

**ASSESSMENT OF DESALINATION TREATMENT PROCESSES  
FOR FUTURE WATER SUPPLIES**

by

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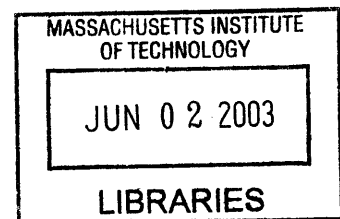
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**BARKER**



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## *Abstract*

Supplies of potable water from traditional sources have been increasingly depleted due to increasing world population and per capita water use. On the U.S. Virgin Islands, no traditional potable water source is readily available. Because of this, desalination has become an accepted alternative for supplying potable water. Determining the most efficient desalination system for the islands is pivotal to their success in supplying potable water to consumers in the future.

A performance assessment was performed using two desalination systems located on the U.S. Virgin Islands. The assessment shows that many, small reverse osmosis plants provide the best system configuration for the islands. This configuration minimizes risk and overall operational costs, while increasing system reliability, flexibility and overall net benefit. This system framework can be used worldwide to provide the most efficient desalination system based on the system indicators and how they are weighted against one another.

Thesis Supervisor: Dr. David H. Marks

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# *1. Introduction*

## *1.1 Desalination*

### *1.1.1 Drinking Water Scarcity*

Freshwater is one of Earth's most valuable renewable resources. Along with the supply of energy, access to freshwater is a fundamental need of all societies. Although water covers approximately 70 percent of the Earth's surface, supplies of potable water are rapidly disappearing. This is because only 0.62 percent of all water on Earth is available in a form that can be traditionally treated for human consumption, as shown in Figure 1 (USGS, 1967).

<b>Water source</b>	<b>Water volume, in mi<sup>3</sup></b>	<b>Percent of total water</b>
Oceans	317,000,000	97.2400%
Icecaps, Glaciers	7,000,000	2.1400%
Ground water	2,000,000	0.6100%
Fresh-water lakes	30,000	0.0090%
Inland seas	25,000	0.0080%
Soil moisture	16,000	0.0050%
Atmosphere	3,100	0.0010%
Rivers	300	0.0001%
<b>Total water volume</b>	<b>326,000,000</b>	<b>100%</b>

Figure 1  
Earth's water distribution

During the last century, these potable water sources from both surface and groundwater sources have been increasingly depleted due to increases in worldwide population and increases in per capita water use (Kufahl, 2002). One study of water scarcity trends estimates that of the approximately 6.3 billion people living on Earth (US Census, 2003), 400 million people now live in water scarce areas, and the number living in water-stressed areas could grow to 4 billion by mid-century (Angelo, 2000). This data is shown in Figures 2a and 2b. Moreover, various human activities have increased the pollution of

these sources, which has decreased the total amount of water available for human consumption.

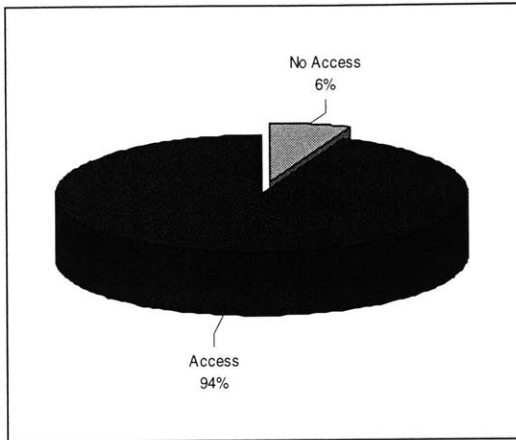


Figure 2a  
Percent of population with or without access to potable water in 2000

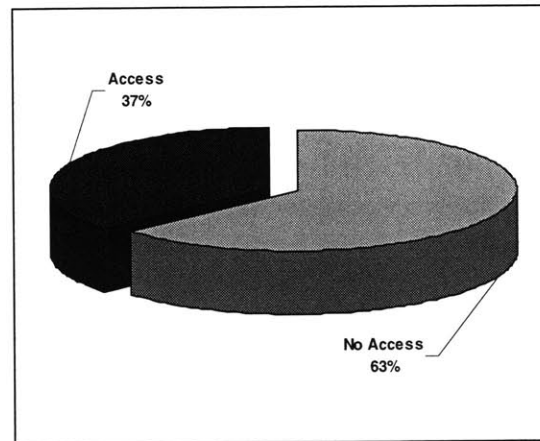


Figure 2b  
Estimated percent of population with or without access to potable water in 2050

While these figures are projections and subject to speculation, solid evidence of water scarcity based on present day trends does exist. Currently, mankind is draining potable water supplies at a rate of over 110 billion gallons per day (Anonymous, 2001). Additionally, the demand for potable water increased six-fold during the 20<sup>th</sup> century while the world's population increased three-fold. At the same time, pollution and overuse of potable water sources reduced the ability of developed potable water sources to meet demand (Kufahl, 2002).

### ***1.1.2 Overview***

Desalination is an industrial process that removes dissolved minerals, typically salts, from seawater or brackish water so that it can be used for human consumption. Water treated through the desalination process can be treated to levels significantly less than the standards outlined by the Safe Drinking Water Act (EPA, 1974) for waterborne pollution. However, due to economic factors, water treated through the desalination process is typically either treated to acceptable potable standards or is treated to much cleaner levels, then blended with more polluted water. The desalination treatment process is highly complex and requires an efficient and accurate control system in order to minimize overall operational costs and maintenance.

Distillation and reverse osmosis are the two dominant desalination treatment systems. One of the two is in operation in most desalination plants worldwide. Three different types of distillation exist: multi-stage flash, multi-stage effect, and vapor compression. As of 1999, distillation, the older of the two systems, constituted more than 65% of the total market share with multi-stage flash processes accounted for 55% and other evaporative techniques accounted for the other 10%. Reverse osmosis processes make up



the remaining 35% of the total market share (Alatqi, 1999). These trends are shown in Figures 3a and 3b.

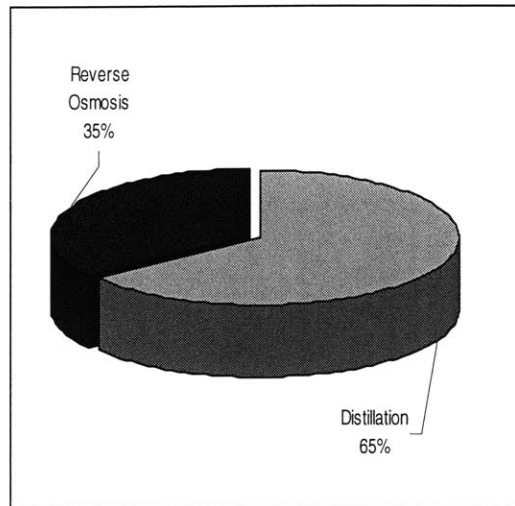


Figure 3a

Percentage comparison of desalination processes used worldwide

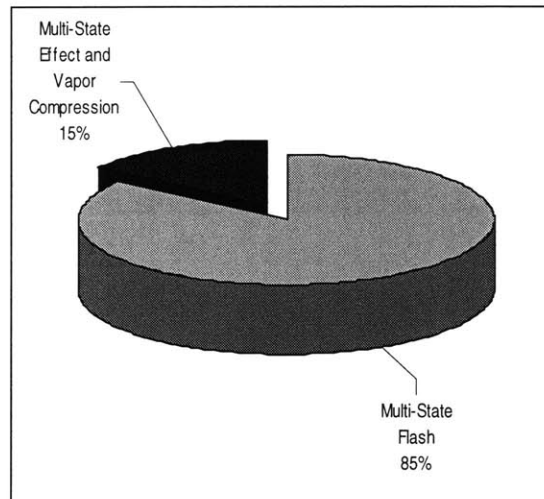


Figure 3b

Percentage comparison of distillation processes used worldwide

The number of desalination plants in operation, or being planned for operation, worldwide has increased dramatically over the last five years. This increase is primarily to support urban and industrial developments in arid, semi-arid, or remote areas of the world. These areas have severe water scarcity where water from any source, especially from traditional sources, is too costly to develop. The market for water in these areas is driven by increasing populations, severe water shortages and increases in the quality of life that demand more potable water (Tsiourtis, 2001). The increase in the number of desalination plants can be attributed to:

- the reduction of available traditional water sources caused by overuse and pollution of the sources
- increases in the costs associated with providing potable water from traditional sources due to scarcity
- increased drinking water treatment standards
- decreases in costs associated with providing potable water from desalination sources

As Figure 4 shows, the number of plants in operation worldwide in 1992 was estimated to be around 7,500 (CCC, 1992). In 1993, 9,910 plants were in operation (Maheshwari, 1995), and according to current estimates, there are approximately 11,000 plants currently in operation worldwide. These plants produce over five billion gallons of potable water per day. In addition to existing plants, many more desalination plants are currently under construction. The majority of industry experts also expect the desalination market to double in size within the next 20 years (Angelo, 2000).

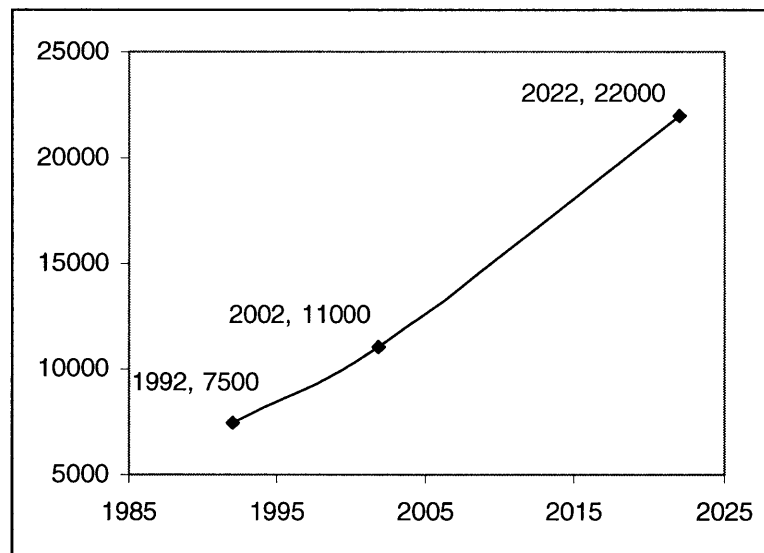


Figure 4

Number of desalination plants in operation worldwide (Year, Number of Plants)

### ***1.1.3 History***

The fundamentals of desalination have been known and practiced for thousands of years. Evidence suggests that around 1400 B.C, ancient mariners knew that seawater could be evaporated and the produced vapor could be collected (Kufahl, 2002), cooled and then used for drinking (Fong, 2001). The United States first started work on desalination technologies in 1771. In that year Thomas Jefferson, then Secretary of State, wrote a technical report describing a simple distillation process. The information was printed on the back of all the papers on board United States ships so sailors would have access to the information in the event of an emergency (RPI, 1995).

More sophisticated desalination processes were researched and developed in the 1800s (Kufahl, 2002). Water desalination began on an industrial scale in the early 20<sup>th</sup> century (Alatqi et al, 1999) with the first plant being built in 1907 (Al-Munaz, 1996). Experiments were conducted on the first municipal plant in 1928 in Saudi Arabia (Al-Munaz, 1996). Then, in the 1950s the first widespread commercial desalination plants were built (Fong, 2001) for public water supplies in water deprived regions like the Caribbean and the Middle East. In 1952, the United States created the Office of Saline Water within the Department of the Interior to research and to investigate desalination as a solution to the drinking water shortage that developed shortly after World War II (RPI, 1995). From 1960-1980, the desalination industry began to expand and spread. During this period, the technological industry standard for the process was multi-stage flash treatment. Typical production was around 6 million gallons per day. From 1980-1999, the industry standard for treatment shifted from multi-stage flash to reverse osmosis (Alatqi et al, 1999). Figure 5 presents a summary of this information as a timeline.

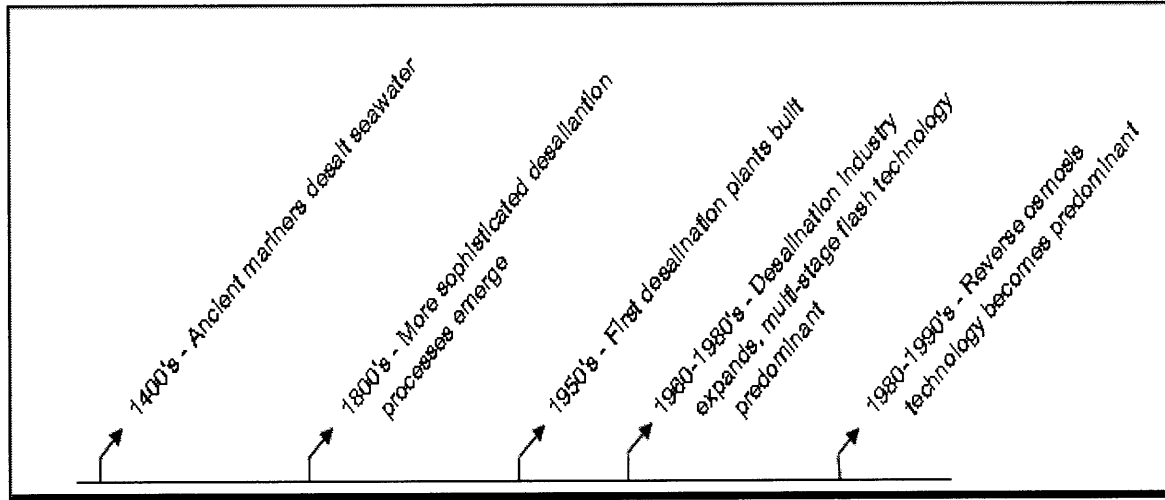


Figure 5.  
Timeline of selected events in desalination history

Desalination as a potable water source for public supplies was typically economical only in cases where no other reliable source of water could be found. However, in the last 10 years desalination has become economical in many more situations.

#### **1.1.4 Costs**

Traditionally, it has been thought that the cost per unit volume of potable water supplied by a desalination plant is much greater than from other drinking water sources (Sajwani, 1998). While historically true, Figure 6 shows that the gap in costs between desalination and traditional water sources per unit volume of potable water is rapidly narrowing (Angelo, 2000 and Kufahl, 2002).

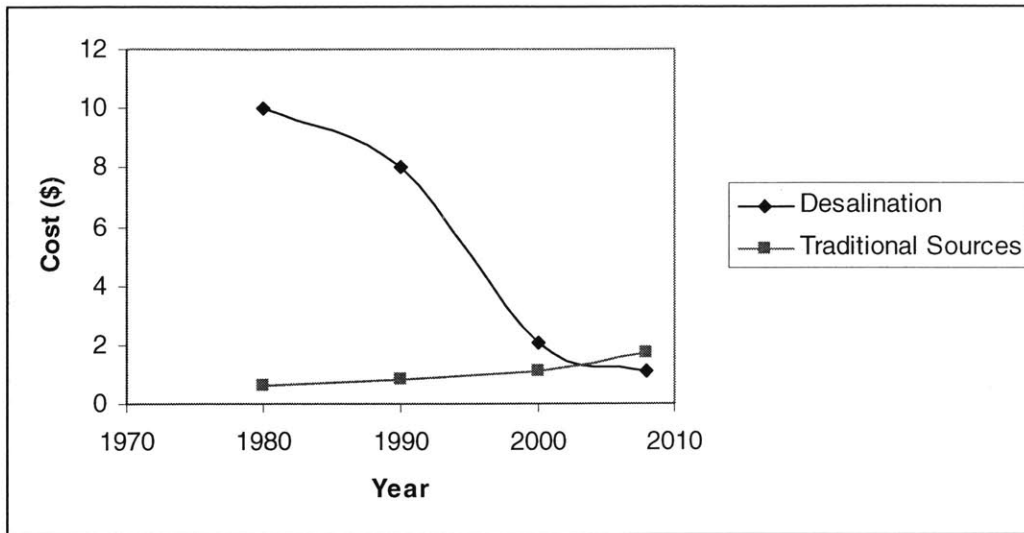


Figure 6

General comparison of potable water costs from desalination and traditional sources

Two primary costs, energy consumption and operation of the chosen desalination system, affect the overall cost per unit water of a desalination system. The amount of energy required by a desalination system depends on plant performance, the quality of energy used and operational temperature. How the energy is applied, whether directly or indirectly, affects costs as well. The true cost of energy in the desalination process depends on the efficiency of transferring the supplied fuel into consumable energy that the desalination treatment process can use (Darwish and Al-Najem, 1987). Operation of the chosen desalination system can also greatly affect cost. Plant maintenance, operations, and monitoring all contribute to the cost of the supplied, potable water. Typical operational parameters that contribute to costs are summarized below (Darwish et al, 1989).

- Size of plant
- Type and cost of desalination process in operation
- Costs of chemicals
- Quality of feedwater
- Energy use
- Required quality of output

Desalination techniques for supplying potable water have become more popular within the last five years due to increases in the cost of potable water supplied from traditional freshwater sources. Decreases in the cost of desalinated water due to technological advances made through research on the process and increased competition among suppliers have also made desalination more popular (Fong, 2001). The reduction in the cost of desalination results from improvements in the reverse osmosis process; the increased usage of reverse osmosis rather than distillation methods; and a better understanding, through research, of how to control the process to minimize total costs

and decrease energy consumption. For example, salt rejection from membranes in reverse osmosis plants has increased from 99.2 to 99.8 percent. This eliminates the need for a second membrane and drastically reduces costs (Angelo, 2000). Recently, scientists have found a new method that uses two membranes and requires only 75 percent of the pressure required in the one membrane treatment method. This has reduced costs by another 20 to 30 percent, but is still in the experimental phase (Landers, 2003). In addition, operating pressures have dropped by two or three times in the last 10 years, reducing energy requirements by 50 percent.

Generally, as desalination plants increase their output capacity, economies of scale increase that reduce overall operating costs. This is particularly true for distillation plants. They can use the heat generated by the distillation process to increase overall efficiency, recovery rates and economies of scale.

### ***1.1.5 Feedwater***

Feedwater can be defined for the desalination process as the raw, untreated water that enters the process for treatment. In processes with more than one stage or series, feedwater is the water that enters the stage or series for treatment. Desalination plants use seawater, brackish water or reclaimed water as feedwater. Desalination plants are typically designed to treat only one of these types of water because desalination plants are built in areas with access to only one of these sources of feedwater.

### ***1.1.6 Processes***

Although many different types of desalination plants exist, the two most prevalent desalination systems are distillation and reverse osmosis (Hanson et al., 2002). Three types of distillation processes exist: multi-state flash, multi-effect flash, and vapor compression. Traditionally, multi-state flash processes have been the preferred method of desalination, but recently the industry has shifted towards reverse osmosis (Al-Mutaz, 1996). Other methods of desalination that have been researched, but have seen very little implementation due to high costs, include freezing, electrodialysis (Buros, 1983), recovered energy heating and humidification-dehumidification (Bourouni, 2001).

The multi-state effect distillation process is the oldest technique employed for commercial seawater desalination. In the process, feedwater is heated while the ambient air pressure is decreased until water “flashes” into vapor phase, which then condenses. It can then be collected, treated as necessary and used for drinking. Figure 7 (CCC, 1992) shows a flow diagram of the multi-state effect process. Multi-state effect distillation typically involves a series of heating/condensing stages, each of which is performed at lower pressures using recycled heat and water from the last stage to increase overall efficiency. In each effect, steam passes through and heats either horizontally or vertically aligned tubes. Then feedwater is sprayed evenly onto the extremely hot tubes, which causes the water to evaporate and the salt to remain on the tubes. Thus, the water is separated from the salt and can then be condensed and collected (Van der Bruggen and

Vandecasteele, 2002). The steam from the first effect becomes the feedwater for the second effect. Traditionally, 24 effects or stages are used in the multi-state process (Alatiqi, 1999), but technological advancements have reduced the number of necessary effects to between 8 and 16 in newer plants (Van der Bruggen and Vandecasteele, 2002).

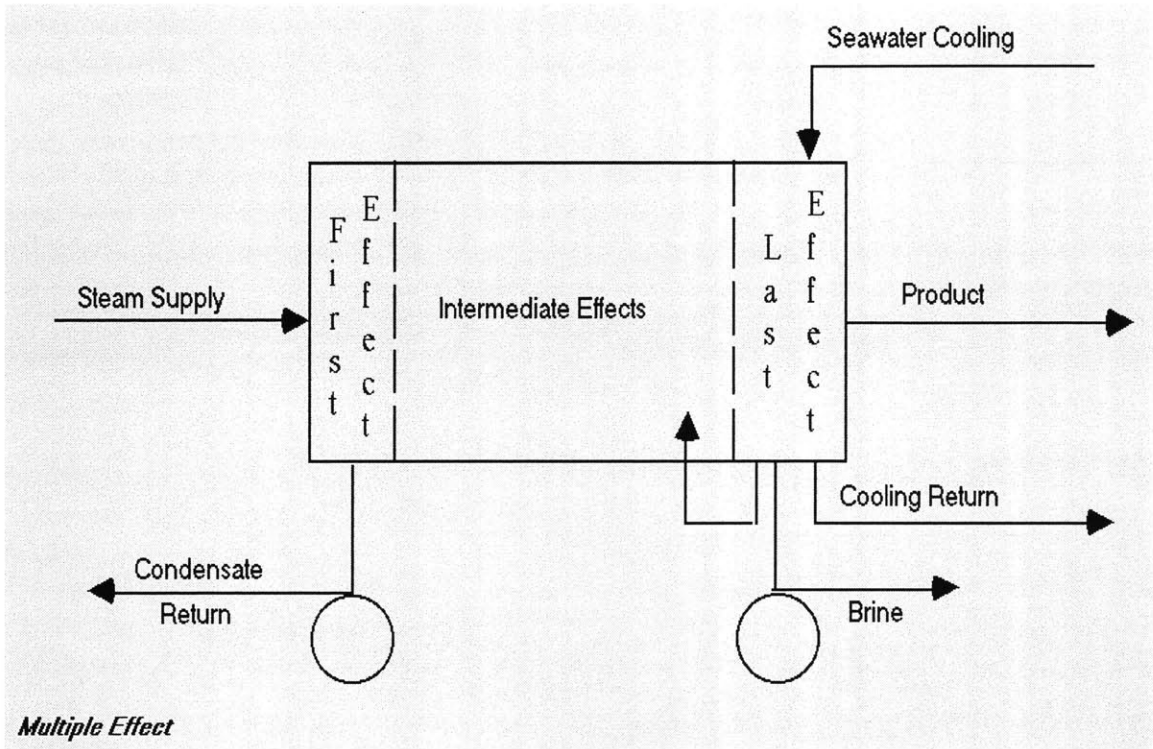
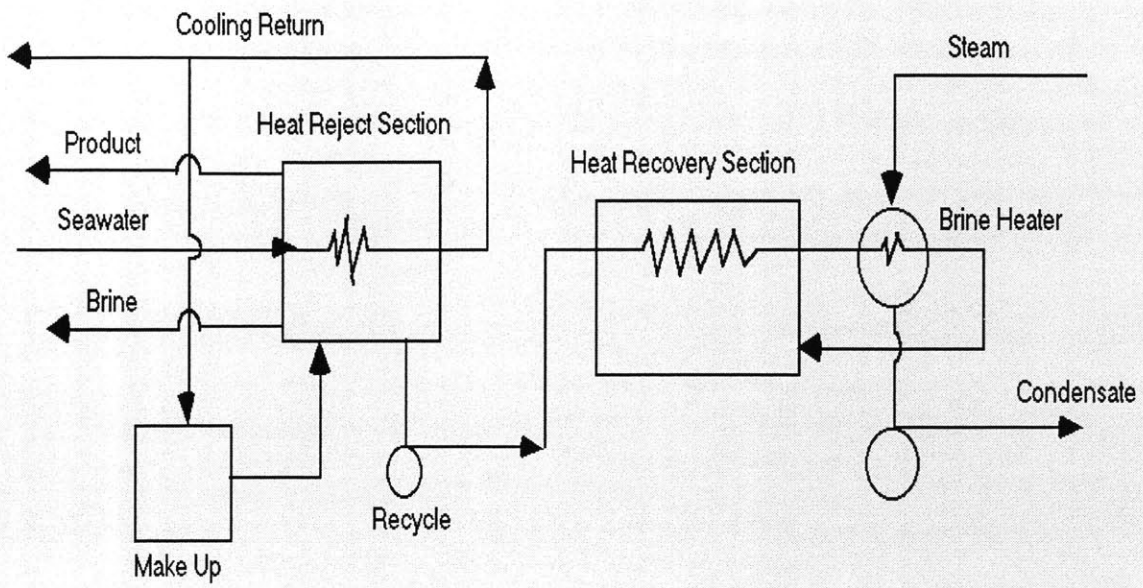


Figure 7  
Flow diagram for the multi-state effect distillation process

Multi-state flash distillation came into practice in the 1960s. This process is easier to operate and more reliable than multi-state effect distillation. In the multi-state flash process, water passes through a number of evaporators operated in series. In each evaporation chamber, a fraction of feedwater is heated until it changes phase and becomes steam. This allows the water to be separated from the salts. The remainder of the feedwater is kept at low temperature and is passed through a series of closed pipes. The steam condenses through heat exchange as it comes in contact with these cool pipes and is collected by trays (Van der Bruggen and Vandecasteele, 2002). Waste heat from one series is subsequently used to evaporate water in the next series. The fraction of the feedwater that is not converted to steam is used in the closed pipes in one series and becomes the steam used in the next series. Figure 8 (CCC, 1992) shows a flow diagram of this process.



*Multi-State Flash (Recycle)*

Figure 8

Flow diagram for the multi-state flash distillation process

The vapor compression process involves evaporating feedwater and then compressing the vapor. The compressed vapor is sprayed into a reaction chamber through a very fine nozzle. The rapid expansion of the vapor causes the salt to separate from the water. Differences in the molecular weight of water and salt allow the two to separate. The water vapor has a much lower molecular weight than salt. Because of this, it is sprayed high into the chamber and collected by trays. The collection trays are placed at a height in the chamber that salt can not be sprayed to. Figure 9 (CCC, 1992) shows a flow diagram of this process.

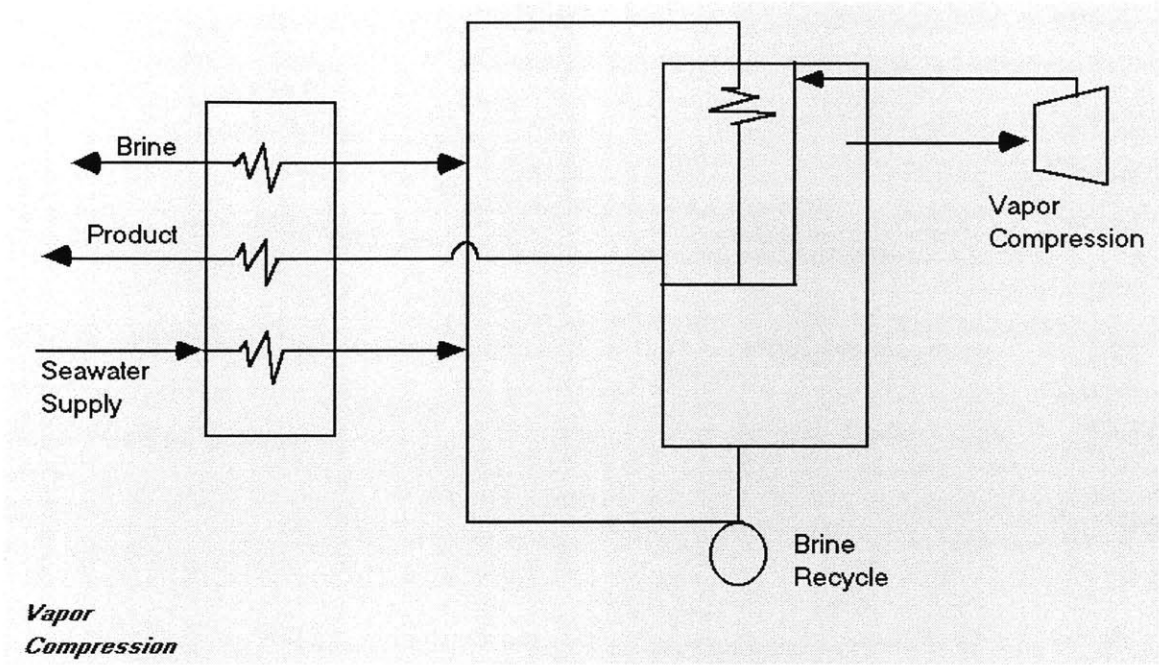


Figure 9  
Flow diagram for the vapor compression distillation process

In reverse osmosis, the feedwater that is to be treated is pumped at pressures higher than the osmotic pressure of seawater (Van der Bruggen and Vandecasteele, 2002). This forces feedwater to flow against its natural osmotic gradient and through a semi-permeable membrane that allows smaller water molecules to pass through, but not larger dissolved salt ions. This is shown as a flow diagram in Figure 10 (CCC, 1992).

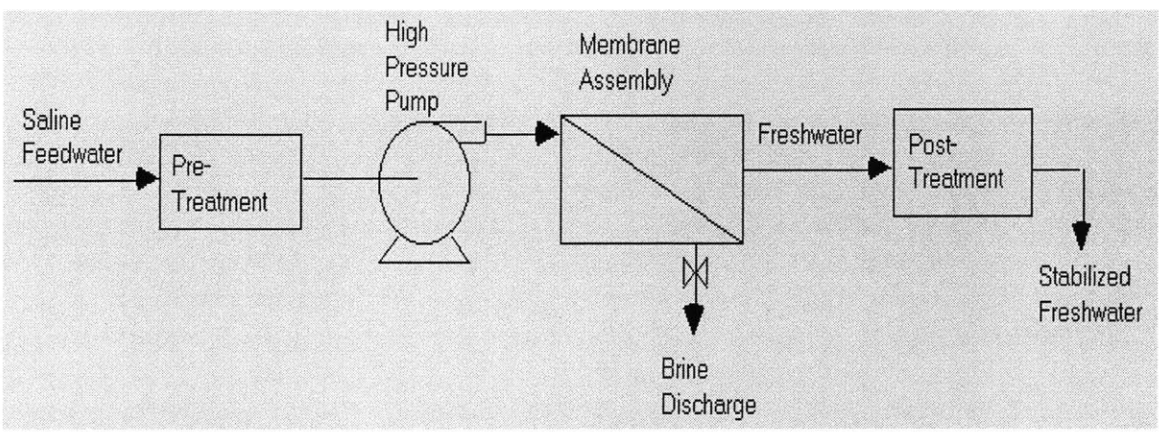


Figure 10  
Flow diagram for the reverse osmosis process

Feedwater that enters the reverse osmosis process is pretreated in order to remove contaminants that would clog the membranes and reduce efficiency. Desalination plants that are currently being designed use one membrane. This one membrane will treat water



to recommended standards, but two membranes are still often used to improve effluent water quality. In the past, two membranes were always used due to poor membrane quality.

Reverse osmosis membranes are made from ultra-thin polymeric composites layered upon one another. They are typically configured as spiral-wound nodules. In this configuration, seawater flows between two flat membranes wound around a tube. An alternative to spiral-wound membranes are hollow fiber membranes. These membranes form tubes through which the water passes (Van der Bruggen and Vandecasteele, 2002).

Originally, reverse osmosis was an expensive desalination option (in comparison to the distillation processes) due to the high cost and low life span of the membranes used in the process, as well as high maintenance costs involved (Fong, 2001). Numerous developments have decreased the costs involved with operating a reverse osmosis plant. Improvements in membrane efficiency have eliminated the need to use a second membrane and have decreased maintenance costs. Additionally, increased competition among membrane manufacturers is driving down costs. Finally, research conducted on reverse osmosis treatment process have cut energy requirement by 50% or more due to reductions in the process's operating pressures and energy inputs (Angelo, 2000).

Distillation techniques have many advantages over reverse osmosis.

- Distillation plants do not shut down portions of their operations for maintenance, such as replacement, cleaning or updating of equipment as often.
- Distillation plants have fewer pretreatment requirements because coagulants do not need to settle out. In reverse osmosis, coagulants do need to settle out particles before water passes through the membranes to prevent clogging.
- Distillation plants do not generate waste from backwash of pretreatment filters because, unlike reverse osmosis, they do not have filters.

Reverse osmosis has many advantages over distillation techniques.

- Feedwater does not require heating so discharged water has less thermal impact on the environment.
- Reverse osmosis produces more potable water per unit of feedwater.
- Less energy is required for reverse osmosis.
- Removes unwanted contaminants that can adversely affect human health, such as trihalomethanes, volatile organic compounds, and bacteria. These particles are rejected by the membrane based on their size.
- Reverse osmosis has fewer problems with corrosion
- Reverse osmosis requires less space per unit of water

### ***1.1.7 Pretreatment***

Pretreatment processes aim to remove substances from the desalination process that would interfere or reduce overall efficiency if they were allowed to remain. Traditional

pretreatment employs two methods: mechanical and chemical. Mechanical methods are the use of filters which physically separate the harmful substances from the feedwater. Chemical pretreatment methods are the addition of various chemicals that serve several purposes like coagulation or flocculation. Microorganisms, like algae and bacteria, are the most common organisms that pretreatment processes seek to eliminate. The most common pretreatment methods for removing these microorganisms are chlorination, ozone exposure and ultraviolet light exposure. Chlorination is a chemical method. Ozone and ultraviolet exposure can be considered chemical methods that kill the microorganisms which are then removed by either a physical method, typically a filter, or another chemical method like coagulation or flocculation. If chlorine is used, the water must be dechlorinated in the reverse osmosis before reaching the membranes because some reverse osmosis membranes can be destroyed or severely damaged by prolonged exposure to chlorine. Similarly, if ozone is used, it must be removed with chemicals before reaching the membranes to prevent damage (CCC, 1992).

Reverse osmosis plants and distillation plants have many of the same pretreatment requirements, but each process does have specific requirements that are not necessary in the other. In reverse osmosis plants, suspended solids present in the feedwater must be removed before reaching the membranes to reduce clogging, improve membrane efficiency and reduce cost. Typically, the pretreatment processes utilized to remove suspended solids from feedwater entering the reverse osmosis process are coagulation and filtration.

In distillation plants, metals, because of their corrosive properties, need to be removed by pretreatment processes. Typically, the pretreatment process utilized to remove metals from the distillation process is the addition of anti-corrosive chemicals that either settle the metals out or neutralize the chemicals' corrosive properties.

### ***1.1.8 Product Water***

Both distillation processes and reverse osmosis produce a high-quality water product. Distillation plants produce water that ranges from 1.0 to 50 ppm total dissolved solids (TDS), while reverse osmosis plants produce water that ranges from 10 to 500 ppm TDS (CCC, 1992). Extra precautions are taken with product water from desalination plants where the effluent is intended for domestic use. Post-treatment processes ensure that the water delivered by the desalination plants to consumers meets appropriate state, federal and recommended international drinking water health standards as well as other non-mandatory, secondary drinking water standards.

Water delivered to consumers from desalination processes is usually much cleaner than required by the region's drinking water standards. Because of this, when the product water is intended for municipal use, it is often mixed with water that contains higher levels of TDS from other traditional sources to cut overall costs for the water supplier. In addition, pure desalination water normally has extremely low pH levels. These pH levels can be extremely corrosive to the distribution pipes and cause additional maintenance

costs. Mixing water from the desalination process with other sources of water prevents corrosion and typically saves the water supplier money (Alatqi, 1999).

### ***1.1.9 Waste Discharges***

Desalination plants produce liquid wastes with many different types of individual constituents. These wastes may include:

- high salt concentrations from the brine water
- chemicals used during pretreatment, post-treatment, plant maintenance, and plant cleaning
- filter backwash containing suspended solids like microorganisms and organic debris
- non-toxic and toxic metals

Desalination plants can dispose of these wastes by:

- discharging them directly into the ocean
- combining them with other discharges like power plant cooling water or sewage treatment plant effluent before ocean discharge
- discharging them into a sewer for treatment at a wastewater treatment plant
- drying them out and disposing of them in a landfill.

According to the Florida Department of Environmental Protection, Tampa Bay has natural dissolved salt concentrations of about 26,000 mg/L while the Gulf of Mexico has dissolved salt concentrations that range from 32,000-35,000 mg/L. The Florida DEP estimates that returning salt brine from the new desalination plant being built for the City of Tampa Bay to Tampa Bay will only result in a 1.5 percent increase in local salinity levels, well within acceptable environmental standards (Angelo, 2000). This is only one example of acceptable operations, but these discharges can still cause severe damage when not handled appropriately.

### ***1.1.10 Energy***

Desalination plants have high energy requirements. The energy used in the desalination process is primarily electricity and heat. Energy requirements for desalination plants depend on the following criteria (Kufahl, 2002):

- salinity of the feedwater
- temperature of the feedwater
- source of feedwater
- the quality of the water produced
- the desalination technology used (distillation technologies, due to their elevated operating temperatures, require more energy than reverse osmosis technologies)

The energy used in desalination plants can either be applied as mechanical or thermal energy (Darwish and Al-Najem, 1987). Mechanical energy is energy that is possessed by an object as a result of its motion or of its stored energy resulting from its relative position. Thermal energy is energy that results from heat produced by increasing the temperature of a system.

Feedwater is heated in the desalination process to make the process more efficient (Kufahl, 2002). As the temperature of the system increased, the total amount of potable water produced per unit time increased.

In general, the energy required to produce a specific volume of potable water from any desalination process is much greater than the energy required to produce the same volume of potable water from traditional drinking water sources. For example, for the City of Santa Barbara's desalination plant to deliver the same amount of potable water as the Colorado River Aqueduct to Santa Barbara, it would require 2 to 3 times more energy (CCC, 1992).

Both reverse osmosis and distillation plants can benefit from cogeneration plants, where potable water and electricity are produced at the same plant to reduce energy use and total costs. This is sometimes called "piggybacking" (Tsiourtis, 2001). In piggybacking, the electricity-producing power plant supplies energy to the desalination plant when the cost of electricity is low. The electrical plant sends its wastewater, which has a very high temperature, to the desalination plant where the heat is used to heat the feedwater to increase the processes efficiency and reduce energy requirements. By piggybacking, the desalination plant gets electricity for free, or at a reduced rate, in return for dissipating heat generated by the electricity-generating process that it would have to pay to cool otherwise (Kufahl, 2002).

### ***1.1.11 Environmental Effects***

Desalination processes can have several severe environmental impacts (Sajwani, 1998). The most important environmental concerns for the desalination process are:

- location of the plant
- brine disposal
- energy considerations
- chemical disposal
- atmospheric emissions
- various other factors

A desalination plant must be constructed in a place where it will have minimal environmental impact and be acceptable to the community, owner and local stakeholders. It should be located in a rural area, near a source of energy, close to a source of feedwater and near a water supply system (Tsiourtis, 2001).

Wastewater from desalination plant effluent has extremely elevated salt concentrations. This wastewater is normally referred to as brine. When discharged into bodies of water, brine can cause ecological damage to the discharge area and harm marine life if the discharge area is not planned appropriately, or the plant exceeds its permitted or recommended effluent concentrations. At the new Tampa Bay desalination plant, for every 4.4 gallons of potable water produced, 1.9 gallons of concentrated saltwater is discharged. Most environmentalists agree that if this wastewater is discharged far away from land in deep waters that it would have minimal effects. However, the wastewater is currently discharged into lagoons or near shore, which may have environmental impacts. These discharges have been deemed to have little to no environmental affect as long as the effluent is within the legal limits of brine concentration (Mahi, 2001).

The desalination process requires a substantial amount of energy. The use of such a large amount of energy can have serious environmental impact if it supplied by fossil fuels, which cause the emission of greenhouse gases, like carbon dioxide. The use of renewable energy sources such as geothermal energy, wind power, solar energy, tidal kinetics and hydropower can reduce these emissions (Tsiourtis, 2001). In addition, piggybacking decreases the net environmental effect of desalination plants through the reduction of required energy.

A variety of chemicals are used throughout the desalination process. In general, they are used for the following reasons:

- Pre and post-treatment of water
- Anti-scaling
- Anti-fouling
- Anti-corrosion
- Anti-foaming
- Anti-corrosion
- Oxygen-scavenging
- Membrane cleaning

The chemicals used in these processes must be properly managed and disposed of to reduce environmental impacts. If not properly disposed of, these chemicals can have a wide variety of affects on ecosystems. Anti-scaling agents can cause eutrophication of the water in the discharge area through macronutrient addition. Anti-fouling agents can cause halogenations to occur, which are known to produce trihalomethanes, a known carcinogen. Anti-foaming additives disturb the intracellular membrane systems of microorganisms. Oxygen-scavengers remove oxygen from the ecosystem, which, among other effects, also results in eutrophication (Hoepner, 1999).

The desalination process produces atmospheric emissions resulting from power generation required to power the process. For example, reverse osmosis requires a large amount of pumping and distillation requires large amounts of steam generation. In addition, the input of thermal or mechanical energy required to separate salt from water requires energy. All of these processes result in environmental emissions of various

compounds. One such compound, carbon dioxide, is a major factor in the acceleration of global warming (Van der Bruggen and Vandecasteele, 2002).

Other environmental problems can result from feedwater intake, disposal of toxic metals and noise pollution (Sajwani, 1998). Toxic metals form as a result of corrosion within desalination plants. Different metals have different affects on organisms, but all metals are known to have some toxic affect on the cellular level (Hoepner, 1999).

## ***1.2 The United States Virgin Islands***

### ***1.2.1 Overview***

The United States Virgin Islands are an unincorporated territory of the United States of America (U.S. Department of the Interior, 1998). The islands were placed under the administration of the Secretary of the Interior in 1931 by Executive Order 5566. The territory consists of three major islands: St. Thomas, St. Croix, and St. John as well as approximately 50 other minor islands (Bruno-Vega and Thomas, 1994). The islands are located at the northern end of the leeward islands in the Eastern Caribbean that separate the Atlantic Ocean from the Caribbean Sea. The capital of the United States Virgin Islands is Charlotte Amalie and is located on St. Thomas.

#### ***1.2.1.1 History***

The United States Virgin Islands have a prestigious and storied history. They were discovered by modern civilization on Christopher Columbus's second voyage in 1493 while sailing for Spain. He christened the archipelago of islands "Las Islas Virgenes" or the Virgin Islands. After their discovery, many different nations including Spain, Holland, France, England, Denmark and The Knights of Malta claimed the Virgin Islands of their own. Eventually, Denmark claimed half of the archipelago, which would eventually become the U.S. Virgin Islands, while England claimed the other half, which are to this day the British Virgin Islands (USVI Travel Guide, 2000).

The 1600s were a tumultuous time for the U.S. Virgin Islands under Danish rule. The Danes established the first permanent settlement in the islands on St. Thomas in 1617. The first settlers traveled to St. John in 1684 (United States Department of the Interior, 1998). In 1685, the Danish monarchy signed an agreement with the Dutchy of Brandenburg to allow the establishment of the Brandenburg American Company, which established an active slave-trading post on St. Thomas. Slavery played a major role on the islands until it was abolished in 1848. Soon after 1685, the early governors of St. Thomas made an agreement with pirates which would allow pirates to use the islands as a refuge. The governors knew that the local economy would benefit greatly from the trade of pirate conquests in an open market on the islands (USVI Travel Guide, 2000).

The 1700s and 1800s were a time of legitimate economic growth and prosperity on the islands. From 1700-1750, the influence of piracy declined on the islands but continued to be important. In 1718, the Dutch established their first settlement on St. John. This

settlement was a fort constructed in Coral Bay. The Dutch chose Coral Bay because it was, and continues to be, one of the safest harbors in the Caribbean. St. Thomas was declared a free port in 1724 by the Danish Monarchy. The Danish government then purchased St. Croix from France in 1733. The united the three major islands of the current U.S. Virgin Islands under one government for the first time. The two primary economic activities on the islands during these two centuries were the raising of sugar cane on large plantations, and the resulting major trading economy (USVI Travel Guide, 2000).

The 1900s marked the beginning of United States rule over the islands. The islands were purchased by the United States as part of a military defense strategy in 1917 from the Danish Crown for \$25 million. The government of the United States was concerned that the island might become a German sub base. Native islanders were granted United States citizenship in 1927. The islands were developed as a defense base during World War II, but they were passed over as a major military base due to a lack of an adequate supply of potable water. After World War II, the U.S. Virgin Islands prospered as a popular tourism destination.

### 1.2.1.2 Location

The United States Virgin Islands are located at geographic coordinates 18 20 N, 64 50 W. The islands cover an area approximately two times the size of the District of Columbia and are located east of Puerto Rico dividing the North Atlantic Ocean from the Caribbean Sea (CIA World Factbook, 2002). The locations of the islands in relation to the rest of the Caribbean are shown in Figure 11 (Britannica, 2002).

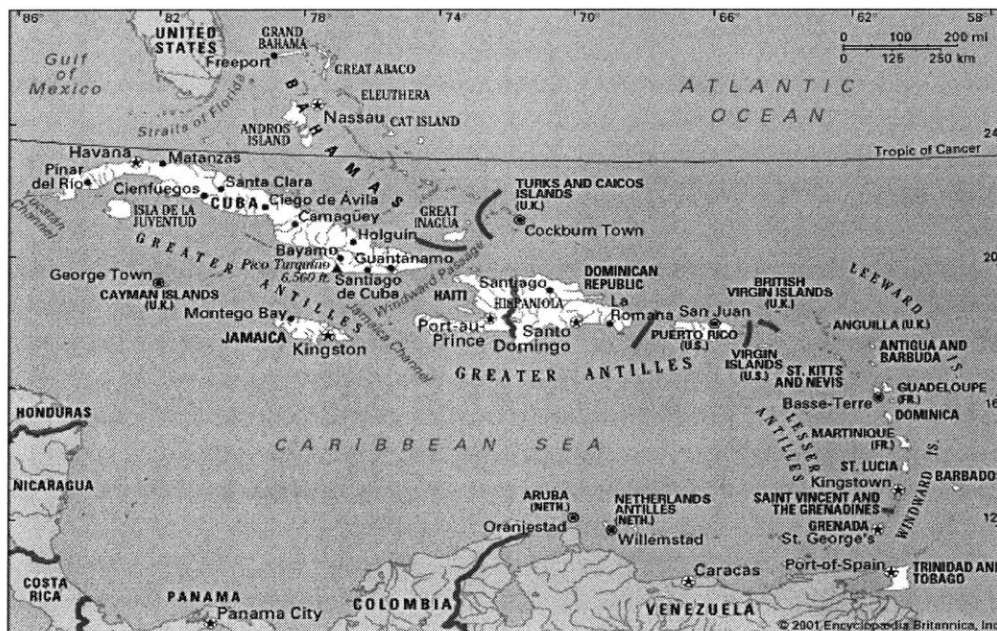


Figure 11  
Map of the Caribbean

St. Thomas has an area of approximately 64 mi<sup>2</sup> and is located 64 miles southeast of Puerto Rico and approximately 1100 miles southeast of Miami, Florida. St. Croix has an area of approximately 84 mi<sup>2</sup> and is located approximately 40 miles southeast of St. Thomas. St. John has an area of 19 mi<sup>2</sup> and is located 2 miles east of St. Thomas (Bruno-Vega and Thomas, 1994). Figure 12 (USVI Tourism Guide, 2003) shows the relative size of the three islands.

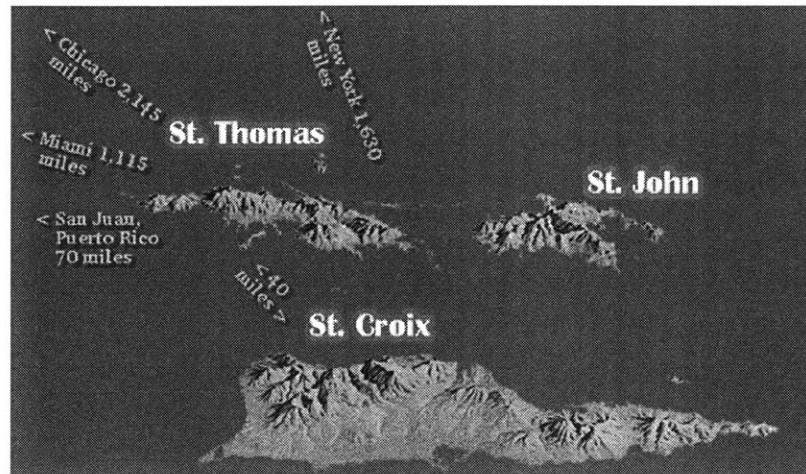


Figure 12  
Map of the U.S. Virgin Islands

### ***1.2.1.3 – Government***

The Virgin Islands are a unincorporated territory of the United States of America and thus, are subjected to the United States Constitution and laws.

The islands, like the 50 states within the United States of America, have their own independent territorial government. Since 1970, the U.S. Virgin Islands have had a democratic government where officials are elected in an open, popular vote election. Before 1970, the Secretary of the Interior, under the territory’s 1954 revised Organic Act, appointed a governor for the islands (United States Department of the Interior, 1998).

The U.S. Virgin Islands, like the United States of America, have executive, legislative, and judicial branches of their government. Of the three parties; the Democratic, the Republican and the Independent Citizens’s Movement, the Democratic Party traditionally has held power. The executive branch is lead by a governor and lieutenant governor, each of whom serve four-year terms. The current governor, the Honorable Dr. Charles Wesley Turnbull, and lieutenant governor, the Honorable Gerald Luz James, were elected in 2002 and sworn in on January 6<sup>th</sup>, 2003 (CIA World Factbook, 2002). The legislative branch consists of fifteen senators who are also elected by popular vote and serve two-year terms. In addition, the Virgin Islands also elect a member of the Congress of the United States of America. Currently, this representative is the Honorable Donna Christian-Chistensen who possesses the same rights as any other House Representative



from the states with the exception of voting rights on the House floor (Department of the Interior, 1998).

#### ***1.2.1.4 – Economy***

Tourism is the main economic force on the three major islands on the U.S. Virgin Islands. Each island has a unique economy of its own. St. Thomas can be characterized economically as a commerc-driven market, while St. Croix and St. John can be characterized as agriculturally-driven markets (Buros, 1984).

Today the U.S. Virgin Islands have a prospering economy. Much of this prosperity is due to the islands' burgeoning tourism industry (USVI Travel Guide, 2000). This industry accounts for over seventy percent of the island's gross domestic product and employment (CIA World Factbook, 2002). Numerous cruise lines make the islands a weekly port of call and many major airlines offer daily flights to the islands. From 1970 to 1990, the tourism industry on the islands increased more than thirty-fold and now brings in over \$500 million annually for the islands. In addition to tourism, the islands also have a large manufacturing industry. Manufactured goods include rum, oil, alumina production, pharmaceuticals and watch assembly. A new tax incentive program administered and initiated by the government of the U.S. Virgin Islands has begun to attract new industries to the islands. The government is offering special tax incentives and export allowances. These factors, along with the island's excellent infrastructure, modern communications, regular transportation to major cities and use of American currency have already attracted many new industries, like the pharmaceutical industry, to the islands (U.S. Department of the Interior, 1998).

#### ***1.2.1.5 Population***

As shown in Figure 13, the United States Virgin Islands have experienced a tremendous increase in population over the last fifty years due to a dramatic increase in the tourism industry on the islands (Bruno-Vega, 1994 and U.S. Census Bureau, 2001).

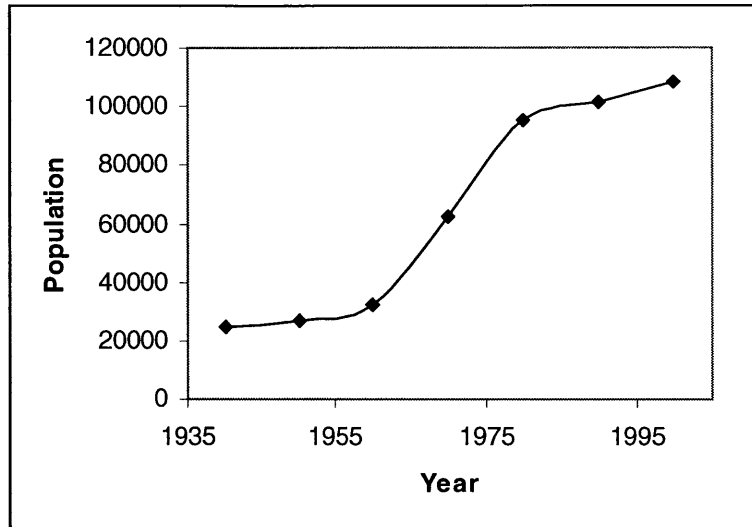


Figure 13  
Population of the US Virgin Islands

The population of the U.S. Virgin Islands today is estimated to be approximately 124,000 (CIA World Factbook, 2002) and is expected to continue to gradually increase due to economic growth experienced on the islands.

#### ***1.2.1.6 Climate***

The climate of the United States Virgin Islands is classified as subtropical (CIA World Factbook, 2002). Temperature highs range from 72.6 degrees Fahrenheit to 87.2 degrees Fahrenheit with an average yearly high of 79.9 degrees Fahrenheit (USVI National Park Service, 2002). Average lows range from 50 to 60 degrees Fahrenheit. There is very little seasonal variability in temperature on the islands. The islands are cooled by the easterly trade winds and have relatively low humidity year-round. The rainy season typically occurs from May to November (CIA World Factbook, 2002), but this season can change dramatically from year to year.

### ***1.2.2 Water Resources***

#### ***1.2.2.1 Introduction***

The United States Virgin Islands have a climate, geology, and location that greatly limit the amount of potable water available from groundwater and surface water sources. The ability to provide an adequate amount of potable water to its citizens has always been a major concern for the government of the U.S. Virgin Islands. Water scarcity is the only current environmental issue listed for the islands by the CIA World Factbook (CIA World Factbook, 2002). The islands have an arid tropical climate where very little rain falls on an annual basis. In addition, the amount of rainfall varies greatly from year to year. The islands also have very little topsoil, a characteristic typical of tropical, arid

islands, and they are very mountainous, with the exception of St. Croix, which is very flat. These factors prevent the accumulation of groundwater in the subsurface of the islands. The islands' small surface area also prevents the accumulation of groundwater and prevents the formation of viable surface water sources.

### ***1.2.2.2 Water and Power Authority***

The Virgin Islands Water and Power Authority, also known as WAPA, was created on August 13<sup>th</sup>, 1964 (Bruno-Vega and Thomas, 1994), to provide the major islands of the U.S. Virgin Islands with potable water and electricity. Desalination would provide potable water to the three major islands and oil burning electrical power plants would provide electricity. At the time of its creation, the Water and Power Authority was to produce and distribute electricity, but only produce desalinated water. The Department of Public Works was to purchase the water from the Water and Power Authority and distribute it. In 1983, a legislative amendment transferred potable water distribution responsibility from the Department of Public Works to the Water and Power Authority. Today, the Water and Power Authority is responsible for all production and distribution of potable water and electricity on the three major U.S. Virgin Islands (Bruno-Vega and Thomas, 1994).

### ***1.2.3.3 Groundwater***

Historically, groundwater has been a major source of potable water for the U.S. Virgin Islands. It was the first solution the islands found for meeting increasing demand as population increased.

Today, St. Croix is the only island that still uses groundwater as a major source of potable water. Groundwater accounts for approximately 33% of the total supply of potable water that the Water and Power Authority distributes on St. Croix. This groundwater has extremely poor water quality due to elevated hardness and salt content (Bruno-Vega and Thomas, 1994). Because of its poor water quality, the groundwater has been troublesome, causing the corrosion of distribution pipes as well as causing complaints about poor taste.

The Water and Power Authority explored a variety of solutions aimed at improving the water quality of its groundwater sources. It ultimately chose to blend its developed groundwater sources with desalinated water to alleviate these problems and to attempt to meet the Environmental Protection Agency's Safe Drinking Water Act Standards. The groundwater sources have elevated levels of chlorides and total dissolved solids, which cause them to exceed their permitted Safe Water Drinking Act levels. Blending groundwater with potable desalinated water improved water quality in areas close to the point where the blended water was introduced, but provided little help the further in the distribution system because of accumulation of brackish water intrusion. The Water and Power Authority then looked for another solution to help these water sources meet Environmental Protection Agency standards. It renovated its distribution system to

prevent brackish water intrusion and installed reverse osmosis plants at each well head to improve water quality (Bruno-Vega and Thomas, 1994).

#### 1.2.3.4 Water Catchment

Another method that has been historically employed by the U.S. Virgin Islands to supply water to its residence has been the harvesting of water through water catchment cisterns. In 1964, the legislative body of the U.S. Virgin Islands brought forth and passed legislation requiring all new buildings constructed on the islands to use their roof for rain catchment and diversion into cisterns (Bruno-Vega and Thomas, 1994). To “catch” water, the roofs of homes and other man-made structures divert water from their surfaces into cisterns where they can be stored for use rather than running off into bodies of water or seeping into the ground. Cistern water is used primarily by homes that have no other means of access to water. Lack of access to other sources of water is primarily dictated by either inadequate water generation and distribution capability by the Water and Power Authority, or lack of physical access to an economically feasible distribution route caused by the islands’ topography. While the U.S. Virgin Islands Water and Power Authority aims to provide all residents with access to potable water, it also considers cisterns a valuable source of water for domestic purposes, as well as for use in emergency situations.

For cisterns to be an effective source of potable water, rainfall must be plentiful and reliable. In the U.S. Virgin Islands, rainfall is neither plentiful nor reliable. As Figure 14 (National Weather Service, 2002 and United State Geological Survey, 2002) shows, rainfall on all three islands is widely variable from year to year when compared to the 30 year rainfall average for the islands.

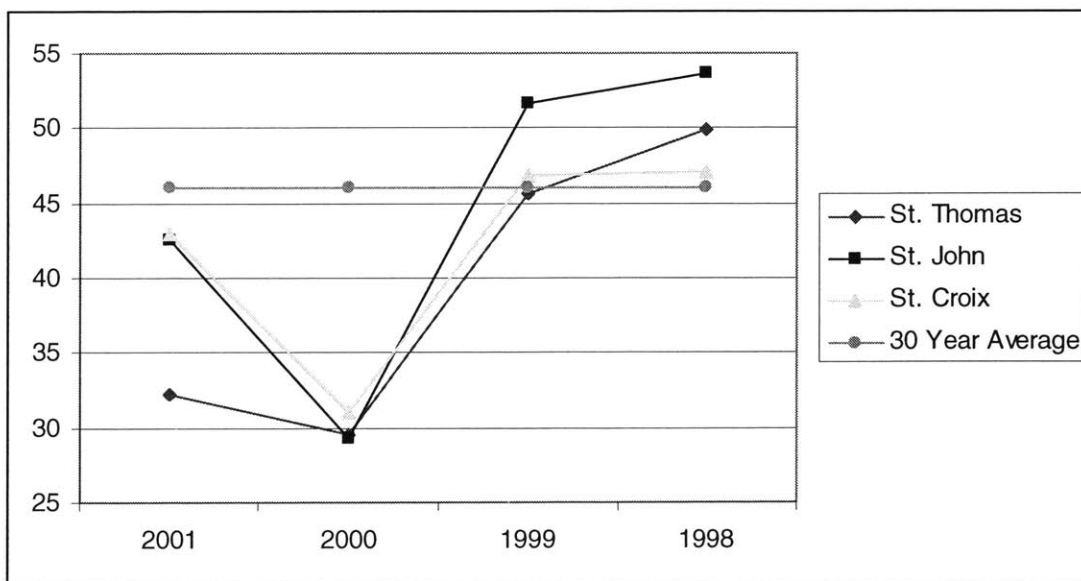


Figure 14

Annual rainfall in the three major U.S. Virgin Islands compared to the thirty year average

Figure 15 (National Weather Service, 2002 and United States Geological Survey, 2002) shows the average rainfall for all three major islands compared to their 30 year average.

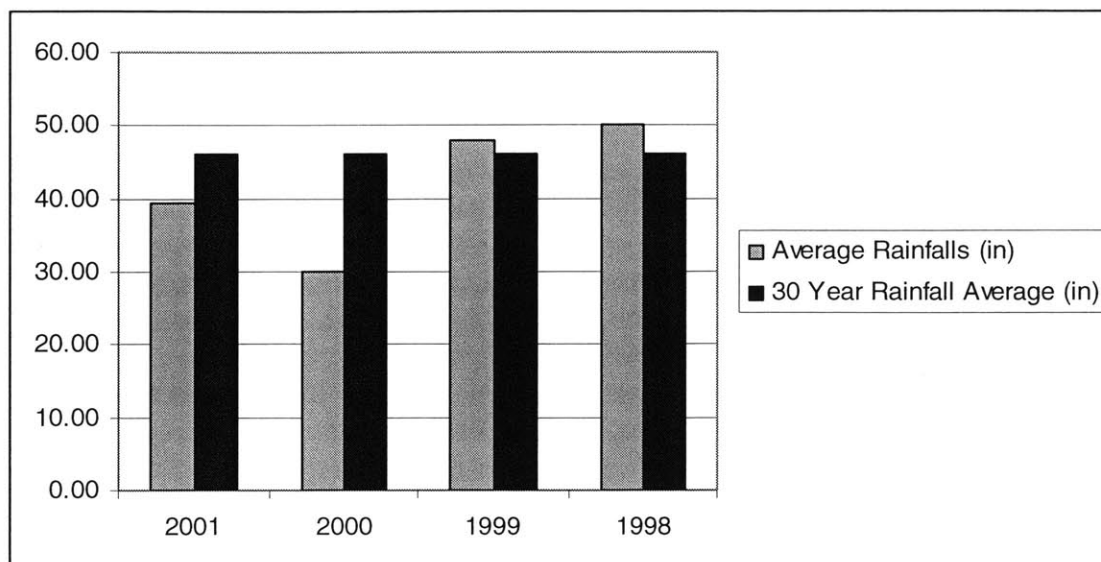


Figure 15

Average annual rainfall of the three major U.S. Virgin Islands compared to the thirty year average

As these figures show, rainfall in the U.S. Virgin Islands low in comparison to other areas of the world and varies in quantity from year to year. Within a year, rainfall varies widely from month to month. This widespread variability in year-to-year and month-to-month rainfall makes the use of water catchment into cisterns a very unreliable source of potable water for the U.S. Virgin Islands.

Cistern water quality can be very poor. Poor water quality in cisterns primarily results from bacterial contamination. In the U.S. Virgin Islands, homeowners who employ water catchment systems do not typically employ any means of disinfection due to high costs and lack of education. While few illness have been directly linked to drinking water from a cistern, most residents of the U.S. Virgin Islands use cistern water only for domestic uses and purchase bottled water from local vendors for drinking purposes (Bruno-Vega and Thomas, 1994).

### ***1.2.3.5 Desalination***

Desalination has historically played a major role in supplying clean, potable water to the residents of the U.S. Virgin Islands and continues to do so. The U.S. Virgin Islands is the pioneer of many types of desalination technology. Because of their extreme lack of other potable water sources, they have commercially applied every type of desalination technology. The process of desalination contributes approximately 80 percent of the total

amount of water supplied by the Water and Power Authority to the three major islands (Buros, 1984).

Since the early 1900s, desalination has been in use on the U.S. Virgin Islands. In 1915, the government of the U.S. Virgin Islands began to investigate the possibility of using desalination as a source of potable water for the islands. At that time, it was rejected due to extremely high costs. It was not until 50 years later that the idea was revisited and employed; costs associated with the process were still extremely high, but increases in the islands' populations left the government with no other choice. In 1948, a small greenhouse-type glass-covered solar humidification still was constructed on the islands for experimental purposes. The unit only produced two gallons per day (Buros, 1984). The first real attempt at commercial desalination on the islands came in 1958 when the Congress of the United States authorized the Territory of the U.S. Virgin Islands to construct a 0.275 million gallons per day, 28 stage multi-stage flash distillation desalination plant. The plant was operational in 1962. In the 1960s, distillation was the only accepted commercially available desalination process. Researchers were searching for a new and innovative, cost-effective approach to desalination. The most heavily researched alternative was freezing. Although the process never became commercially available, research on the process allowed for a company called Israel Desalination Engineering to develop the first commercially available vapor compression unit in 1967. In addition, experimentation done on the freezing process also allowed Israel Design Engineering to produce the horizontal tube multi-effect distillation process. It sold its first multi-effect distillation to the U.S. Virgin Islands in 1980. The first reverse osmosis plant constructed and operated in the U.S. Virgin Islands was built in 1972. It was a 0.07 million gallon per day plant and was used for two years, after which it was shut down due to excessive scaling on its membranes. Numerous other reverse osmosis plants have been built on the islands for desalination of brackish water and seawater (Buros, 1984). Most of these pioneering desalination plants were built for a wide variety of customers, which included the Water and Power Authority, hotels, condominiums and resorts.

The Water and Power Authority itself has operated numerous types of desalination plants. Figure 16 (Bruno-Vega and Thomas, 1994; Buros, 1984) is a summary of these plants, which were built on either St. Thomas or St. John.

Year	Design Capacity (mgd)	Type*	Current Status
St. Thomas			
1962	0.275	MSF	Scrapped in 1980
1965	1.000	MSF	Scrapped in 1980
1968	2.500	MSF	Scrapped around 1984
1975	2.250	VTE-MSF	Scrapped
1981 (IDE #1)	1.250	HTME	Operational
1982 (IDE #2)	1.250	HTME	Operational
1983 (IDE #6)	0.550	HTME	Operational
1992(IDE #8)	1.440	HTME	Operational
St. John			
1991(IDE #7)	0.155	VC	Operational

Figure 16  
Desalination plants built on either St. Thomas or St. John

\* MSF = Multi-state flash, VTE = Vertical Tube Evaporator (multiple-state distillation), HTME = Horizontal Tube Multi-Effect (distillation), VC = Vapor Compression

All potable water, except in the capitol of Charlotte Amalie, produced by desalination is delivered to residents by tanker trucks. This has dramatically increased costs associated with delivering potable water to consumers.

All of the plants that are still currently operational were built by Israel Desalination Engineering. The Water and Power Authority of the U.S. Virgin Islands have shared a long and productive relationship with Israel Design Engineering. Initially, the United States Navy provided Israel Desalination Engineering with the funding to research and design the plants for the U.S. Virgin Islands (Elovic and Willocks, 1998). Currently, they have a total of 9 desalination plants in operation, all of which were designed by Israel Desalination Engineering. In its first order to Israel Desalination Engineering in 1979, the Water and Power Authority ordered three 1.25 million gallons per day multi-effect distillation plants. At that time, only one plant of that type was in operation worldwide. The risk turned out to be a productive one for The Water and Power Authority as all three plants are still operational and are producing quantities of water above their design capacity. The United States Virgin Islands' Water and Power Authority was Israel Desalination Engineering's first client in the western hemisphere and they have used the first three plants they designed for the Water and Power Authority as examples of their design capabilities to numerous other western hemisphere clients.

In addition to desalination plants operated by the Water and Power Authority, numerous private-companies operate small desalination plants that serve private customers or businesses.

## ***2. Performance Assessment of the Desalination Industry***

### ***2.1 Overview***

Like many other areas in the world, the U.S. Virgin Islands can only produce potable water reliably from desalination systems. No other source of potable water is economically or technologically available. For this reason, maximizing the net benefit and reducing risk of the island's desalination systems is pivotal. The islands need a reliable and flexible system that can provide them with adequate potable water supplies at low costs through extreme natural events, like hurricanes, and during times of normal operation.

Numerous studies have been conducted to evaluate the relative advantages and disadvantages of each desalination treatment process (Al-Mataz, 1996; Darwish, et al, 1989; Kamal, 1995; Madani, 1990). Most of these studies examined the economics of the processes or the environmental impacts of each process. Very few studies have been conducted to examine the complex interactions of social, economical, and environmental factors into the study. The purpose of this study is to determine which set of available treatment options, plant sizes, and timing of construction schedules maximizes net benefit and minimizes risk in the U.S. Virgin Islands. Analysis of existing treatment options on the U.S. Virgin Islands are used to determine relative strengths and weaknesses of each process in terms of cost, size and long-term reliability and flexibility. Two desalination treatment systems are used: plants operated by the Water and Power Authority and plants operated by Aqua Design. The study also determines the best-long term policy for operation of a desalination treatment system on the U.S. Virgin Islands. The goal is to provide a framework that any nation or area can use to determine the most appropriate configuration of desalination treatment options, number of desalination plants and size of desalination plants. The framework will be constructed through the use of system indicators selected to represent the crucial aspects of the system. By analyzing these indicators the U.S Virgin Islands can balance their needs with the associated costs as well as understand how each choice for each indicator will affect their desalination system.

Analysis of system indicators is used to determine which configuration presents the U.S. Virgin Islands with the least risk by maximizing flexibility and reliability of the system as a whole. By maximizing these factors, the U.S. Virgin Islands will have the best long-term plan in terms of when to build new plants, how many plants to build, what size plants to build, and what treatment technologies to use.

### ***2.2 Scope of Study***

This study focuses on desalination units located on the U.S. Virgin Islands, although this model could be used for other areas around the world. The assessment aims to determine; which treatment process is the most efficient; what time schedule to follow in building new plants; how many plants to build; what size plant to build in order to create the most favorable system that minimizes costs and risks, as well as maximizes system



flexibility and reliability. It is important to maximize flexibility and reliability so that the overall system can respond to a variety of changes with minimal impact on the system as a whole.

Desalination plants in operation on the U.S. Virgin Islands are used in the study. Specifically, the Water and Power Authority Plants on both St. Thomas and St. John, as well as an old and new plant in operation at Caneel Bay, operated by Aqua Design, are used.

The St. Thomas Water and Power Authority desalination plant operates IDE unit #1, #2, #6, and #8. All of these units are multi-effect distillation units. The St. John Water and Power Authority desalination plant operates IDE unit #7, which is a vapor compression unit. The Aqua Design units in this study are all single pass reverse osmosis units.

Due to wide variability in plant input parameters such as quality of feedwater, treatment standards, and costs of operational and essential supplies, choosing plants from different regions of the world would produce misleading results in the evaluation of the treatment processes based on factors not within the scope of this study. The plants located on the U.S. Virgin Islands can be considered as a representative sample of plants worldwide for many reasons.

- There are many desalination plants located on the islands, which can be analyzed to provide a large set of data.
- The data is reliable and easy to obtain.
- Most plants have many years of continuous data and have been in operation for many years
- The islands have many years of operational experience with every major type of desalination, with many different treatment processes still in operation with varying levels of new technology incorporated.
- Desalination plants on the islands range from very large to very small.
- Nearly every variation and type of plant and related technology can be found on the islands.
- The islands' desalination facilities, along with the Middle East, have become the standard for desalination research due to numerous studies conducted on their facilities.

Because of their long, well-recorded history and operational performance, as well as the factors outlined above, desalination plants on the U.S. Virgin Islands are very well suited for an assessment aimed at determining the most appropriate overall desalination system configuration for the nation.

### ***2.3 System Indicators***

The system indicators chosen for the assessment represent essential system factors related to the desalination treatment process or plant size. Each indicator was chosen based on its relative importance to desalination systems. The indicators are used to make an

objective assessment of which treatment process more effectively minimizes risk while maximizing net benefit. The indicators are also analyzed to make a subjective the most appropriate desalination system configuration in terms of treatment process, number of plants, size of plants, and relative timetable for construction of each plant.

Since many indicators are necessary to study a system, the indicators are chosen to represent various aspects of the desalination treatment process, as well as aspects of the overall system assessment. It is important to note that some indicators can be used to directly make conclusions about the most appropriate configuration for that indicator in the system. Other indicators can be used indirectly or can be used with another indicator to make conclusions about the most appropriate configuration. Many of the indicators are intimately related to one another and rely directly on one another to make a conclusion. The chosen sustainability indicators are as follows.

- Cost required to produce 1000 gallons of potable water
- Fuel required to produce 1000 gallons of potable water
- Effluent brine water temperature
- Effluent brine maximum and minimum pH
- Effluent brine flow rates per amount of potable water produced
- System and plant reliability
- System and plant flexibility
- Desalination plant size
- Number of plants
- Relative construction timetable

These indicators were chosen because of their importance to the system assessment. The indicators are only affected by changes that occur within the system or by changes that are directly related to the system.

Each indicator can be directly related to the concepts of overall operational costs of the system or relative risk of the system.

The cost indicator is a direct measurement of overall costs associated with operation of the treatment process. Higher treatment process costs increase overall operational costs. This increases relative risk and decreases the overall net benefit of the system.

The fuel indicator represents another measurement of overall costs. The cost of buying fuel required to operate a desalination plant constitutes the highest single cost for a treatment process. Increases in the cost of fuel also increase overall operational costs and environmental impact. This results in increasing the relative risk of the system and decreasing the system's net benefit.

The effluent brine water temperature, effluent brine minimum and maximum pH, and effluent brine flow rate indicators represent the environmental impact that the desalination plant has on water quality. Deviations in these indicators outside of their permitted levels, as outline by the Environmental Protection Agency's Clean Water Act,

represent increases in overall operational costs and environmental impact. This increases the relative risk of the system and decreases net benefit. Economical costs are increased by these deviations as a result of fines and sanctions. Social and environmental costs are increased by destruction of natural habits and ecosystems as a result of increased strain from brine effluent.

Plant and system reliability is essential to a system. Decreases in reliability increases costs, increases risks and thus, decreases net benefit. A system that is unreliable increases economic and social costs. An unreliable system may also increase environmental costs through increased pollution resulting from an unexpected event. Economic costs are increased as a result of system downtime. When the system is not operational, it not producing potable water that can be sold for a profit. It also increases social costs by causing strife within the community that the plant supplies. Consumers will not trust a system that is unreliable to provide them with their drinking water. Risk is increased in an unreliable system for the same reasons, downtime increases the risk that an event could occur to completely or temporarily disrupt the system.

Plant and system flexibility is also essential to a system. Decreases in flexibility increase costs and risks, thus reducing net benefit. A system that is inflexible cannot efficiently respond to varying conditions. The more inflexible a system is, the greater the chances are for increased costs and risk. A system that cannot respond to a variety of changes or fluctuations has a greater chance of experiencing failures. These failures could be complete destruction of the system; temporary shut downs, damage to the system, etc. All of these scenarios would increase total costs as well as increase overall risk.

Desalination plant size indicator can affect both cost and risk. Plant size can affect cost by affecting the treatment process and by affecting overall plant performance. More importantly, plant size affects risk by affecting both flexibility and reliability. A larger plant has a larger economic and time commitment associated with it. Larger plants are typically expected to last longer due to the larger initial investment in capital. This decreases the flexibility and reliability of the plant. If a far superior treatment technology comes to market that dramatically decreases costs after a larger plant is built, it is far harder for the officials in charge of the plant to invest in the new technology after they have invested so much in the large plant. This decrease in flexibility can greatly increase costs and risk. If the system is not flexible, it will not be able to take advantage of cost-cutting or risk-reducing measures. In addition, a large plant may become unreliable as it ages. The large initial capital investment will again keep officials from making any change. Rather, they will be forced to rely on the older, antiquated treatment system.

The number of plants indicator can indirectly affect costs, but directly affects risk. The more plants you have, the more flexible and reliable your system is. Having more plants reduces risk by allowing a collection of plants to be responsible for the overall responsibility of producing potable water. If one desalination plant is unavailable, the others can make up for it. If the system had one plant and it shut down, the system would suffer increased costs associated with the lost profit and repairs associated with the shut down.

The relative construction timetable indicator is not directly related to costs or risks. Rather, it uses the above system indicators to construct the appropriate timetable for building new desalination plants. The most effective timetable would effectively incorporate and balance all of the above indicators in relation to the overall system plan to both reduce overall costs and reduce risks. This indicator should be proactive so that it could incorporate new cost cutting or risk-reducing measures as they are introduced to the market.

## ***2.4 Plant Location***

The desalination plants that will be used to perform the assessment are located on the U.S. Virgin Islands. Systems that have similar characteristics are used in the study to eliminate uncertainty and errors in the assessment. Specifically, using systems located in the same geographic location eliminates discrepancies that are caused by:

- the costs of chemicals and other goods necessary for the process
- the varying quality of the feedwater introduced into the process
- the required quality of potable water
- the varying brine discharge water quality emission standards

By using plants located in the same area, the study ensures that each plant pays approximately the same price for chemicals and other goods. Indicators will only take into account the desalination system, not costs associated with transporting these materials to different locations that have different suppliers and costs based on regional demand markets.

Feedwater quality of the desalination plants is similar because the plants are drawing water from similar, if not the same, water sources. Because of the similar feedwater quality, sustainability indicators are influenced only by differences in the performance and operation of the plants within the system. All plants in this study draw their feedwater from the Caribbean Sea.

All of the plants in the U.S. Virgin Islands are regulated by the Safe Water Drinking Act; (EPA, 1974) thus, the potable water they produce should be similar. In addition, by studying plants located in the same geographical area, the assumption can be made that all product water is similar based on taste and texture demands of the citizens of the area. Specifically, citizens of the U.S. Virgin Islands prefer their potable water to be acidic for better taste (Bramble, 2003). All of these factors ensure that the indicators are influenced only by the differences in the performance and operation of the plants within the system.

All of the plants in the U.S. Virgin Islands have brine emissions that are regulated by the Clean Water Act (EPA, 1977), and all plants must ensure that their brine is treated to those Clean Water Act standards. Accordingly, s indicators are influenced only by plant performance and operation and not by varying emission requirements that could result with plants in different parts of the world that are not regulated by the Clean Water Act.

## 2.5 Plant Descriptions

The assessment focuses on the desalination plants operated by either the U.S. Virgin Islands Water and Power Authority or by Aqua Design Incorporated. The plants operated by the U.S.V.I. Water and Power Authority represent large and small, older, distillation processes. These plants were all built between 1981 and 1992, and they are among the newest, most advanced distillation plants currently in operation. The plants operated by Aqua Design at Caneel Bay represent older and newer, small, reverse osmosis technologies. These plants were built during the 1960s and in 2003, respectively (Di Cola, 2003).

Comparison of these two sets of plants presents many ideal situations for a system analysis. Each plant represents a desalination process vital for the assessment's success. The two main types of desalination treatment processes are represented and plant sizes range from very large to very small. These factors influence all of the other system indicators. Because of these facts, a complete assessment can be made of the current systems in operation in the U.S. Virgin islands and the most appropriate system configuration can be found that maximizes reliability, flexibility and net benefit while decreasing risk, and cost by manipulating the other system indicators. Figure 16.5 presents of brief summary of each plant.

Plant	Treatment Type	Description
WAPA – St. Thomas	Multi-Effect Distillation	Very large, “best” distillation technology and configuration
WAPA – St. John	Vapor Compression	Very small, “worst” distillation technology and configuration
Aqua Design - New	Reverse Osmosis	Small, “best” reverse osmosis technology
Aqua Design - Old	Reverse Osmosis	Small, “worst” reverse osmosis technology

Table 16.5  
List of desalination plants used for assessment

### 2.5.1 Water and Power Authority – St. Thomas

Four of the five desalination plants operated by the Water and Power Authority are located in Krum Bay on St. Thomas. Figure 17 shows the Krum Bay plant. In all Water and Power Authority plants, green pipes carry feedwater, yellow pipes carry waste brine, and blue pumps carry potable, product water.

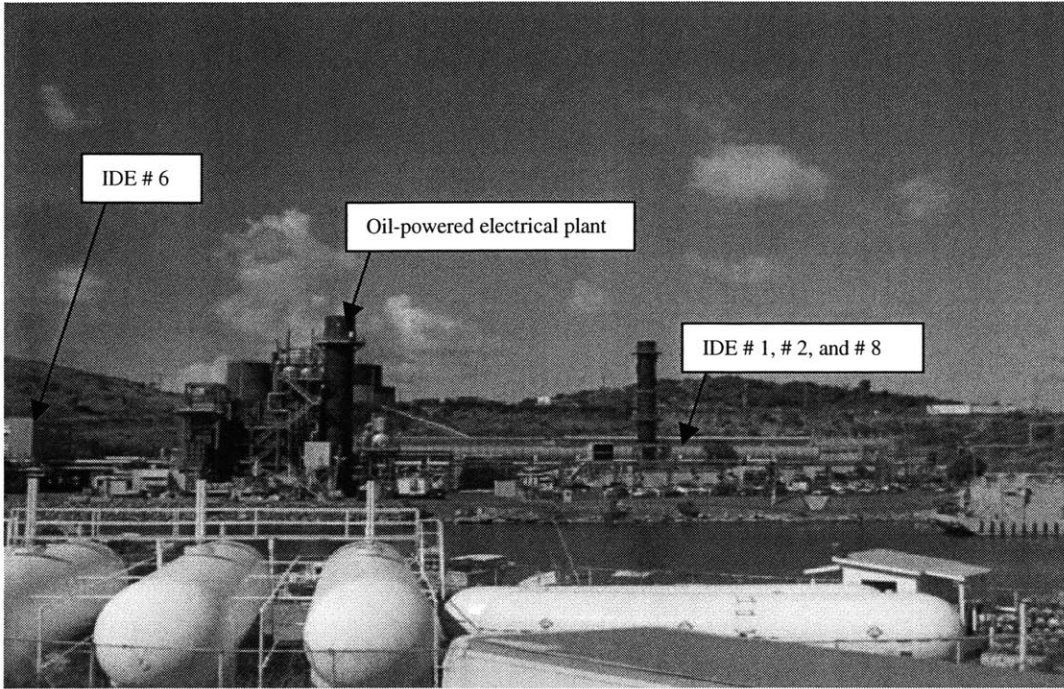


Figure 17  
Krum Bay desalination plant

The Krum Bay desalination units take their feedwater from Krum Bay. Water is sent to each of the four desalination units through one of three feedwater pumps. These pumps are shown in Figure 18.



Figure 18  
Feedwater intake pumps at the Water and Power Authority Krum Bay Plant

After being taken from Krum Bay, feedwater goes through pretreatment. Pretreatment at Krum Bay, like in most desalination facilities, consists of chlorine dosage aimed at killing bacteria and viruses present in the water. Figure 19 shows typical chlorine storage tanks used at a facility like Krum Bay and Figure 20 shows typical chlorine dosage units where chlorine is fed into the water.



Figure 19  
Chlorine storage tanks

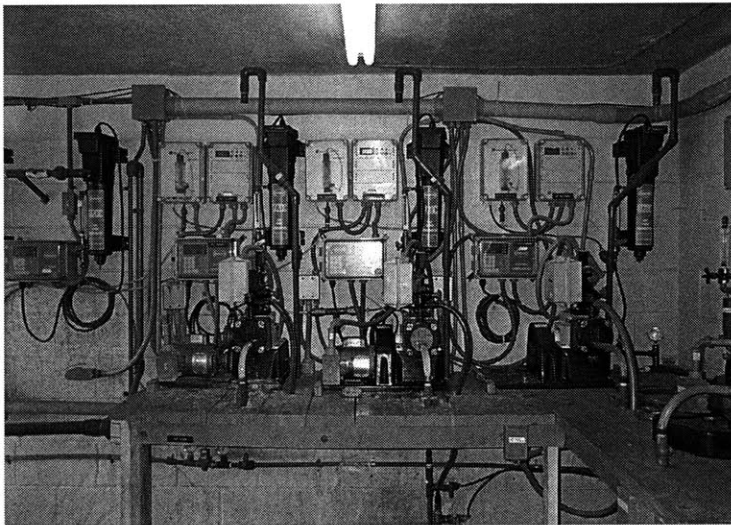


Figure 20  
Chlorine dosage units

The feedwater intake pumps deliver the water to each unit. Each individual unit then uses its own feedwater pumps to pump the water up into the first effect. Each unit has a unique set of feedwater pumps. These pumps also remove most of the air trapped in the water. Two pump configurations are shown in Figure 21a and 21b.

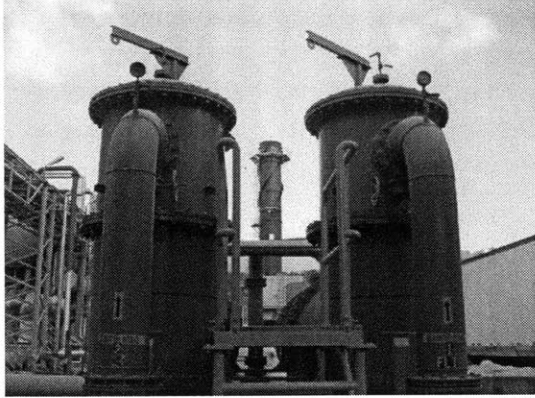


Figure 21a  
Feedwater intake pumps for IDE #8

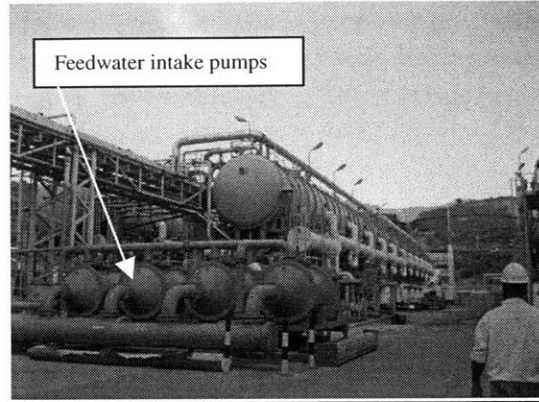


Figure 21b  
Feedwater intake pumps for IDE #1 and  
IDE #2

The feedwater then enters the desalination unit. The first series of effects constitute the condensing stage. Feedwater is used to condense recycled steam back into feedwater so that it can go through the treatment process to increase overall efficiency and recovery rates. It is also in this series of effects that chemicals are added to the process. Figure 22 shows a chemical storage tank that contains sodium sulfite, an oxygen scavenger, used to prevent corrosion of the pipes. The plant also begins to introduce ID-104, a scale inhibitor, at this point at a rate of 5-6 parts per million, depending on the unit. An anti-foaming agent is also introduced at a rate of 1 part per million (Chung, 2003).

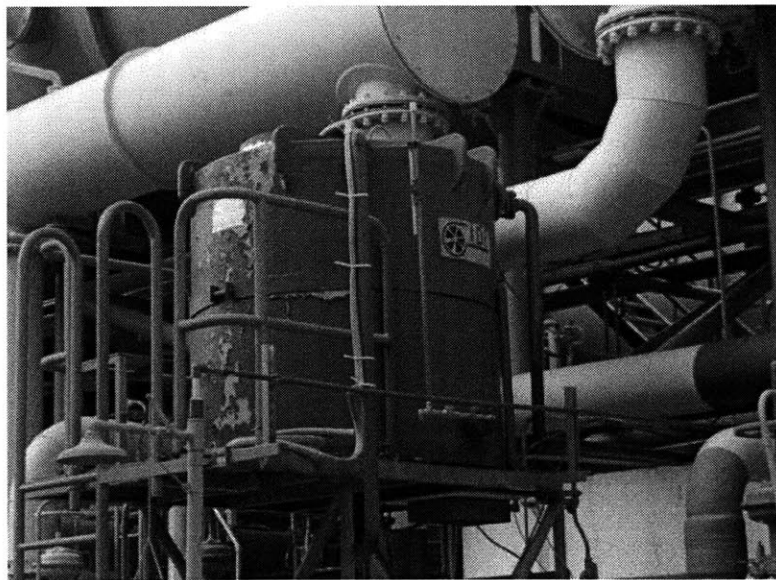


Figure 22  
Chemical storage tank containing sodium sulfite, an oxygen scavenger



After the condenser effects, feedwater enters the evaporator effects where it is sprayed over horizontally placed tubes filled with steam. The feedwater then evaporates and is either recycled or is used to wash the brine off the pipes and becomes wastewater. The steam condenses and is collected for drinking purposes. In this set of effects the water is subject to laminar flow, flowing at a rate of 0.5 feet per second. Laminar flow reduces corrosion on the metallic parts of the system. Figure 23 shows potable water being taken from IDE #1 and brine being taken from IDE #2.

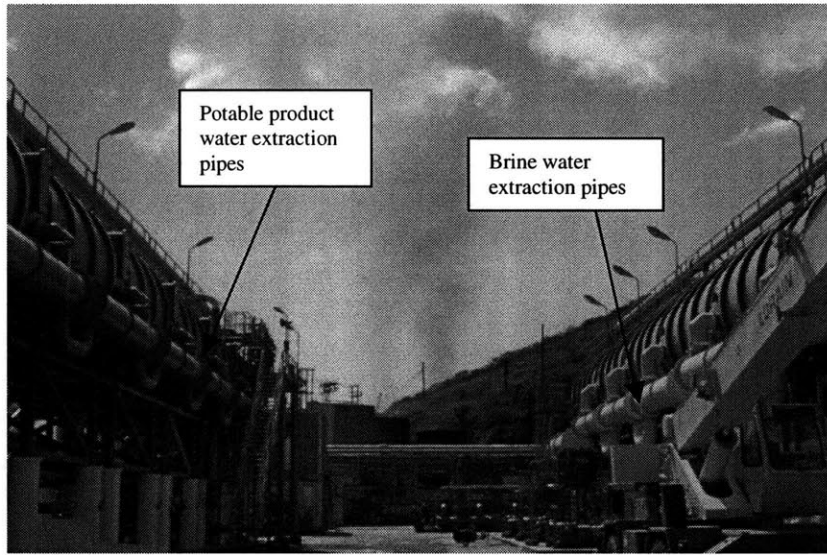


Figure 23

Brine and product water extraction from IDE #1 (product) and IDE #2 (brine)

At the end of the unit, steam is recycled back to the beginning of the process for reuse, which increases system efficiency and recovery of potable water. This steam travels through a pipe located on top of each unit. This is shown in Figure 24.

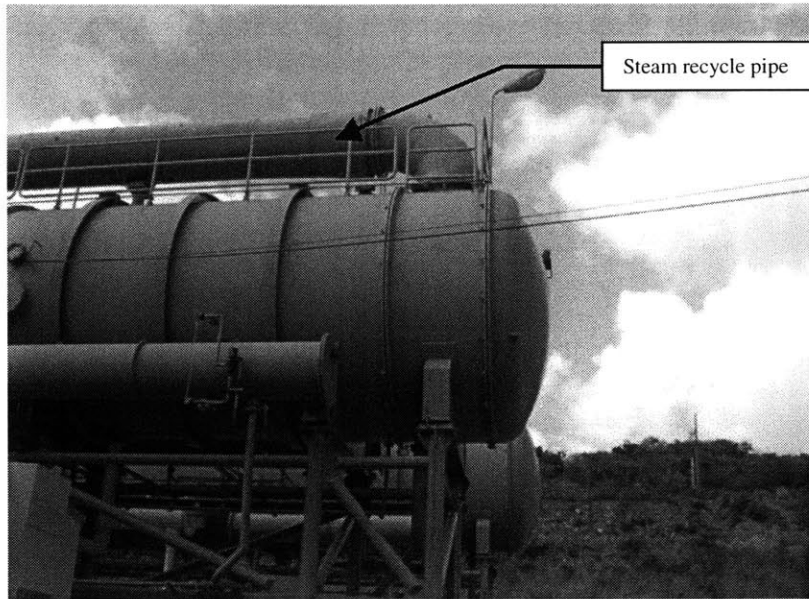


Figure 24  
Steam recycle pipe at end of unit

The brine from the unit is then pumped to its effluent discharge point. Figure 25a shows a brine effluent pipe and Figure 25b shows the discharge point. Brine leaving the units never has a temperature greater than the brine in the first effect, which has a temperature of 160 degrees Fahrenheit (Elovic and Willocks, 1999).



Figure 25a  
Brine discharge pipe



Figure 25b  
Brine discharge point

The unit gets its energy from the adjoining oil-powered electrical power plant. Figure 26 shows the electrical power plant. This power plant supplies the islands of St. Thomas and St. John with electricity. The plant consists of 2 oil-powered turbine units that are designed to produce 156.5 megawatts per day (Creque, 2002). Thermal energy, in the

form of waste steam, is sent from the turbines to the desalination units. The steam recycling unit is shown in Figure 27.

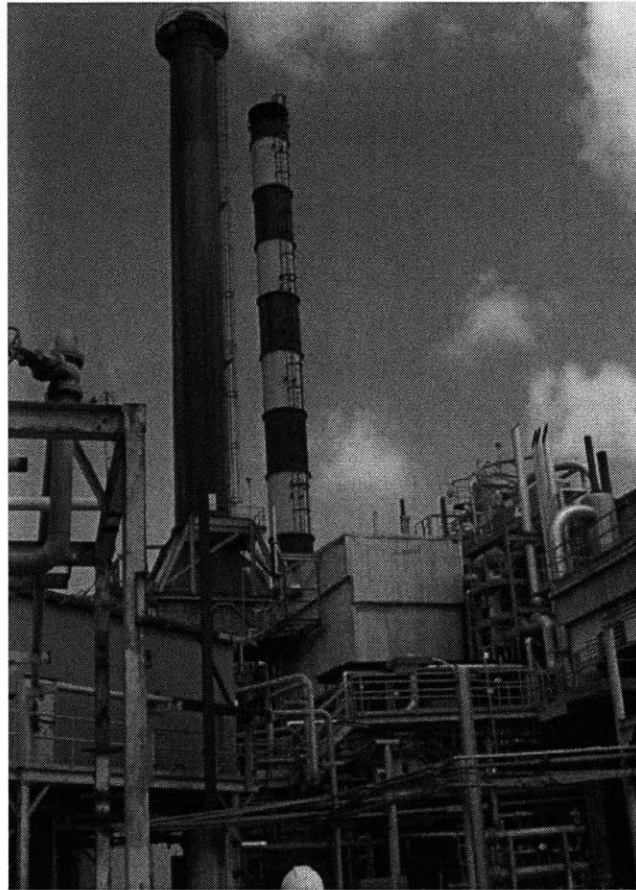


Figure 26  
Oil-powered electrical power plant

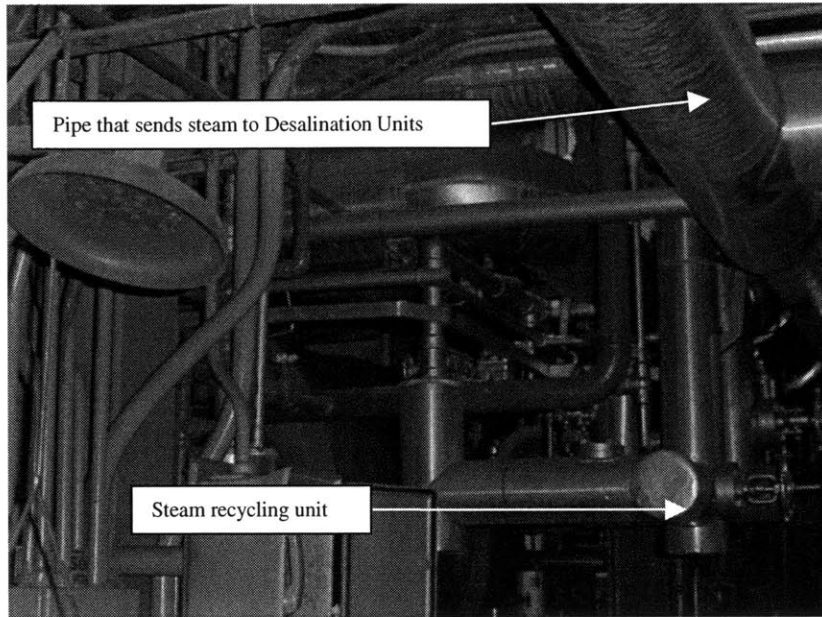


Figure 27  
Waste steam recycling unit

### ***2.5.2 Water and Power Authority – St. John***

The other Water and Power Authority desalination plant studied is located in Frank Bay on St. John. Figure 28 shows the Frank Bay plant.

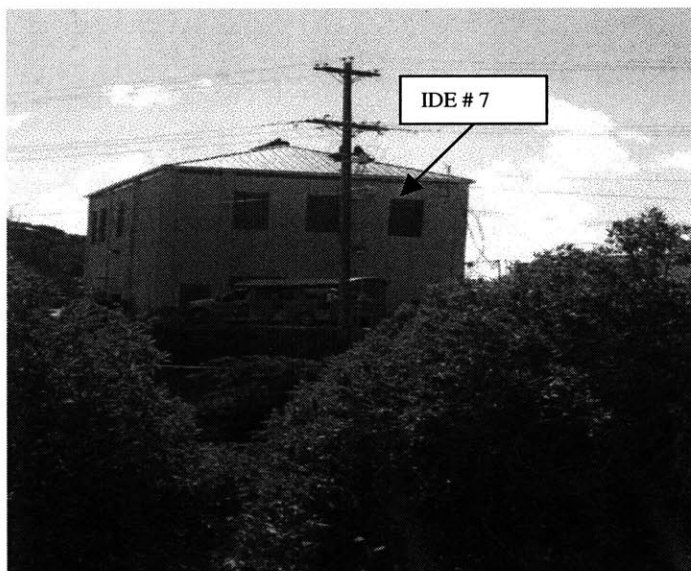


Figure 28  
Frank Bay desalination plant

The Frank Bay plant takes its feedwater from Frank Bay. The water is then pumped into the plant by two feedwater intake pumps. Figure 29 shows a picture of the intake pumps.

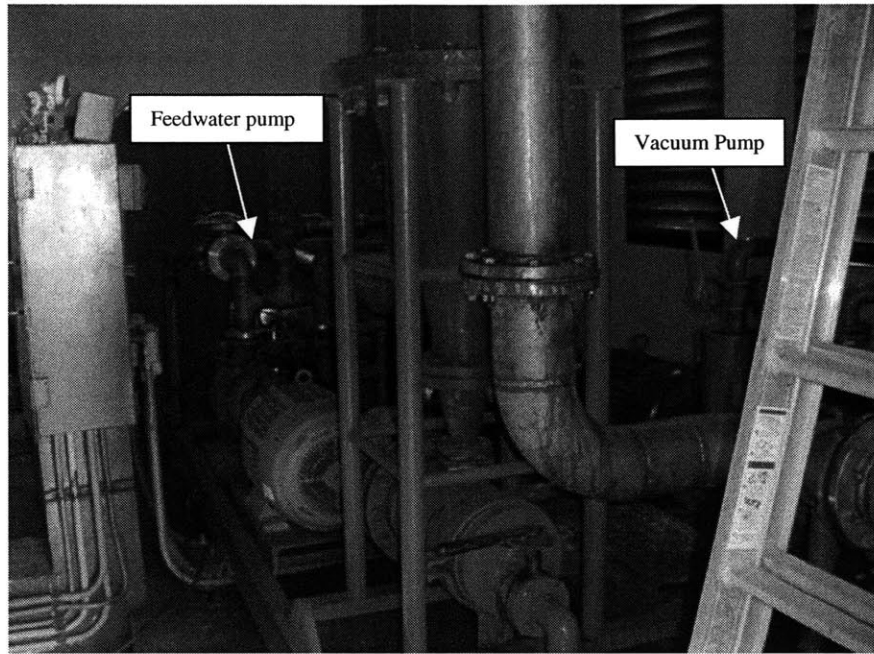


Figure 29

Intake pumps and vacuum pump at the Frank Bay desalination plant

The vacuum pump is also located in the same building as the feedwater pumps. This pump is essential for plant operation. During startup, this pump removes air from the system and provides the hydraulic head necessary to start the process. This pump is also pictured in Figure 29. The Frank Bay plant has both a vapor compression unit and a reverse osmosis unit. The reverse osmosis unit is a mobile unit that is operated by the Seven Seas Water Company and was brought to the plant to increase supply due to increasing demand on the island. Feedwater is pumped by the feedwater pumps through a pretreatment process and into the plant. The pretreatment process chlorinates the water to kill any water-borne bacteria that may be present. Pretreatment is only used when the reverse osmosis unit is not in use because chlorine destroys the membranes used at the plant. Figure 30 shows the chlorine storage tank as well as the pretreatment injection point.

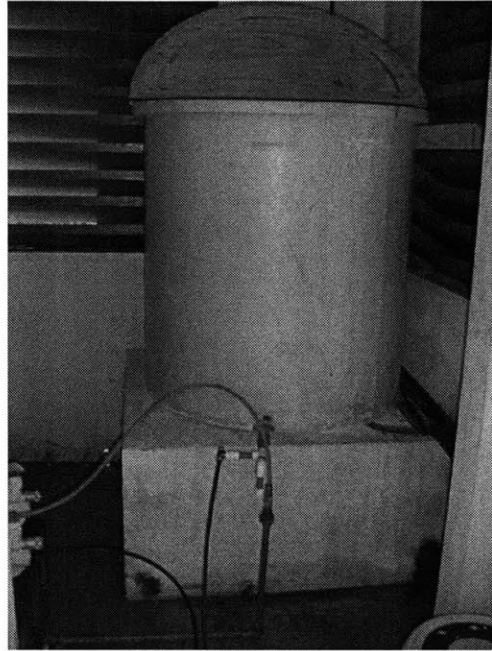


Figure 30  
Pretreatment at the Frank Bay plant

After pretreatment the feedwater is either sent to the vapor compression unit or the reverse osmosis unit. If sent to the vapor compression unit, the water passes through filters to increase efficiency and prevent the spray nozzles from clogging. Figure 31 shows the filters at Frank Bay.



Figure 31  
Filters at the Frank Bay plant

After filtration, feedwater passes through a heat exchanger, which heats the water. Feedwater with a higher temperature allows the process to operate more efficiently. The heat exchanger warms the water by using heat generated by the desalination process itself and generally needs no outside source of heat although, there is a backup boiler present. Figure 32 shows the heat exchanger.

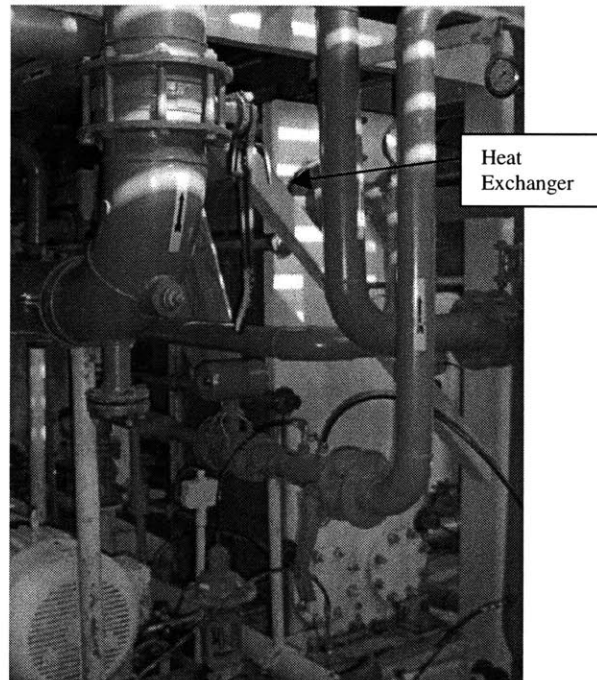


Figure 32  
Heat exchanger at the Frank Bay plant

After passing through the heat exchanger, the heated feedwater is pumped into the vapor compression chamber. The feedwater enters the compression chamber through spray nozzles. These nozzles compress the vapor so that it is forced into the chamber. This allows the water to separate from the salt, which is much heavier. Most of the water sprays onto the top of the chamber, which is shown in Figure 33, and is collected in trays. The rest of the water becomes part of the brine.

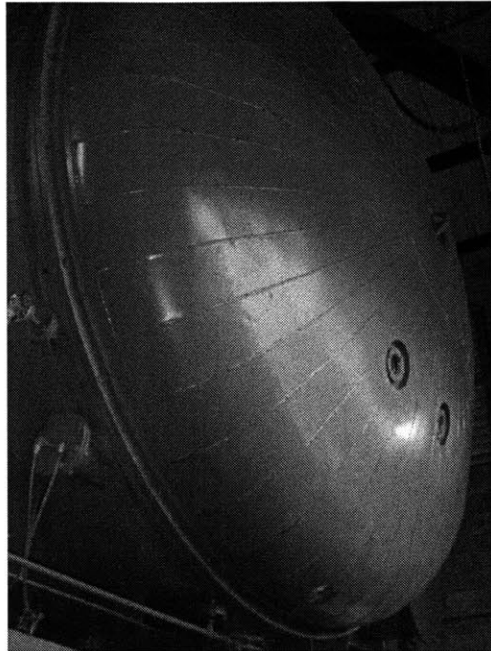


Figure 33

Vapor compression unit in Frank Bay desalination plant

The potable product water and brine leave the unit through the bottom. This is shown in Figure 34 (Hendrickson, 2003).

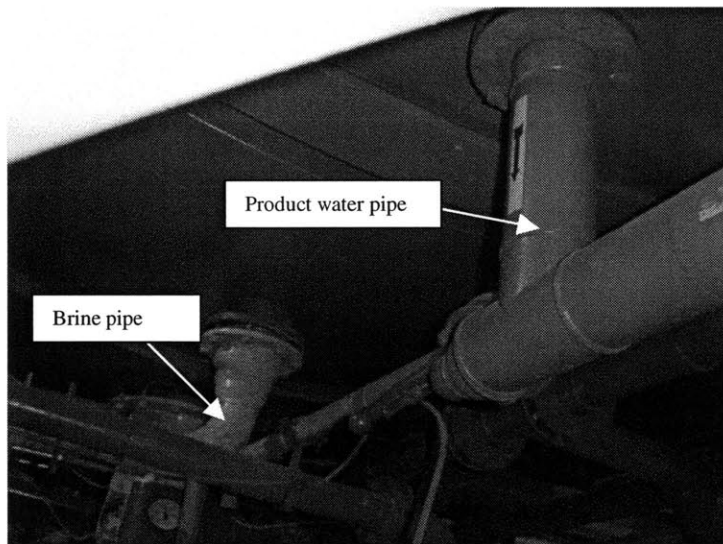


Figure 34

Brine and product water pipes leaving vapor compression unit

Feedwater that is sent to the reverse osmosis unit is also filtered to remove contaminants that would clog the membranes and reduce overall efficiency. The water then is pumped through the membranes. The pump that forces the water through is shown in Figure 35.



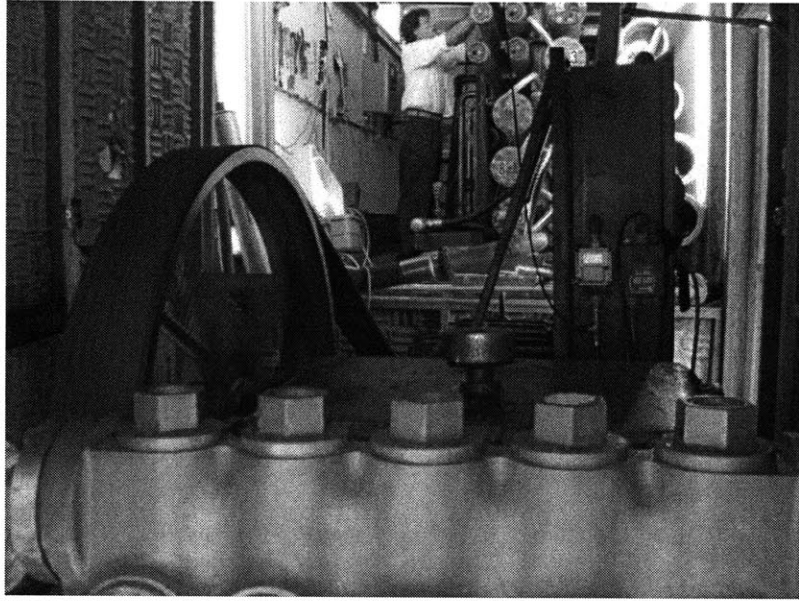


Figure 35  
Reverse osmosis pump at Frank Bay desalination plant

The membranes allow water to pass through, but block salt from passing through. The membranes at the Frank Bay plant are shown in Figure 36.

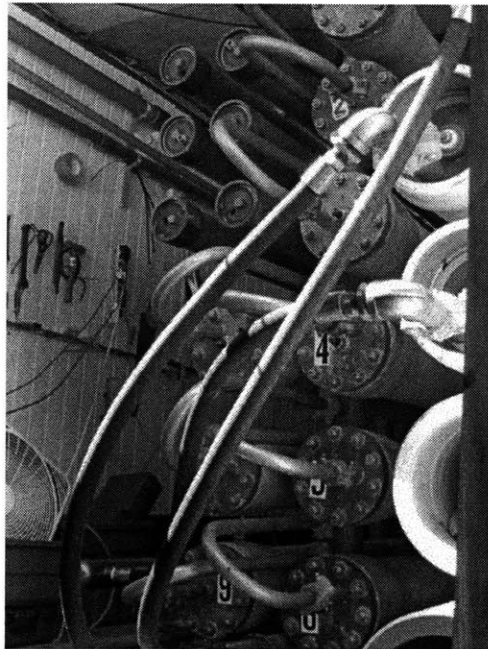


Figure 36  
Reverse osmosis membrane tubes at Frank Bay desalination plant

After feedwater has been treated by either the vapor compression unit or the reverse osmosis unit, product water is sent through a post treatment filter. This filter is an activated carbon filter filled with charcoal. This filter is shown in Figure 37.

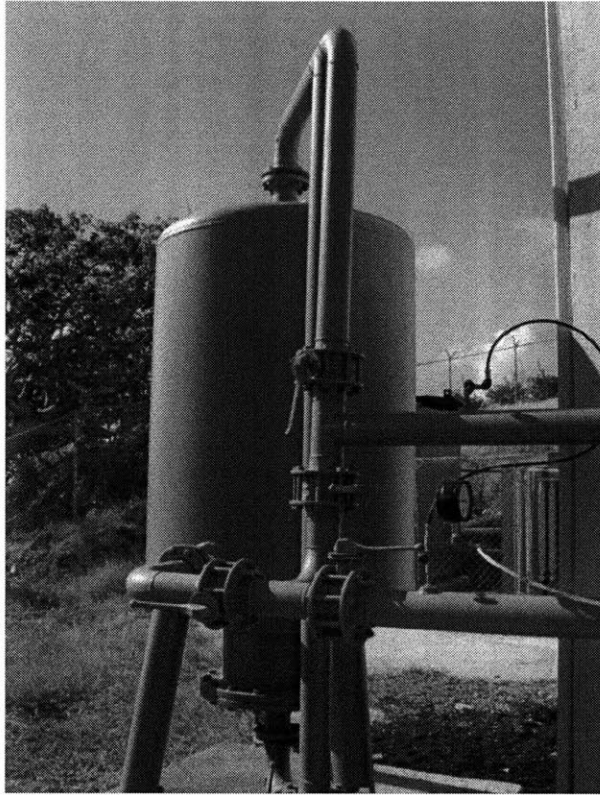


Figure 37  
Post treatment filter at Frank Bay plant

Brine from the processes is sent through by discharge pipes (Bramble, 2003). These pipes are shown in Figure 38.



Figure 38  
Brine discharge pipe at Frank Bay desalination pipe

The brine is discharged into Turner Bay. The plant effluent discharge point is shown in Figures 39a and 39b.

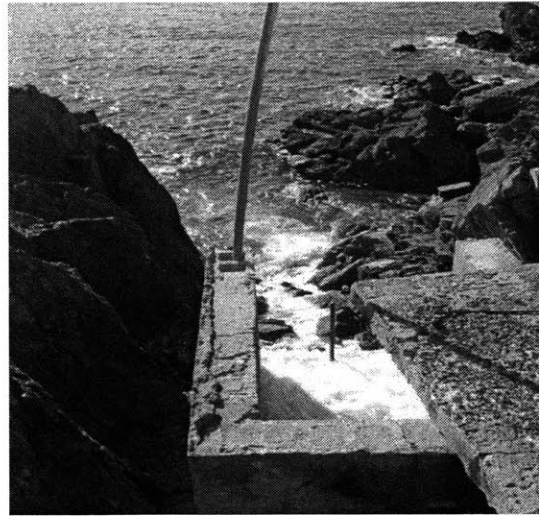
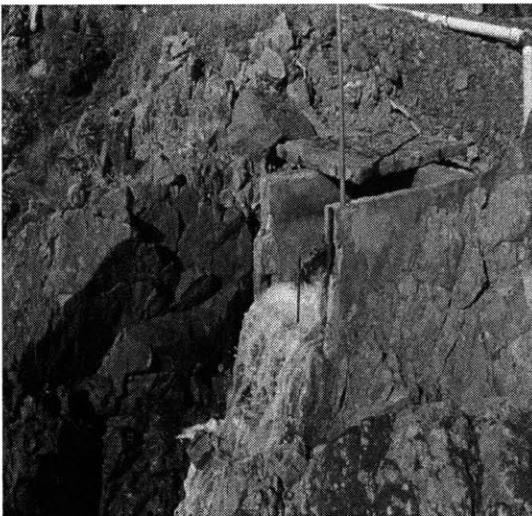


Figure 39a and 39b  
Brine discharge at the Frank Bay desalination plant

### ***2.5.3 Aqua Design***

Aqua Design, a subsidiary of The Ionics Corporation, designs, builds and operates approximately thirty desalination plants on all three U.S. Virgin Islands for small, non-municipal establishments, such as hotels, resorts, and condominiums, as well as a few

municipalities (Ionics, Inc., 1996). The desalination plants they operate are small to medium-sized reverse osmosis units.

The Caneel Bay Resort desalination plant is a classic example of the technology that Aqua Design is utilizing to produce potable water. Aqua Design recently purchased the rights to design, build, and operate a state-of-the-art desalination plant for the resort. Currently, Aqua Design is removing the old plant and replacing it with their new plant. Figure 40 shows a picture of the old plant. The old reverse osmosis plant consists of three reverse osmosis units. This old plant is characteristic of the typical size of a desalination plant operated by Aqua Design. The new plant will be located in the same building but will incorporate the latest reverse osmosis technology to reduce energy consumption and overall operating costs. Both the old and new plants' operational data will be used for analysis. Operational data for the new plant at Caneel Bay is based on design estimates. Caneel Bay's new reverse osmosis plant is characteristic of all of the plants currently being operated by Aqua Design. It incorporates the latest technology and control measures to reduce costs associated with the plant's operation, maintenance, and energy consumption (Di Cola, 2003).

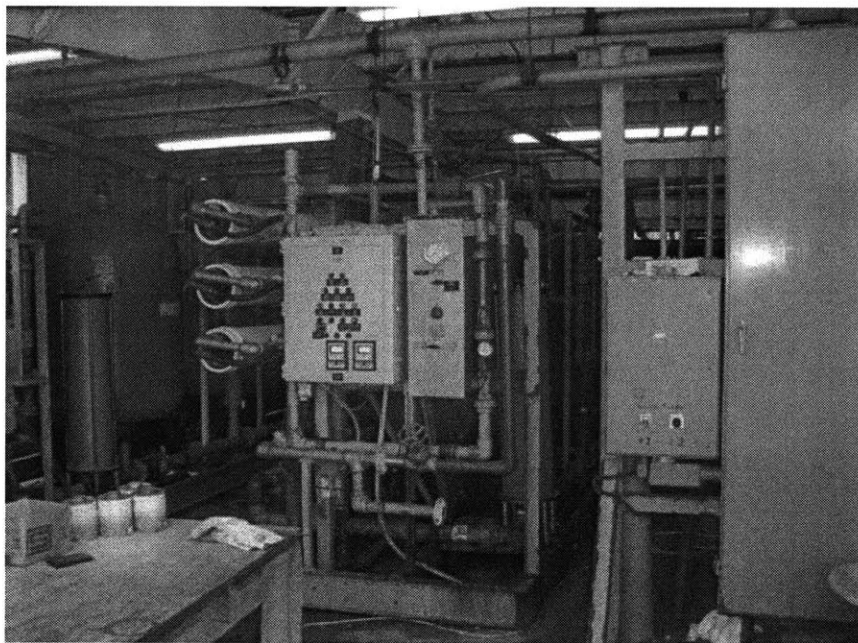


Figure 40  
Caneel Bay Resort desalination plant

Feedwater for the Caneel Bay plant is taken from Caneel Bay. The uptake pipe is shown in Figure 41.

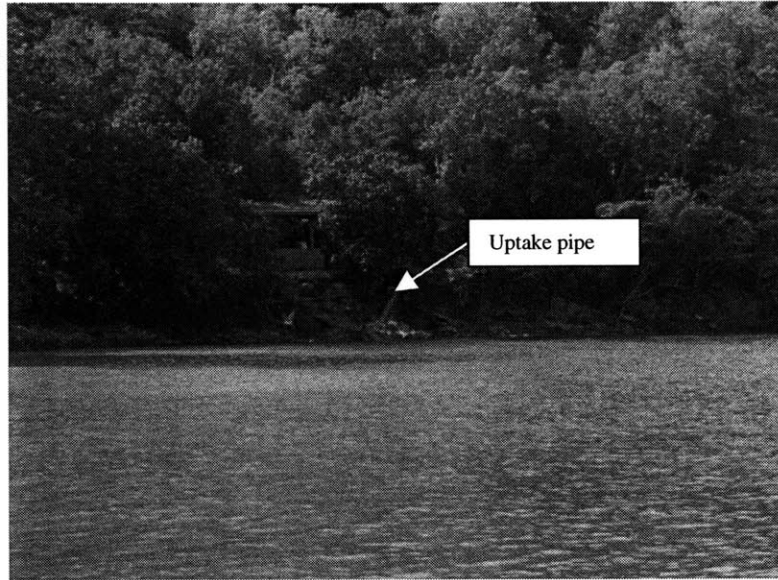


Figure 41  
Caneel Bay feedwater intake pipe

Feedwater taken from Caneel Bay was then pumped into cistern tanks to increase storage capacity in the event of an emergency. These cistern tanks are shown in Figure 42.



Figure 42  
Old cistern tanks at Caneel Bay desalination plant

The water shown in the cisterns was being pumped and sent back to Caneel Bay. The cisterns were used in the old plant but will not be used in the new plant. After the tanks were emptied they were filled in as part of the new plant construction process.

Feedwater is now directly introduced into the treatment process. It first enters a series of filters designed to remove any particles or biological agents that would destroy or clog the membranes. These filters are shown in Figure 43.

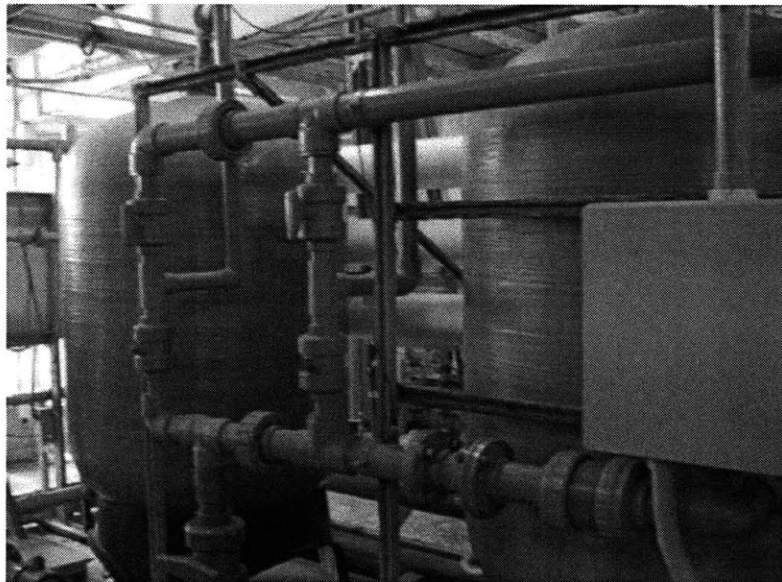


Figure 43

Filtration units at the Caneel Bay Resort desalination plant

After filtration, feedwater is pumped through the reverse osmosis membranes where the water is separated from the salt. These membranes are located in PVC pipes designed to hold the membranes and are shown in Figure 44.

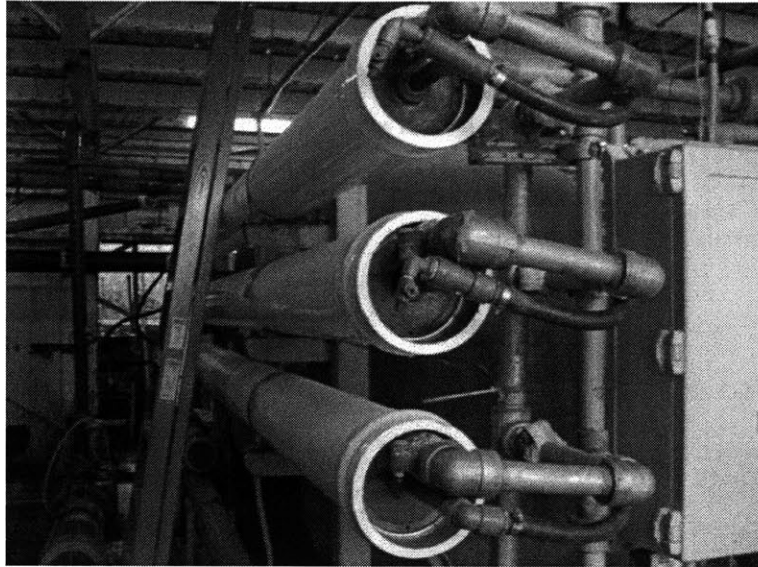


Figure 44

PVC pipes containing reverse osmosis membranes at the Caneel Bay desalination plant

After passing through the membranes, feedwater is separated into potable product water and brine. Product water is sent to a storage tank while brine is piped back to Caneel Bay to be discharged. Figure 45a shows the brine discharge pipe, as well as the feedwater influent pipe. Figure 45b shows the brine discharge point.

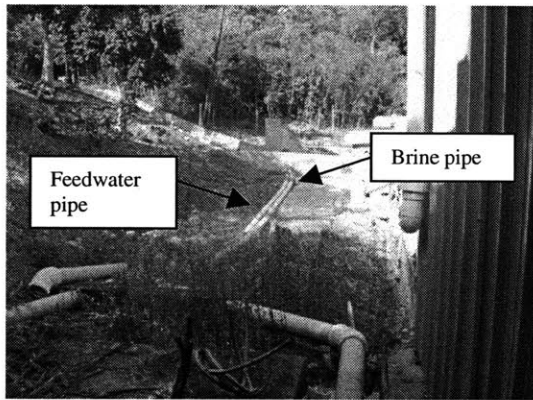


Figure 45a

Brine and feedwater pipes at Caneel Bay plant

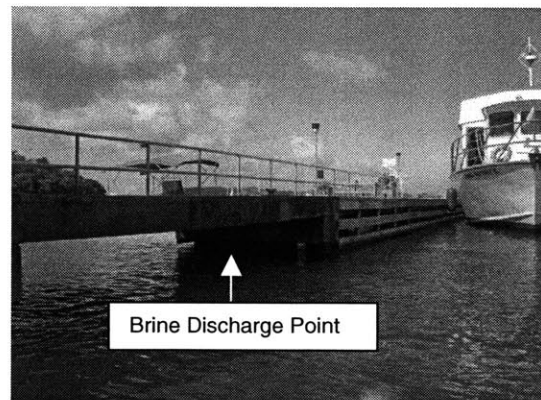


Figure 45b

Brine discharge point at Caneel Bay plant

In Figure 24a, the feedwater pipe and brine pipe are placed together. Feedwater travels towards the point from which the picture was taken in the left pipe and brine travels away from the point from which the picture was taken in the right pipe. Brine is discharge under the dock at the Caneel Bay Resort for aesthetic purposes. Resort management did want the brine discharge at a point where resort guests would find it unappealing (Di Cola, 2003).

## ***2.6 Methods***

To determine the best desalination system for the U.S. Virgin Islands, each desalination plant and desalination plant system is used to create a framework for decision-making through analysis of each system indicator.

Raw data for the Water and Power Authority plants was obtained from the December 2002 and July 1998 operating months, as well as through interviews with system officials Louin Chung, Krum Bay Plant Supervisor, and Glen Rothberg, Assistant Executive Director. Raw operational data was averaged to provide more representative results of the system. Raw data for the Caneel Bay plants was obtained from January 2003 operational data, as well as through interviews with Ron Di Cola, U.S. Virgin Islands Manager. Each desalination plant and desalination system was then compared to all other plants and systems for each indicator. Conclusions regarding the most appropriate desalination system for the U.S. Virgin Islands are drawn from these comparisons. Through this process a framework for future decision-making can also be established.

To analyze the cost of water sustainability indicator, interviews with plant officials and operators were necessary. These people have the best knowledge of plant performance and operation and could detail the cost of potable water production. For the Water and Power Authority Plants, an Authority official was able to provide their actual cost to produce the potable water (Rothberg, 2003). In the case of the Caneel Bay plants, the district supervisor was only able to provide what the plant charged the Caneel Bay Resort for the water (Di Cola, 2003).

To analyze the fuel consumption sustainability indicator, fuel consumption data for each treatment process was necessary. Next, raw data was converted into the comparable units. For consistency, billion barrels (bbls.) was chosen as the standard unit for this indicator.

The St. John Water and Power Authority Plant provided raw data in megawatts. To convert this to bbls, the megawatt input was converted to megawatt hours by converting to BTU/second and then to BTU's by multiplying by the number of seconds in the month. Then BTU's were converted to MWhr's. This could then be multiplied by a performance ratio obtained by dividing the number of bbl of fuel used to produce a certain amount of electricity in MWhrs. The end result of the calculation is the amount of fuel consumed in bbls (Bramble, 2003; Chun, 1998; Creque, 2002).

The Aqua Design Plants also reported energy consumption in electrical form. Raw data was provided in kWhr/1,000 gallons of water produced. To convert this to bbls it was multiplied by daily production and then by the number of days in the month. Then it was converted to MWhrs and multiplied by a performance ratio obtained from averaging the performance ratios obtained above. These two ratios deviated by only one one-hundredth.



To analyze the effluent water temperature, pH, and effluent conduit flow indicators, raw data was obtained from the United States Environmental Protection Agency’s Water Discharge Permits (EPA, 2003). Raw data for each plant was taken from the December, 2001 and July, 1998 operating months.

To analyze the system and plant reliability, system and plant flexibility, desalination plant size, number of plants, relative construction timetable indicators plant officials from both systems were interviewed. System officials were used because of their knowledge of the desalination treatment process and industry. Each official was asked to discuss each system’s and plant’s effectiveness at meeting the following requirements for each indicator: cost-effectiveness, relative risk, and net benefit.

Each system indicator was assigned a score for each desalination system, from one to four, based on relative strength compared to the other desalination systems in the study. These scores were summed and entered into the assessment framework. The assessment framework was evenly weighted so that each indicator’s score held the same weight as every other indicator.

## 2.7 Results

To more effectively display the results of the cost, fuel and environmental indicators, each desalination plant was assigned a number. These are shown in Figure 46.

Desalination Plant	Assigned Number
Water and Power Authority – St. John	1
Water and Power Authority – St. Thomas	2
Aqua Design Caneel Bay Old Plant	3
Aqua Design Caneel Bay New Plant	4

Figure 46  
Assigned plant numbers

The results of the cost indicator analysis are summarized in Figure 47. As shown in the figure, the reverse osmosis units at Caneel Bay have significantly lower costs than the Water and Power Authority Plants. As mentioned before, the Water and Power Authority plants’ (#1 and #2) costs represent actual cost of production while the Aqua Design plants’ (#3 and #4) costs represent the costs paid by the resort for the potable water. True cost of production for plant #3 and #4 are actually lower than displayed in Figure 47.

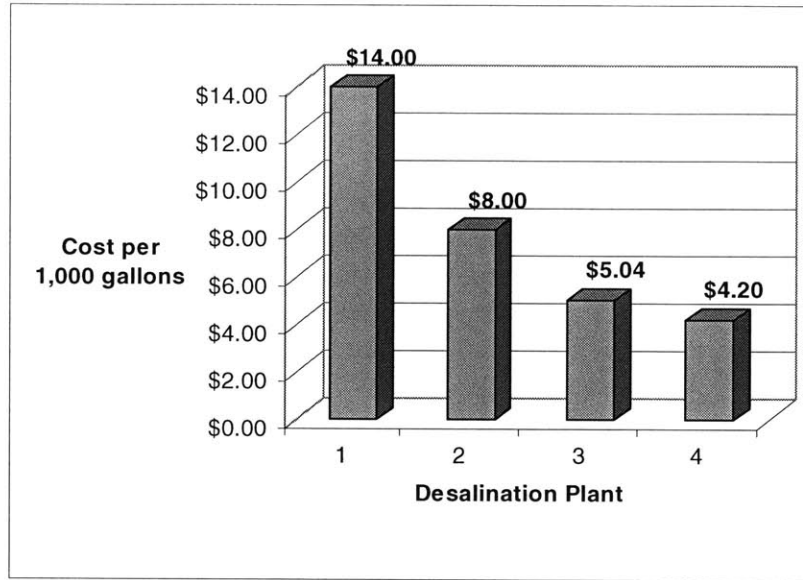


Figure 47

Cost to produce 1,000 gallons of potable water for the 4 desalination plants studied

The results of the fuel indicator analysis are summarized in Figure 48. As shown in the figure, the new reverse osmosis plant at Caneel Bay uses the least amount of fuel to produce a thousand gallons of potable water. It is followed closely by the St. Thomas Water and Power Authority plant. The old reverse osmosis plant, as well as the St. John Water and Power Authority Plant, used significantly more fuel than either of the other two plants.

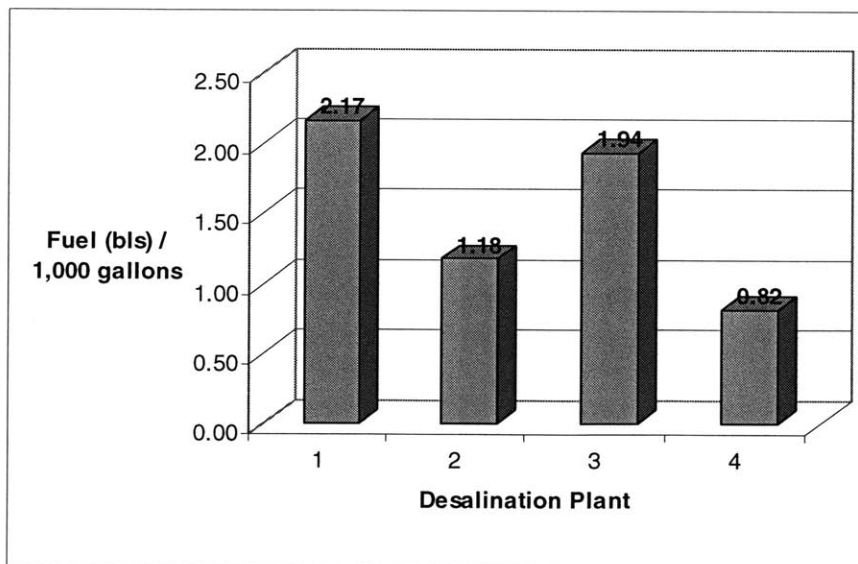


Figure 48

Fuel required to produce 1,000 gallons of potable water for the 4 desalination plants in question

The results of the effluent water temperature indicator analysis are summarized in Figure 49. Each plant's effluent water temperature was found by averaging monthly water samples temperatures collected from the December, 2002 and July, 1998 operational months and tabulated in the Environmental Protection Agency's PCS database. As shown in the figure, the St. Thomas Water and Power Authority plant has a significantly higher effluent temperature than the other three plants.

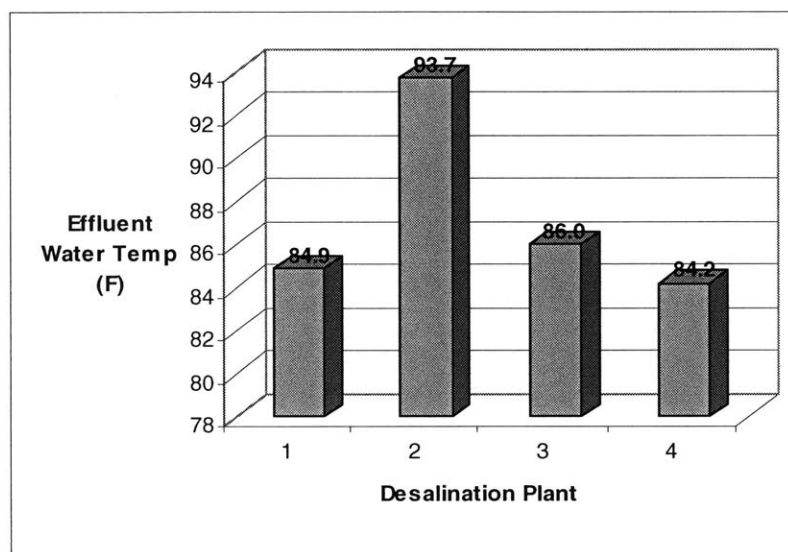


Figure 49  
Effluent water temperature at the 4 desalination plants in studied

The results of the pH indicator analysis are shown in figure 50. Each plant's maximum and minimum pH readings were taken from average monthly water samples collected from the December, 2002 and July, 1998 operational months in the Environmental Protection Agency's PCS database. All four plants have similar effluent maximum and minimum pH values.

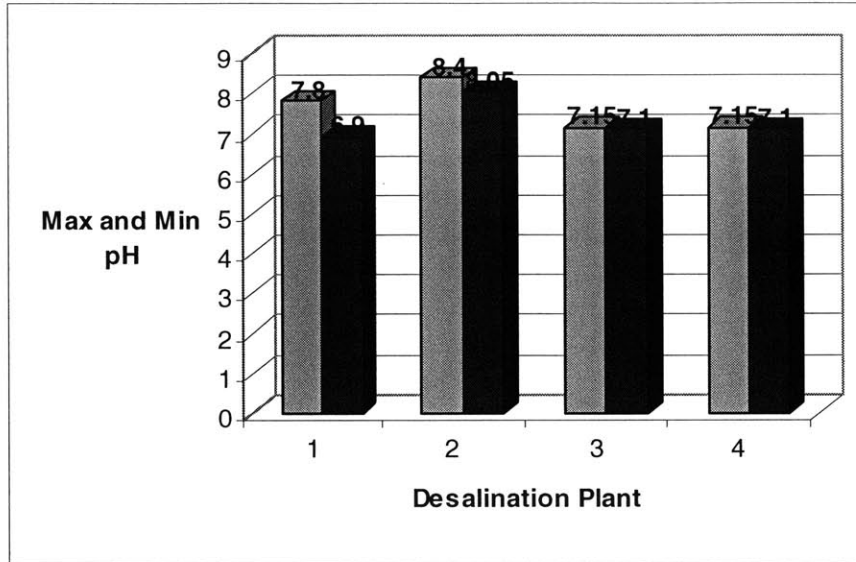


Figure 50

Maximum and Minimum pH at the 4 desalination plants studied

The results of the effluent water flow per amount of potable water produced are shown in Figure 51. Each plant's effluent flow displayed below was taken from average monthly water samples collected from the December, 2002 and July, 1998 operational months in the Environmental Protection Agency's PCS database. As shown in the figure, the St. John Water and Power Authority Plant has a significantly higher effluent flow rate per unit of potable water produced than the other three plants.

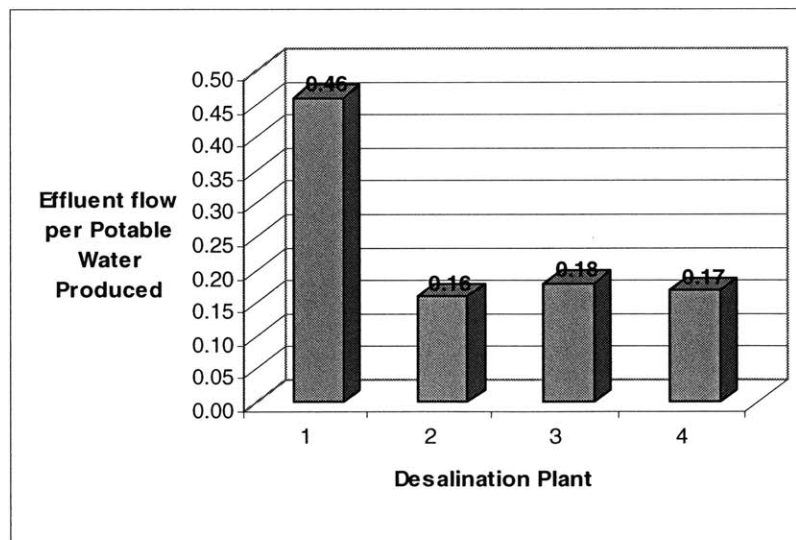


Figure 51

Effluent water flow per amount of potable water produced at the 4 desalination plants studied

The figures above also show that the new Caneel Bay Plant has the lowest cost and fuel consumption of all four plants and the St. John Water and Power Authority Plant has the highest cost and fuel consumption of all four plants. In addition, the environmental indicators show that the reverse osmosis plants generally have more favorable values but not to any significant extent. The reverse osmosis plants were given the highest scores for all three environmental indicators while the distillation plants each scored lower than the reverse osmosis plants in one of the three indicators.

For the system and plant reliability indicator, each official agreed that the St. John plant was the least reliable. The St. Thomas plant and the old Caneel Bay plant were ranked in the middle, but far more reliable than the St. John plant. The new Caneel Bay plant was ranked highest in reliability.

For the system and plant flexibility indicator, each official agreed that the Water and Power Authority plants were least flexible and that the Caneel Bay plants were more flexible in responding to changes.

For the remaining indicators, officials agreed that more desalination plants and smaller plants were better at meeting the outlined requirements. For these indicators officials were asked to rank their entire system, not just the plants in this study. Officials also noted that although the St. John plant was very small it still was not a favorable condition. They also agreed that having a proactive construction timetable that allowed for quick responses to developments in the desalination industry was the best approach.

After the raw data was obtained, it was converted, if necessary, to consistent units, and compiled. Charts were created for each system indicator for analysis. Then scores from one to four, four being the most favorable condition for that indicator, were assigned to each plant for each indicator. These scores were then summed to obtain system and plant scores.

The results the system scoring are shown in Figure 52 and in graphical form in Figure 53.

Plant	Cost	Fuel	Temperature	pH	Flow	Flexibility	Reliability	# of Plants	Plant Size	System Score
1	1	1	4	4	2	1	1	1	1	17
2	2	3	2	4	4	1	2	2	1	23
3	3	2	4	4	4	4	2	4	4	34
4	4	4	4	4	4	4	4	4	4	40

**Figure 52**  
Results of system scoring assessment

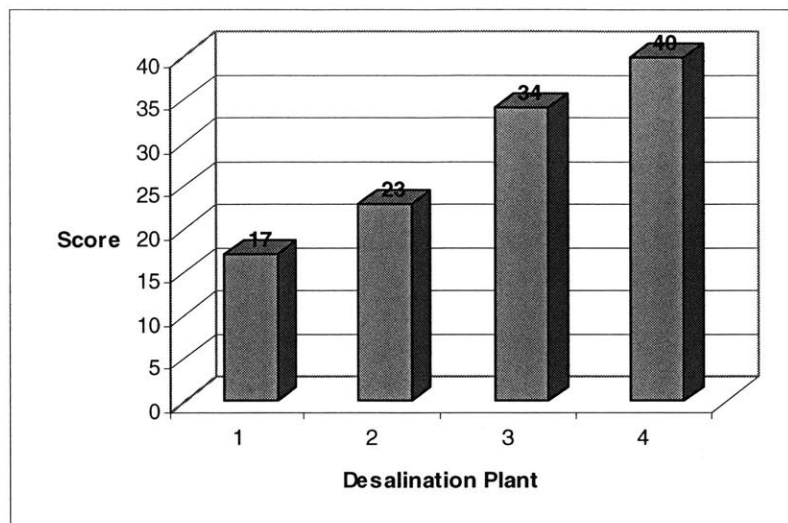


Figure 53  
Graphical results of system scoring assessment

The results show that the Aqua Design desalination plants and system produced the most favorable results. The new Caneel Bay plant received a perfect score, while the old Caneel bay plant received the second highest score. Conversely, the Water and Power Authority system and plants received the lowest scores. The St. John plant scored the lowest, while the St. Thomas plant scored second lowest.

## ***2.8 Discussion***

The results above show a clear trend. The best desalination system for the U.S. Virgin Islands is one that uses reverse osmosis treatment technology in a relatively large number of small plants. This configuration allows for the greatest flexibility and reliability of the system. In addition, overall costs are reduced; risk is minimized; and net benefit increases.

Reverse osmosis is the most suitable treatment technology to lower costs and increase net benefit. The desalination industry has shifted its preference in treatment process away from distillation and towards reverse osmosis. This is a result of increased research in the reverse osmosis field that has drastically reduced overall operational costs, as well as fuel requirements. Improvements in process efficiency can be attributed to lowered required operating pressures, which reduce energy requirements; to improvements in membrane efficiency, which reduce costs; and to research that has led to increased levels of treatment efficiency. Unlike distillation technologies, reverse osmosis technologies also do not require heating of feedwater, which reduces fuel requirements and thus operational costs. Effluent emissions from reverse osmosis treatment technologies seem to also cause a slightly less environmental damage. The results show that large distillation plants, which incorporate piggybacking and uses economies of scale, are not as cost-effective as small reverse osmosis desalination plants.

A relatively large number of small, reverse osmosis plants produce the most efficient desalination system. This configuration reduces risk by increasing the number of plants responsible for supplying potable water. It allows other plants to make-up for permanent or temporary deficiencies in one plant. With this configuration, system integrity can be maintained through larger overall disruptions. If only one plant is used, risk is dramatically increased because if the plant fails, the system also fails. Through the use of many small plants, system flexibility and reliability is increased. In the case of the U.S. Virgin Islands, this configuration would allow the desalination system to survive through extreme natural events. In addition, potable water is supplied through a network of tanker trucks to consumers and not through a distribution system of pipes, more small plants would decrease costs required to truck water over the mountainous islands.

Using small plants also allows for a more dynamic system. Small plants require less initial capital investment. This allows system officials to more readily respond to improvements in treatment technology. By incorporating new technology on an appropriate construction timetable, as shown by the Aqua Design system, overall system costs can be reduced and net benefit can be increased. Through this configuration, net benefit, flexibility, and reliability are maximized, while costs and risks are reduced. With many small plants, the system can easily be upgraded on a continual basis. As one plant is shut down for incorporation of new technology, the other plants can still produce water to minimize impact on the system. This would allow for continuous improvement of the system, which is not feasible with larger plants.

It is important to note that the Water and Power Authority system is operated by a government agency and that the Aqua Design system is operated by private company. These facts could result in skewing of the data as funding and politics inside each system can vary greatly, but this also leads to another important factor. It appears that private firms, because of their internal politics and motivations, can better respond to variations in the industry. Thus, they can produce a more effective and dynamic system capable of responding to change. It appears that a privatization of the drinking water supply industry on the U.S. Virgin Islands would produce the most favorable system.

The system assessment, in which all indicators are used, and weighted, equally, is a comprehensive and appropriate model. Each system indicator produced significant, interpretable results that could be incorporated into the model.

A framework for future decision-making of the desalination system on the U.S. Virgin Islands is evident from the assessment. This framework could be applied to other desalination systems worldwide. The evenly-weighted numerical ranking system used in the framework allows for other system stakeholders to easily adapt the model to suit their own preferences. Stakeholders can easily add or remove indicators, as well as assign greater or lesser weights to indicators with this model.

System officials must consider each system indicator separately and then as a whole to minimize risk and costs, as well as increase flexibility, reliability, and net benefit.

Creating a desalination system of many, small reverse osmosis plants that can rapidly respond to various changes proactively is the key. Through this method, the system can operate at maximum efficiency. This approach allows system officials to balance the costs and risks associated with each configuration to produce the most desirable system based on their priorities and the circumstances surrounding the system.

Weaknesses in the assessment are associated with the data used and the linearity of the ranking system. The model relied on raw data that was obtained from a wide variety of sources. Numerous system indicator data was provided by operators and plant officials. This data could have been intentionally or unintentionally misrepresented. The data also was subject to bias associated with each operator ranking his system, in addition to other systems. The model also relied on an evenly weighted linear ranking system. This system appropriated even weight to each indicator, which may not be the best approach because one indicator may be more important to the assessment. Also, the ranking system could have been subject to bias as a result of how the ranking values were assigned.

To improve the model, adjustments in how data was collected and analyzed could be made. The data could be collected from documented data, which was not available for this study, rather than word of mouth. More system officials participating in the rankings, some with no interest in either of the systems would increase the model's objectiveness. This would provide the model with solid, documented data, which is more convincing than abstract data collected from interviews. Available plant effluent water quality samples and more operational data would also strengthen the reliability of the assessment.

## ***2.9 Conclusions***

Many small, reverse osmosis desalination plants would provide the U.S. Virgin Islands with the most efficient desalination system to provide their citizens with potable water. This configuration minimizes risk by spreading out potable water supply to many reliable treatment plants located in various locations on each island. System integrity can be maintained with this system through even very large disruptions. The configuration also minimizes costs by proactively incorporating reverse osmosis technologies and advancements in this technology as they become available. Smaller plants make implementing this system much easier due to lower initial investment requirements. This configuration also minimizes costs by using the most efficient treatment technology. Many small plants also increase system flexibility and reliability by distributing risk to each of the plants. For these reasons, this configuration maximizes net benefit.

This configuration and decision-making process can be used as a framework both for the U.S. Virgin Islands and for many other areas around the world. The framework presents system officials with key system indicators necessary to produce and maintain the most efficient system that reduces risk and cost while maximizing flexibility, reliability, and net benefit.



Continued progress towards efficient desalination systems can be expected as the desalination field gains more acceptance as a public water supply source due to falling costs in its operation and increasing costs associated with traditional water sources. Continued research and technological developments will drive economic forces to reduce operational costs and will drive the industry's progress towards finding the most effective systems for their needs.

Areas of further study could include a more comprehensive study similar to this study. Incorporating more desalination plants, as well as obtaining documented data and opinions from sources outside of the study would produce a more convincing model with more convincing results. Expanding the study to include a weighting system for the system indicators in which the most important indicators carried more weight based on system requirements would further improve the study.

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