desalination Economic Evaluation Program (DEEP), developed by the International Atomic Energy Agency (IAEA), was used to estimate water production costs for conditions similar to those in eastern Virginia. DEEP version 2.1 is based on a hybrid Microsoft Excel spreadsheet and Visual Basic methodology. It is designed for research purposes and does not perform industry cost analysis [25]. The Virginia Water Resource Research Center at Virginia Tech established a license agreement with the IAEA to acquire permission for using DEEP in this study.[9]

DEEP was originally developed to demonstrate the economic competitiveness of large-scale implementation of desalination technologies using nuclear energy versus other alternative energy supply options. DEEP performs the following three functions:

- Calculates the cost of electricity and freshwater production as a function of feedwater quality, plant capacity, energy source, type of desalination technology, and site-specific parameters.
- Provides a side-by-side comparison of several design alternatives on a consistent basis with common assumptions; and
- Facilitates quick identification of the lowest cost options for providing specified quantities of desalted water and/or power at a given location.

In eastern Virginia, reverse osmosis (RO) is the common desalination technology and commercial electricity is the most likely energy source for a desalination plant. Therefore, it was necessary to modify

[9] DEEP software can be obtained from the IAEA. For details the reader is referred to the IAEA website at www.iaea.org.

the original DEEP to be applicable to Virginia conditions. An IAEA programming specialist provided assistance to design a new reference case: Stand-Alone Reverse Osmosis Powered by Commercial Electricity (CE+SA-RO case) to be used in this study. The modified DEEP model was installed on a Virginia Tech computer and a number of test cases were run to evaluate the model's overall performance. Test cases were run for different water plant capacities and different concentration levels of total dissolved solids (TDS). Test results, in general, were consistent with those documented findings in the literature related to RO technology.

5.9.5.5. DEEP input requirements

The required input data can be divided into three categories:

Model data. It refers to certain technical parameters and their defaulted values that are built within the model and are specified by DEEP designers to maintain the model's integrity. The user cannot change these parameters.

User input data. Data in this category are usually site-specific, such as the case name, the site location, the plant capacity, and the type of technology and must be input by the user. For example, in eastern Virginia, it was assumed that the plant type is a stand-alone reverse osmosis plant with spiral wound RO membrane. The plant capacity range was assumed from 0.1 MGD to 50 MGD.

Default data. For each type of desalination technology, DEEP specifies a number of default technical parameters that characterize plant performance and economic parameters such as discount rate, interest rate, etc. For a generic study, users normally use the default data. But for more specific studies, users can change the default data accordingly. Table 5.15 shows the input variables (excluding the model data) used in the study.

Table 5.15. Input Variables Used in DEEP

Input Variables	Unit	DEEP Default Value	Value Used
Case identification and site characteristics			
Case Name	Text	Case	Case X
Assumed site location	Text	Site	Geographic area 1, 2, 3
User (required) water plant capacity at site	m^3/d	24001	0.1,0.5,1,5,10,25,50 (MGD)
RO membrane type	Text	SW	SW
Desalination plant type	Text	SA-RO	SA-RO
Technical parameters input data			
Average annual cooling water temperature	°C	21	default
Total dissolved solids	mg/L	38,500	1,000, 5,000, 10,000, 20,000, 35,000, 45,000
Factor auxiliary load	°C	0.0526	default
Electric motor efficiency		0.96	default
RO plant performance input data			
Stand-alone RO design cool water temp	°C	0	default
Optional unit size specification:	m^3/d	0	default
Saline water pump head	Bar	1.7	default
Saline water pump efficiency		0.85	default
Booster pump head	Bar	3.3	default
Booster pump efficiency		0.85	default
High head pump pressure rise	Bar	66	default
High head pump efficiency		0.85	default
Hydraulic pump hydr., coupling efficiency		0.97	default
Energy recovery efficiency		0.85	default
Other specific power use	kWh/m^3	0.7	default
RO plant planned outage rate		0.032	default
RO plant unplanned outage rate		0.06	default
Economic parameters input data			
Discount rate	% /year	8	default
Interest rate	% /year	8	default
Currency reference year		1998	2003
Initial year of operation		2005	2008
Plant economic life	year	30	default
Purchased electricity cost	$ / kWh	0.06	0.04
RO plant cost input data			
Base unit cost	$\$/(m^3/d)$	800	default
Optional in/outfall specific base cost	$\$/(m^3/d)$	0	default
Membrane equipment cost to total cost		0.1	default
RO plant cost contingency factor		0.1	default
RO plant owners cost factor		0.05	default
RO plant lead time	month	12	default
Average management salary	$ /year	66,000	Site-specific
Average labor salary	$ /year	29,700	Site-specific
O&M membrane replacement cost:	$\$/m^3$	0.05	default
O&M spare parts cost	$\$/m^3$	0.04	default

Specific O&M cost for pre-treatment	$/m^3$	0.03	default
Specific O&M cost for post-treatment	$/m^3$	0.01	default
RO plant O&M insurance cost:	%	0.5	default

5.9.5.6. Model output

DEEP output performance indicators include: recovery ratio, total power use, annual and average daily water production, and product TDS. Table 5.16 shows the cost items calculated by DEEP.

Table 5.16. DEEP Cost Breakdown for Stand Alone RO Water Plant

Items	**Unit**	**Test result**
Cost Calculation		
Correction factor for unit size		1.1096
Correction factor for number of units		0.8960
Correction factor for TDS and temperature		1.0424
Adjusted water plant specific cost	$/(m^3/d)$	829.0355
Stand-alone in/outfall specific cost	$/(m^3/d)$	289.9505
Stand-alone water plant specific cost	$/(m^3/d)$	1,118.9860
Stand-alone water plant adjusted base cost	M$	40.2835
Water plant owner's cost	M$	2.0142
Water plant contingency cost	M$	4.2298
Stand-alone water plant total construction cost	M$	46.5274
Number of management personnel		2
O&M management cost	M$/year	0.1320
Number of labor personnel		15
O&M labor cost	M$/year	0.4455
Annual materials cost	M$/year	1.7360
Annual insurance cost	M$/year	0.2326
Water plant O&M cost	M$/year	2.5461
Economic Evaluation		
Interest during construction	M$	1.8253
Total investment	M$	48.3527
Specific investment cost	$/(m^3/d)$	1343.1314
Annual water plant fixed charge	M$/year	4.2950
Annual water plant electric power cost	M$/year	2.1935
Annual water plant purchased electric power cost	M$/year	2.1935
Total annual required revenue	M$/year	11.2282
Total water cost	$/m^3$	0.9391

5.9.5.7. Model Results

Table 5.17 shows the calculated unit water costs (column 3) and the calculated O&M costs (column 5) for various plant capacities. The data reflects feedwater TDS concentrations for conditions similar to eastern Virginia when the electricity cost is assumed as a constant (0.04 $/kWh) and the water plant operates 365 days a year. Table 5.18 shows the estimated costs when electricity costs vary but the other conditions remain the same. Note that the unit water cost estimated by DEEP is the cost to the plant to produce the water. This is not the cost to consumer. To deliver water to the consumer, additional costs beyond water treatment must be added. For example, the costs for the distribution system's maintenance and replacement, the pumping station's O&M, other plant upgrades, the capital cost for plant and infrastructure upgrades and other equipment, quality insurance and compliance, billing and tracking, customer services, source protection efforts and increased security, etc. These costs apply to all systems and are in addition to the cost of the selected treatment technology. Therefore, the cost to the consumer will be higher than this number by some mark-up.

The results show that DEEP does not adequately calculate costs and model performance for small capacities but is more sensitive to large plant capacities (>25 MGD). This observation is based on the fact that the model shows no increase in water cost when TDS varies from 1,000 mg/L to 20,000 mg/L for varying capacities. It is known that higher TDS concentration result in higher energy (electricity) consumption and, consequently, a higher production cost. In addition, an inconsistent result is shown for the desalination plant capacity below 1 MGD. Table 5.17 shows that for such low capacities, the unit O&M cost is greater than the unit total water cost. Theoretically, total water cost includes O&M cost. This problem is caused by the limitation of DEEP for low-capacity inputs. DEEP design is based on the basic RO unit size with a default value of 12,000 cubic meters per day (about 3.2 MGD). When the water plant capacity in the model is specified below the default value of 3.2 MGD (in this case 0.1 MGD and 0.5 MGD), DEEP calculates the total water production cost per 1,000 gallons based on the default basic water capacity (3.2 MGD). Results in Table 5.17 are based on the basic default value of 3.2 MGD.

Table 5.17. Calculated Costs for Various Plant Capacities and TDS Concentrations

Water Plant Capacity (MGD)	TDS Concentration (mg/L)	Water Cost ($/1,000 gal)	Water Plant Annual O&M Costs (M$)	O& M costs ($/1,000 gal)
0.1	1,000	3.90	1.03	28.22
	5,000	3.90	1.03	28.22
	10,000	3.90	1.03	28.22
	20,000	3.90	1.03	28.22
	45,000	4.40	1.16	31.78
0.5	1,000	3.90	1.03	5.64
	5,000	3.90	1.03	5.64
	10,000	3.90	1.03	5.64
	20,000	3.90	1.03	5.64
	45,000	4.40	1.16	6.36
1	1,000	3.90	1.03	2.82
	5,000	3.90	1.03	2.82
	10,000	3.90	1.03	2.82
	20,000	3.90	1.03	2.82
	45,000	4.40	1.16	3.18
5	1,000	3.60	1.76	0.96
	5,000	3.60	1.76	0.96
	10,000	3.60	1.76	0.96
	20,000	3.60	1.76	0.96
10	1,000	3.20	3.07	0.84
	5,000	3.20	3.07	0.84
	10,000	3.20	3.07	0.84
	20,000	3.20	3.07	0.84
25	20,000	3.00	5.64	0.62
	35,000	3.10	5.81	0.64
	45,000	3.40	6.63	0.73
50	20,000	2.80	10.6	0.58
	35,000	2.90	10.93	0.60
	45,000	3.20	12.57	0.69

Table 5.18. Predicted Cost for Various Electricity Costs

Water Plant Capacity (MGD)	TDS Concentration (mg/L)	Water Cost ($/1,000 gal)	Water Plant Annual O&M Costs (M$)	O& M costs ($/1,000 gal)	Water Cost ($/1,000 gal)	Water Plant Annual O&M Costs (M$)	O& M costs ($/1,000 gal)	Water Cost ($/1,000 gal)	Water Plant Annual O&M Costs (M$)	O& M costs ($/1,000 gal)
		Electricity (0.04 $/kWh)			Electricity (0.05 $/kWh)			Electricity (0.07 $/kWh)		
	1,000	3.9	1.03	28.22	4.28	1.03	28.22	4.92	1.03	28.22
	5,000	3.9	1.03	28.22	4.28	1.03	28.22	4.92	1.03	28.22
	10,000	3.9	1.03	28.22	4.28	1.03	28.22	4.92	1.03	28.22
	20,000	3.9	1.03	28.22	4.28	1.03	28.22	4.92	1.03	28.22
0.1	45,000	4.4	1.16	31.78	4.81	1.16	31.78	5.53	1.16	31.78
	1,000	3.9	1.03	5.64	4.28	1.03	5.64	4.92	1.03	5.64
	5,000	3.9	1.03	5.64	4.28	1.03	5.64	4.92	1.03	5.64
	10,000	3.9	1.03	5.64	4.28	1.03	5.64	4.92	1.03	5.64
	20,000	3.9	1.03	5.64	4.28	1.03	5.64	4.92	1.03	5.64
0.5	45,000	4.4	1.16	6.36	4.81	1.16	6.36	5.53	1.16	6.36
	1,000	3.9	1.03	2.82	4.28	1.03	2.82	4.92	1.03	2.82
	5,000	3.9	1.03	2.82	4.28	1.03	2.82	4.92	1.03	2.82
	10,000	3.9	1.03	2.82	4.28	1.03	2.82	4.92	1.03	2.82
	20,000	3.9	1.03	2.82	4.28	1.03	2.82	4.92	1.03	2.82
1	45,000	4.4	1.16	3.18	4.81	1.16	3.18	5.53	1.16	3.18
	1,000	3.6	1.76	0.96	3.86	1.76	0.96	4.50	1.76	0.96
	5,000	3.6	1.76	0.96	3.86	1.76	0.96	4.50	1.76	0.96
	10,000	3.6	1.76	0.96	3.86	1.76	0.96	4.50	1.76	0.96
5	20,000	3.6	1.76	0.96	3.86	1.76	0.96	4.50	1.76	0.96
	1,000	3.2	3.07	0.84	3.56	3.07	0.84	4.20	3.07	0.84
	5,000	3.2	3.07	0.84	3.56	3.07	0.84	4.20	3.07	0.84
	10,000	3.2	3.07	0.84	3.56	3.07	0.84	4.20	3.07	0.84
10	20,000	3.2	3.07	0.84	3.56	3.07	0.84	4.20	3.07	0.84
	20,000	3	5.64	0.62	3.37	5.64	0.62	4.01	5.64	0.62
	35,000	3.1	5.81	0.64	3.44	5.81	0.64	4.13	5.81	0.64
25	45,000	3.4	6.63	0.73	3.79	6.63	0.73	4.54	6.63	0.73
	20,000	2.8	10.6	0.58	3.26	10.6	0.58	3.82	10.6	0.58
	35,000	2.9	10.93	0.6	3.26	10.93	0.6	3.94	10.93	0.6
50	45,000	3.2	12.57	0.69	3.60	12.57	0.69	4.31	12.57	0.69

Figure 5.4 shows the costs of the water according the TDS concentration of the feedwater (electricity cost set at 0.04 $/kWh) for all capacities. Because the lower capacity plants were less sensitive to TDS concentrations and results didn't vary, these lower capacities (0.1 MGD – 1 MGD) were grouped together in Figure 5.4. Figure 5.4 shows that the 50 MGD facility has the lowest unit water cost

and when the TDS concentration in the feedwater increases, so does the unit cost of the water. The unit water cost decreases as the capacity of the plant increases.

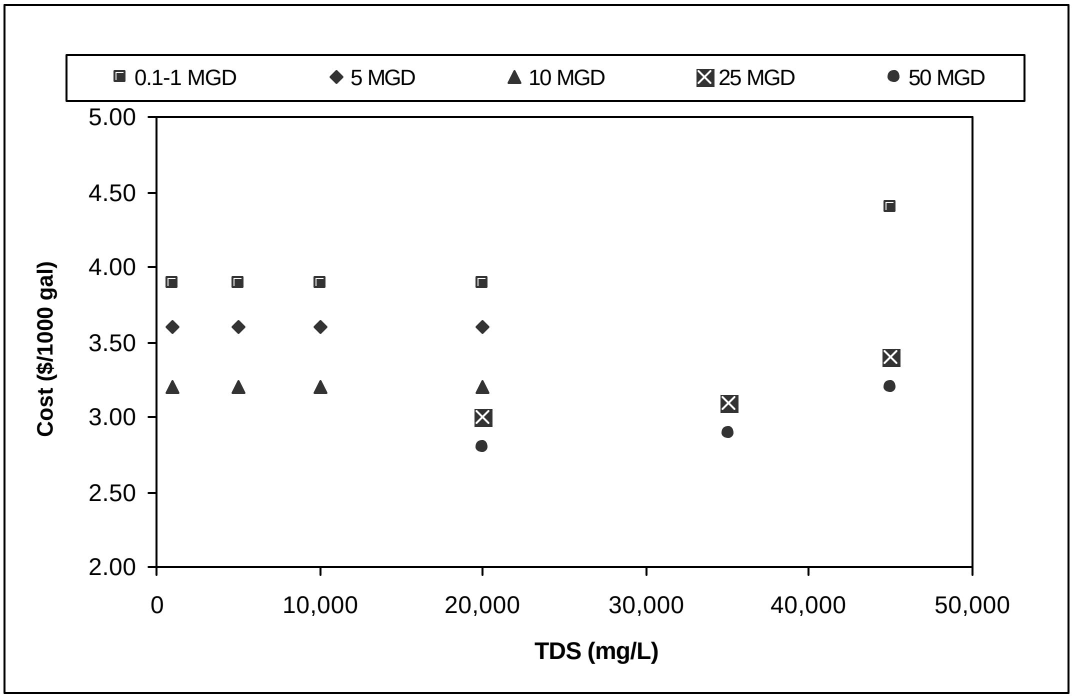

Figure 5.4. Unit Cost vs. TDS Concentration

Figure 5.5 (electricity cost set at 0.04 $/kWh) compares the O&M costs with the TDS concentration and plant capacity. It was necessary to break down the O&M costs to an amount of money per 1,000 gallons produced to accurately compare these numbers. Figure 5.5 shows that as the plant capacity increases the O&M costs per 1,000 gallons of water produced decreases. The O&M costs for a 0.1 MGD facility is high considering the amount of water being produced for the cost. This figure shows the expected result; a large-capacity plant is more economical than a small-capacity plant.

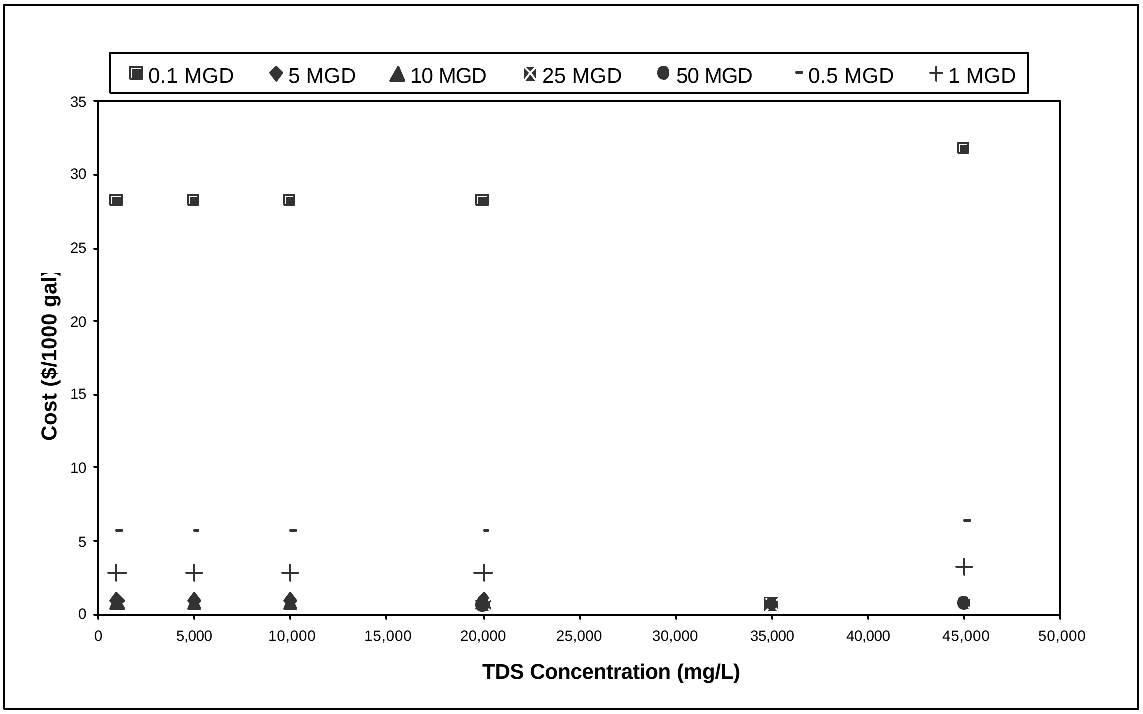

Figure 5.5. Water Plant O&M Cost vs. TDS Concentration

Figure 5.6-Figure 5.8 were generated to compare the O&M costs with the unit water costs for varying plant capacities (electricity cost set at 0.04 $/kWh). O&M costs and unit water costs appear to decrease as the plant capacity increases. However, diminishing returns occur as the amount of feedwater increases. For example, for the 10,000 mg/L TDS level, the total water production cost decreases from $3.9 per 1,000 gallons to $3.6 per 1,000 gallons to $3.2 per 1,000 gallons as the water plant capacity increases from 1 MGD to 5 MGD to 10 MGD, respectively. The production costs for the 5-MGD plant and 10-MGD plant vary little. Similarly, for 20,000 mg/L TDS level, there seems to be little difference between the production costs for a 5-MGD plant and a 50-MGD plant. This indicates that there is an optimum minimum design capacity that can be based on the TDS if all other things are equal.

Although plants with a capacity above the minimum design capacity would yield certain cost savings, the benefit increases at a decreasing rate. Therefore, for a given TDS, if all other things are equal, plants with the optimum, minimum capacity will be more economically sound than those larger or smaller plants. The data also indicates that the TDS level is positively correlated with the total water production cost. As the TDS level increases, the cost increases as well. This is especially the case if the optimum capacity can be reached. This shows that the optimized cost is desalinating feedwater with the least TDS possible and in a plant with the most capacity that demand will support.

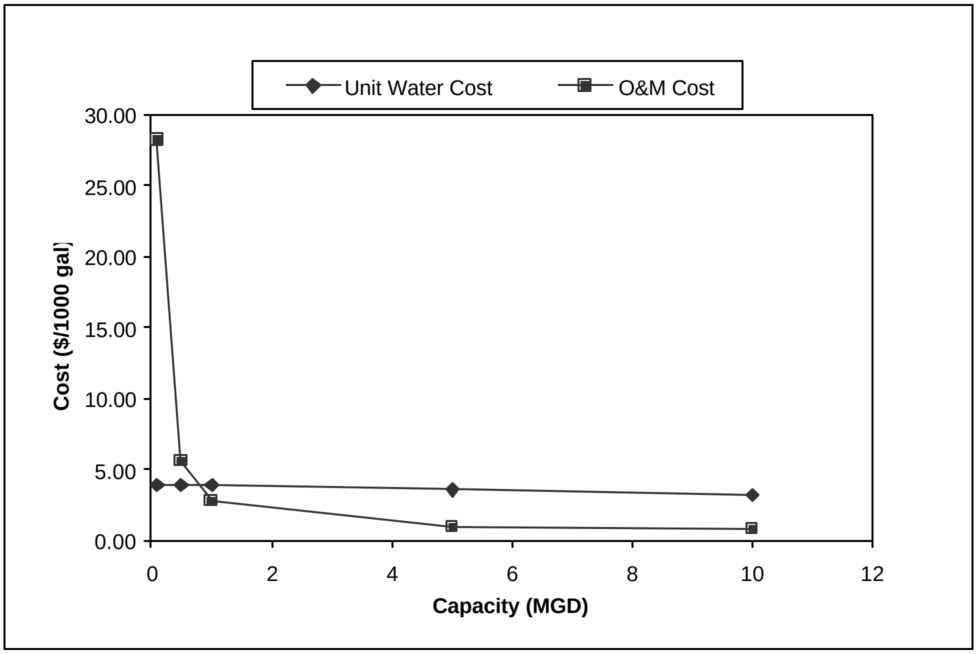

Figure 5.6. Cost vs. Plant Capacity at 10,000 mg/L TDS Concentration

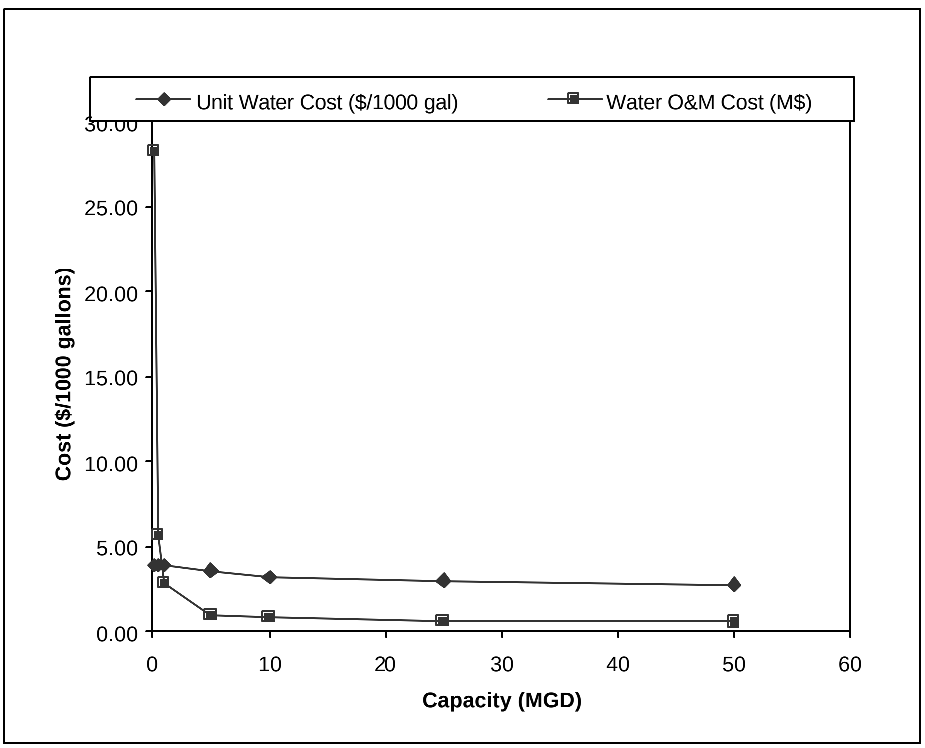

Figure 5.7. Cost vs. Plant Capacity at 20,000 mg/L TDS Concentration

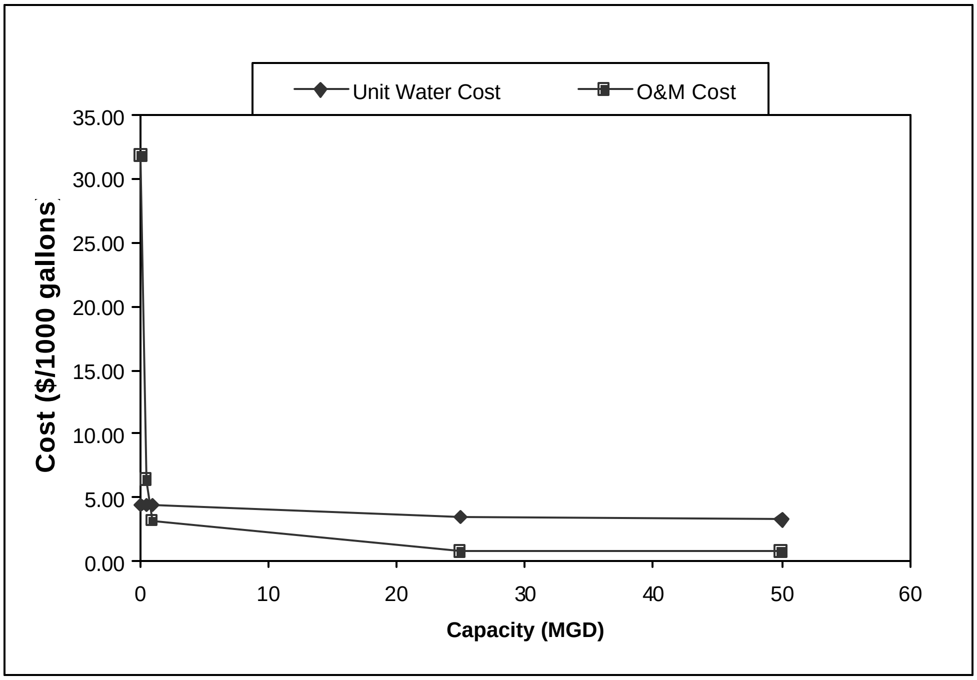

Figure 5.8. Cost vs. Plant Capacity at 45,000 mg/L TDS Concentration

5.9.5.8. Discussion of Economic Analysis

It is necessary to understand how the results of the economic analysis presented above may apply to scenarios in eastern Virginia. These results indicate costs for specific plant capacity and TDS concentrations that could be used as a reference for certain localities. For instance, current population trends show that the Eastern Shore will not be able to support a large-capacity desalination plant, unless industry growth encourages this. The Eastern Shore will most likely need a facility that is in the lower to middle range capacity, between 0.1 MGD and 10 MGD. Depending on the salinity of the water source (groundwater, Chesapeake Bay or the Ocean), any of the TDS value inputs may be applicable. The Virginia Beach area, however, may be able to support any and all of the capacity and TDS concentrations shown in Table 5.17. Virginia Beach may need a small-capacity desalination plant to supplement its current supply or the region may need a very large-capacity plant to replace an existing water source if the current sources were no longer viable, or to supplement the current supply if growth in the area continues.

The results from this economic study compare well to water costs of existing facilities. Unit production costs in North Carolina are between $0.44/1,000 gallons (North Reverse Osmosis Plant) to $4.00/1,000 gallons (Cape Hatteras RO facility). According to an economic study performed using DEEP, RO production costs range between $2.19/1,000 gallons and $8.97/1,000 gallons. So much of these costs are dependent on the site-specific factors of the plant (site conditions, capacity, energy costs) [26]. Unit production costs in this study fall in a reasonable range of values.

The O&M costs determined by the DEEP software seem reasonable. When comparing these values with O&M costs for the Newport News facility it can be seen that they compare nicely. The O&M costs for Newport News are estimated at $664,000 for 1.9 MGD. When the plant is running at full capacity the O&M costs are estimated to be $1.19 million.

The operating and management costs increase with the size of the plant when looking at just overall costs. This is expected, because more management is involved with a larger facility. However when this overall cost is broken down into cost per thousand gallons of water produced we see that O&M costs decrease significantly with an increase in capacity. From analyzing this data it can be seen that larger facilities are more economical when considering price per unit of water produced.

It is noticed that desalination costs increase with feedwater salinity. This is because energy input is related to the TDS concentration of the feedwater. Desalination with membranes requires energy in the form of pressure to pump water through the membranes. At higher salinities, higher amounts of pressure are required to get the desired pure water. An increase in energy inputs will lead to an increase in a plant's energy costs. In turn, there is an increase in the cost of the water per gallon. Another reason for the cost increase is that when handling higher salinities the cartridge filters may need to be replaced more often and membranes may have shorter lifespans than those processing lower salinity water. As already mentioned, optimized costs are when feedwater is at low salinity and the plant capacity is high. It is also noticed that desalination costs increase with the increase of electric rates. It is likely that electricity costs will affect the desalination cost as in some places marginal rates have been charged.

The analyses from this study help explain the cost dynamics of desalination. The main cost parameters are plant size and feedwater TDS concentration. Changes in certain economic parameters (e.g. electricity rate) will also affect the final water production costs. The capacities and feedwater concentrations are typical of existing RO facilities. This analysis is based on using a model that is not designed for industry cost analysis. DEEP is designed for research only and only provides approximations. It was our goal to apply this model, as close as possible, to actual Virginia conditions.

5.9.5.9. Desalination Costs to the Public

The final cost of desalinated water to the customers, in general, is higher than the production cost of water. For example, the current water rates to most customers in Hampton Roads area vary from $3.22 to $3.84 per 1,000 gallons. The cost to actually treat and deliver water varies widely, but in most conventional cases is less than $1 per 1,000 gallons. The customer rates include administrative, billing, meter reading and repair, pipeline and distribution system design-repair-replacement, taxes, planning, leak detection, public information/education, and other costs generally treated as overhead. Some utilities may include a cost factor to stabilize rates or fund other county/city programs. Due to the existence of additional costs, if the actual cost to treat and deliver water ever escalated to the ranges presented in Table 5.17 ($4 to $10 per 1,000 gallons) the actual rate charged to customers would be much higher.

Costs to the public from the existing desalination plants in eastern Virginia can be used as a good reference. For the Lee Hall RO desalination plant in Newport News, the estimated cost to the public is $3.40 per 1,000 gallons; for the Suffolk EDR plant, the estimated cost to the public is $3.55 per 1,000 gallons. For the Northwest River Treatment plant in Chesapeake and the Gloucester desalination plant the estimated cost to the public is $3.83 per 1,000 gallons and $6.63 per 1,000 gallons, respectively. For the Gloucester plant, the $6.63 per 1,000 gallons cost is reflects the high amount of debt. Eliminating the debt, the cost would be $1.75 per 1,000 gallons. A 1997 study compared costs for the Lake Gaston project to seawater desalination to meet the 39.6 MGD need for Virginia Beach. The study estimated the unit cost for the Lake Gaston project as $2.79 per 1,000 gallons and for the desalination of seawater as $5.69 per 1,000 gallons [27].

As a comparison with the national literature, a recent report shows the life-cycle treatment (thirty-year amortization) cost for the Tampa Bay Water utility desalination plant (capacity 25 MGD) as $2.72 per 1,000 gallons and the Long Beach Water Department utility desalination plant (capacity 0.3 MGD) as $2.40-$3.90 per 1,000 gallons [28]. It should be noted that the Tampa and Long Beach desalination projects are located on water sources that are more stable in terms of water temperature and normally the water in those areas is warmer than in coastal Virginia. A higher water temperature reduces the required energy costs.

Current actual costs to treat and deliver freshwater must be identified and presented for eastern Virginia communities. These values can then be compared to the “total water cost” that is output from the DEEP model. Another approach would be to add a general overhead factor for total utility operations to the water costs developed as DEEP model output. This “overhead cost factor” should be developed specifically for water utilities in this region.

6. Conclusions and Recommendations

This report provides a broad overview of desalination issues. These include technologies (water treatment methods), environmental and regulatory issues, energy needs, and economic aspects. The report specifically focuses on using desalination in eastern Virginia.

6.1. Rationale for Using Desalination in Eastern Virginia

A comprehensive database of water resource inventory for eastern Virginia is not available. Based on available information, a significant need exists for using desalination in eastern Virginia:

1. The Hampton Roads area is the home of one of the largest port facilities in the country and hosts a major military complex. As a result, the area has experienced rapid population growth that has strained local water supplies. Because of the population growth and the difficulty in developing new water sources locally, water shortages in the region have become commonplace over the last two decades. Water restrictions resulting from water shortages have occurred in every dry period since 1976.
2. Because of withdrawals from Coastal Plain aquifers, groundwater levels have declined in the region as deep as 160 feet below the sea level near major pumping centers. Groundwater levels in the interior portions of the Middle Potomac (Southampton County), in the Yorktown-Eastover aquifer (Southampton County), and Chickahominy-Piney Point (King William, Caroline, King and Queen counties) are approaching critical condition.
3. Because of withdrawals from Coastal Plain aquifers, groundwater levels have declined in the region as deep as 160 feet below the sea level near major pumping centers. Groundwater levels in the interior portions of the Middle Potomac (Southampton County), in the Yorktown-Eastover aquifer (Southampton County), and Chickahominy-Piney Point (King William, Caroline, King and Queen counties) are approaching critical condition.
4. Major cities in eastern Virginia (Chesapeake, Virginia Beach, Norfolk, Newport News, Portsmouth and Suffolk) are within the Groundwater Management Area. From a regulatory standpoint, the stress on the aquifer system is such that the DEQ may have to start denying permit issuance in some areas of the Ground Water Management Area.
5. Virginia Beach, the largest city in the area has very little fresh groundwater available to meet current or future needs. Virginia Beach relies on interbasin transfer from the Lake Gaston pipeline. If the pipeline is disrupted for any reason, it will have major consequences for Virginia Beach and the region.

6. The Virginia Department of Health has advised the City of Newport News (Newport News Water Works) and James City County for the need to develop additional sources of supply, as the current demands have exceeded the "trigger level" contained in the *Commonwealth of Virginia Waterworks Regulations* for such action. To meet future demand, brackish groundwater or other saline waters will be the only available local resources.
7. Portsmouth and Norfolk, the older cities in the area, developed the limited surface water supplies before the newer cities of Chesapeake, Suffolk, and Virginia Beach came into existence. Portsmouth and Norfolk have sufficient water supplies to meet their current needs and supply their surplus water to Virginia Beach and Chesapeake. However, the surplus is not adequate to meet the needs of these cities where much of the population growth is occurring.
8. The proposed King William Reservoir project will supply only up to 60% of the lower Peninsula's future water needs. Desalination of brackish groundwater is considered as potential way to supplement a portion of the additional demand.
9. Construction of additional reservoirs in eastern Virginia is less likely because of environmental concerns, high cost, and difficulty in purchasing the needed land.
10. Parts of New Kent, Charles City, Hanover, Henrico, and Petersburg are situated within the Eastern Virginia Ground Water Management Area. These localities will compete with Hampton Roads area and Middle Peninsula for available water resources in the region.
11. Accomack and Northampton counties rely solely on groundwater to meet drinking water needs. Future economic growth in the area depends of availability of alternative source of water.

6.2. Recommendations

Desalination cannot be considered as a stand-alone measure to meet increased water demand for public water supplies. Desalination should be considered as a viable component of an overall water supply management that includes all available sources of water (fresh and impure) and all uses of water (public water supplies, agricultural, industrial, etc.). Technologies are available for desalination of brackish and seawater. These technologies are implemented worldwide, and further research and development of more cost-effective desalination technologies are underway. Advanced brackish water desalination technologies are already implemented in the Hampton Roads area with acceptable cost to the public. Therefore, technology is not a factor in implementing desalination in eastern Virginia. However, there are issues related to availability of water sources, institutional needs, and ecosystem impacts that need to be addressed.

Water Source Inventory Need

At present a comprehensive and reliable database of surface and groundwater resources in eastern Virginia is not available. It is important to understand that brackish and saline groundwater resources are not disconnected from other surface and groundwater resources. Extraction of brackish water will have effects on adjacent fresh groundwater reservoirs, and ultimately surface water resources as well. A better inventory of surface and groundwater resources is needed for optimal site selection of desalination plants.

Recommendation. *Legislative guidance and state government leadership is needed to develop a comprehensive database of available water resources in eastern Virginia to be followed by a viable regional water supply and allocation plan based on the scientific evaluation of existing water resources and the potential for developing impure water sources such as saline water.*

Institutional Needs

There is a significant need for regional collaboration for successful implementation of desalination and to meet future water demand.

Recommendation. *Legislative guidance is needed to form a regional utility task force that will coordinate activities of numerous utilities in the region and to develop a strategic plan for future use of large-scale desalination technologies in eastern Virginia. The task force should determine where the needs are and identify potential sites to locate desalination facilities.*

Recommendation. *Legislative guidance is needed to form an inter-governmental task force that will coordinate and expedite permit reviews between various federal and state agencies for the implementation of future desalination plants.*

Recommendation. *Energy costs are a major factor in the production cost for desalination plants, particularly when using high salinity waters such as tidal and seawater. There is a need to develop a mechanism for enhanced cooperation between water utilities and power companies to make existing and future desalination plants more cost-competitive.*

Research Needs for Ecosystem Management

Less is known about various effects of desalination plants on receiving waters and coastal ecosystems. Research is needed to provide science-based information that can facilitate science-based permitting and developing regulatory guidelines.

Recommendation. *Legislative action is needed to provide funds that can support research for developing environmentally sound desalination practices. Research is needed to address ecosystem impacts such as effects of water withdrawal, water intake structure and brine disposal; and cost effectiveness of various brine disposal and management technologies, such as Zero Liquid Discharge and brine reuse potential.*

Appendix 5A

Desalination Plants in North Carolina

North Reverse Osmosis Plant

The Dare County, North Reverse Osmosis Plant in Kill Devil Hills, North Carolina was built in 1989 [29, 30]. It is a reverse osmosis (*Hydronautics* model: 8040-LH4-CPA3 spiral wound membranes) with three sets of 35 pressure vessels, each vessel containing one membrane. The first twenty-five membranes are used for the first pass and the remaining ten are used for the second pass. The RO plant was constructed to provide drinking water to the surrounding beach communities and it is the only provider of drinking water for the towns of Kill Devil Hills and Kitty Hawk. The current production is as high as 3 MGD at peak periods. In the near future the plant will be upgraded to increase its capacity to 5 MGD. The feedwater TDS is approximately 4,000 mg/L and the product water TDS is about 375-400 mg/L. The plant recovery ratio is 75% with 97% salt rejection. Pretreatment consists of passing the feedwater through 5 micron cartridge filters, adding sulfuric acid to reduce the pH of the water to prevent formation of calcium carbonate, and adding a scale inhibitor to prevent scaling of the RO membranes. The product water is then mixed with intake water to add hardness. Posttreatment of the product consists of adding chlorine for disinfection, fluoride for public health, sodium hydroxide for raising the pH of the water, and zinc orthophosphate as a corrosion inhibitor.

Because the feedwater is brackish, relatively low pressure is needed to pump water through the membranes. The plant receives electricity from Dominion Power, a company that powers the entire area. At present, the plant is not using any energy saving equipment, but energy recovery turbines will be installed when the plant is upgraded to 5 MGD.

This plant has obtained an NPDES permit to dispose of concentrate into the Atlantic Ocean. A PVC pipe carries the concentrate from the plant to an outlet in the ocean.

Additionally, there is naturally occurring arsenic in the groundwater and further treatment is required to remove the arsenic. To remove arsenic, the plant performed tests using nanofiltration membranes and filtration through zeolite. Nanofiltration membranes were chosen for arsenic removal and will be installed in the near future.

Table 5.1A. North Reverse Osmosis Plant	
Technology	
Type	Brackish water reverse osmosis
Membrane Provider	Hydranautics
Pretreatment Chemicals	Sulfuric acid, scale inhibitor, cartridge filters
Posttreatment Chemicals	Chlorine, flouride, sodium hydroxide, zinc orthophosphate
Capacity (MGD)	3 MGD
Recovery	75%
Salt Rejection	97%
Product Use	Drinking water
Year built	1988
Energy	
Source	Electricity Grid - Dominion Power
Costs	$0.134/1,000 gal produced (30.5% of costs to produce water)
Amount Consumed	10.2 Btu/gal
Environment	
Brine TDS (mg/L)	1/3 of salinity of receiving water
Posttreatment of Brine	----
Feedwater TDS (mg/L)	Averaging 4,500
Product TDS (mg/L)	375-400
Total Hardness (mg/L $CaCO_3$)	30
Disposal Method	Surface water - Atlantic Ocean via NPDES permit
Population Size Served	----
Cost of Product ($/1,000gal)	$0.44
Notes * Product water mixed with raw water before transported to residences (2.55 MGD product mixed with .45 MGD raw water) * Cost of project was $11 million * Current problems with arsenic in water, adding nanofiltration in posttreatment * Plant expanding to 5 MGD * Pumps use variable speed drives to control energy use	

Cape Hatteras RO/Anion Exchange Plant

The Cape Hatteras RO/Anion Exchange plant started operating in 2000 to meet drinking water demands in the area where saltwater intrusion into the groundwater aquifer has become a problem. Also, the groundwater contains a high amount of organic material. To solve these problems, the plant uses two separate processes: reverse osmosis and anion exchange [31].

The feedwater to the RO plant is pumped from 4 deep-drilled wells. The feedwater TDS is 8,000-10,000 mg/L. Due to the high TDS concentration, high pressure (about 500 psi) is needed to pass the feedwater through the one-pass RO process. The plant uses one energy recovery turbine that reduces total energy consumption by 9.1%. Pretreatment consists of passing the feedwater through 5 micron cartridge filters, adding sulfuric acid to reduce the pH of the water to prevent formation of calcium carbonate, and adding a scale inhibitor to prevent scaling of the RO membranes. Then the water flows through one of the 16 pressure vessels housing reverse osmosis membranes. These vessels can process 1.4 MGD. Discharge permits were attained to allow disposing of the concentrate into the Palimar Sound.

The plant has three anion exchange units. Feedwater (TDS 349 mg/L) is pumped from 19 shallow wells and transferred to one of the anion exchange units to remove organic material in the water. As the water passes through ion exchange resin (sodium ions), the organic material is replaced with sodium ions, which is released to the product water. Therefore, the TDS concentration in the product water from the anion exchange units is slightly higher than the feedwater.

Table 5.2A--Cape Hatteras RO / Anion Exchange	
Technology	
Type	Brackish water RO & Anion Exchange
Capacity (MGD)	2 MGD
Recovery	68%
Product Use	Drinking water
Year built	2000
RO Process	
Purpose	Remove salts from water
Capacity	1.4 MGD
Feedwater TDS (mg/L)	9,000-12,000
Membrane Provider	Hydranautics
Pretreatment	Acid, scale inhibitor, 5 micron cartridge filters
Brine TDS	----
Concentrate Disposal	Surface water - Pamlico Sound
Ion Exchange	
Purpose	Removes organics from freshwater wells
Capacity	0.6 MGD
Feedwater TDS (mg/L)	349
Regeneration	$4\ 10^6$ gallons before regeneration needed
Post-treatment	Iron removal pressure filters (use chlorine to settle out iron)
Regeneration disposal	Pumped to settling basin and emptying to Brigand's Bay
Product	
Posttreatment	Chlorine, flouride, corrosion inhibitors, pH adjustment using caustic soda
Product TDS (mg/L)	445
Total Hardness (mg/L as $CaCO_3$)	110
Cost of Product ($/1000 gal)	$4.00, projected to be $2.02
Notes * Problems with open hole drilled wells. Sediments entering cartridge filters. * Plant costs projected to be $1,283,500	

The product from the anion exchange is transferred to one of the plant's two pressure filters, where iron and manganese are removed from the water. The iron and manganese in the water combine with the chlorine (added to product from an ion exchange unit) to form a precipitate, which is filtered out in these pressurized filters. The TDS of the final product is acceptable (445 mg/L). For posttreatment, chlorine (bleach) is added as a disinfectant; zinc orthophosphate as a corrosion inhibitor, and fluoride for public health purposes.

Tables 5.3A to 5.4A provide a summary of two other desalination plants in Dare County, North Carolina.

Table 5.3A. Dare County Rodanthe, Waves, and Salvo Reverse Osmosis	
Technology	
Type	Brackish water reverse osmosis (Spiral Wound)
Membrane Provider	Hydranautics
Pretreatment Chemicals	Sulfuric acid, scale inhibitor, cartridge filters
Posttreatment Chemicals	Chlorine, flouride, sodium hydroxide, zinc orthophosphate
Capacity (MGD)	0.5 MGD
Recovery	75%
Salt Rejection	97%
Product Use	Drinking water
Year built	1994
Energy	
Source	----
Costs	(25.3% of total cost to produce water)
Amount Consumed	802 10^3 Btu/hr ?
Environment	
Brine TDS (mg/L)	1/3 salinity of receiving stream
Posttreatment of Brine	----
Feedwater TDS (mg/L)	1,310
Product TDS (mg/L)	200
Total Hardness (mg/L as $CaCO_3$)	8
Disposal Method	Surface water - Blackmar Gut via NPDES Permit
Costs of Disposal	----
Population Size Served	----
Cost of Product ($/1000 gal)	$0.54

Notes

* Product water mixed with raw water before transported to residences
  About 10% of product water is raw water
* Cost of project was $6.4 million
* Two-stage RO process
* Pumps operate with variable speed drive controllers to reduce energy

Table 5.4A. Dare County Stumpy Point Reverse Osmosis Water Plant	
Technology	
Type	Reverse Osmosis
Membrane Provider	Aqua Pro TW-8040
Pretreatment Chemicals	Scale inhibitor [1], cartridge filters
Posttreatment Chemicals	Sodium hypochloride, flouride, sodium hydroxide, zinc orthophosphate
Capacity	60,000 gal/d
Recovery	60%
Salt Rejection	----
Product Use	Drinking water
Year built	2002
Energy	
Source	----
Costs	----
Amount Consumed	----
Environment	
Brine TDS (mg/L)	3,210
Posttreatment of Brine	----
Feedwater TDS (mg/L)	1,050
Product TDS (mg/L)	92
Total Hardness (mg/L $CaCO_3$)	52
Disposal Method	Surface water - Stumpy Point Bay via NPDES permit
Costs of Disposal	----
Population Size Served	118 current residences, 177 projected
Cost of Product ($/gal)	----

[1] GE Betz Hypersperse MDC 120

Notes

* Total projected cost of plant was $1,396,000
* Stumpy point is an isolated very small community

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