WATER RESOURCES AND WETLANDS STUDY FOR HAITI AND THE US VIRGIN ISLANDS

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I. INTRODUCTION

Christopher Columbus first discovered the US Virgin Islands in 1493 (Donahue and Johnston, 1998). During his second voyage to the Americas Columbus arrived at St Croix (formerly called Santa Cruz). Sailing further north, he found endless islands and christened them Las Islas Virgenes, The Virgin Islands. In the 1500's, resistance to outside settlers caused war and the destruction of the native population. Denmark established the first European settlement in St. Thomas in 671. In 1733, Denmark purchased St. Croix from the French crown, unifying the three Virgin Islands. From 1733 to 1750 sugar cane production, rum production, and the slave industry experienced economic prosperity. As a result of water scarcity and decreasing soil fertility, agriculture production began to decline in 1750. In 1750, St. Thomas became the marketplace of the Caribbean due to its excellent harbor. 1848 to 1878 were a time of turmoil and economic decline plagued with illness and hurricanes. In order to mitigate harbor pollution and epidemics, the first channel was built in Charlotte Amalie, St. Thomas to increase water movement.

The United States purchased the three islands of St. Croix, St. Thomas, and St. John from Denmark for 25 million dollars in 1917, forming the US Virgin Islands (Donahue and Johnston, 1998). Purchase of the islands was part of a military strategy to stop Germany from installing submarine bases. US citizenship was granted to the islanders in 1927. In the 1950's tourism accounted for over 50 percent of the island's economy. The 1960's brought about various changes in the US Virgin Islands. Hess Oil established a refinery on St. Croix, resulting in rapid economic growth. Due to increased demand for clean water on the islands, the first desalination plant was built in 1962. The promulgation of the Virgin Islands Safe Drinking Water Act in 1975 brought about specific monitoring and quality requirements for the island's water distribution. Presently, the overall water demand is not met by desalination. The use of rainwater cisterns and some groundwater wells supplement this demand. In 1996, the U.S. Virgin Islands government signed a consent decree with the U.S. Environmental Protection Agency in order to increase compliance of the effluent from the islands' wastewater treatment facilities with water quality standards.

Per our proposal dated December 9, 2002, the Caribbean Research Association for the Betterment of Water reSources (CRABS) is submitting this report regarding water quality of salt ponds in the U.S. Virgin Islands, and water resources management in the U.S. Virgin Islands and Haiti. After reviewing your request, CRABS assembled a team of engineers and scientists to address your concerns regarding the water quality status of wetland areas and watershed management on the islands of St. John, St. Thomas, and Haiti due to an increased need for this information by local managers, contractors, and planners. Team members from CRABS have the experience necessary to provide quality and comprehensive solutions for the USVI Wetlands Association. Our experience lies in water quality analysis, watershed modeling and analysis, groundwater and sediment analysis, geographic information systems application, and water resources master planning.

Knowing that wetlands and water resources are precious and scarce in the Caribbean, CRABS developed the following mission statement.

To study and understand the water resources in the Caribbean so they can be maintained and preserved.

During the course of this project CRABS has gathered data to assess the present conditions of water quality, desalination, and water resources on St. John, St. Thomas, St. Croix and Haiti, and will develop strategies to address each of these areas.

A description of the study and its results are described in further detail in the following sections. Section II presents the results of our evaluation of the Safe Water System for point-of-use drinking water treatment in Haiti; Section III presents evaluations of water resources management on the U.S. Virgin Islands; and Section IV describes studies of the water quality, ecology, and hydrology of salt ponds on St. John in the U.S. Virgin Islands. Further detail on these studies is provided in the following Master of Engineering theses: Brin (2003), Bossi and Rose (2003), Buscemi (2003), Cheslek (2003), Gangemi (2003), Miilu (2003), and Stevens (2003).

II. WATER RESOURCES – HAITI

WHY A SAFE WATER SYSTEM IN HAITI?

CONTEXT

Haiti has a long history of political and economic instability. Therefore, few international monetary aid agencies have been willing to invest in Haiti. As a result, access to safe water and sanitation is available to only 50 percent of the population. Unsafe drinking water causes illness and can be lethal for children. In Haiti, this is reflected in only 45 and 54 years of life expectancy and 118 and 103 per thousand births infant mortality rates for Haitian males and females, respectively (WHO, 2003).

In reaction to the cholera epidemic that strangled South America in 1992, the Centers for Disease Control and Prevention (CDC) and the Pan American Health Organization (PAHO) developed a point-of-use water treatment called the Safe Water System (SWS) (CDC, 2002). The SWS is a low cost solution using simple technology that provides clean drinking water, which could easily be implemented in Haiti. The SWS is a combination of: 1) water treatment with locally produced sodium hypochlorite disinfectant, 2) safe storage of the drinking water in adapted containers, and 3) community education.

THE SAFE WATER SYSTEM IN JOLIVERT

Missions of Love Incorporated (MOL) is a not-for-profit evangelical Christian mission (MOL, 2003). Its president, Dr. Robert Johnson ("Dr. Bob"), and his wife Betty Johnson, have been working in Northern Haiti for the past fifteen years. Four years ago, MOL decided to build their own clinic, and now is providing health care for Haitians in the Jolivert area. William Gallo, who has worked with water projects throughout Haiti for more than five years, was invited by MOL to start an in-home water purification program in Jolivert and the surrounding communities, which would be based at the clinic.

Jolivert is a village located on the shore of the Trois-Rivieres River, in northwestern Haiti (see Figure 1). The river provides a large amount of water low in suspended sediments, a condition necessary for optimizing the electrolysis process. Weekly electrolytic chlorine solution production under such conditions could easily supply 2000 families. Since Jolivert has only about 300 households, the targeted area reaches many surrounding villages from Bassin Bleu (about 2 miles north of Jolivert) to Frage (about 2 miles south of Jolivert).

The Jolivert Safe Water for Families (SWF) project began in January 2002 with a preliminary study of the local population. After locating a Haitian supplier for buckets to adapt as SWS containers and importing bottles in which to store the hypochlorite solution and other materials needed in order to start the project, a pilot project was implemented with 200 participating households in December 2002.

FIGURE 1
MAP OF HAITI
(World Bank, 2002)

The project is run by local personnel. Christophe Velcine, who works as a laboratory technician at the clinic, directs the project and handles the administrative and material management work. Elédère Odin is the SWS full-time technician who prepares and sells the hypochlorite solution. He also visits the homes and ensures the transmission and understanding of educational information throughout the community.

In April 2002, an initial meeting was held by Dr. Bob Johnson and Bill Gallo with community leaders to explain the project. In September 2002, Christophe and Elédère explained the use of the buckets and associated health issues with the first twenty people to receive systems. Then, Christophe and Elédère conducted a series of meetings and distributed the remainder of the 200 SWS buckets that were to be used for the pilot project. Elédère then began visits to the households to verify that the system was being used properly and that users were aware of the health implications of unsafe water.

The locally generated hypochlorite solution is called Dlowòks. A highly concentrated chlorine solution currently used in Haiti is called Klowòks, which is a calcium hypochlorite solution. "Dlo" means "water" in Haitian Creole. Dlowòks therefore suggests clean water through using a chlorine solution.

The special SWS containers used in the pilot project are adapted from buckets similar to the ones Haitians normally use to store water. They are standard plastic 5-gallon (20-liter) buckets. They meet many of the CDC criteria, but not all. The CDC recommends a translucent material for the bucket; however, the bucket used in Jolivert is opaque. The CDC also recommends an opening large enough to facilitate filling and cleaning though small enough to prevent even children from dipping out water out with a cup. The bucket used in Jolivert has a wide opening that does not meet this requirement. Another issue is that the lid needs holes drilled in it to let air enter since when it is completely closed, suction prevents water from flowing through the spigot. The bucket and chlorine bottle used in Jolivert for the Safe Water System are presented in Figure 2.

FIGURE 2
JOLIVERT SWS MATERIAL

JOLIVERT'S SOURCES OF DRINKING WATER

As mentioned earlier, Jolivert and the nearby communities are located along the Trois-Rivieres River. It is no surprise that the river constitutes the main source of water for the population.

Most people harvest their drinking water from what they call "sous dlo", the Haitian Creole word for "spring water." This choice of wording shows that the Haitian people differentiate groundwater and surface water. However, the "sous dlo" is not a groundwater spring, but only river water filtered by the soil. People dig a small hole in a dry spot in the riverbed and wait until it fills with water (Figure 3). They then harvest it with a bowl or a glass to fill their buckets.

Groundwater sources, true springs, are also available for drinking water. Three groundwater sources were mentioned during surveys: De Riyon, La Boule, and Tiboukan. De Riyon is located near La Hatte, about a 20-minute walk from the clinic, but on the other side of the river. La Boule is on Jolivert's side of the river, but is in the hills above La Boule district, about a 30-minute walk from the clinic. Tiboukan is just north of Bassin Bleu, but we did not have the chance to visit it.

FIGURE 3
WOMAN HARVESTING WATER FROM A "SOUS DLO"

OBJECTIVES OF THE RESEARCH

CRABS proposed to evaluate future possibilities for the Safe Water System of Jolivert. The goals of the study are:

1. Evaluate the Safe Water System in Jolivert
2. Evaluate possibilities for growth of the project

In order to reach these goals, CRABS conducted a health survey by interviewing fifty-six households that use the Safe Water System and sixty-four that are not included in the pilot project. For each household, questions related to their water and sanitation practices were asked. Also, two samples of their drinking water were collected to run membrane filtration tests on later. The results of these survey and bacteriological analyses guided our evaluation and helped us suggest adequate possibilities for the growth of the Safe Water System to a larger scale.

SURVEY RESULTS

This section summarizes the main results that were found from the survey. We analyzed the answers in a way to point out the positive and negative outcomes of implementing the Safe Water System from a health perspective. Also, we identified different sanitary practices that improve health, regardless of the quality of drinking water consumed.

DESCRIPTION OF THE SURVEYED POPULATION

In the first question of the survey, we asked for the age and gender of the people residing in the household. The total population surveyed was distributed as shown in Table 1.

TABLE 1
DEMOGRAPHIC CHARACTERISTICS OF THE SURVEYED POPULATION

Age (year)	Female	Male
Under 5	62	53
5-16	126	110
Over 16	224	163
TOTAL	412	326

It seems that the number of children under five is low compared to the other age categories. In fact, some people did not mention their presence in the house until it was specifically asked. Therefore, some may have been omitted. This omission may be a sign that children under five are not considered since their survival is so uncertain, as previously mentioned.

The majority (52 percent) of the surveyed people reported to have two rooms per household. This proportion is similar for those with and without the system. Also, only 10 households out of 120 had electricity. These two metrics suggest that the people surveyed had the about the same socio-economic status.

HEALTH

Question 14 was one of the most important of the survey. This question determined the diarrhea incidences by age group (Table 2).

TABLE 2
DIARRHEA INCIDENCES DATA

SWS	People	Less than five years old				From 5 to 16 years old				More than 16 years old				Total	
		Female		Male		Female		Male		Female		Male			
Without	Total	35	**33%**	25	**29%**	62	14%	70	8%	112	19%	84	21%	388	**18%**
	With diarrhea	11		7		8		5		21		17		69	
With	Total	28	**32%**	27	**40%**	64	7%	40	2%	112	6%	79	7%	350	**11%**
	With diarrhea	9		11		5		1		7		6		39	
With residual*	Total	18	**28%**	20	**38%**	45	4%	26	4%	85	1%	60	5%	255	**8%**
	With diarrhea	5		8		2		1		1		3		20	

* This category includes families with the system and with chlorine residual at the time of the survey

Families with the Safe Water System had 40 percent fewer diarrhea incidences than the population without the system. However, no improvement is seen in the main target population, children under five years old. Moreover, these children do not see significant health benefits even when the system is used correctly, that is to say when there was chlorine residual in the water. Our hypothesis regarding the issue of no health benefits for children under five is that children under five are exposed to bacteriological contamination by means other than water with or without the system. Therefore, a Safe Water System will not prevent them from contracting diarrhea if no sanitary improvement is done.

DRINKING WATER

From the total 120 homes we visited, 109 (91 percent) took their drinking water from the "sous dlo." Six were taking it from the "sous" plus other places such as harvesting rain water, groundwater or directly from the river. Seven people (6 percent) said their primary source of drinking water was from a groundwater source and three (3 percent) said it was their secondary source of water. Only one person reported getting their water directly from the river. Two (2 percent) said rain was their primary source of water. It is a little unfortunate to see that almost nobody harvests rainwater though this is surely due to the absence of inexpensive cisterns. Also, only very few people use groundwater as their primary drinking water source.

In addition, 63 percent of the total population (71 households) thought that the harvested water was good for drinking. Fifty percent of the people who do not have the system use an alternative way to treat their water. Though, even if some of this 50 percent gave answers that were not true, it shows, at least, a certain degree of concern.

STORAGE AND HANDLING

Eighty percent of the people without the system and without diarrhea say they use a specific container for their drinking water, compared to only 60 percent for the ones without the system but with diarrhea incidences. Since people without the system have to dip into the container to scoop out water, when water is used exclusively for drinking, there is less exposure to hands (and bacteria) and there is more attention to keeping the water clean. Therefore, using this water only for drinking can prevent people from contracting diarrhea. However, the reverse happens in the "with the system" category. The people with the system but without diarrhea use the clean water for more purposes than the ones with diarrhea. In that case, due to the presence of a spigot, the potential contamination due to frequent handling of the water is reduced. Therefore, using clean water for many purposes will help reduce diarrhea incidences.

Moreover, it is noticed that there are fewer diarrhea incidences when people scoop their drinking water with a tool that has a handle. The cup, the pitcher, the direct spill or the mug, and the use of a spigot put together show a higher rate of "no diarrhea" (55 percent) compared to people using a tool without a handle (48 percent). In fact, a scoop with a handle reduces the risk that the hand touches and contaminates the water. By the same means, it reduces the risk of contracting diarrhea.

Regardless of the tool used to scoop out water from the container, we also asked people if they ever touched the water when scooping it out. From that question, we see a net difference between the ones who did and the ones who did not have diarrhea incidences. That is to say, 85 percent of those who did not have diarrhea did not touch the water with their hands while scooping out water, compared to only 45 percent for the ones with diarrhea. This is evidence that hands transport bacteria and contaminate the drinking water.

Education towards safe sanitary practices could help increase the health benefits brought by a SWS. People should be aware of safe storage and handling of the drinking water, such as using a tool with a handle to scoop water out of the container and not touching the water with hands before drinking it.

QUESTIONS SPECIFIC TO THE HOUSEHOLDS WITH THE SAFE WATER SYSTEM

The majority of the households are using the system properly. Only one person reported adding 2 caps full of Dlowòks per bucket and 95 percent (42 out of 44 households) add only one, which is the necessary quantity. The 12 for whom we do not have specifications on the quantity of Dlowòks they add to the water are the ones where the interviewee was not the one taking care of this duty.

Another interesting fact is that when only one person is responsible for adding the Dlowòks, there is less chance to develop diarrhea. Particularly when women are responsible, there are fewer diarrhea incidences in the family. In fact, for the category of people without diarrhea, females were responsible for adding the Dlowòks in 94 percent of the cases (29 households out of 31) compared to only 72 percent in the category of people with diarrhea.

CHLORINE RESIDUAL RESULTS

The chlorine residual test verifies that there is a chlorine residual in the drinking water. Chlorine reacts with the bacteria molecules and other oxidizable matter in the water until there is either no more chlorine to react or no more bacteria to inactivate. If the chlorine residual test indicates the presence of residual chlorine, it means that there are no more bacteria. On the other hand, if the test shows no presence of free chlorine, there is a possibility that bacteria remain in the water.

The chlorine residual tests were conducted with a colorimetric swimming pool test kit. After adding one drop of the testing solution, a yellow color develops in the presence of chlorine. Our analysis relies on the following grading of color: a) no coloration, b) pale yellow, c) yellow, d) dark yellow, and e) very dark yellow/orange. The plastic vial in which the test was performed was rinsed with the household's drinking water before performing the test.

Fifty-five percent of the population had a normal level of chlorine residual in their drinking water, which includes level b) and c) as explained previously. However, 33 percent did not have any chlorine residual, and 7 percent had too much chlorine in their water. The three households with no answers are the ones in which there was not enough water to do the chlorine residual test when we visited them. It is interesting to point out that people with no chlorine residual have a higher rate of diarrhea incidence (60 percent or 11/18) than those with chlorine residual (35 percent or 12/35). This shows the importance of the chlorine residual in the drinking water.

BACTERIOLOGICAL RESULTS

Almost every household provided a sample of their drinking water. Seven, however, did not have drinking water at the moment of the interview. The samples were stored in a cooler for no longer than four hours, and a membrane filtration test was conducted in the laboratory set up in the clinic.

This membrane filtration test consists of filtering a specific amount of water through a membrane filter (pore size 0.45μm), which traps the bacteria (Maier et al., 2000). The filter is then placed in a petri dish saturated with a culture medium, which enhances the growth of certain bacteria.

The petri dishes are then incubated for 18 to 24 hours (24 hours in our case) at 35°C to let the microbial colonies grow. The culture medium used is mColiBlue24 broth, from Millipore Corporation. It grows *E. coli* colonies blue and the remaining total coliform colonies red.

Table 3 shows that the system improves the quality of water. In fact, the mean total coliform forming units (cfu) is reduced by a factor of 10 while the *E. coli* forming units are reduced by factor of 20. Also, if one were to take out all households where there was no chlorine residual, the mean drops to 35 cfu for total coliform and to ~0 cfu for *E. coli* (only one household had one cfu). This shows that the Dlowòks is very efficient at killing bacteria.

TABLE 3
AVERAGE BACTERIOLOGICAL CONCENTRATIONS IN THE DRINKING WATER OF THE POPULATIONS WITH THE SYSTEM AND WITHOUT THE SYSTEM

	Without system (all)	With system (all)	With system (with chlorine residual)
Total coliform (cfu/100mL)	3000	300	35
E. coli (cfu/100mL)	160	8	0

The answers to the health survey are not significantly different for those who have no chlorine residual than the rest of the population. The main difference is that this category of the population has a higher rate of diarrhea incidences (65 percent) compared to the rest of the people with the safe water system (35 percent). This shows the importance of the chlorine residual in the drinking water.

CRABS also verified that the farthest people had no chlorine residual more often than the others. As was expected, four out of the five households of Bassin Bleu who had water did not have chlorine residual. However, the situation is not as bad in the other communities. This is possibly because Bassin Bleu is more urban the other communities, and its residents do not tend to go out of town as often as people who live far from services. The issue of providing Dlowòks to remote regions will be discussed in the next section.

PROJECT GROWTH ANALYSIS

After we compared the surveys on health issues and analyzed the bacteriological results, we completed a preliminary analysis and presented some early results of our study to the Jolivert Safe Water System staff. After hearing our report, we joined the staff in a discussion of the issues raised by the report. The meeting included Bill Gallo, Christophe Velcine, Eledere Odin, Madame Evelyn, Daniele Lantagne, and Genevieve Brin.

One of the main issues in expanding the program is that a new bucket is too expensive for the majority of the families. Since most people already store their drinking water in buckets, CRABS recommends that it be possible for them to join the program without buying another bucket. Used buckets could be adapted for Safe Water System storage by adding taps and labels with directions for use. However, for people who do not have buckets, it is our recommendation that they buy one to prevent the administrative complications of loaning buckets.

Another issue is how to make it easer for people some distance from the clinic to buy Dlowòks. Results from the survey showed that this problem is especially apparent in Bassin Bleu, where people tend to refill their chlorine bottles less often. CRABS suggests that small shops sell the Dlowòks solution, and supply it at a higher price to provide profit for the kiosk owner. A permanent provider of Dlowòks in regions some distance from the clinic will enable customers to obtain Dlowòks when they need it and possibly increase the proportion of people using it.

Finally, another issue is whether or not schools should enter the program during the early stages. The consensus was that the educational benefits would be great, but the health benefits might be minimal since most of the students would not have systems at home, at least at the beginning of the project. CRABS recommends that schools be included in the project expansion plan. Their participation in the SWS project would be mostly educational, and students should be involved in promoting the SWS along with sanitary practices.

CONCLUSION

From a health perspective, the use of the SWS reduces diarrhea incidence by 40 percent. If there is chlorine residual in the drinking water, diarrhea incidences are reduced by 60 percent. However, it does not reduce diarrhea incidences for children under five years old, which is the main target age-category population. It is hypothesized that this age group is exposed to pathogens via other mechanisms than drinking water. The use of the system reduces the number of total coliform colonies by a factor of 10 and the number of *E. coli* colonies by a factor of 20. Moreover, if the water presents chlorine residual (indicating safe use of the system), the presence of total coliform units is lowered by a factor close to one hundred and the tests show no presence of *E coli*.

The results show that the project is successful and should be expanded. However, logistic issues need to be resolved. First, a correct pricing needs to be chosen to ensure the project's sustainability. Second, the hypochlorite solution has to be easily available in remote regions. Third, schools should play a role in the expansion of the project as promoters and educators. Lastly, further research is recommended to determine why a health benefit was not seen for children under five years old.

III. WATER RESOURCES – USVI

According to the United States Environmental Protection Agency (USEPA), the average American citizen uses approximately 150 gallons (568 Liters) of water per day (1996). Of that amount only one-half gallon is used as drinking water while the remaining amount is used for cooking, cleaning, flushing, irrigation, or non-consumptive uses.

Water sources are scarce on the US Virgin Islands due to increased development, poor economic conditions, geology, and climate. Because of this, CRABS has analyzed the US Virgin Islands' water resources and desalination process both from an economic and environmental standpoint. Based on this analysis, strategies for water reuse, conservation, and watershed management have been developed. In addition, assessments of current desalination practices and processes to maximize efficiency have been completed.

INTEGRATING WATER RESOURCES MANAGEMENT - ANALYSIS OF THE ST. THOMAS, U.S. VIRGIN ISLANDS, WATER MARKET

Water scarcity has been a historical problem in the US Virgin Islands (USVI). The combination of extreme events such as hurricanes and floods and the lack of holistic planning in infrastructure have conditioned the US Virgin Islands population to a state of constant drought. Because of annual rainfall (102 centimeters (40 inches) annually concentrated between July and November (Donahue and Johnston, 1998)) and due to low capture and storage in the small basins and limited aquifers, water conservation is of critical concern for the population and requires constant attention by the water resources managers and planners. Available water supply comes from three systems:

- Catchments of rainwater with cistern storage,
- Saltwater conversion (desalination), and
- Wells (mainly in St. Croix, because of contamination and different type of geology in the St. Thomas main aquifers).

Due to the high cost of water from desalination, the daily average per capita water consumption is substantially less than the US average, totaling 190 L/day per capita (OIA, 1999). Because each island is substantially different, analyzing the islands as a whole is difficult. St. Thomas is the center of tourism and commerce, St. Croix is the industrial center, and St. John is mainly a natural reserve with low population.

The scope of this study is focused on the island of St. Thomas. The pressure to meet tourism demand must be added to the overall local water demand on St. Thomas. Some authors estimate the peak population of this island during high tourism season to be around 130,000, a figure that almost triples the permanent population (Donahue and Johnston, 1998). On St. Thomas, research has been done in the following areas:

- Available water supply.
- Water demand by water use.
- Evaluation of alternative and feasible water supply options to augment current water resources.

- Identification of the existing and alternative supplies, with the potential to provide the water quantity and quality required for St. Thomas.
- Comparison of the main potential supply strategies for St. Thomas, taking in consideration economic, environmental, and equity criteria.
- Paths for future development and management of water resources in the island.

The stakeholders in the water market are WAPA (Water and Power Authority), which is responsible for generating and supplying electricity and desalinated water, DPW (Department of Public Works), which is responsible for wastewater collection, treatment, and disposal, and DPNR (Department of Planning and Natural Resources) which is responsible for controlling and enforcing potable water and wastewater permits, codes, and regulations through the Division of Environmental Protection. Understanding the position and interrelation between the major stakeholders regarding water resources is crucial for evaluating the particular dynamics of the water market. Representatives of all these major stakeholders have been interviewed in order to establish a datum during the month of January of 2003.

WHY INTEGRATING WATER RESOURCES MANAGEMENT?

> "Integrated Water Resources Management - IWRM - is a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (Global Water Partnership, 1996).

To take into account social, natural, and economic conditions three criteria should be addressed: economic efficiency in water use, environmental and ecological sustainability, and equity in the access to water for the population. Three fundamental complementary elements should be encouraged and developed as part of effective water resources management:

- The enabling environment, as a framework.
- The institutional roles at each level and representing every stakeholder.
- The management and development instruments, as a useful "tool-box" for implementing IWRM.

Water is a resource that has no frontiers, and there are many neighboring islands that can play a complementary role in water augmentation.

HISTORIC AND ECONOMIC BACKGROUND FOCUSED ON THE WATER SITUATION

For a better understanding of the actual water situation in this U.S. territory a chronology of key events is presented. The water situation is embedded in the greater social, economical, and political picture of the islands and analysis of the water market without taking into account all this information is not possible. It is important to note that institutionally the islands are a young autonomous territory. Only since 1970, have the citizens elected their own governor. Similar to other institutions in the islands, the ones of the water sector are young.

In the past fifty years the history of water resources development in the islands can be summarized as follows. Until 1960, hillside rainfall catchments and dug wells composed the major sources of water supply. Rainwater harvesting was the source of water for most rural and urban domestic supplies. As proof of the importance of this practice, in 1964, the legislature of the US Virgin Islands passed a law that required all new residential, commercial, and industrial buildings to have minimum cistern storage proportional to roof surface. In 1955, as population started to grow, water was barged from Puerto Rico as a supplemental water supply. In the 1960's and early 1970's population grew rapidly (Figure 4) as a consequence of the shift in the economic activity of the island. During this period the economy that was traditionally based in agricultural production, shifted to tourism and industry. This continuous growth in population provoked an unprecedented stress on the available water resources. The population rose from 32,100 in 1960 to 85,800 in 1975 (USGS, 1987).

To mitigate water scarcity the first desalination plant was implemented in 1964. The Virgin Islands Water and Power Authority (VIWAPA) directed its operation. The initial production doubled the capacity of the existing supply system consisting of rainwater catchments and groundwater extraction (USGS, 1987).

In the 1970's, water production by seawater conversion continued to expand. But at the end of that decade, due to aging equipment and lack of maintenance, a water crisis appeared again on the islands. These problems, in addition to periods of drought, over-pumping of wells, failures in the distribution systems, and a lack of adequate storage capacity resulted in rationing of water in order to mitigate frequent shortages. In 1979, barging from Puerto Rico started again (USGS, 1987).

From 1981 to 1982, the VIWAPA expanded its desalination capacity by 2.5 million gallons per day (MGD) on St. Thomas and by 1.25 MGD on St. Croix, ending the need for rationing. Although supplies were improved, water demands were not fully satisfied (USGS, 1987). During the last two decades, population growth has decreased and in the last decade, negative growth has been registered. Not much has been invested in the expansion of the water system. All the efforts made were directed towards more efficient operation of the existing system. If population forecasts from the 1980's (156,000 inhabitants by the year 2000) materialized, a water crisis would have been inevitable today. The fact that the actual population is only 108,000 (US Bureau of the Census, 2000) has mitigated the failure to meet the planned goals in the water resources sector.

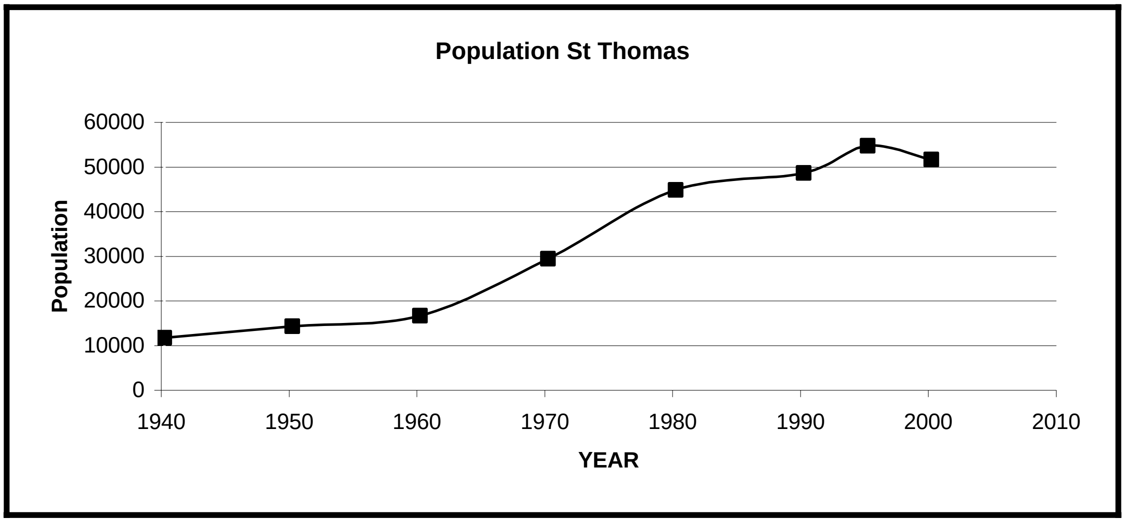

FIGURE 4
TOTAL PERMANENT POPULATION ST. THOMAS
(Data taken from the US Census Bureau-2002 and OIA, 1999)

WATER SUPPLY ON ST. THOMAS

CONJUNCTIVE USE OF RAINWATER HARVESTED WATER AND DESALINATED WATER

General information has been given on the water resources of the three main islands that compose the US Virgin Islands. A more thorough description of the water use and perspectives for water supply for St. Thomas will be analyzed.

Many of the practices described pertaining to water use are common to the three islands as well as some of their neighboring Caribbean islands.

> "In most of the smaller islands of the Caribbean, there is no single natural source of water that may be used to satisfy the ever rising demand for consumption and sanitary purposes brought on mainly by increasing standards of living and visitors arrival. Mountainous terrain makes buildable land dear, and along with high evaporation rates make larger surface water impoundments impractical. Groundwater supplies are limited due to high runoff rates and little opportunity for recharge" (Smith, 1987).

As of 2003, the only reliable and available water supply for all the population in St. Thomas is rainfall water catchments (RWC). Although desalination has been present on the island since 1962, it is not distributed throughout the island. Desalinated seawater is only allocated in urban areas and in places where population is dense. Groundwater is used throughout the island but is only privately operated. Because of groundwater contamination, the use of groundwater as a water source is considered a last resort. On the other hand, many of the resorts in the island utilize privately owned reverse osmosis systems (R/O) to meet their water needs. The actual water use situation depends on the location of the resorts since public supply is not available in all areas of the island. In some cases there total reliance on R/O system for all uses while others partially use privately desalinated water for irrigation. Three resorts use R/O systems with an input of brackish ground water, and the remainder (around twenty-seven) use seawater as input (Simon, 2003).

TABLE 4
POPULATION, SOURCE OF WATER, SEWAGE DISPOSAL AND PERCENTAGE OF WATER PURCHASED FROM VENDOR BY SUBDISTRICT FOR ST. THOMAS

Relevant Datum	1 Charlotte Amalie Sub district	2 East End Sub district	3 North side Sub district	4 South side Sub district	5 Tutu Sub district	6 West End Sub district	Total for St. Thomas (*)
Total Population	18.914	7.672	8.712	5.467	8.197	2.058	51.020
Source of Water (% of housing units)							
Public System only	44	17	6	24	18	2	25
Public System and Cistern	36	7	8	13	15	4	20
Cistern, tanks, drums only	20	73	85	62	66	93	54
Other means	1	3	1	1	1	1	1
Sewage disposal (% of housing units)							
Public Sewer	90	29	19	48	80	20	60
Septic tank or cesspool	7	66	76	50	17	75	36
Other means	3	5	5	2	3	5	4
Water purchased from water vendor (% housing units at least once in year)							
Purchased	30	42	32	38	31	32	33
Not purchased	70	58	68	62	69	68	67

As shown in Table 4, the allocation of water from the public system does not cover most populated areas, leaving the rest of the population with no other option than to use RWC. Of the permanent residents only forty-five percent have access to public potable water, while sixty percent of the population has access to public sewer system. In an island of these geographic and topographic characteristics, it is far more costly to develop and maintain a sewer system than to develop and maintain a water supply system, taking into account that desalination plants already exist and are in operation. Despite this fact and because of economic considerations, WAPA is not planning to extend its distribution throughout the island. On the other hand, DPW is working on extending the sewer system.

TABLE 5
SUMMARY OF ESTIMATED WATER SUPPLY FOR ST. THOMAS

Water Supply	lpd	gpd
Rainwater	6,590,000	1,740,000
Desalinated	13,240,000	3,500,000
Estimated R/O	1,420,000	375,000
Groundwater	1,510,000	400,000
Total	22,760,000	6,015,000

WATER DEMAND

Water is allocated only for residential household and community uses (schools, hospitals, government), resorts, and commercial demand. Water demands for irrigated agriculture and for industry are negligible on the island. A summary of the total estimated water demand is presented in the following table:

TABLE 6
SUMMARY OF ESTIMATED WATER DEMAND FOR ST. THOMAS

Water Use	Water Demand LPCD	Population Considered	Demand lpd	Total Demand lpd
Residential	190	51,200	9,720,000	
School	57	14,300	818,000	
Workforce	38	24,100	919,000	
Hospitals	757	240	182,000	
Miscellaneous(irrigation, other intensive)			872,000	
UAFW			3,310,000	
Total local demand				**15,821,000**
Tourism Peak stay overs	400	19,200	7,680,000	
Tourism Peak for the day	55	60,800	3,340,000	
Total tourism related demand	**At peak**			**11,020,000**
TOTAL DEMAND				**26,841,000**

SUPPLY AND DEMAND

Calculations result in the following estimates of supply and demand:

ESTIMATED AVAILABLE SUPPLY VS. PEAK DEMAND

Supply = 22,800,000 lpd (6,020,000 gpd)
Demand = 28,000,000 lpd (7,400,000 gpd)
Demand-Supply = 5,20,000 lpd (1,370,000 gpd)
This value represents the theoretical deficit in available supply during peak demand.

ESTIMATED AVAILABLE SUPPLY VS. LOCAL DEMAND

This represents the low season on the island.
S = 22,800,000 lpd (6,020,000 gpd)
$\mathbf{D_{NT}}$ = 15,800,000 lpd (4,170,000 gpd)
$\mathbf{S - D_{NT}}$ **=** 7,000,000 lpd (1,850,000 gpd)

This value represents the theoretical available base local supply surplus in tourism low season. It is clear from this summary that in order to provide for the local water demand and continue successful operations of the fundamental tourism industry at the same time, freshwater augmentation is a major concern.

EVALUATION OF ALTERNATIVE AND FEASIBLE SUPPLY OPTIONS THAT CAN AUGMENT THE ACTUAL WATER RESOURCES

The main objective is to discuss the available alternative technologies based on the experience of volcanic islands with similar characteristics as St. Thomas. The purpose of this evaluation is to provide an inventory that can be taken into account by the different actors to make informed choices in maximizing the resources of the island.

TABLE 7
TECHNOLOGIES FOR FRESHWATER AUGMENTATION ON ST. THOMAS

Technology Group	Technology	Actual Use	Past Use	Evaluate/ improve
Specific freshwater augmentation	RWC	Yes		Yes
	Wells	Yes		Yes
	Importation		Yes	Yes
	Submarine piping			Yes
Water quality improvement technologies	Desalination by distillation	Yes		Yes
	Desalination by reverse osmosis	Yes		Yes
Wastewater treatment technologies and reuse	Wastewater reuse			Yes
	Alternative dry sanitation			Yes
Water conservation	Water conservation and protection measures	Yes		Yes

Some of the technologies enumerated in Table 7 have been applied previously in the USVI, the rest of them should be considered as part of an evaluation of the overall water resources strategies to be discussed between actors of this particular market.

COMPARISON OF THE THREE POTENTIAL STRATEGIES FOR FRESHWATER SUPPLY AND AUGMENTATION

Of all the sources of augmentation available, only distillation, reverse osmosis desalination, and submarine piping can provide water in the quantity and quality needed on a continuous basis. In an IWRM framework, the analysis of these options should take into account three different elements: 1) economic efficiency in water use, 2) environmental and ecological sustainability, and 3) equity in the access to water for all people. An evaluation of these three principles follows.

ECONOMIC ANALYSIS OF THE MAIN SUPPLY ALTERNATIVES

This analysis has been done, for the purpose of fair comparison, with the operation data of WAPA for the year 1995. The cost of alternatives of R/O and submarine piping, were calculated for supplying the peak supply of distillation water that WAPA's plant in Krum Bay, St. Thomas. The alternatives were run for a period of 50 years of operation of each of the different supply strategies. Detailed calculations are provided by Buscemi (2003).

SUBMARINE PIPING BENEFIT/COST ANALYSIS

Four different alternatives were run.
First Alternative: WAPA operates the pipe and fully finances the construction of dual parallel flexible pipe of 10-inch diameter (2x10").
Second Alternative: WAPA operates the pipe and fully finances the construction of a dual parallel flexible pipe of 8-inch diameter (2x8").

Third alternative: The water seller in Puerto Rico, and/or possible users in Isla de Culebra and Vieques pays for half of the cost of the works. Work consists of a 10-inch diameter dual pipe alternative.

Fourth alternative: The water seller in Puerto Rico, and/or possible users in Isla de Culebra and Vieques pay for half of the cost of the works Work consists of an 8–inch diameter dual pipe alternative.

DESALINATION BY DISTILLATION BENEFIT/COST ANALYSIS

The actual data published by WAPA for the year 1995, was projected from year 1 to 50, to compare it with the other alternatives.

DESALINATION BY REVERSE OSMOSIS BENEFIT/COST ANALYSIS

Two different alternatives have been run.
First Alternative: WAPA operates the RO plants.

Second Alternative: A private operator is contracted by WAPA and sells water produced at a fixed value of $\$3/m^3$.
Detailed calculations are provided by Buscemi (2003).

PROJECT COMPARISON

The alternatives developed are ranked according to the PVBREV/PVCOS ratio, or benefit–cost ratio in Table 8. As all the alternative projects have a cost constraint, the benefit-cost ratio is a good indicator of the choice of project from a purely economic point of view. These projects are not considered as mutually exclusive, because they are part of an augmentation strategy. The proper combination of different alternatives can be suitable for the objectives of water resources planning.

TABLE 8
RANKING BY BENEFIT–COST RATIO, ALL PROJECTS

Ranking by PVRev/PVCos	DISC RATE	IRR	NPV	PVREV	PVCOS	PVRev / PVCos
Submarine Piping 2 x 10" Shared	0.07	0.330	51,909,040	188,608,436	(136,699,396)	1.380
Reverse Osmosis	0.07	0.270	33,014,739	188,608,436	(155,593,697)	1.212
Submarine Piping 2 x 10"	0,07	0.142	32,437,545	188,608,436	(156,170,891)	1.208
Submarine Piping 2 x 8" Shared	0.07	0.289	32,238,440	188,608,436	(156,369,996)	1.206
Submarine Piping 2 x 8"	0.07	0.126	18,295,917	188,608,436	(170,312,519)	1.107
Private Reverse Osmosis	0.07	---	12,248,307	188,608,436	(176,360,129)	1.069
Desalination by distillation	0.07	---	(19,571,548)	188,608,436	(208,179,984)	0.906

ENVIRONMENTAL IMPACT COMPARISON

The criteria for environmental assessment are:

- Energy intensity of the process
- Water quality
- Marine eco-system impact
- Land use

TABLE 9
SCORING OF ENERGY EFFICIENCY OF SELECTED PROCESSES

Process	Energy intensity Kwh/m³
Submarine Piping 2 x 8"	1.59
Desalination by reverse osmosis	4.50
Submarine Piping 2 x 8"	4.87
Desalination by distillation	23.82

EQUITY IN THE ACCESS TO WATER FOR ALL PEOPLE

Regarding the distribution of the public water system, it has been noted that the main problem lies in the centralized distribution of water. As system expansion has not been accomplished as planned in the last two decades, 55% of the permanent population does not have access to the public distribution system. It is also to be highlighted that, lack of access to the public system does not depend, as in many other cases, on the income composition of the population. This adds to the challenge of extending the distribution in a hilly terrain of volcanic soils, the opportunity of the willingness, and ability to pay of the potential new customers.

ANSWERS TOWARDS INTEGRATING WATER RESOURCES MANAGEMENT

There are several water resources management issues that are crucial for facing the challenges of the constrained St. Thomas water market.

Returning to the main questions about the key issues on water resources management described earlier in this section, and after careful analysis of the actual situation it is possible to discuss the answers to them.

ENVIRONMENTAL CONSEQUENCES OF SEPARATE OPERATION OF WATER SUPPLY AND WASTEWATER

Is it desirable to have two different entities operating water supply and water disposal? By understanding that water is a renewable and reusable resource, a recommended practice is to integrate the management and operation of these two services in order to ensure that wastewater flows can be an effective addition to resource flows of water supply. Although in the case of a water-limited economy as the one under consideration, it does not seem rational to operate with different companies water supply and sewage collection. Given the extreme necessity on considering ways of reusing water, it will be highly recommendable to operate and design water supply and wastewater collection and reuse conjunctively. Today two different agencies with no points in common are operating separately these two services, and until now, the government has implemented no significant water reuse policies. Some resorts have been applying the principle of water reuse in the island by recycling treated water for irrigation uses. This is a direction to which to point in the near future.

RELIABILITY OF PUBLIC WATER SYSTEM BASED IN DESALINATION. FREQUENCY OF EXTREME EVENTS

Is it possible to operate a reliable water system based only in one supply strategy (desalination) in a place where the occurrence of extreme events is of high frequency?
After the analysis of the water sector situation in the island it is clear that desalination, although having played an important role in the island development in the decade of the sixties and seventies, could never give a full response to water needs of the island. At present, although a valuable and secure supply for freshwater, and after beginning to charge full price from the water they are selling, WAPA still faces operational problems, and has to think about future alternative technologies that can be more suitable to the St. Thomas needs. Careful consideration should be given to the alternatives that have been developed in this work.
It is possible to apply more cost-effective alternatives as the main supply strategy to the island. It has been proven in this work that importing water from Puerto Rico through submarine pipelines is a feasible alternative. Moreover, in the long term it will allow WAPA to focus in the extension of the system.

On the other hand, private resorts have been successful in incorporating R/O plants with up-to-date technologies. In addition, they are reporting huge savings over water bought from WAPA. Two years ago an attempt to privatize part of WAPA as a concession failed. The legislature of the Virgin Islands did not approve the arrangement between WAPA and Southern Waters. Still today, all the major services are in government hands and although improvements have been made in the water sector, privatization can be a possibility that ought to be analyzed in the near future. All the facilities operated by resorts and other private owners report better yields than the government-owned WAPA.

It is also important to note that the actual institutions have been going through great changes in the last three decades. In 1971, the first elected governor assumed office in the islands, before that the U.S. federal government designated the governor. Institutions are not yet mature, although they have many of the requirements that the continental states have, but lack the proper solid institutional background needed for the task. That is why enforcement of EPA regulations, for instance, is slow and has fewer results than expected.

Water Costs and Prices in this Market

How can proper prices on water be managed in a market with these characteristics? The idea of equitable prices has been undergoing drastic changes in the last decade. Full pricing of water has become a necessity because of the large debt that the VI government has contracted with the federal government. But there are some gray areas that need to be defined and clarified. For instance the housing projects managed by VIHA (Virgin Island Housing Authority) as well as other territorial government agencies remain the main clients of WAPA and rarely pay their bills. This sort of cross-subsidy should be corrected, but it seems to be a long road yet to be taken.

Health Consequences and Water Quality: Rainfall Harvesting as Main Source of Water Supply

How can overall water quality be assured when catchments of rainfall is the main water supply for more than 70% of the population? Water quality for human consumption is still an issue to be solved in the islands. Because 70% of the population relies on water catchments for their daily water consumption, a strict control of water quality should be implemented in households. This task can be done by DPNR and the Department of Public Health. Public campaigns for instructing the population on a regular basis are sporadic and only applied when an outbreak of waterborne disease appears on the horizon. No up-to-date studies founded on statistical data have examined waterborne diseases linked with the exposure of the majority of the population to water related health risks.

US VIRGIN ISLANDS DESALINATION SUSTAINABILITY ASSESSMENT

It has traditionally been thought that the cost per unit volume of potable water supplied by a desalination plant is much greater than from other traditional drinking water treatment. While that statement has historically been true, the gap in costs between desalination and traditional water sources per unit volume of potable water is narrowing rapidly (Angelo, 2000; Kufahl, 2002).

This narrowing is largely due to improvements and research in desalination technology that have drastically driven down costs. Main factors have been improvements in the reverse osmosis process (Fong, 2001). Increases in the costs of drinking water from traditional sources caused by increased treatment standards and requirements as well as ever-increasing water shortages also support this narrowing trend (Kufahl, 2002; Tsiourtis, 2001).

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. Distillation typically involves a series of these heating/condensing stages, each of which is performed at lower pressures using recycled heat and water from the last stage to increase overall efficiency. The process simply heats water and lowers the ambient air pressure until water "flashes" into vapor phase which is then condensed so that it can be collected, treated if necessary, and used for drinking. In reverse osmosis the water that is to be treated is pumped at high pressures, against the natural osmotic gradient, through a semi-permeable membrane that allows smaller water molecules to pass through but not larger salt ions. Water that goes through the reverse osmosis process is pretreated to remove contaminants that would clog the membranes and reduce efficiency. Typically, one membrane will treat water to recommended standards, but two may be used to improve water quality.

SUSTAINABILITY ASSESSMENT OF THE DESALINATION INDUSTRY

INTRODUCTION

The concept of a sustainability assessment stems from the emerging concept in the environmental field of sustainable development. Sustainable development can be defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (IISD, 2002). Sustainability assessments are empirical methods used to quantify and assess how well a particular project, area, or industry meets needs of the current generation while maintaining the ability of future generations to meet their needs.

Numerous studies have been conducted to evaluate the relative advantages and disadvantages of each desalination treatment process (Al-Mataz, 1996; Darwish and Jawad, 1989; Kamal, 1995; Madani, 1990). Very few studies have been conducted to examine the complex interactions of sustainability indicators; none have incorporated social, economical, and environmental factors into the study. An evenly weighted numerical scoring system will be used in order to assure that each indicator will equally affect the assessment's results. This scoring system produces clear and interpretable results that can easily be relayed to stakeholders.

SCOPE

The scope of this study focuses entirely on desalination treatment processes. The sustainability assessment aims to determine whether trends in the processes currently used are more sustainable than previous processes. Specifically, this study attempts to determine if the industry's shift from distillation desalination techniques to reverse osmosis desalination techniques has moved the industry towards sustainable operation.

No consideration will be given to factors outside of actual treatment processes performance. This approach allows for a narrowly focused study where reliable data can be found and applied to the entire industry from an engineering perspective.

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. These plants are used to represent the desalination industry worldwide. 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 that can be analyzed, providing a large set of consistent, reliable data.
- The data are reliable and easy to obtain.
- Desalination plants on the islands range from very large to very small.
- The islands' desalination facilities, along with those in the Middle East, have become the standard for desalination research.

Because of their long, well-recorded history and operational performance, as well as the other factors outlined above, desalination plants on the U.S. Virgin Islands are very well suited for a sustainability assessment aimed at determining a trend toward or away from sustainable operation of the desalination treatment process.

SUSTAINABILITY INDICATORS

The sustainability indicators chosen for the sustainability assessment represent essential factors related to the desalination treatment process. The indicators were also chosen based on their relative importance to the desalination industry. To examine only the treatment process it is important that the sustainability indicators are only affected if factors related to the treatment process change.

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

The most important factors that can vary between the plants in the study that would change these indicators and that are a part of the treatment process are size of plant; type and cost of desalination process in operation; and energy required by the chosen desalination process.

Plant Descriptions

The sustainability 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 older distillation processes. The plants operated by Aqua Design at Caneel Bay represent both older and newer reverse osmosis technology.

Table 10
Desalination Plants Used for Sustainability Assessment

Plant	Treatment Type	Description	Assigned Plant Number
WAPA – St. Thomas	Multi-Effect Distillation	Best-case scenario for distillation	1
WAPA – St. John	Vapor Compression	Worst-case scenario for distillation	2
Aqua Design - New	Reverse Osmosis	Middle-of-the-road scenario for RO	3
Aqua Design - Old	Reverse Osmosis	Best-case scenario for RO	4

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 5 shows the Krum Bay plant.

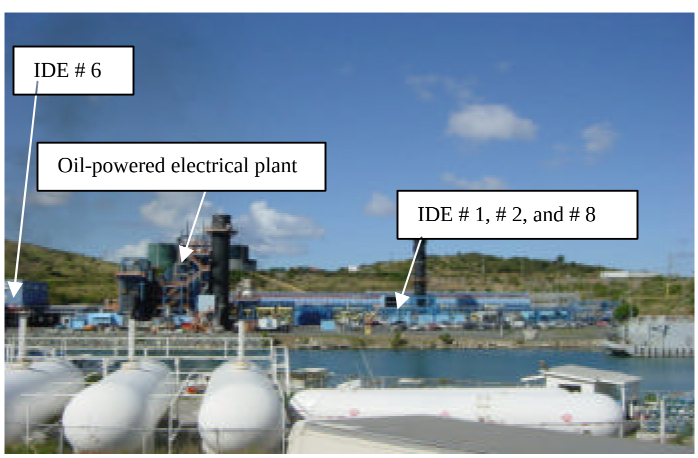

Figure 5
Krum Bay Desalination Plant

Water and Power Authority – St. John

The other Water and Power Authority desalination plant studied is located in Frank Bay on St. John. Figure 6 shows the Frank Bay plant.

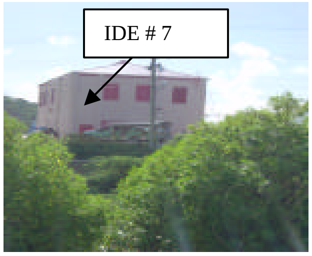

FIGURE 6
FRANK BAY DESALINATION PLANT

Aqua Design

The old Aqua Design reverse osmosis plant is shown in Figure 7, the new plant will be built on the same location.

FIGURE 7
CANEEL BAY RESORT DESALINATION PLANT

METHODS

To assess whether or not the desalination treatment process is moving towards sustainable operation, each desalination plant is compared to the others through the use of the five chosen sustainability indicators. For the Water and Power Authority Plants, data were obtained from the December 2002 and July 1998 operating months. For the Caneel Bay plants, data were obtained from the January 2003 operating month from Aqua Design district supervisor Ron Di Cola. Each plant was then compared to all of the other plants for each indicator.

After the raw data were obtained, the data were converted to consistent units and compiled. Charts were created for each sustainability indicator for analysis. Then sustainability 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 for two different assessments to obtain a sustainability score. The first assessment (SS #1) used all five indicators while the second assessment (SS #2) used only the fuel and cost indicators.

RESULTS

To more effectively display the results, each desalination plant was assigned a number. These are shown in Table 11.

The results for each sustainability indicator are shown in Table 12.

TABLE 11
RESULTS FOR EACH SUSTAINABILITY INDICATOR

Plant	Cost / 1,000 gal	Fuel Consumed	Effluent Temperature	Max pH	Min pH	Effluent Flow
1	$14.00	2.17	84.9	7.8	6.9	0.46
2	$8.00	1.10	93.7	8.4	7.9	0.16
3	$5.04	1.94	86.0	7.2	7.1	0.18
4	$4.20	0.82	84.2	7.2	7.1	0.17

The results of both sets of sustainability scoring are shown in Table 14. SS #1 refers to the sustainability scoring where all five indicators were used. SS #2 refers to the sustainability scoring where only the cost and fuel indicators were used. A higher score indicates greater sustainability.

TABLE 12
RESULTS OF SUSTAINABILITY SCORING ASSESSMENTS #1 AND #2

Plant	Cost	Fuel	Temp	pH	Flow	SS #1	SS #2
1	1	1	4	4	2	12	2
2	2	3	2	4	4	15	5
3	3	2	4	4	4	17	5
4	4	4	4	4	4	20	8

The results of sustainability assessment #1 are shown in Figure 8. As shown in the figure, the new Caneel Bay plant scored the highest, followed by the old Caneel Bay Plant, then the St. Thomas Plant, and finally the St. John Plant.

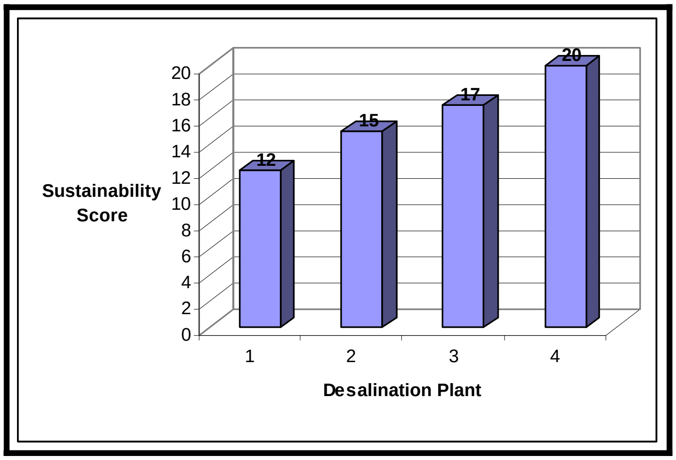

FIGURE 8
RESULTS OF SUSTAINABILITY ASSESSMENT #1

The results of sustainability assessment #2 are shown in Figure 9. As shown in the figure, the new Caneel Bay plant scored the highest, followed by a tie between the old Caneel Bay Plant and the St. Thomas Plant, and finally the St. John Plant.

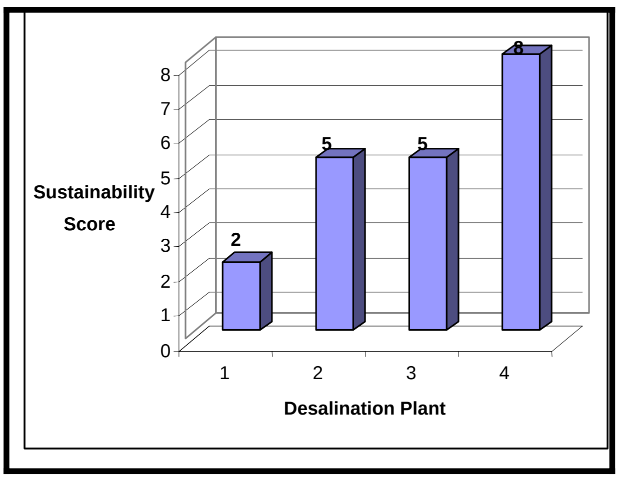

FIGURE 9
RESULTS OF SUSTAINABILITY ASSESSMENT #2

DISCUSSION

The results above show that the desalination treatment process is moving towards sustainable operation. The new reverse osmosis plant in Caneel Bay scores higher than either of the two older distillation plants in both sustainability assessments. In addition, the older plant in Caneel Bay scored higher than the better of the two distillation plants, St. Thomas, in the first sustainability assessment and had the same score in the second assessment. These results indicate that the worst-case scenario for reverse osmosis, the older plant at Caneel Bay, is at worst operating at the same sustainability level as the best-case scenario for distillation processes. The results also show that the best-case scenario for distillation operates at a significantly lower sustainability level than the new Caneel Bay plant, which represents a middle-of-the-road reverse osmosis scenario.

The new Caneel Bay treatment process operates at a more sustainable level than the other plants because it incorporates the newest research and technological advancements made in the desalination treatment process. These advancements allow the process to use less fuel and decrease operational costs.

The old Caneel Bay treatment process and the St. Thomas treatment process operate at a lower level of sustainability. The old Caneel Bay process has low operational costs similar to the new Caneel Bay plant but requires a greater amount of fuel. The St. Thomas process has high operational costs compared to the new Caneel Bay plant and requires about same amount of fuel. The St. Thomas process has a higher operational cost than the new Caneel Bay plant because it operates at higher pressures and because the multi-effect distillation process, like all distillation processes, is less efficient than the reverse osmosis process and can not produce as much potable water per unit of energy added to the process. The larger process creates economies of scale to create this effect but the larger size also increases system inefficiencies which increase overall operational costs.

The St. John plant, which represents the worst-case scenario for distillation treatment methods, operates on the least sustainable level. This result is consistent with expectations because the plant's treatment process costs the most to operate and consumes the most fuel. Process inefficiencies cause the treatment process to use significantly more energy than would be required by other distillation techniques. In addition, high operating pressures and temperatures significantly increase energy requirements and thus increase operational cost.

The first sustainability assessment, in which all five indicators are used, is the most comprehensive model, but the second sustainability assessment model is a more discriminating model. Scoring the environmental indicators produced very similar results for all four plants. Because of this, determining values for each plant based on the ranking system was difficult and subject to ranking bias. To negate this effect, the second sustainability assessment only factored into the model those indicators, cost and fuel, that had clear divisions in values between plants. Neither of the reverse osmosis plants scored less than the best value of four in any environmental indicator's sustainability scoring. Thus, it could be argued that reverse osmosis treatment processes produce less environmentally harmful effects. The data used in this assessment were too inconclusive to make such a claim. It is difficult to be certain that the elevated temperature at the St. Thomas plant or the increased effluent flow at the St. John plant causes more harm than the levels measured at the other three plants.

The fuel and cost indicators produced the most significant, interpretable results while the three environmental indicators produced inconclusive results. All four plants are subject to this Act and are regulated to the same levels of effluent emissions. None of the four plants seems to have made any attempt to reduce these emissions to any point below the regulated level because of a lack of economic incentives.

Weaknesses in the sustainability assessment are associated with the data used and the linearity of the ranking system. The model relies on raw data that were obtained from a wide variety of sources. Operators and plant officials provided cost data that could have been intentionally or unintentionally misrepresented. 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 the data were obtained and analyzed could be made. The data could be obtained from documented data, which was not available for this study, rather than personal interviews. This would provide the model with solid, documented data that are more convincing than abstract data collected from interviews.

ST. JOHN DESALINATION PLANT RENEWABLE ENERGY UTILIZATION ASSESSMENT

Although it is a relatively energy intensive process, desalinating water is and will continue to be a necessary source of potable water. Currently desalination is heavily dependant on fossil fuels to meet its energy requirements. However, fossil fuel use for desalination is not sustainable and may not be necessary. One method of increasing existing desalination processes is through the use of renewable energy. Specific proposals were therefore examined for increasing the sustainability of desalination for the existing mechanical vapor compression plant on St. John, USVI. These include proposals for use of solar thermal, photovoltaic, and wind energy.

BACKGROUND

Sustainability is commonly defined as meeting, "Meeting the needs of the present without compromising the ability of future generations to meet their needs (WCED, 1987)." Although progress towards sustainability is helpful, true sustainability would require maintaining constant equilibrium, or a net gain, with the earth's resources. For example, using energy only at the rate, or more slowly, at which it can be provided by the environment. By definition, renewable energy meets this goal.

Unlike fossil fuels, renewable energy is constantly being replenished. The use of renewable energy not only lessens, or even eliminates, the unsustainable use of fossil fuels, but also the pollutants they produce. These pollutants include sulfur dioxide, particulates, and an annual global discharge of over 20 billion tons of greenhouse gas carbon dioxide (Cassedy, 2000). Pocesses for the production of renewable energy are continuously increasing and more economical with the vast majority of renewable energy sources having their basis from the sun. These solar sources include direct solar power from photovoltaics or solar thermal energy as well as power derived from wind, biomass, and ocean thermal sources.

Since desalination is a particularly energy intensive process and globally the vast majority of this energy is derived from fossil fuels, there is great room for improvement in desalination sustainability. Most efforts which increase desalination sustainability currently consist of using direct thermal energy for distillation. Due to the high energy requirement for desalinating water, it is often economically beneficial to site distillation desalination plants with cogeneration power plants. By this pairing, not only is it possible to avoid any significant electricity transmission losses, but waste heat produced by the cogeneration plant can be used to heat influent water. However, only thermal distillation processes can make use of heat in desalting water. Other methods are limited to the use of higher grades of energy, mechanical or electrical. The Water and Power Authority (WAPA) desalination plant on St. John is one such plant which requires one of these higher grades of energy.

ST. JOHN, USVI PAST AND PRESENT

DESALINATION

The public water utility provider, the Water and Power Authority (WAPA), currently operates a 155,000 gallon/day-maximum capacity mechanical vapor compression desalination plant on the island of St. John. This plant supplies piped water to the city of Cruz Bay and trucked water as needed to the rest of the island. During the winter months of the tourist season and during Carnival (late June/early July), demand exceeds the supply capacity of this plant. Therefore, WAPA is also subcontracting a reverse osmosis plant of equal size to meet the remainder of the water demand until construction of a potable water pipeline from St. Thomas is completed in 2004 (Rothgeb, 2003) or until desalination capacity can be permanently expanded on St. John (Chung, 2003).

TABLE 13
ST. JOHN PUBLIC WATER PRODUCTION

Month	Water Production (m3)
January	17,000
February	18,100
March	13,200
April	6,700
May	14,300
June	22,400
July	21,800
August	18,100
September	13,600
October	13,100
November	14,900
December	18,000
Total	191,200

ENERGY

There is a 2.5 MW diesel power plant in proximity to the St. John desalination facility, but due to the expense of operating it, the entire island power demand of up to 11 MW at average peak times and 15 MW during Carnival (late June/early July) is imported from St. Thomas (Chung, 2003). There are, however, significant issues concerning the reliability of electricity imported from St. Thomas. Outages and surges are fairly common for St. John, occurring at least every two weeks and sometimes multiple times in one day (Hendrickson, 2003). Although this is not as damaging to mechanical vapor compression equipment as it would be for reverse osmosis, it still sometimes requires over an hour to start equipment back up after having been down. All together, the island of St. John experiences approximately 100 hours/year of outages (USDOE, 2001). In addition, electricity production on St. Thomas comes almost entirely from number 2 and 6 fuel oils. As the USVI has no petroleum resource of its own, the cost of importing fuel makes electricity very expensive. The current cost of electricity production is \$0.09/kWh, excluding distribution losses and administrative costs, with retail rates at approximately \$0.14/kWh for large commercial customers and \$0.17/kWh for residential customers (Rothgeb, 2003). Distributed renewable energy would not only move the WAPA desalination facility on

St. John toward sustainability, but could also provide the benefit of increased reliability and reduced cost.

St. John Renewable Energy Analysis

In an effort to move St. John desalination towards sustainability and increase the reliability of energy resources, three renewable energy sources were analyzed. Analysis was made of the potential for solar thermal, photovoltaic, and wind energies to be paired with the existing mechanical vapor compression distillation plant on St. John. Solar thermal energy through use of solar ponds has the advantage of being relatively low cost and having energy storage capacity. Photovoltaic and wind energy, on the other hand, have no inherent storage capacity, but are considered particularly well suited to use with mechanical vapor compression (Delyannis and Belessiotis, 1995). All systems were designed to be grid-connected and do not use batteries since batteries are problematic, particularly in warm climates. Plant data indicate that in the time from July 1998 to December 2002, WAPA's fuel costs increased from $15.56/bbl and $15.37/bbl for numbers 6 and 2 fuel oil respectively to $29.52/bbl and $29.18/bbl. Therefore benefits are based on about half this rate of increase and a cost of $0.09/kWh to produce electricity. Costs assume 3 percent inflation. And present value analysis is based on WAPA's current loan rate of 5.25 percent (Rothgeb, 2003).

Solar Pond

Solar ponds are a type of thermal solar technology where thermal energy is stored at the bed of a pond by suppression of convection by a salinity density gradient. An analysis of the potential for use of solar pond technology found that, economically, this is a fairly beneficial project (Table 14). As the local utility is hesitant about using unproven technologies, another benefit of this project is that it is well established. Although, solar ponds are not common in the US, they have been used widely in Israel for over 40 years. The greatest advantages, however, are its storage capacity and reliability for consistent energy output. This is particularly important as the desalination facility operates 24 hr/day. Literature recommends that solar ponds be designed to meet average annual energy requirements. As such, although average energy needs can be met by a solar pond, additional energy will be needed from grid-supplied energy though the pond would be able to sustain the desalination process during power outages. A disadvantage of a solar pond, however, is that it is an extremely diffuse resource. Therefore, approximately 19.5 acres of land would be required for the 18 acre solar pond to meet a design capacity of 254 kW. Also, as long as 5 months can be expected for establishing a high enough LCZ temperature for energy use. As a result, no cost savings is expected in the first 6-8 months of the project.

Photovoltaics

As seen in Table 14, supplying power to desalination by photovoltaics is not financially beneficial, although only marginally so. The main reason for this is that photovoltaics exhibit minimal economies of scale. Where rebates are available, though, small photovoltaic systems (since rebate programs tend to have a ceiling payment) are particularly beneficial in areas of high solar insolation. Although St. John has significant insolation, the project is not economically feasible. Furthermore, since no batteries were factored into the design, photovoltaic energy would not be available for 24-hour plant operation. Therefore, at least half of the energy in this situation would need to come from grid-supplied electricity. In addition, approximately 1 acre of land would be required for this project.

WIND

As indicated in Table 14, wind energy is the most economically beneficial project for moving St. John's vapor compression desalination toward sustainability. In this design, a 900 kW wind turbine is proposed. Although wind speed will depend to a great extent on the turbine location, class 3 areas are present in the immediate vicinity of the desalination plant. St. John is a former volcanic island and, as a result, is quite hilly. Nearby ridge-tops are classified as class 3, while only class 1 winds exist along the coast. Although there is no inherent storage capacity with wind energy, wind is available throughout the day and so storage is not necessarily needed. It is expected that some grid energy will be required. Wind energy also has the benefit of not requiring significant expanses of land. It is expected that proposed turbine could be located on existing WAPA property. For this project, 2002 wind speed data were used to estimate both the electricity savings for desalination and the amount saved by supplying excess electricity back to the grid.

TABLE 14
BENEFIT-COST ANALYSIS

	Solar Pond	**Photovoltaic**	**Wind Turbine**	
			Without Reverse Metering	With Reverse Metering
Present Value of Benfits	$2,202,657.27	$1,170,845.88	$3,006,032.28	$4,427,976.25
Present Value of Cost	($1,945,496.15)	($1,571,657.33)	($1,682,056.83)	($1,682,056.83)
Benefit/Cost Ratio	1.13	0.74	1.79	2.63

Despite St. John's significant solar resources and only fair wind resources, wind energy has been found the most promising renewable energy to move St. John's vapor compression desalination plant toward sustainability. Not only is the proposed wind energy design able to meet a greater proportion of the energy needs of desalination, but it also has a relatively low land area requirement, compared to solar thermal and even photovoltaics, and is available throughout the day for 24 hour/day desalination plant operation. Furthermore, as it is a well established energy source, used in small scale by others on the islands, it is likely to be well accepted by WAPA officials as well.

WATER REUSE AND CONSERVATION

WATER REUSE OVERVIEW

The initial guidelines developed in 1980 by the USEPA included information on proven technologies in the area of water reuse (Ammerman and McCullen, 2002). In 1992, through funding from the USEPA and the US Agency for International Development's (USAID) Water and Sanitation for Health (WASH) program, these guidelines were updated to reflect technological advances in water reuse practices. In 2002, the USEPA decided to update the water reuse guidelines due to significant technological advancements since the last update in 1992. These updates are planned to be completed and published by the USEPA in 2004.

As was described in the proposal dated December 9, 2002, various types of reuse projects can be applied in a community. All of the reuse categories described in the proposal were evaluated as possible reuse, conservation, and disposal alternatives for St. Thomas and St. Croix.

WATER CONSERVATION OVERVIEW

The USEPA has published guidelines regarding conservation practices that can be undertaken by all water users and suggests changing a few personal habits to effectively conserve water (USEPA, 2002c). In the home, the most water is used in the bathroom. Turning off the faucet while brushing teeth and taking a three to five minute shower instead of a bath can conserve approximately 35 gallons of water per day. Flushing the toilet also uses a large percentage of water. Installing products from water conservation equipment vendors helps to conserve water. Operators of residential and commercial irrigation systems can also conserve water by implementing the more efficient Xeriscaping concept (USEPA, 2000b).

USVI WATER REUSE AND CONSERVATION SURVEY AND INTERVIEW RESULTS

In order to assess the current water reuse and conservation practices in the US Virgin Islands, surveys were distributed and interviews were conducted with facility managers. Of the 79 potential survey participants identified as TPDES permit holders, 68 surveys were mailed to businesses in the Virgin Islands since address information was not available for 11 businesses. Fifty-four of those surveys were presumed to have reached the intended business or municipality and ten completed surveys were returned. Nine out of ten of the surveys completed showed reuse programs consisting of irrigation; only one facility discharged their treated wastewater via an ocean outfall. Six of these ten facilities use primary treatment with chlorine disinfection, three utilize secondary treatment with chlorine disinfection, and one sends wastewater to the local municipal plant for treatment. Five of the ten surveys indicated conservation practices were in place. Notices indicating the importance of conserving water are posted at three facilities, 1.6-gallon toilets were installed at two facilities, and 2.5-gallon per minute showerheads were installed in each of the 290 rooms of a local resort.

Of the ten facilities that completed and returned the survey discussed in the previous section, the managers of six agreed to be interviewed. Many businesses in the US Virgin Islands have implemented various levels of water reuse and conservation practices in order to decrease operating cost and the amount of potable water needed and to avoid filing a wastewater permit. The information gained from the six interviews is summarized in the following paragraphs.

INTERVIEW 1: BEST WESTERN EMERALD BEACH RESORT

The Best Western Emerald Beach Resort is located in Lindbergh Bay in St. Thomas. This 90-room resort averages between 60 and 80 percent occupancy throughout the year and uses between 14,000 and 17,000 gallons per day (gpd) of water. Since 1999, a reverse osmosis (R/O) desalination plant is permitted under the TPDES program and treats water extracted from a brackish well located on the resort's property. When demand exceeds output of the desalination plant, supplemental water is purchased from the Virgin Islands Water and Power Authority (WAPA). The brine discharge from the R/O process is sent to an on-site 100,000-gallon cistern to be utilized for irrigation and toilet flushing.

The Emerald Beach Resort sends wastewater to the municipal treatment plant located at the airport. At the time of this interview, all wastewater flows to the airport treatment plant were being sent without treatment to an ocean outfall until upgrades to the treatment plant are completed. Conservation practices at the hotel were few. In each room a card is present on the wall that gives hotel guests the choice of having their towels and bedding washed and changed every day. Beyond this there are no other conservation practices in place. Unfortunately, when I stayed at the hotel, staff disregarded the card in my room and changed the bedding and towels even though I had chosen the water conservation option. Thus, currently, no reuse and minimal conservation measures are utilized at this hotel.

In order to decrease operating costs, the manager of the Emerald Beach Resort and Carib Beach Resort asked CRABS to determine if a well of sufficient yields could be drilled on the site of the Carib Beach Resort. By looking at USGS maps showing the geological makeup of the area in question as well as performing a site walk-through, a well would result in low yields (5 to 10 gpm) due to the igneous rock formation on which the Carib Resort is built.

INTERVIEW 2: ANCHORAGE CONDOMINIUMS

Located in Cowpet Bay the east end the island of St. Thomas, this condominium complex has 50 2-bedroom units and 25 3-bedroom units. On average, the complex is 35% occupied mid-May to mid-November (off-peak season) and 70% occupied mid-November to mid-May (peak season). This causes water usage to increase from an average of 4,000 to 8,000 gpd and wastewater flows to increase from 4,000 to as much as 10,000 gpd. Currently, WAPA drinking water service lines do not extend to this complex. Therefore, desalination is used for drinking water production since rainwater cisterns cannot meet the demand of the residents. This complex is permitted to utilize R/O technology, but unlike the Emerald Beach Resort this facility treats seawater withdrawn from an intake located in Cowpet Bay and discharges waste brine into the ocean. Rainwater is collected and utilized to backwash the filter used after withdrawal from the bay.

Built in 1978, the on-site wastewater facility utilizes a primary clarifier with extended aeration, chlorine tablets for disinfection, and a sand filter. Treated wastewater effluent is sent to a 25,000-gallon cistern prior to being reused as irrigation supply. If irrigation cannot be carried out each night the cistern has capacity for approximately two and a half days of average flow. According to the manager, the complex does not have a permit for an ocean discharge. Therefore, discharge through the irrigation system is the only option. Since no samples of either the raw influent or treated effluent are analyzed by a laboratory, there is no indication of treatment efficiency. In addition to reuse practices, water conservation such as 1.6-gallon toilets were installed in each of the condominium units.

INTERVIEW 3: SAPPHIRE VILLAGE CONDOMINIUMS

Overlooking St. John Bay on St. Thomas, this condominium complex has 135 studio apartments and 90 one-bedroom apartments, which are occupied by 70 permanent and approximately 145 temporary residents. Utilizing R/O technology due to lack of WAPA service in the area, the facility is permitted to treat and deliver an average of 8,000 gpd during peak season and 5,000 gpd during off-peak season.

The wastewater treatment facility is approximately 20 years old and currently utilizes secondary treatment processes without first going through primary treatment. After passing through secondary treatment, the wastewater is disinfected using chlorine tablets. Treated effluent is then stored in a 27,000-gallon cistern and used for irrigation. Because of the inefficient treatment scheme and clogging of sprinkler heads, the manager is working on improving the treatment process with the addition of minimal infrastructure.

A 24,000-gallon cistern is located underneath one of the condominium units. This L-shaped cistern is currently not being utilized and would be a convenient place for the raw sewage from the complex to collect and settle before being pumped up to the current secondary treatment tank. My recommendation is to utilize the 24,000 gallon cistern tank as a primary settling tank. Doing so will increase TSS and BOD removal as well as possibly decrease the amount of chlorine necessary to disinfect. I recommend that a lab analysis of the effluent from the current treatment scheme be performed as well as after the primary treatment process is put online in order to determine the efficiency and benefits of this process.

INTERVIEW 4: COMPASS POINT MARINA

Compass Point Marina, a complex consisting of a marina, commercial offices, restaurants, and apartments, is located near Benner Bay on St. Thomas. Compass Point also utilizes R/O technology to generate its drinking water. This facility is permitted for and produces approximately 2,500 gallons of drinking water per day by utilizing a seawater intake. The manager of Compass Point Marina would be very interested in connecting to a water main along route 30 to the Red Hook area if and when WAPA installs this line.

Wastewater at Compass Point Marina is treated at an on-site treatment plant that utilizes primary treatment. Raw sewage enters the treatment system into a 2,500-gallon tank and is then sent to one of two clarifying tanks that aerate the sewage. Treated water is then disinfected by chlorine tablets prior to being stored for use in irrigation and toilet flushing. Approximately 750 gpd is utilized for irrigation and 1000 gpd for toilet flushing since the marina does not have a permit to discharge treated effluent to the ocean. Unfortunately, no testing of effluent has been performed so no indication of treatment efficiency and effluent quality is known. Currently, this complex has not implemented water conservation practices.

INTERVIEW 5: POINT PLEASANT RESORT

Point Pleasant Resort is located in Smith Bay on the eastern end of St. Thomas. There are 125 permanent residents that utilize approximately 10,000 gpd of drinking water and send approximately 10,000 gpd to an on-site wastewater treatment plant. Drinking water is obtained by extracting brackish water from an on-site well and treated using R/O technology.

The wastewater treatment plant at Point Pleasant Resort was upgraded in 2001 with aeration and ultra-filtration membrane technology. As indicated by an increase in removal levels of TSS and BOD, this technology seems to be a good investment for the resort. The only problem to report is that the system can become fouled if the grease trap is not working properly. Once wastewater travels through the filtration system, it passes through an automated chlorine disinfection unit and then is stored in one of two 25,000 gallon cisterns. All treated grey water is used for irrigation and toilet flushing. Currently, no water conservation practices, other than reuse of wastewater effluent, or equipment have been put into place at this complex.

Interview 6: Coral World

Located on the point of Coki Bay in St. Thomas, Coral World is a well-known aquarium whose livelihood depends on the state of the environment. Coral World has a drinking water demand of 3,000 to 3,500 gpd and a large amount of waste to treat and dispose of. In order to meet drinking water demand, water is not only generated using the permitted R/O desalination plant, but rainwater cisterns and tanker trucks also provide water for the complex since Coral World's location prohibits the use of WAPA service. Unfortunately, the R/O facility is not obtaining the yield that is typical for the rest of the facilities on the island that were toured. Currently, the R/O plant produces 2 gallons per minute (gpm) of drinking water and 12 gpm of waste brine.

Along with drinking water, Coral World also must also treat its own wastewater. Traditional treatment processes consisting of extended aeration and chlorine disinfection are utilized. The wastewater treatment plant has a capacity of 20,000 gpd. Treated effluent is then stored in a 4,200-gallon holding tank before being used for irrigation around the park. Early in 2002, several ducks at the park showed signs of illness and eventually perished. In July, a sample of effluent was sent to the Ocean Systems Laboratory on St. Croix for analysis of TSS, BOD, and fecal coliforms. The analysis showed a very high fecal coliform level. The manager believes that the treated effluent/irrigation water was the most likely cause of the illness amongst the duck population at the park. Grey water is no longer used to irrigate around the duck pond but is still used for irrigation at other locations around the park and the disinfection unit was adjusted to add more chlorine to the primary effluent.

Coral World had problems with its irrigation system: disinfection of gray water as well as clogging of the irrigation system. After looking at the setup of the grey water irrigation system, I recommend that Coral World purchase and install a typical pool filter of the appropriate size similar to decrease the total suspended solids in the grey water prior to being sent through the irrigation system. In order to make sure that the grey water is being disinfected to the appropriate level, a litmus test to detect the total free chlorine in the system is recommended.

Reuse, Conservation, and Disposal Alternatives

Because the two large municipal wastewater plants, the St. Thomas Mangrove Lagoon Wastewater Treatment Plant (MLWWTP) and the St. Croix Wastewater Treatment Plant (SCWWTP), in the US Virgin Islands have not developed comprehensive reuse and conservation programs, preliminary plans and costs for eight potential reuse and conservation alternatives have been developed.

BASIS FOR COST ESTIMATING

In order to provide analysis of the various alternatives, the costs of standard activities for all projects were estimated. These costs are then used on a per-alternative basis. All total costs include a 25% factor to cover contingency, engineering, and startup. Table 18 summarizes the unit costs that will be used to evaluate each reuse alternative.

A unit cost for residential irrigation systems was determined using data given by Sheikh, Castle, Kasper and Roxon (2002). This unit cost includes materials, permit fees, installation, maintenance, and annual inspections. Using Engineering News Record (ENR) construction cost indexes of 6283 and 6627, a cost per typical residential irrigation system of $3375 in December 2000 was increased to $3560 in March 2003. Operation and maintenance cost were not included since individual residences are responsible for those costs.

A distribution network is needed to transport the reclaimed water to its intended use. The cost per foot of polyvinylchloride (PVC) pipe was determined using unit costs from the CostWorks © program developed by R.S. Means Company (2003). Unit costs include materials, labor, and equipment to install a distribution network in San Juan, Puerto Rico since cost information is not available for the US Virgin Islands. Annual operation and maintenance cost was estimated to be 10% of the construction cost. Excavation and backfilling of the ditches are not included in the unit cost per linear foot. Therefore, a unit cost of $37.20 per cubic yard of excavated soil was determined.

The EPA Manual for Constructed Wetlands Treatment of Municipal Wastewaters includes a case study of nine constructed wetland systems throughout the United States used to meet secondary effluent standards (USEPA, 2000a). The study examined both free water surface wetland (FWS) systems and vegetated submerged bed (VSB) systems. For the purpose of this study, FWS systems will be examined. Utilizing ENR indexes of 5854 and 6627, a unit construction cost of $52,700 per acre in August 1997 was increased to $59,650 per acre in March 2003. It was assumed that the US Virgin Islands Government already owns the land needed for each wetland system. Annual operation and maintenance cost will also be included using a factor of 7%.

There are currently many water and energy conservation vendors that supply products and information to promote conservation of water and energy resources. AM Conservation Group Inc. offers the E'Town Water Conservation Kit that includes a 2.5-gallons per minute (gpm) showerhead, 1.5-gpm bath aerator, toilet tummy, dye tablet and instructions (2003).

TABLE 15
REUSE, CONSERVATION, AND DISPOSAL COST ESTIMATING BASIS

ITEM	COST ($)	UNIT
Residential Irrigation System	3560.00	$/irrigation unit
Distribution Network Piping – 6 inch	14.35	$/foot
Distribution Network Piping – 8 inch	19.50	$/foot
Distribution Network Piping – 10 inch	23.00	$/foot
Distribution Network Piping – 12 inch	31.50	$/foot
Distribution Network Piping – 14 inch	39.50	$/foot
Distribution Network Piping – 16 inch	43.50	$/foot
Distribution Network Piping – 18 inch	55.50	$/foot
Distribution Network Piping – 24 inch	83.50	$/foot
Distribution Network Labor and Equipment	37.20	$/cubic yard
E’Town Water Conservation Kit	5.99	$/kit

REUSE, CONSERVATION, AND DISPOSAL ON ST. THOMAS

In August of 2002, construction of the MLWWTP was completed. Currently, the MLWWTP is operating in conjunction with a subset of the seven original wastewater treatment plants. As of January 2003, only 130,000 gpd is being treated by the MLWWTP plant, but the average flow is expected to reach 750,000 gpd by 2005 with a maximum flow of 1.25 million gallons per day (MGD) after all of the other treatment plants are taken off-line (DeRossett and Senn, 2003). A majority of secondary effluent from the MLWWTP is discharged into Stalley Bay with a small portion of the flow used for irrigation on the grounds of the treatment plant.

Three alternatives were examined for the MLWWTP. Combinations of irrigation to nearby residential customers and wetland augmentation reuse with and without conservation prove to be viable reuse options for the MLWWTP. Preliminary design options for residential irrigation and wetland augmentation were developed and are presented in the following paragraphs. Financial information for all alternatives is presented in Table 16.

Residential Irrigation

Many residential units are located near the MLWWTP. Through the use of a 7.5-minute series topographic map updated by the United States Geological Survey (USGS) in 1982 it was estimated that reclaimed water for irrigation could be provided to approximately 260 housing units along Route 30 with the installation of approximately 17,000 feet of piping.

A 1996 USGS report dealing with the use of reclaimed water for golf course irrigation in Florida, reported that 297 MGD were utilized to irrigate 65% of Florida’s 1448 golf courses (USGS, 1996). As a result, an average of 2303 gpd is used for irrigation. Using this irrigation rate and the approximate acres requiring irrigation from topographic maps, an estimated average of 200,000 gallons per day is required. For design purposes a peaking factor of three was used. A design flow of 595,000 gallons per day can be fed via one 8-inch PVC pipe.

Habitat Restoration Utilizing Wetlands

Based on the USEPA case study described previously and utilizing land owned by the Virgin Islands Government, wetlands can be constructed to supply additional treatment, provide a habitat for various plant and animal species, and provide an educational tool for St. Thomas residents and visitors. Using design principles and examples presented in Chapter 4 of the EPA Manual for Constructed Wetlands (USEPA, 2000a) and assuming the entire flow of 750,000 gallons per day flows through the wetland, 5 acres are needed.

Community-wide Conservation and Habitat Restoration

Distributing water conservation kits and information throughout the St. Thomas community could potentially reduce the amount of wastewater needing treatment by the MLWWTP. Utilizing the conservation estimates cited previously, a household could conserve approximately 35 gpd by implementing the kits distributed. Based on the 2000 US Census, an estimated 24,030 households on St. Thomas could receive water conservation kits (2002). The reduced wastewater flow from 13,748 households having connections to the municipal sewer system results in a flow of 269,000 gallons per day requiring treatment. Assuming that 100 percent of the flow is treated by the wetland, 1.75 acres are needed.

Reuse, Conservation, and Disposal on St. Croix

The SCWWTP discharges treated effluent via an ocean outfall. Since the early 1970's, primary treatment with chlorine disinfection has been utilized treating an average of 2.5 MGD. The current TPDES permit for this facility allows a maximum effluent discharge of 4 MGD. In the past, the St. Croix WWTP has had problems meeting their TPDES permit limits and was covered under a consent decree with the USEPA in 1984 that was also placed on the St. Thomas wastewater treatment plants. In January 2003, the St. Croix Department of Public Works published a Request for Proposals (RFP) for the design of secondary treatment facilities for the SCWWTP. As a result of this RFP and growing community awareness of water scarcity issues, a group called the Coalition for Comprehensive Development has been advocating reuse options (Glogger, 2003).

Five alternatives were examined for the SCWWTP. Preliminary design options these options are presented in the following paragraphs. Financial information is presented in Table 19.

Airport Irrigation

Due to the proximity of the St. Croix wastewater facility to the airport, reclaimed water could be distributed via a new distribution network for irrigation needs with little to no disruption to the surrounding businesses. Through the use of USGS 7.5-minute topographic maps (Topozone, 2003), it was determined that approximately 7.5 acres would require irrigation and 4800 feet of piping would be necessary to distribute irrigation water from the SCWWTP along Route 64 to the Airport main entrance. Using the irrigation rate used previously and the area requiring irrigation at the airport, an estimated 17,000 gpd is required. For design purposes a peaking factor of three was used. The peak flow rate of 51,000 gpd can be fed via 6-inch PVC pipe.

Commercial Irrigation and Industrial Process/Cooling Water

A local developer is looking to renovate the former ALCOA facility into an eco-industrial park that would include facilities for commercial, industrial, and retail clients as well as recreational parks and wetlands (York, 2003). Utilizing the same irrigation rate used previously and a rough estimate of the acres requiring irrigation at the new industrial area, the total flow needed was estimated as 276,000 gpd. Utilizing a peaking factor of three, irrigation flow can be transported to the site via one 10-inch diameter PVC pipe with approximately 2000 feet of new piping. Industrial tenants have not been identified as of January 2003. Therefore, water demand and required water quality are not known. Because of this, a cost estimate for this portion of the alternative was not developed.

Agricultural Irrigation

Approximately 700 acres of agricultural land is productive (James, 2003). According to the Virgin Islands Department of Agriculture, a new marketing campaign is being implemented to increase the amount of productive land used for agriculture. Based on a projected increase in demand and the fact that water is supplied to these areas via a combination of wells, ponds, and trucked water from WAPA, an alternative source of irrigation water may be supported by local advocacy groups such as the St. Croix Farmers in Action for economical reasons.

Based on GIS information (USVI CDC, 2001), it was estimated that approximately two-thirds of the 700 acres of productive agricultural land is both relatively close to the SCWWTP and grouped together. Using the previously mentioned irrigation rate, the average demand was estimated to be 1,080,000 gpd. Utilizing a peaking factor of two, the distribution system was designed to transport 2,160,000 gpd via 27,000 feet of 16-inch diameter PVC pipe.

Habitat Restoration Utilizing Wetlands

Utilizing a combination of land owned by the Virgin Islands Government, wetlands could be constructed to supply additional treatment, provide a habitat for various plant and animal species, and provide an educational tool for St. Croix residents and visitors. Currently, this alternative is being proposed by one group of engineers in answer to the January 2003 RFP administered by the US Virgin Islands DPW. Using design principles and examples presented Chapter 4 of the EPA Manual for Constructed Wetlands (USEPA, 2000a) and assuming the maximum design flow of 4 MGD flows through the wetland, 71 acres are needed.

Community-wide Conservation and Habitat Restoration

A water conservation program implemented throughout the St. Croix community involving the distribution of water conservation kits and information could potentially reduce the amount of wastewater needing treatment by the SCWWTP. Using the water savings described previously and the 2000 US Census information, an estimated 23,782 households on St. Croix would receive water conservation kits (2002). The reduced wastewater flow from 11,758 households having connections to the municipal sewer system results in a flow of 3,590,000 gallons per day requiring treatment. Using this flow, 65.5 acres are needed.

RECOMMENDED REUSE, CONSERVATION, AND DISPOSAL ALTERNATIVES

The previous paragraphs presented information leading to construction cost for each alternative. Table 19 summarizes those costs. Determining the net present cost of a project allows for a comparison of alternatives on a similar financial basis. The net present cost was calculated assuming a 3% discount rate over a 20-year useful life of the project. The total net present cost for a project equals the sum of the net present cost for each year (Brealey and Myers, 2000).

TABLE 16
SUMMARY OF ESTIMATED COST FOR REUSE PROJECTS IN THE US VIRGIN ISLANDS

Reuse Project	Total Construction Cost ($)	Annual Operating Cost ($)	Total Net Present Cost after 20 years ($)	$ per gallon of reused and conserved water
St. Thomas Residential Irrigation	1,860,000	186,000	4,573,000	23
St. Thomas Habitat Restoration	373,000	21,000	2,969,000	4
St. Thomas Conservation and Habitat Restoration	274,000	9,000	2,861,000	4
St. Croix Airport Irrigation	155,000	16,000	2,753,000	159
St. Croix Commercial Irrigation & Industrial Process Water	95,000	10,000	2,689,000	10
St. Croix Agriculture Irrigation	2,139,000	214,000	4,871,000	5
St. Croix Habitat Restoration	5,294,000	296,000	8,014,000	2
St. Croix Conservation and Habitat Restoration	5,027,000	274,000	7,733,000	2

USVI WATER RESOURCES CONCLUSIONS

The future of water resources in the US Virgin Islands lies in the implementation of innovative water resources management and planning. As has been discussed throughout the CRABS project and in more detail in individual theses, the combination and improvement of different augmentation strategies are possible in the islands. CRABS has developed ten recommendations for water resources strategies in the US Virgin Islands that are presented below.

1) Desalination plants by distillation should be gradually phased out as the only source of public water. The options that should be analyzed have been discussed in this report. Technologies such as reverse osmosis (RO) desalination and submarine piping should be considered as future options. These alternatives are preferred based on both cost analysis and sustainability considerations. Submarine piping from Puerto Rico can be combined with strategically distributed smaller RO plants, to achieve what has been postponed for many years in the islands, an equitable distribution of the available water resources.

2) The desalination industry is making progress toward sustainable operation. The new Caneel Bay plant, which represents the newest technological advances and incorporates the newest research, had the best score for each of the social, economic, and environmental indicators. For a few individual indicators other plants had similar sustainability scores, but when the scores for all five indicators were summed in the first sustainability assessment and when the scores for the fuel and cost indicators were summed in the second sustainability assessment, the new Cannel Bay plant clearly was operating at a more sustainable level. The fact that the newest desalination plant in operation in the U.S. Virgin Islands had the highest sustainability score is clear evidence that the treatment processes in the desalination industry are moving towards sustainable operation. Because of this trend in the U.S. Virgin Islands, in which processes are moving towards sustainable operation, this study can conclude that the desalination industry worldwide is moving towards sustainable operation. Due to decreasing costs and fuel consumption, desalination treatment processes are making less of a social, economical, and environmental impact on the ability of future generations to meet their own needs.

   Continued progress towards sustainability is 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 sustainable operation.

3) Despite St. John's significant solar resources and only fair wind resources, wind energy has been found the most promising renewable energy to move St. John's vapor compression desalination plant toward sustainability. Not only is the proposed wind energy design able to meet a greater proportion of the energy needs of desalination, but it also has a relatively low land area requirement, compared to solar thermal and even photovoltaics, and is available throughout the day for 24 hour/day desalination plant

operation. Furthermore, as it is a well established energy source, used in small scale by others on the islands, it is likely to be well accepted by WAPA officials as well.

4) Water reuse, conservation and disposal should be the other fundamental component of an integrated water resources innovative management and planning policy. CRABS presents an assessment of water reuse and conservation practices in the US Virgin Islands and identifies eight reuse alternatives that could be implemented by local municipalities. Out of those eight alternatives, habitat restoration on both St. Thomas and St. Croix, community-wide conservation and habitat restoration on both St. Thomas and St. Croix, and agricultural irrigation on St. Croix, are the most economical based on the normalized cost per gallon of reclaimed and conserved water. However, agricultural irrigation on St. Croix and community-wide conservation and habitat restoration on St. Thomas and St. Croix provide the most benefit to the community. Agricultural irrigation provides farmers a low-cost option to meet water demand and production requirements. Community-wide conservation and habitat restoration alternatives provide an educational environment and promote conservation practices thus reducing water consumption, water cost, and wastewater production.

5) From the assessment it is apparent that reclaiming wastewater effluent results in a reduction of nutrient-rich effluent discharged to the ocean, conservation of fresh-water sources, reduction of energy and pollution due to lower production needed by WAPA, and avoidance or delay in WAPA expansion to meet non-potable water needs. The next step before undertaking design of a reuse project is to incorporate several components prior to ensure success. Those components include:

   a) Public information and participation,
   b) Public health impact identification, and
   c) Local and federal government participation.

6) Another issue is the necessity to monitor the water quality of rainwater catchments (RWC) and groundwater sources. RWC and groundwater are fundamental sources of water in the islands and should be treated as other water supplies, investing in new technologies for proper conservation of the resource as well as its augmentation.

7) It is also fundamental that innovative technological change be backed with legal reforms that will enable water trading. These policies, combined with a higher level of interconnectivity, will enable the gradual development of a regional water market. Voluntary water transfers are a good response of the government's legal authority that and serve as a complementary mechanism of water augmentation and demand–management policies. If properly implemented from both the operational and water use regulation perspectives, water trading can bring greater economic efficiency to the market. Water transfers represent an efficient economic alternative in response to the combination of increasing water demands, environmental concerns, and exhaustion of the most economic water sources over the last several decades (Mays, 2002).

8) By applying in whole or in part the technologies and guidelines of CRABS recommended by CRABS, funds will be saved as the result of more cost effective alternatives. In turn, these funds should be applied to expand the public system. This can result in a positive

cyclical pattern. Incorporating 54% (in the case of St. Thomas) of the population to the system will increase in time the revenues generated by the water sector and will result in a benefit to the community. This cycle will make more funds available over time, which can be applied in turn to face the future challenges of the water resources sector.

9) Interconnectivity within and between islands for allocating water from different sources should be encouraged. In addition, the interconnection between islands has the advantage of expanding the economy of scale of a reduced island market, which will generate the beneficial economic effect of market expansion. Another strong reason for interconnection of available regional resources has to do with the pattern of occurrence of extreme events like hurricanes. Hurricanes take different paths in different years, and do does not always hit twice in the same island. In the event of a given hurricane that affects any of the interconnected islands, the rest of them that have not suffered the hurricane's full rigor will be readily able to supply water until damages can be corrected.

10) Water scarcity is not only the result of climatic and geographical conditions, but it also depends on adequate management and planning of the present and future resources. The inventory of the available water resources mentioned throughout this work in addition to an adequate conjunctive use strategy and a planned augmentation of sources will make water scarcity past history.

IV. St. John Salt Pond Water Quality

The climate of St. John is classified as subtropical with the winters being mild and dry, and summers warm and humid. Precipitation increases with altitude due to the moist air being forced up the slopes into the cooler air of the higher altitudes. Since the mountains are not very high as compared to other larger Caribbean islands, most of the precipitation falls in the Caribbean Sea. Annual rainfall ranges from 40 to 60 inches (Colon-Dieppa et al., 1989). February or March are the driest months and September, October, or November are the wettest (see Figure 11 below). High evapotranspiration rates reduce the quantity of surface water available (Jordan and Cosner, 1973).

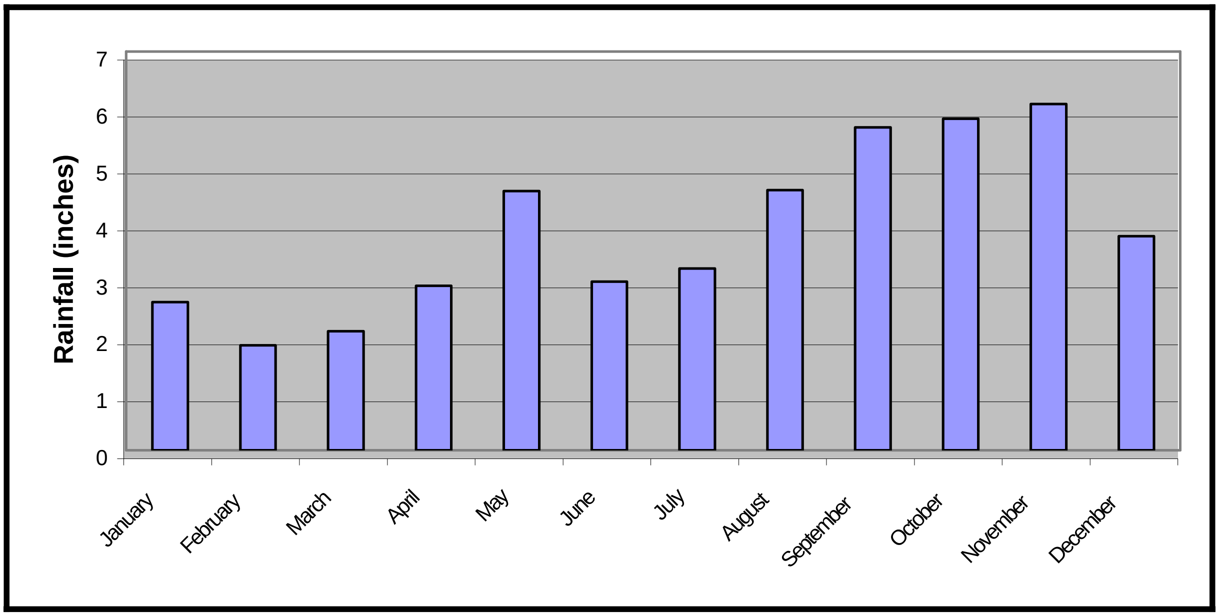

Figure 10
Average Annual Rainfall for St. John, USVI
Soil Survey of the United States Virgin Islands (USDA, 1998)

The islands are composed of volcanic rock and have steep slopes and irregular coastlines. Groundwater on the islands is scarce. Surface runoff and groundwater recharge are low due to high rates of evapotranspiration. Runoff ranges from 2 to 8 percent of annual rainfall (Santiago-Rivera and Colon-Dieppa, 1986).

Formed by the gradual closing of sheltered bays as neighboring reefs grow upwards and create a berm, salt ponds are eventually closed off from the neighboring seawater. While exceptions do exist in the USVI (as some ponds have been opened to the ocean to allow for intertidal flushing), the hydrology of salt ponds is dominated by inflows from groundwater seepage, surface runoff, coastal wave overwash, and precipitation, and outflows from evapotranspiration and groundwater seepage.

Salt ponds serve several valuable ecological functions in the USVI, two of which are especially relevant to this report. First, salt ponds serve as a habitat for many indigenous as well as migratory species, some of which are endangered or threatened under the classifications developed in the Endangered Species Act (ESA). Second, salt ponds act as a buffer between areas of human development and the sensitive reef ecosystems, as sediment and pollution carried by groundwater flow and surface runoff is filtered by salt ponds before they reach the reefs.

As human development increases in the USVI, protection of salt ponds is becoming a major concern. Due to their proximity to beaches, many salt ponds have been destroyed for the construction of beachfront property or marinas. Population growth has not been accompanied by improvements in the sewage infrastructure, so salt ponds are bearing a greater nutrient load from the greater number of septic tanks in use. In addition, increases in deforestation and the use of unpaved roads are leading to heightened erosion, which results in sedimentation in salt ponds.

In order to understand how human development is affecting salt ponds, CRABS focused on three specific areas of investigation. First, we attempted to develop a hydrologic model to characterize the inputs to salt ponds. Second, we analyzed the water quality of salt ponds with respect to nutrients and sedimentation to quantify human impact. Third, we analyzed salt pond ecology to determine how this impact is affecting the ecosystems of the ponds.

WATER QUALITY ANALYSIS

As mentioned above, salt ponds on St. John are experiencing increased threats as human development expands on the island without adequate infrastructure upgrades. The most direct and pervasive threat is, of course, deliberate destruction. Many salt ponds have been opened to the sea, made into marinas, or deliberately filled in order to meet the demands of an expanding population. Specifically, residents have complained about the smell of salt ponds, their indirect roles as waste disposal sites, and the desire to create space, both on land and at sea, for development of the island. However, the increase in development may also have a significant, though less intentional, impact on the chemistry of salt ponds. The two primary threats to salt pond chemistry are nutrient loading and excess sedimentation.

Nutrient loading occurs when groundwater or surface runoff passes through an area where septic tanks are used and carries with it compounds that have diffused away from the tank. This leads to nitrogen and phosphorus enriched water flowing down the hydraulic gradient, and eventually entering salt ponds. While these nutrients are necessary for life in water bodies, when excess nutrients enter the water, algal growth is stimulated, leading to a process known as eutrophication. Eutrophication has two notably deleterious effects on pond life. First, algal mats that may develop can block sunlight from entering the pond and being used photosynthetically by other plants. Second, eutrophication results in oxygen depletion in water, which can kill fish or other species that need dissolved oxygen to survive. As septic tanks are the primary source of sewage treatment on St. John, and since their usage is increasing as the population of St. John continues to grow without significant developments in infrastructure, the problem of nutrient loading may escalate. In addition, the geology of St. John renders traditional septic tank technology less efficient. As topsoil is rarely greater than two feet deep, and in some places not present, leach fields are often impossible to implement as part of sewage treatment.

Sedimentation is also increasing on St. John due to increased population and little concern for erosion control. As more unpaved roads are built, more trees are cut down, and more people walk around, erosion occurs at a greater rate. This erosion results in high levels of sediments being carried by surface water runoff, which can eventually end up in coastal waters such as salt ponds. Sedimentation can also impact photosynthetic plant life, as sediment particles can lead to light scattering in water. In extreme cases, a condition known as siltation may occur. Common in coral reefs, siltation results in a plant species being covered in sediments and thus starved of light and oxygen. In addition, sedimentation rates may play a role in the decomposition of dead plant life.

A common tool used by engineers to understand the processes that lead to sedimentation is hydrologic modeling. Hydrologic models are tools used, among other things, to predict the rate and volume of runoff that will occur under a given set of conditions. These conditions include rainfall, soil types, coverage types, slope of land, and watershed area. In this project, hydrologic models were used to determine the inflows to the pond by overland flow from rainfall runoff. It was theorized prior to arrival on St. John that a correlation existed between the characteristics of runoff and the general health of the pond.

The purpose of this study was to assess the impact of human development on salt ponds by investigating the relationships between the chemistry of salt ponds and the hydrology of the surrounding area. Therefore, aspects of pond health such as nutrient levels, sedimentation parameters, and water quality indicators were analyzed in conjunction with development metrics, watershed descriptions, and runoff characteristics. In addition, the feasibility of groundwater seepage measurement was investigated, as this seepage could play a key role in determining the role that human development may play in salt pond chemistry.

PROJECT METHODS

WATERSHED MODELING

A GIS dataset for the island of St. John, which provided a background for the hydrologic analysis of St. John, was collected. It includes a soil survey, hydrologic unit code (HUC) 14 watershed boundaries, subwatershed boundaries of the HUC 14 watersheds, and an aerial photograph of St. John. Following the assembly of the GIS dataset, hydrologic watershed modeling was implemented to determine the watersheds tributary to the ponds being studied. Several methods were used to determine the size of the watersheds hydrologically connected to each pond. First, the watershed tool imbedded in the Spatial Analyst extension of ArcView 3.2 software was used. Second, since some of the smaller ponds are actually smaller than the 30-meter cell size of the DEM, the watershed tool could not be used. For these ponds, ArcView drawing tools were used to virtually trace the watershed boundaries and measure the traced area. Finally, some areas were measured using a planimeter, a drafting instrument used to measure the area of a graphically represented planar region.

The calculations performed by HydroCAD were the primary descriptor of runoff used in this study, and provided valuable information regarding the relationships between nutrient loading, sedimentation, and runoff. These calculations used inputs of watershed area, soil type, coverage type, and curve number to generate outputs describing the rate and volume of runoff. Detailed information regarding the HydroCAD inputs (watershed areas and soil descriptions) for the HydroCAD implementation is presented in Rose and Bossi (2003).

ANALYSIS OF AMBIENT CONCENTRATIONS OF NUTRIENT LEVELS

As the equipment and chemicals used in this study had to be transported on passenger aircraft, the resources available to CRABS determined that the following nutrients could be analyzed in samples taken from salt ponds: nitrate [NO_3^-], nitrite [NO_2^-], ammonia [NH_4^+], and reactive phosphate [PO_4^-], which is also known as orthophosphate. These compounds represent the inorganic nutrients which are available for consumption by biological processes. All four of these nutrients were analyzed using a Hach DR2010 Portable Spectrophotometer and the Hach reagents appropriate for each parameter.

Water samples were collected from salt ponds and kept on ice pending analysis. Pursuant to the protocol suggested by Hach, all samples were allowed to return to room temperature before reaction with Hach reagents. All samples were filtered to remove particles which may have scattered light, thus interfering with the constant absorption path length necessary to obtain consistent results. In addition, all samples were diluted to 35‰ salinity to mitigate the effects of salt interference. All calibration curves were also established for this salinity level.

ANALYSIS OF SEDIMENTATION CHARACTERISTICS

The two primary characteristics associated with sedimentation are turbidity and total suspended solids (TSS). Turbidity is a parameter used to describe the level of light scattering that results from particles suspended in the water. Scattering results in a lower portion of the incident light being able to penetrate to the deeper portions of a body of water, and high levels of turbidity are associated with poor pond health. Measurement of turbidity levels was performed on site at each salt pond studied by means of a Hach Turbidimeter, an instrument that shines light at a known wavelength through a sample cell of known length and measures the incident and resultant strength of the light beam to determine how much has been scattered.

Total suspended solids reflect the amount of suspended particles in a given volume of water. By using a Millipore filtration device, a known volume of water collected from each salt pond was filtered through pre-tared (pre-weighed) filters, thus trapping all solids present in the water. The filters were then dried overnight in an oven, allowed to cool in a dessicator, and then weighed. The difference in mass before and after filtration, when combined with the volume of water filtered, yields the concentration of suspended solids.

ANALYSIS OF CHEMICAL HEALTH INDICATORS

The appropriate indicators for judging the chemical health of salt ponds were determined to be temperature, salinity, dissolved oxygen, and pH, which are important indicators for pond health for the following reasons:

- Temperature – Biological activity and growth are extremely dependent on temperature, as are aquatic chemical processes. As temperature increases, water becomes saturated with oxygen at a lower concentration, which may be insufficient to sustain life.

- Salinity – The speciation of the ecosystems present in salt ponds is highly dependent on salinity. Salinity shows a high degree of natural variation, as the salt concentration is dependent on evaporation and precipitation.
- Dissolved Oxygen – The organisms present in salt ponds depend on the oxygen that is dissolved in the water surrounding them. The concentration of dissolved oxygen is also susceptible to human activity by a number of mechanisms. Especially relevant in the salt ponds of St. John are inputs of nutrients, which lead to increased biological growth and oxygen consumption, and the deposition of organic matter such as tree leaves which, when decomposing, take up oxygen.
- pH – While extreme levels of pH will obviously render life difficult for the ecosystems of salt ponds, minor fluctuations can also impact the aquatic chemical processes occurring. For example, the form that nutrients take upon entering a pond and their subsequent availability for life is highly dependent on the pH of the pond water.

These parameters were measured using a submersible YSI-600XLM sonde with a digital display. Due to the threshold of 85‰ salinity associated with the YSI equipment, salinity readings for ponds with salinity levels greater than 85‰ were also taken using a handheld refractometer.

Feasibility of Groundwater Measurement and Collection Methods

Two methods of measuring and collecting groundwater flow were evaluated to determine their applicability for larger scale experiments on St. John. Seepage meters were deployed in Southside Pond and functioned well, but were unable to be used in any other pond due to incompatible sediment conditions. Piezometers were also used at Southside Pond, but issues arose quickly due to the soil conditions and the lack of well development equipment.

Results

The initial proposal of extensively sampling two to four ponds at extreme ranges of development was expanded to include ten ponds of varying development levels. Sampling for temperature, salinity, pH, DO, turbidity, TSS, and nitrates was carried out at all ponds. Initially, levels of nitrite and ammonia were also measured, but analysis of these nutrients consistently resulted in levels lower than the tolerances associated with the tests. Hence, sampling for nitrite and ammonia was discontinued, and testing for phosphates was added as the study proceeded. In addition, GIS and HydroCAD models were developed for the watersheds surrounding each of the ponds sampled.

In order to quantify the level of development surrounding each pond, a development matrix was created by visually surveying the area near the pond and determining its relative development in the following areas:

- Number of surrounding houses
- Proximity of surrounding houses
- Slope of surrounding land
- Predominant sewage treatment methods
- Number of surrounding roads and paths
- Proximity of surrounding roads and paths
- Condition of roads and paths (dirt or paved)

- Presence of agriculture or livestock

The ten ponds sampled represent a range of development, from the pristine pond adjoining Hanson Bay to Frank Bay pond in the heavily developed Cruz Bay area.

The data collected from sampling salt pond water were combined with the outputs of the hydrologic modeling (which included runoff characteristics and watershed descriptions) and of the development matrix. Multivariate regressions were run on this data set to find the relationships between the chemistry of salt ponds and the hydrology of the surrounding area. The data set can is presented in Table 17.

TABLE 17
CHEMICAL DATA ANALYSIS

Pond Name	Temp [deg C]	Salinity [ppt]	DO [%]	DO [mg/L]	pH	Turbidity [NTU]	TSS [mg/L]	Nitrate as N [mg/L]	Phosphate as P [mg/L]
Frank Bay	27.48	61.80	100.60	5.66	8.23	9.12	0.00013	1.2	
Frank Bay	28.19	69.14	102.70	5.45	8.35		0.00016	2.0	
Frank Bay	27.70	68.87	91.00	4.87	8.34	7.77		1.8	
Choc. Hole E.	28.90	33.63	62.80	4.00	8.06	10.40	0.00013	1.2	
Choc. Hole E.	28.58	33.62	58.70	3.77	8.07	8.69		1.4	
Choc. Hole E.	28.49	33.50	59.60	3.83	8.23		0.00008	1.4	
Choc. Hole W.	36.20	75.60	172.00	7.80	8.39	4.50	0.00010	2.9	
Choc. Hole W.	33.70	66.90	99.70	4.95	8.25	5.22	0.00004	2.1	
Choc. Hole W.	31.90	65.90	56.60	2.96	8.18			2.9	
Popilleau Bay	31.10	42.10	131.80	7.78	8.66	12.00	0.00007	1.3	
Popilleau Bay	29.10	30.90	87.40	5.55	8.64	14.83	0.00009	0.7	
Elk Bay	29.85	58.42	97.90	5.41	8.27	13.50	0.00012	1.4	
Elk Bay	29.21	58.85	82.70	4.60	8.22	16.00	0.00011	1.9	
Elk Bay	29.25	57.82	79.90	4.60	8.22	14.70	0.00013	2.2	
Elk Bay	29.83	59.07	75.90	4.16	8.12			2.6	
Frank Bay	26.89	72.64	40.10	2.13	8.37	10.30	0.00011	1.8	
Frank Bay	27.50	73.00	47.90	2.57	8.48	6.56	0.00011	2.2	
Frank Bay	29.20	75.60	64.20	3.26	8.66	5.35	0.00021	2.2	
Hanson Bay	31.25	30.15	54.60	3.48	8.12		0.00009	1.1	
Hanson Bay	31.06	31.16	51.00	3.20	8.09	40.50		0.0	
Hanson Bay	30.98	31.70	51.20	3.18	8.09	63.50	0.00022	0.9	
Friis Bay	25.65	70.00	45.50	3.67	8.96		0.00014	2.6	
Friis Bay	25.85	59.01	35.00	2.02	8.88	5.39	0.00017	2.2	
Friis Bay	25.95	59.91	35.90	2.07	9.01	6.54	0.00012	2.4	
Salt Pond	31.49	254.55	66.00	2.00	7.67	3.07	0.00050	13.5	
Salt Pond	30.88	262.50	42.20	1.51	7.68	1.96	0.00019	7.7	
Salt Pond	30.96	268.33	42.90	1.56	7.68	2.72	0.00049	9.2	

TABLE 18
CHEMICAL DATA ANALYSIS CONTINUED

Southside	27.30	105.00	60.90	2.78	8.21	1.59	0.00021	3.0	0.12
Southside	27.22	105.00	42.30	1.94	8.19	1.07	0.00022	3.6	0.93
Southside	27.18	105.00	35.40	1.63	8.20	0.79	0.00023	3.9	4.65
Southside	27.20	105.00	29.40	1.35	8.21		0.00017	3.9	0.33
Southside	27.27	105.00	28.70	1.31	8.22		0.00020	3.0	0.48
Southside	27.24	105.00	29.30	1.34	8.22		0.00016	3.9	0.06
Southside	27.66	105.00	41.60	1.90	8.18	1.93	0.00019	4.5	0.06
Southside	27.37	105.00	37.40	1.71	8.18	1.03	0.00012	3.9	0.12
Southside	27.70	105.00	38.00	1.74	8.19	1.00	0.00020	5.1	0.03
Southside	28.54	105.00	40.30	1.82	8.18	8.18	0.00019	3.6	
Southside	28.40	105.00	41.00	1.85	8.17	8.17	0.00021	3.9	0.15
Southside	28.60	105.00	54.20	2.40	8.18	8.18	0.00019	4.5	0.81
Frank Bay	26.92	76.34	40.10	2.09	8.55	8.78	0.00011	3.3	0.3
Frank Bay	26.73	76.50	69.30	3.61	8.56	8.76	0.00011	3.3	0.625
Frank Bay	26.35	75.31	57.10	3.04	8.45	10.40	0.00010	3.8	0.275
Salt Pond	26.55	175.00	50.30	1.73	7.68		0.00051	7.0	0.2
Salt Pond	26.29	210.00	32.00	1.12	7.65		0.00063	9.0	3.18
Salt Pond 2	24.93	60.56	57.30	3.35	8.85		0.00020	2.4	0.256
Salt Pond 2	24.48	59.38	50.10	2.97	8.81		0.00023	1.6	0.8

Little correlation was seen between nutrient levels and any aspect of development or runoff. However, a significant correlation was found to exist between nitrate levels and salinity, as seen in the Figure 11.

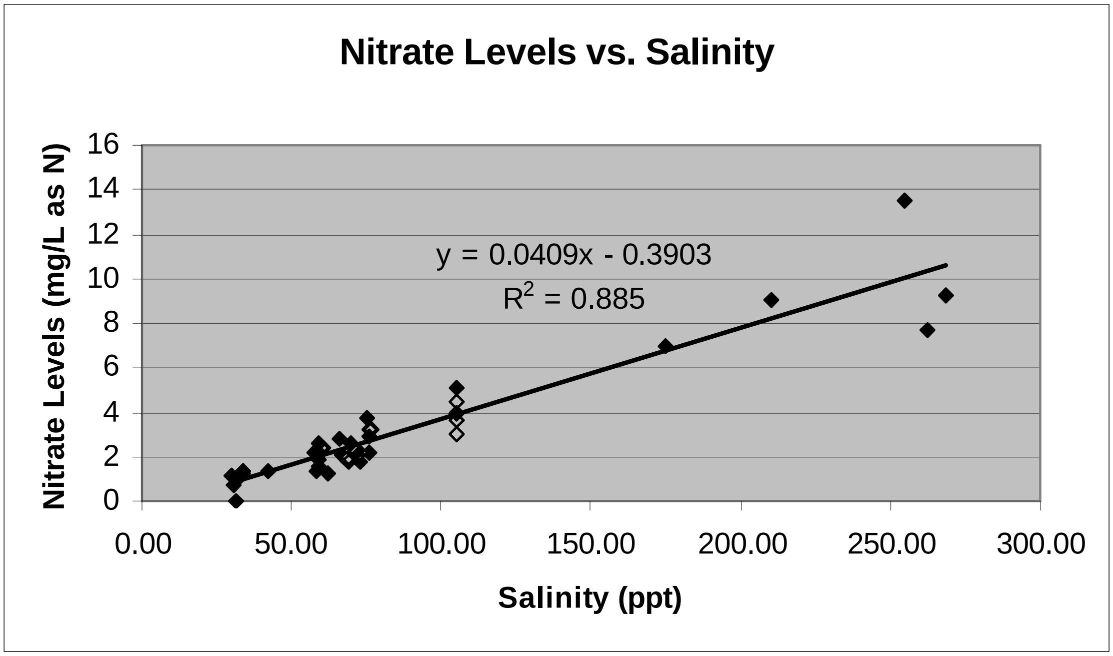

FIGURE 11
SALINITY VS. NITRATE LEVEL

The linear relationship between nitrate and salinity levels suggests that concentration by evaporation is the main mechanism leading to elevated nutrient concentrations. In order to verify this suggestion, a plot was constructed by calculating the nitrate concentration that would result from evaporation. Chocolate Hole East, which is a pond that has been opened to the surrounding bay to allow for flushing, showed salinity readings (average 33.58‰) which were extremely close to the surrounding bay water (34.52‰). The close salinity values suggest that the bay water has thoroughly mixed into the pond. If the average nitrate concentration in the pond is assumed to be the same as that in the bay, the same evaporation calculations can be run to generate a range of nitrate concentrations at differing salinities corresponding to those that would be found if evaporation took place. These calculations were performed, and a graph was generated. Figure 12 shows that the measured values of nitrate correspond very closely with those values expected at varying salinity levels, as their slopes only differ by 0.001. Despite this minimal difference, the deviations from expected values were still analyzed to search for possible relationships with development. No significant correlations were found, as all regression runs resulted in F-tests and R^2 values that were insignificant. The results of all regressions run with Stata are provided by Bossi and Rose (2003).

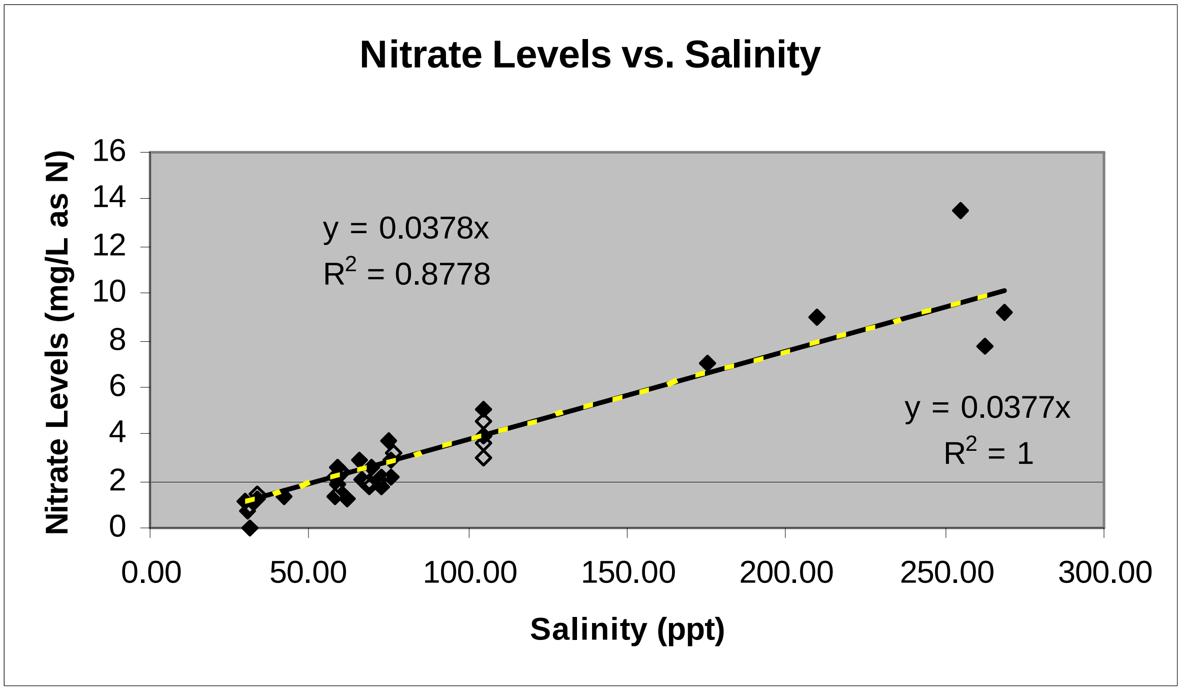

FIGURE 12
DEVIATION OF NITRATE LEVELS FROM EXPECTED EVAPORATIVE VALUES AS CALCULATED FROM CHOCOLATE HOLE EAST NITRATE CONCENTRATIONS
(Solid line represents measured values; dashed line represents calculated values; trendlines forced through origin.)

The groundwater measurement feasibility study also produced interesting results. Results were obtained from the seepage meter implementation at two separate locations in Southside Pond. The location for January 14th and 15th was on the far end of the pond from the berm (see Figure 13). The slope of the land near this deployment location was less steep than the other sides (excluding the berm), but grew steeper near the northern side of the deployment. At this location, a pattern of groundwater flow was seen. While almost all of the meters at this location lost water from their bags, a behavior known as downwelling, those closest to the steeper northern slope showed higher rates of downwelling. The location for January 16th and 17th (see Figure X) in contrast, showed more consistent evidence of flow into the seepage meter bags, otherwise known as upwelling. Downwelling did occur in those meters furthest from the berm, but it appeared that there was a hinge point around the third column. Thus, the closer to the berm, the greater the upwelling of the seepage meter (see Bossi and Rose (2003) for further analysis).

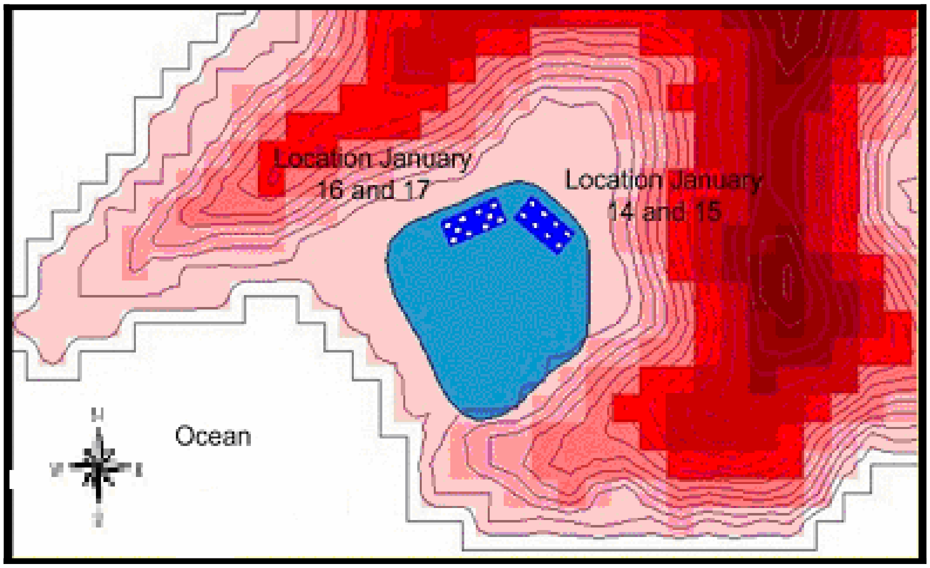

FIGURE 13
SOUTHSIDE POND SEEPAGE METER DEPLOYMENT MAP

RECOMMENDATIONS & AREAS FOR FURTHER RESEARCH

Several recommendations can be made that would improve the conclusions reached in this study. The first is an improvement in the development matrix to more accurately quantify the level of development surrounding each pond. While a cursory inspection was able to estimate the number of homes and their apparent sewage treatment methods, a more rigorous examination could determine which homes are hydrologically connected to the salt ponds. In addition, a survey could be made to determine the actual treatment methods in place and a better sense of the seasonal variations, if any, exist in the activity around each pond.

In addition, coordination with other scientific bodies interested in researching salt ponds could improve the difficulties faced with inadequate resources. Specifically, the chemicals and apparatus needed to analyze the levels of total nitrogen and total phosphorus could significantly advance the understanding of nutrient inputs to salt ponds.

A lack of confidence exists in those measurements taken with the YSI in ponds with salinities higher than 85‰. Other methods of measuring dissolved oxygen and pH should be implemented in these ponds. Similarly, the high levels of salinity encountered resulted in corrosion of the packaging of the TSS filters, resulting in a lack of confidence. Employing other methods of packaging or transportation, or finding the laboratory equipment necessary to analyze the samples on site, would result in higher levels of confidence.

ECOLOGICAL ANALYSIS

OVERVIEW

As previously discussed, salt ponds serve several valuable ecological functions in the United States Virgin Islands (USVI), although they have traditionally been undervalued and poorly understood. Although species diversity may be lower than in other systems (Montgomery, 1966), salt ponds are some of the most biologically productive ecosystems in the world. So far, however, only preliminary research has been performed to document ecosystems living in and depending on USVI salt ponds.

Salt ponds are considered "unfriendly" places to live because their ambient conditions can change drastically in short periods of time. Although they are quite important in the ecosystem, it is extremely difficult to live permanently in a salt pond because of the large range and sometimes rapid changeability of the conditions. Because of the difficulty associated with surviving in the variability of salt ponds, only the hardiest species are able to live there. The organisms that are able to survive in the ponds are various species of macroinvertebrates, bacteria, and phytoplankton (Maho, undated).

Four types of mangroves exist on St. John and were identified during this study. "Mangrove" is a term used to characterize a group of water- and salt-tolerant plants typically found in warmer climates (Burke, 2001). Over 50% of all mangroves in the USVI have been destroyed due to anthropogenic and natural sources (particularly hurricanes) in the last 50 years. Due to their thick and complex root networks, mangroves are believed to provide highly effective sediment filtration for runoff that would otherwise adversely affect the marine environment. These root networks also serve to prevent bank erosion of the ponds and shore erosion where the trees are found on the seashore. Mangroves are particularly susceptible to damage via trampling and branch breaking, as well as anchoring practices, ropes, or other gear. Therefore, mangrove population characteristics may signal magnitude and types of disturbances at the ponds.

The purpose of this project is to gather and analyze information on salt ponds to allow informed decisions on how to understand and treat them over time. This objective breaks down into three important pieces.

1. Provide a preliminary snapshot of the permanent ecosystem in the salt ponds

Because of the current lack of knowledge about what organisms live in the ponds, sampling was performed to determine characteristics of each pond. Quantitative measurements included (among others) macroinvertebrate identification, chlorophyll levels, housing density, salinity, nitrates, dissolved oxygen, temperature, berm characteristics, and pH. Qualitative measurements included (among others) fringing mangrove community characteristics, sediment descriptions, conversations with landowners, and items of interest specific to each pond. This information is meant to create a baseline for decision making, as well as to provide a basis for additional research and monitoring of salt ponds.

2. Recommend a range of indicators to determine the water quality of a salt pond

Although salt ponds on St. John demonstrate a wide range of conditions both compared to each other and over time, relationships between different variables are evident and are analyzed in this study. The water quality of a pond may be determined using a subset of these indicators, and management strategies can then be implemented for each individual pond.

3. Suggest areas for further research

After the establishment of baseline data on the salt ponds, additional research areas are suggested to further knowledge of the ponds. Additional field research and ongoing monitoring can refine the pond characteristics and quality indicators to improve long-term oversight strategies.

RESULTS

A summary of all measurements taken can be found in Table 19.

MANGROVES

Mangroves were discovered at all except one pond in the study (93%). Red mangroves were observed at three ponds (20%), black mangroves at three ponds (20%), white mangroves at eight ponds (53%), and gray mangroves at nine ponds (60%). The four species were found co-existing at only one of the ponds observed (Elk Bay East Pond). Mangrove occurrences as related to pond salinity levels were consistent with the literature (Nellis, 1994). In general, red mangroves were found at lower salinity ranges (31-63‰), black mangroves at slightly higher ranges (59-69‰), and gray (45-262‰) and white (59-136‰) mangroves had large ranges reaching higher salinities.

SALINITY

For the fifteen ponds sampled, salinity ranged from more than 8 times that of seawater (262‰) to slightly below that of seawater (31‰) with an average of 93‰.

HOUSING DENSITY

Housing density data varied from zero houses per square kilometer in more remote sections of the island to just over 400 houses per square kilometer in the most densely populated areas. The wide range of values indicates a range of pond conditions from pristine to strongly influenced by human development. Higher housing density probably indicates more runoff into the pond due to construction and traffic, and may also indicate increased nutrient influx from residential septic systems.

NITRATE LEVELS

In this study nitrate as nitrogen was measured for eight ponds. “Nitrogen compounds enter the environment as nitrates or are converted to nitrates. The nitrates come from many sources including agriculture, fertilizers, sewage, and drainage from livestock” (Coulston and Mussington, 1987). Elevated nitrogen levels often signal current or impending algal blooms in a body of water, which may be harmful for other pond inhabitants.

DISSOLVED OXYGEN

Oxygen in the water enables oxygen-dependant organisms to live in it. EPA states “waters classified for the protection of fish and wildlife must contain sufficient dissolved oxygen to support aquatic life” (EPA, 1988). Dissolved oxygen levels fluctuate over the course of the day as well as seasonally, but very low levels of dissolved oxygen in a pond indicate ecological problems. According to EPA, invertebrates experience some production impairment at levels of

5 mg/L, and reach an acute mortality limit at 4 mg/L (EPA, 1999). The average level of dissolved oxygen measured in the ponds is 3.95 mg/L.

TABLE 19
SUMMARY OF POND MEASUREMENTS

		Mangrove Species Percent					Percent of Cover														
Pond Number	Pond Name	Red	Black	White	Gray	Cover	Mangroves	Other Species	Unvegetated	Berm Height (m)	Land Use Value	Boundary width	Bank Erosion	Water Depth (ft)	Temperature (Degrees C)	Dissolved Oxygen (mg/L)	pH	Turbidity (NTU)	Salinity (ppt)	Chlorophyll a (ug/L)	Species Richness
14	Frank Bay Pond	0	0	85	15	75	30	45	25	1	402	>10 m	5	3	27.79	5.33	8.31	8.45	67	2300	6
5	Chocolate Hole W	0	50	10	40	95	85	10	5	2.5	215	>10 m	5	4	33.93	5.24	8.27	9.55	69	6800	3
7	Elk Bay East	50	5	30	15	70	70	0	30	1	0	>10m	0	1	29.54	4.69	7.27	14.43	59	12000	0
27	Popilleau Bay	0	0	0	0	0	0	60	40	2	35	1 m	20	0.5	30.10	6.67	8.65	13.70	37	4000	0
13	Francis Bay	0	0	100	0	100	100	0	0	1.5	21	>10m	0	0.5					136	43000	6
34	Hanson Bay	100	0	0	0	0	100	0	0	3	54	>10,	0	1	31.10	3.29	8.10	52.00	31	5800	0
19	Kiddel Point	0	0	0	100	95	90	5	5	3.5	40	>10m	20	1					120	3100	6
20	Lagoon Point	0	100	0	0	100	90	10	0		76	>10m	15	2					66	12600	5
15	Friis Bay	25	0	75	0	50	35	15	50	3.5	106	>10m	0	2	25.82	2.59	8.95	5.97	63	3600	5
30	Salt Pond	0	0	0	2	0	0	67	33	4	0	>10m	0	3	31.11	1.69	7.68	2.58	262	430	2
18	Hart Bay	0	0	50	50	100	65	35	0	5.5	40	>10m	0	0.5					192	2600	0
11	Europa Bay	0	0	100	0	100	30	70	0	2.5	0	>10m	0	4.5					90	500	0
32	Southside Pond	0	0	0	100	25	5	20	75	1	5	>10m	35	15	27.23	2.12	8.20	1.15	105	50	3
28	Privateer Bay	0	0	0	100	75	70	5	25	2.5	0	6 m	30	1					45	14000	6
6	Drunk Bay	0	0	50	50	95	70	25	5	1	0	>10m	0	1.5					60	8100	4

MULTIVARIATE REGRESSION RESULTS

Multivariate regression analysis determines the strength of correlation among an independent variable and one or more dependent variables. This analysis was performed on an iterative basis in Microsoft Excel until all dependent variable p-values are less than 0.05, indicating a confidence level of greater than or equal to 95% that the variables are correlated. Multivariate regression results are presented for species richness, chlorophyll a, and dissolved oxygen.

SPECIES RICHNESS

In the multivariate regression analysis of species richness, the most significantly correlated factors were berm height, temperature, pH, dissolved oxygen, and nitrate levels.

Species Richness = 0.70*Berm Height (m) – 0.60*Temperature (°C) – 1.66*pH + 0.94*Dissolved Oxygen (mg/L) – 0.19*Nitrate (mg/L as N) + 30.98

$$R^2 = 0.9944$$

With p-values of:

Variable	P-value
Berm Height (m)	0.0081
Temperature (Degrees C)	0.0020
pH	0.0057
Dissolved oxygen (mg/L)	0.0021
Nitrate (mg/L as N)	0.0127

Berm height may be an indicator for the age of the pond. Since salt ponds are born as bays that close over because of coral growth, a higher berm probably indicates the maturity of a pond. Ponds that have been well established are also expected to have a well-developed ecosystem due to lessened variability of pond conditions. Newer ponds may be subject to more ocean influence and their ecosystems may be in the process of evolving from the original to a more sustainable one.

Temperature and pH are also indicators of the health of a pond, although these factors do not vary widely amongst the ponds measured. Variability of these two factors should be assessed during ongoing pond monitoring to determine whether fluctuations in temperature or pH are something to be concerned about as opposed to “normal” seasonal fluctuations.

It is no surprise that dissolved oxygen is so closely related to species richness because of the ecosystem’s dependence on oxygen. The solubility of oxygen in water decreases as temperature and salinity increase, which affects DO levels in ponds on St. John. Many of the types of invertebrates found in the ponds are able to sustain periods of depleted oxygen by forming protective barriers or modifying other activities, so ponds with lower oxygen levels would likely be capable of sustaining larger communities if the DO levels were allowed to increase (Guenther, undated).

Elevated nitrates are usually considered to be indicative of current or future problems with macroinvertebrate populations. Algal blooms may be caused by an overabundance of nitrates; when this occurs, the algae eventually blocks the light and chokes the pond, subsequently dying and decaying which leads to hypoxic conditions (Thomann and Mueller, 1987). Even if the nitrates are not leading to these eutrophic conditions, they indicate an external source of nutrients in the pond that will likely result in unfavorable conditions for the pond invertebrates.

CHLOROPHYLL A

In the multivariate regression analysis, chlorophyll was significantly related to temperature, pH, dissolved oxygen, nitrate levels, and salinity levels.

Chlorophyll a (µg/L) = – 1318.2*Temperature (°C) – 15125.5* pH + 1889.0*Dissolved Oxygen (mg/L) + 15368.8*Nitrate (mg/L as N) – 666.7*Salinity (‰) + 173000.69

$$R^2 = 0.955$$

With p-values of:

Variable	P-value
Temperature (Deg C)	0.0442
pH	0.0134
Dissolved Oxygen (mg/L)	0.0372
Nitrates (mg/L as N)	0.0236
Salinity (‰)	0.0211

Chlorophyll a levels have a measured correlation with all the elements that enhance or hinder phytoplankton growth. First, chlorophyll levels in the ponds are correlated with dissolved oxygen levels. Oxygen is generated by photosynthesis by phytoplankton at the base of the pond food chain (Grove, 1998), and this is evident in the positive correlation between the two data sets. Nitrates are positively correlated with chlorophyll levels due to the nitrogen-dependence of the plants growing in the ponds. Increased nitrate levels lead to increased phytoplankton growth, which can be detrimental to other pond biota.

Consistent with the literature, salinity is negatively correlated with chlorophyll a levels (Bayrakdar, 1994). Even if a species is highly tolerant of salinity levels, that species will generally do better in the lower part of its salinity range. This is because less energy needs to be devoted to osmoregulation of the organism and can be devoted to growth (Swanson, 1998). Also, less oxygen is able to be dissolved in ponds with higher salinity levels.

Again, correlation with temperature and pH should be further measured to determine the variability in these two factors in an average year in the ponds, and whether greater fluctuations have any significant effects.

DISSOLVED OXYGEN

Dissolved oxygen levels were also measured for a pond subset, and these data may also be used to indicate or explore ecosystem "friendliness." In the multivariate analysis of dissolved oxygen, there was significant correlation determined with depth, berm height, temperature, and pH.

Dissolved Oxygen (mg/L) = -0.24*Depth (ft) – 1.4*Berm height (m) + 0.37*Temperature (°C) + 1.85* pH – 17.98

$$R^2 = 0.9041$$

With p-values of:

Variable	P-value
Depth (feet)	0.0151
Berm Height (m)	0.0059
Temperature (Deg C)	0.0294
pH	0.0259

Dissolved oxygen is inversely correlated with berm height. This correlation may be explained by the amount of shelter from wind that the berm provides. Higher wind speed increases the amount of oxygen that can diffuse into a water body from the atmosphere; a lower berm would provide less shelter from the wind and therefore more oxygen could dissolve into the water from the air (WOW, undated). Inverse correlation with water depth may simply be a result of the ratio changes as a result of more water volume in deeper ponds.

Temperature and pH are also related to dissolved oxygen levels although these values are fairly constant across the range of ponds sampled. Again, measurement of fluctuations in these values would help to determine the extent and significance of the correlation.

RECOMMENDATIONS & AREAS FOR FURTHER RESEARCH

To date, few data have existed about the species living in the salt ponds, their relationships to each other and the ponds, and the external factors that affect them. To fully understand and preserve the ecological value of these salt ponds, several actions are recommended as next steps.

1. Monitor sentinel species and metrics

This thesis concludes that several habitat characteristics and species may be considered "sentinels" for the relative health of a salt pond. These parameters are easily monitored and may be observed on an ongoing basis by trained volunteers. Changes in mangrove community composition or distribution may signal important changes in the ponds. Presence or absence of fiddler crabs is also easy to monitor in ponds. Disappearance of fiddler crabs in ponds indicates a "red flag" that a pond is having problems sustaining its ecosystem. Trash levels in salt ponds are also an obvious signal that ponds may be in danger. Additional study will suggest other sentinel metrics available for monitoring.

2. Begin an ongoing salt pond measurement program

Although fifteen ponds were sampled during this research trip, there are more than thirty ponds on the island. Accessibility issues, time constraints, and pond dryness all contributed to the choice of ponds for this study. A larger sample size of ponds will extend the data sets and increase the statistical accuracy of the results. Due to the lack of seasonal data, variations due to migratory patterns, rainfall, and other seasonal changes will not be adequately represented by this study. Seasonal pond measurements will provide a more complete picture of pond conditions and responses to external factors.

3. Perform nitrogen balance for ponds

Although the nitrate levels seem to indicate that more nitrates are present in the ponds than would occur simply from seawater evaporation, there are not enough data at present to speculate about additional sources of nitrogen in the ponds. There are many nitrogen sources and sinks that are unaccounted for in this study. For example, the microbial mats common in hypersaline, evaporative environments act as a nitrogen sink for the water column (Stal and Caumette, 1994), but may also block nitrogen from entering through the groundwater. Use of the pond basins by livestock and domestic and feral animals is a source of nitrogen, and phosphorus levels may impact nitrogen cycling in the salt ponds. Pond usage by birds may also affect nutrient levels in the salt ponds. Additional processes including denitrification, sorption, bacterial fixation, and atmospheric deposits should be considered. A detailed nitrogen balance would help to determine sources, sinks, and impacts of nitrogen levels on the salt ponds.

4. Conduct sediment studies for ponds

Salt ponds serve as sediment filters for runoff on St. John. Increased sedimentation rates due to the construction practices and lack of erosion control pose a serious risk to macroinvertebrate communities as well as the ponds in general. Sediment composition and history may provide some insight on the ecological development of the salt pond as well as the chemical makeup of each salt pond environment. Sedimentation rates and content should be studied to determine whether this is a significant source of nutrients in the ponds, as well as whether and to what extent human activities are affecting the ponds.

5. Consider implementation of buffer zones

An adequate buffer is crucial to preserving salt ponds. Implementing a buffer will be easier for some ponds than others, but this practice may be best suited to pond basins where new home construction is light or has not been started. Buffered ponds may be used as controls for ongoing monitoring as well. Buffering ponds may consider more than just construction practices. Limiting foot traffic within several meters of the pond and/or installing fences to keep goats, donkeys, and domestic animals away from the ponds should also be considered.

SALT POND CONCLUSIONS

SENTINEL SPECIES

Conclusions can be drawn about some of the taxa observed in the salt ponds in this study and the range of conditions in which they were observed. Based on the data collected in this study, it is possible to identify species that can be viewed as "sentinels" for conditions in the pond. One suggested organism is *ocypodidae*, which is present in a wide range of ponds over a range of salinities (31 to 192‰) and are less tolerant of other conditions that are correlated with a decline in species richness. These macroinvertebrates, commonly known as fiddler crabs, are easy to identify because of their relatively large size and their burrows around the shallow edges of the pond. Presence of *ocypodidae* is a useful and relatively easy factor to monitor during long-term oversight of the salt ponds as a high-level indicator of other factors at work in the pond. In addition to their range of presence and tolerance to environmental factors measured in this study, crabs are viewed by the literature as a sign of ecosystem health. "Crabs are currently regarded as a key ecological element in mangrove forests" (Drude de Lacerda, 2002). Also, "fiddler crabs are perhaps the most common macrospecies in the mangrove and are an important indicator species of changes in hydrology and water quality; they are among the first organisms to leave a disturbed system" (Fifth, 1999).

NITRATE SOURCES

Nitrate levels are shown above to be correlated strongly with salinity, which suggests that the water in salt ponds may be composed primarily of evaporated seawater. This suggestion is reinforced by the lack of appreciable runoff (as predicted by hydrologic models) and the downwelling seen in the seepage meters at Southside Pond. In addition, nitrate levels and their deviations from expected levels were not found to be correlated with any aspect of development or runoff used in this study.

Thus, the results of this study seem to contradict the original hypothesis that salt pond health is adversely affected by human development. In addition, since species richness, chlorophyll, nitrate, and dissolved oxygen measurements are not significantly correlated with housing density, it appears that human population density measured in houses per square kilometer does not currently cause eutrophic conditions in salt ponds, algal blooms, hypoxia, or decreased number of species. These results do not suggest that if land development continues unchecked there will be no impact on salt ponds, but rather that more research is needed to determine the extent that other human activities have on salt ponds. As the human population density increases on St. John, human contributions to nutrient loading in the ponds is an issue with which to be concerned.

It is also possible that the full extent of human development is not accurately measured by the "housing density" metric or the "development matrix" metric. Other factors may come into play including runoff from different types of roads and the amount of travel they receive, livestock contributions to nutrient levels, or other non-residential land uses. Further pond study will help to resolve these and other questions.

V. REFERENCES

AM Conservation Group Inc. "Product Price Guide." 2003.

Ammerman, D., Crook, J., Matthews, R., and Okun, D.A. "Guidelines for Water Reuse." Camp Dresser & McKee Inc, 1992.

Ammerman, D. and McCullen, K. "Update to the EPA Guidelines for Water Reuse." Water Reuse for the Future: Use it again America! Water Reuse Association 2002 Annual Symposium. Orlando, Florida. September 8-11, 2002.

Angelo, W. "Taking Out Salt is Sweet Market." Engineering News Record. Vol. 245, Issue 5. pp. 46-52. October 16, 2000.

Baustert, R. Personal Interview. Sapphire Village Condominiums. St. Thomas, USVI. January 10 2003.

Bayrakdar, S. "Distribution of Phytoplankton (>55µM) Along the Turkish Coast and at the North-Western Area of the Black Sea." Institute Of Marine Sciences, Middle East Technical University, September, 1994.

Bossi, L and Rose, D. "Hydrologic and Chemical Analysis of Salt Ponds on St. John, U.S. Virgin Islands". Master of Engineering Thesis, Dept. of Civil and Environmental Eng., MIT. Cambridge, MA. 2003.

Brin, G. "Evaluation of the Safe Water System in Jolivert Haiti by Bacteriological Testing and Public Health Survey". Master of Engineering Thesis, Dept. of Civil and Environmental Eng., MIT. Cambridge, MA. 2003.

Brealey, R. and Myers, S. "Principles of Corporate Finance." McGraw Hill, 2000.

Bruno-Vega, A. and Thomas, K. "Water Costs from the Seawater Desalting Plants at the US Virgin Islands." International Desalination & Water Reuse Quarterly. 5(2) 25-31. August/September 1995.

Bruno-Vega, A. and Thomas, K. "The Virgin Islands Desalination Experience." Desalination. Vol. 98. pp. 443-450. 1994.

Burke, L., Kura, Y., Kassam, K., Revenga, C., Spalding, M., and McAllister, D ; "The Pilot Analysis of Global Ecosystems: Coastal Ecosystems." World Resources Institute, April 2001.

Buros, O. "A History of Desalting Water in the Virgin Islands." Desalination. Vol. 50. pp. 87-101. 1984.

Buros, O. “Desalination In the Virgin Islands.” Desalination. Vol. 45. pp. 1983.

Buscemi, P. “Integrating Water Resources Management- Analysis of the St. Thomas USVI Islands, Water Market” .Master of Engineering Thesis, Dept. of Civil and Environmental Eng., MIT. Cambridge, MA. 2003.

Cassedy, E. “Prospects for Sustainable Energy: A Critical Assessment.” Cambridge, UK: Cambridge University Press. 2000.

CDC (Center for Disease Control and Prevention), “Safe Water System Manual.” 2002. <http://www.cdc.gov/safewater/manual> (cited April 20, 2003)

CDC (Center for Disease Control and Prevention), “Effect of Chlorination on Inactivating Selected Microorganisms.” 2002. <http://www.cdc.gov/safewater/chlorinationtable.htm> (cited April 4, 2003)

Cheslek, H. “Water Reuse and Conservation in the United States Virgin Islands”. Master of Engineering Thesis, Dept. of Civil and Environmental Eng., MIT. Cambridge, MA. 2003.

Chritchley, L. USVI Department of Planning and Natural Resources Environmental Protection Division Environmental Specialist. 9 January 2003. Personal interview.

Chung, L. “Office Memorandum: July Production Report.” Virgin Islands Water And Power Authority. August, 1998.

Chung, L. Krum Bay Plant Supervisor. Personal Interview. January 22, 2003.

Colon-Dieppa, E., Torres-Sierra, H., and Ortiz, J. “National Water Summary 1988-89-Floods and Droughts: U.S.Virgin Islands.” In: Paulson, R. W., E. B. Chase, R. S. Roberts, and D. W. Moody, 1991. “National Water Summary 1988-89--Hydrologic Events and Floods and Droughts. Water-Supply Paper 2375.” *U.S.* Geological Survey, Washington, D.C. pgs. 521-526. 1989.

“CostWorks.” Version 7 for Windows. Computer Program. Kingston, MA: R.S. Means Company, 2003.

Coulston, M. and Mussington, J. “Environmental Impact of Depositing Dredge Spoils in an Area Northeast of Hansons Bay, St. John’s, Antigua.” Island Resources Foundation. September 12, 1987.

Darwish, M. and Al-Najem, N. “Energy Consumptions and Costs of Different Desalting Systems.” Desalination. Vol. 64. pp. 83-96. 1987.

Darwish, M. and Jawad, A. “Technical and Economical Comparison Between Large Capacity MSF and RO Desalting Plants.” Desalination. Vol. 76. pp. 281-304. 1989.

Delyannis, E. and Belessiotis, V. "Solar Desalination: Is It Effective? Part II: Solar Assisted Distillation." International Desalination & Water Reuse Quarterly. 5(1) 28-33. May/June 1995.

DeRossett, R. and Senn, M. Personal Interview. VIESCO. St. Thomas, USVI. January 22, 2003.

Di Cola, R. Aqua Design Manager. Personal Interview. January 21, 2003.

Donahue, J. and Johnston, B., eds. "Water Culture and Power-Local Struggles in a Global Context." Washington DC : Island Press, 1998.

Drude de Lacerda, L. ed. "Mangrove Ecosystems: Function and Management." New York: Springer, 2002.

Encyclopedia Britannica. <http://us.yimg.com/i/edu/ref/ebce/l/1056483.gif> 2001.

Engineering News Record Home Page: 3 Mar 2003. Engineering News Record. 18 Mar 2003. <http://enr.construction.com/features/conEco/costIndexes/mostRecentIndexes.asp>

Fong, P. "A Sea Of Change in the Search For Water." Business Week. January 22, 2001.

Gallo, B. "A Safe Water System for Jolivert." Missions of Love Inc. Miami. 2002.

Gallo, B. "Project Update on the Jolivert Safe Water for Families Program." Missions of Love, Inc. Miami. 2002.

Gangemi, A. "Ecological Assessment of Salt Ponds on St. John, USVI". Master of Engineering Thesis, Dept. of Civil and Environmental Eng., MIT. Cambridge, MA. 2003.

Global Water Partnership, "Integrated Water Resources Management." Technical Advisory Comitee (TAC), 1996.

Glogger, K. Phone Call. Sustainable Systems and Designs International Inc. St. Croix, USVI. April 11, 2003.

Grove, K. Estuaries and San Francisco Bay Home Page, 1998. <http://geosci.sfsu.edu/courses/geol103/labs/estuaries/estuaries.home.html>

HACH. "Water Analysis Handbook." 3rd Edition. Loveland, Colorado. HACH Company. 1997.

Hanson, J., L. MacKoul, J. Murphy, and P. Parise. "Desalination for Drinking Water Production." Presentation to the Ipswich River Watershed Association. October 2002.

Hendrickson, D. WAPA Operator 3rd Class. Personal interview. January 17, 2003.

Hersh, L. Personal interview. January 2003.

HydroCAD Stormwater Modeling System. Owner's Manual. Version 6. "Applied Microcomputer Systems." Chocorua, NH. 2001.

Island Resources Foundation. Website <http://www.irf.org/>. 2002.

James, R. Phone Call. United States Virgin Islands Department of agriculture. April 11, 2003.

Jarecki, L. "A Review of Salt Pond Ecosystems." Proceedings of the Nonpoint Source Pollution Symposium,. Eastern Caribbean Center, University of the Virgin Islands, St. Thomas, USVI. 1999.

Jarecki, L. Lavity Stoutt Community College. Personal interview. January 4, 2003.

Jordan, D. and Cosner, O. "A Survey of the Water Resources of St Thomas, Virgin Islands." U.S. Geological Survey open file report, 1973.

Jordan, D. "Land-Use Effect on the Water Regimen of the U.S. Virgin Islands." U.S. Geological Survey Professional Paper 800-D, pgs. D211-D216. 1972.

Kamal, I. "An Assessment of Desalination Technology for the Rosario Repowering Project." Desalination. Vol. 102. pp. 269-278. 1995.

Kling, J. Personal Interview. Best Western Emerald Beach Resort. St. Thomas, USVI. January 8, 2003.

Kufahl, P. "Tapping the Ocean." Utility Business. Vol. 5, Issue 6. pp. 30-39. June 2002.

Lantagne, D. "Environmental Issues: Haiti in the Global Context, PowerPoint presentation." MIT. Cambridge, MA. 2002.

Lantagne, D. "Trihalomethane Formation in Rural Household Water Filtration Systems in Haiti." Master of Engineering Thesis, Dept. of Civil and Environmental Eng., MIT. Cambridge, MA. 2001.

Madani, A. "Economics of Desalination for Three Plant Sizes." Desalination. Vol. 78. pp. 187-200. 1990.

Maier, R., Pepper, I., and Gerba, C. "Environmental Microbiology." Academic Press. San Diego, California. 2000.

Mays, L. "Urban Water Supply Handbook." New York, NY: McGraw Hill , 2002.

Miilu, M. “Desalination and its Potential for Harnessing Brine and Solar Energy in the US Virgin Islands”. Master of Engineering Thesis, Dept. of Civil and Environmental Eng., MIT. Cambridge, MA. 2003.

Missions of Love Inc. 2003. <http://members.sigecom.net/jude/index.html> (cited April 10, 2003)

Montgomery, G. "Riparian Areas: Reservoirs of Diversity." Natural Resources Conservation Service North Plains Regional office, Lincoln, NE. 1966.

Murcott, S. Verbal Correspondence, MIT. Cambridge, MA. April, 2003.

Nellis, D. “Seashore Plants of South Florida and the Caribbean.” Sarasota, FL: Pineapple Press, 1994.

Prior, T and Stephens, A. Personal Interview. Coral World. St. Thomas, USVI. January 21, 2003.

Salinity Gradient Solar Technology Page. University of Texas El Paso. 10 October 2002. <http://www.ece.utep.edu/research/Energy/Pond/pond.html>

Santiago-Rivera, L. and Colon-Dieppa, E. “U.S. Virgin Islands Surface-Water Resources, in U.S. Geological Survey, National Water Summary 1985-Hydrologic Events and Surface-Water Resources.” U.S. Geological Survey Water-Supply Paper 2300. pgs 447-452. 1986.

Sheikh, B., Castle, Kasper, and Roxon. “Comparing Costs and Benefits of Water Recycling Options with Seawater Desalination and Gray Water.” Water Reuse Association 2002 Annual Symposium. Orlando, Florida. September 8-11, 2002.

Simon, D. E-mail correspondence, US Virgin Islands Department of Planning and Natural Resources. St. Thomas, USVI. February 6, 2003.

Smith, K. Personal Interview. Point Pleasant Resort. St. Thomas, USVI. January 13, 2003.

Stal, L. and Caumette, P. “Microbial Mats: Structure, Development, and Environmental Significance.” New York: Springer-Verlag, 1994.

Stata Corporation, 2002. Intercooled Stata: Statistical Software Package.

Stevens, C. “Assessment of Desalination Treatment Processes for Future Water Supplies”. Master of Engineering Thesis, Dept. of Civil and Environmental Eng., MIT. Cambridge, MA. 2003.

Sullivan, H. “Household Water Chlorination for the Developing World: A Case Study in Lumbini Nepal.” Master of Engineering Thesis, Dept. of Civil and Environmental Eng., MIT. Cambridge, MA. 2002.

Thomann, R. and Mueller, J. "Principles of Surface Water Quality Modeling and Control." New York: Harper & Row Publishers, 1987.

Topozone Homepage: 1982. Topozone.com. 7 March 2003. <http://www.topozone.com>

Tsiourtis, N. "Desalination and the Environment." Desalination. Vol. 141. pp.223-236. 2001.

UN Economic Commission for Latin America and the Caribbean. "The Water resources of Latin America and the Caribbean-Planning Hazards and Pollution." Santiago, Chile: United Nations, Economic Commission for Latin America and the Caribbean, 1990.

USAID, "Haiti: Country Environmental Profile, A Field Study." 1985.

U.S. Census Bureau Home Page: February 2002. U.S. Census Bureau. 24 April 2003. <www.census.gov/prod/cen2000/island/VIprofile.pdf>

U.S. Department of Agriculture, NRCS. Soil Survey of the United States Virgin Islands. 1998. <http://soils.usda.gov/soil_survey/surveys/main.htm#pr>

US Department of Commerce, U.S. Census Bureau. "Population and Housing Profile-2000 Census of Population and Housing-U.S. Virgin Islands." 2002.

US Department of Energy. Federal Energy Management Program. "Federal Facilities in the US Virgin Islands: Opportunities for Energy and Water Efficiency Investments." RFQ-00-004. Atlanta. July 2001.

U.S. Department of Interior Home Page*:* September 2000. U.S. Department of Interior Bureau of Reclamation. 6 Nov 2002. <http://www.lc.usbr.gov/scao/titlexvi.htm>

U.S. Department of the Interior, Office of Insular Affairs (OIA). Report on the State of the Islands, 1997.

U.S. Department of the Interior, Office of Insular Affairs (OIA). "Report on the State of the Islands." 1999.

U.S. Environmental Protection Agency. (EPA 625-R-99-010): "Constructed Wetlands Treatment of Municipal Wastewaters." September 2000 (a).

U.S. Environmental Protection Agency. "National Recommended Water Quality Criteria - Correction." Office of Water, Washington DC, April 1999.

U.S. Environmental Protection Agency. Region 4. Home Page: 26 Oct 2000 (b). U.S. Environmental Protection Agency. 19 Feb 2003. <http://www.epa.gov/region4/water/drinkingwater/waterconservation.htm>

U.S. Environmental Protection Agency. Region 9. Home Page: 13 Sept 2002 (a). U.S. Environmental Protection Agency. 7 Oct 2002. <http://www.epa.gov/region9/water/recycling/index.html>

U.S. Environmental Protection Agency. "Stressor Identification Guidance Document." Office of Water, Washington DC, 2000.

U.S. Environmental Protection Agency Water Conservation Home Page: 28 June 2002 (b). U.S. Environmental Protection Agency. 19 Feb 2003. <http://www.epa.gov/owmitnet/water-efficiency.html>

U.S. Geological Survey. "Digital Elevation Models, Data Users Guide 5." U.S. Department of the Interior, USGS, Reston, VA. 1993.

U.S. Geological Survey. "Eastern St. Thomas Quadrangle: Virgin Islands 7.5 Minute Topographic Series." 1982

United States Geological Survey-Nace. "Earth's Water Distribution." 1967.

U.S. Geological Survey. "Water Resources Data: Puerto Rico and the United States Virgin Islands Water Year 2001." 2002.

U.S. Geological Survey. "Water Quality, Pesticide Occurrence, and Effects of Irrigation with Reclaimed Water at Golf Courses in Florida." Water Resources Investigation Report 95-4250. 1996.

U.S. Virgin Islands Caribbean Data Center Home Page: August 2001. U.S. Virgin Islands Caribbean Data Center. 28 February 2003. <http://cdc.uvi.edu/reaweb.html>

U.S. Virgin Islands Coastal Zone Management Program, 2002. <http://www.viczmp.com/>

U.S. Virgin Islands National Park Service. "Virgin Islands National Park Weather Information." 2002.

U.S. Virgin Islands Tourism Guide. <http://www.usvi.net/usvi/maps/topo2.htm>. 2003.

U.S. Virgin Islands Travel Guide. "A Brief History of the United States Virgin Islands." <http://www.virginisles.com/history.html>. 2000.

World Bank Group. "Our Work in Haiti." 2002. <http://lnweb18.worldbank.org/External/lac/lac.nsf/3af04372e7f23ef6852567d6006b38aq3/be0614ec8b422d70852567de0058a2a0?OpenDocument> (cited April 4, 2003)

World Health Organization (WHO). "Haiti country profile." 2003. <http://www.who.int/country/hti/en/> (cited April 2, 2003)

World Health Organization (WHO). “Access to Improved Drinking Water Sources.” 2001. <http://www.childinfo.org/eddb/water/latam/haiti_water1.pdf> (cited April 2, 2003)

World Health Organization (WHO). “Disinfectants and disinfectant by-products.” 2001. <http://www.who.int/water_sanitation_health/GDWQ/Summary_tables/Tab2d.ht > (cited May 5, 2003)>

York, N. “A Renaissance for St. Croix May Spring from a Discarded Industrial Site.” St. Croix This Week. Vol. 33, No. 1, January 2003: 16-17

SOURCES OF GIS INFO INCLUDE THE FOLLOWING:

<http://edc.usgs.gov/glis/hyper/guide/1_dgr_demfig/states/VI.html>
<http://www.maproom.psu.edu/dcw/>
<http://edc.usgs.gov/>
<http://www.irf.org/irinfgis.html>
<http://www.nps.gov/gis/park_gisdata/virginislands/vi.htm>
<http://www.gisdatadepot.com/catalog/VI/>
<http://www.epa.gov/region02/gis/data/geographicdata.htm#usvi>
<http://freegis.org/geo-data.en.html>
<http://www.ftw.nrcs.usda.gov/ssur_data.html>
<http://biogeo.nos.noaa.gov/products/benthic/data/mosaic/zip/stjohn.zip>