Water Pollution in the Simpson Bay Lagoon: Analyzing the Causes, Extent and Public Perception of the Issue

A case study on the island of St. Martin

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EPIC

Title:	Water Pollution in the Simpson Bay Lagoon: Analyzing the Causes, Extent and Public Perception of the Issue.
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Abstract

Simpson Bay Lagoon is one of the largest inland lagoons in the Caribbean and provides a range of ecosystem services to the island's residents. During the past decades, it has suffered from extensive development and urbanization, resulting in poor water quality and impaired ecological function. This study investigates a relationship between anthropogenic pressures, water pollution, and public perception and behavior. DPSIR framework was used to conduct an integrated assessment of the issue. Water testing was conducted to assess water quality, and literature review and key informant interviews carried out to investigate pollution sources. Geographic Information System (GIS) was used to map out water pollution and its sources using new and existing data. A household survey of 219 households on the island was used to collect data about environmental awareness and behavior. Choice experiment and contingent valuation were used to determine the monetary value of the lagoon. Results geographically show the extent of water pollution in the lagoon and confirm a relationship between pollution sources and water quality. Densely populated urban areas correspond to the highest levels of pollution. Survey results show a high level of environmental awareness and a low level of environmental behavior. Mean Willingness to Pay (WTP) is $18.16 per month for environmental management and $25.66 per month for water quality improvement. Aggregate WTP is $5,975,580 per year for environmental management and $8,443,464 per year for water quality improvement. Policy recommendations include sewage treatment plant, improvement in and enforcement of environmental regulations, and environmental awareness and education campaigns.

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Key Terms and Abbreviations

Nature Foundation	Nature Foundation St. Maarten, an NGO operating on St. Maarten
EPIC	Environmental Protection in the Caribbean, an NGO operating on St. Maarten
VROMI	Ministerie van Volkshuisvesting, Ruimtelijke Ordening, Milieu & Infrastructuur (Ministry of Public Housing, Spatial Planning, Environment and Infrastructure at St. Maarten)
NOAA	National Oceanic and Atmospheric Administration, United States
GIS	"An organized collection of computer hardware, software, geographic data, and designed to efficiently capture, store, update, manipulate, analyze, and display all forms of geographically referenced information" (ESRI, 2019).
St. Martin	The entire island, encompassing Saint-Martin (part of France) and Sint Maarten (former Dutch territory)
St. Maarten	The country of Sint Maarten, a constituent country within the Kingdom of the Netherlands
Saint-Martin	French side of the island, part of the French Republic
DEAL	Direction de l'Environnement, de l'Amenagement et du Logement
SDAGE	Schémas directeurs d'aménagement et de gestion des eaux (Master plans for water management and management)
WTP	Willingness to Pay (in choice experiment and contingent valuation)

1. Introduction

The Caribbean is one of the most biodiverse marine regions in the world. It contains a variety of marine and coastal ecosystems such as coral reefs, mangroves, and seagrasses that harbor a high diversity of flora and fauna. Besides natural beauty, the region is also characterized by relative poverty and a strong focus on exploitation of resources (Gasparini & Molina, 2006). Many of the Caribbean nations lack strong institutions and suffer from ineffective environmental management. As a result, the fragile biodiversity hotspots in the region are coming under increasing pressure from development and pollution (Miloslavich *et al*., 2010).

St. Martin is a small island in the Caribbean that is divided between France and St. Maarten, a former Dutch territory and now a constituent country within the Kingdom of the Netherlands. The island has experienced particular challenges. Rapid pace of tourism-related development and population growth during the 20th century have led to significant ecological consequences for the island. Many of the natural areas have been destroyed and replaced with urban and commercial development. Environmental laws and monitoring are lagging behind, in particular for St. Maarten. The island's infrastructure is in a failing state, particularly with regards to sewage treatment, road maintenance, and waste management (Sint Maarten National Recovery, 2017). Solid waste management has become a pressing issue for St. Maarten. In addition, hurricanes frequent the area and have a devastating effect on the island's infrastructure and natural areas. In September 2017, the island was hit by Irma, a Category 5 Hurricane, which caused widespread destruction.

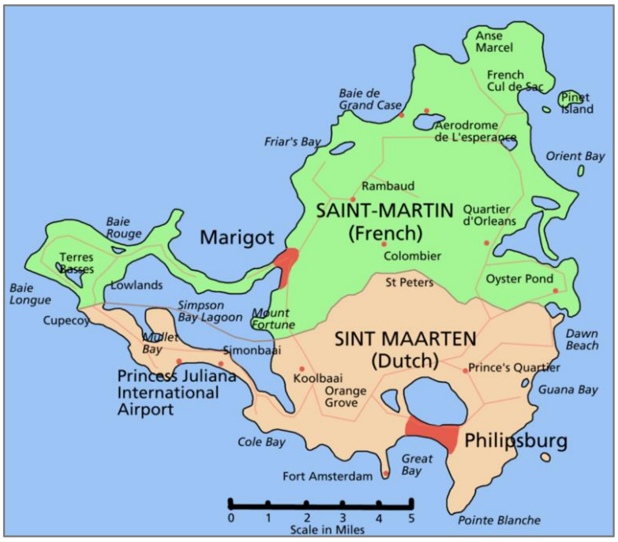

Figure 1. The island of St. Maarten and Simpson Bay Lagoon.

Simpson Bay Lagoon is a large saltwater lagoon on the island and is one of the largest lagoons in the Caribbean (Conservation Areas, 2019) (Figure 1). It has an area of 8.8 km2, comprising approximately 10% of the island's territory (Bervoets & Cahagnier, (n.d.)). It is separated in the middle by the border between the two countries. The lagoon has experienced many changes that degraded its environmental condition. Historically, the lagoon had limited development along its waterfront, was surrounded by areas of mangrove forests, shrubs, and sandy beaches (Johnson, 2014) (Figure 2). However, beginning in the 1960s, heavy development occurred around the lagoon at a rapid pace. The lagoon became an important location for the boating industry and tourism. Many of the natural areas were replaced by new developments and infrastructure, native mangroves were removed, the lagoon was filled and dredged in many areas (EPIC, 2019a). Due to lax environmental regulations and general neglect, the lagoon has experienced overall degradation and pollution, resulting in a severely impaired ecological state (Nature Foundation, 2013b).

Figure 2. View of Simpson Bay Lagoon from Cole Bay side in 1951 and 2017 (Speetjens, 2002).

1.1 Problem statement

Poor water quality is a particularly pressing issue for the lagoon. Water in the lagoon shows elevated levels of nitrate and phosphate and presence of coliform bacteria (Nature Foundation, 2013a). A study by Environmental Protection in the Caribbean (EPIC) has found significant levels of fecal coliform bacteria in the water, indicating sewage pollution (Lips & van Slooten, 2009). The water exhibits mats of algae, has bad odor and discoloration (EPIC, 2019a) (Figure 3). Finally, some areas of the lagoon are polluted with litter and plastic.

Water pollution in the lagoon has a negative effect on its marine ecosystems. An ecological assessment of the lagoon was conducted in 2013 and identified areas of the lagoon which are considered dead zones and where no marine life can exist due to high level of toxicity (Nature Foundation, 2013b). The native seagrasses in the lagoon have almost completely disappeared as a result of pollution, anchoring, eutrophication, and invasive seagrasses (Nature Foundation, 2013b). In the past, the lagoon was a productive fishery which supplied neighboring towns with food, but currently is degraded to a point where almost no fish exist and are dangerous for human consumption (Bervoets, 2019).

Water pollution in the lagoon also has a negative effect on the health and well-being of the communities that surround it. Some of the residents still swim and fish in the lagoon, which may lead to negative health consequences. Additionally, water quality in the lagoon may affect the residents' economic, social, and environmental well-being by negatively affecting tourism, and esthetic and cultural value.

Figure 3. Algae blooms in the lagoon (Nature Foundation, 2018).

1.2 Knowledge gap

There are significant gaps in knowledge that need to be addressed. There is currently no peer-reviewed research investigating the degree of water pollution in the lagoon. Available literature consists of reports and assessments conducted by NGOs on the island over the past several decades. Nature Foundation, an NGO operating on the island, conducts water quality testing in the lagoon. However, it is done at a limited number of locations (Nature Foundation, 2013). Several studies by EPIC have addressed sewage and litter pollution in the lagoon (Lips & van Slooten, 2009; Vang, 2008). Yet, these studies were conducted almost a decade ago and only focus on the Dutch side of the lagoon. On the French side of the lagoon, water quality is monitored by the French Collectivite, but this data is not easily accessible. There is a need for an integrated overview of existing water quality reports and a more updated water quality assessment.

Although water pollution is known as an issue for the lagoon, there have not been any comprehensive studies investigating the main sources of water pollution. There has also been limited investigation into the spatial distribution of human activities around the lagoon that contribute to pollution. Scientific literature points to a connection between land use and water quality and it is important to analyze this link for St. Martin.

Finally, there have not been any studies on the island that address the issue from a more sociological perspective. It is important to investigate awareness, environmental behavior, and the value that St. Martin's residents assign to the lagoon. This is needed to gain insight into possible solutions and policy measures to address this issue.

This research and fieldwork were conducted in conjunction with EPIC, a local environmental NGO. This study provides insights with regards to sustainable management of Simpson Bay Lagoon that would be useful to decision-makers on St. Martin.

1.3 Research Questions

In order to fill these gaps in knowledge, this study will answer the following research questions and sub-questions.

What is the causal relationship between water quality in the lagoon and the environmental behavior and perception of St. Maarten's residents?

1. *What is the state of water quality in the lagoon? How does the current state compare to previous water quality tests?*
2. *What are the dominant sources of water pollution in the lagoon?*
3. *Is there a spatial relationship between the sources of pollution and water quality?*
4. *How do residents of St. Maarten perceive the lagoon water pollution? Is the residents' behavior pro-environmental? Do they assign any value to Simpson Bay Lagoon?*
5. *Do the residents support improvement measures towards better water quality in the lagoon?*

<u>Innovation</u>

This study uses an innovative approach by analyzing the problem from an interdisciplinary perspective. It relies on natural science to investigate water pollution, and on social science to investigate pollution sources and public perception. Finally, it incorporates a spatial element through GIS which is used to investigate a spatial relationship between water quality and pollution sources. The Driver-Pressure-State-Impact-Response (DPSIR) framework is utilized to combine all elements together in an integrated assessment of the issue.

2. Academic Background

2.1 Academic literature

The body of scientific literature related to water pollution in inland lagoons is quite large. In particular, many studies investigate the extent of water pollution in developing countries, such as water pollution in Africa (Boadi & Kuitunen, 2002; Scheren *et al*., 2004). Lagoons and estuaries in these countries suffer from sewage, nutrient over-enrichment, and plastic and toxic chemical pollution. In particular, many studies focus on the ecological consequences of pollution, such as its effect on marine ecosystems within the lagoons themselves, as well as on coastal zones that are affected by pollution.

What makes Simpson Bay Lagoon unique is the fact that it is located in the Caribbean, an area of particular marine biodiversity which has been suffering from increasing anthropogenic pressures. The World Resources Institute has conducted an extensive study analyzing threats facing marine ecosystems in the Caribbean (Burke *et al*., 2004). This project highlighted important connections between human activities and areas where degradation is occurring (Figure 4).

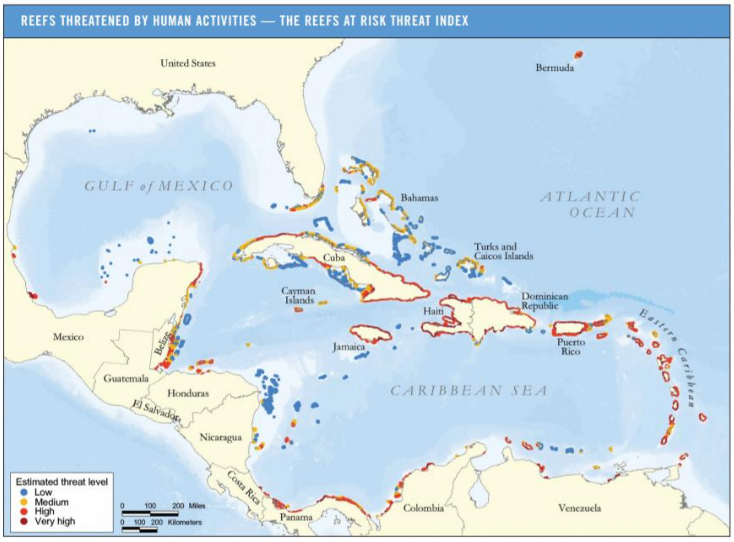

Figure 4. Reefs threatened by human activities: The Reefs at Risk threat index (Burke et al., 2004).

In the Caribbean context, raw sewage discharge in particular is found to be a very harmful type of pollution to marine life. A study of anthropogenic impacts and coral reef mortality in Curacao has demonstrated that the highest values of tissue mortality were found at reef sites which experienced chronic pollution by raw sewage (Nagelkerken, 2006). Data also suggest that additional anthropogenic influences, such as eutrophication, increased sedimentation and seawater temperature, have an additional negative effect on marine organisms (Nagelkerken, 2006). According to Fanning *et al*., most countries in the Caribbean region are still behind in their environmental standards, pumping screened raw sewage directly into the ocean, despite affecting water and beach quality nearby (2011).

Land use is known to be a factor that contributes to riverine and marine pollution. For example, runoff from agricultural fields and associated eutrophication in water bodies has been examined in depth in many case studies (e.g. Strittholt *et al*., 1998; Goetz *et al*., 2004; Packett *et al*., 2009). Such studies use GIS and hydrological modeling to quantify the concentrations and total loads of pollutants that are discharging into lagoons or coastal areas (Packett *et al*., 2009). Other studies use GIS and regression analysis to identify a relationship between water quality and land use (Kelsey *et al*., 2004). According to Dalton *et al*., combining existing data on spatial distribution of physical and biological components of the ecosystem, as well as data on its current state, together with human use or human activity patterns can help researchers identify areas with the highest human pressures on the natural environment (2010). Over the years, spatial and temporal patterns of the human use of Simpson Bay Lagoon have shaped the landscape surrounding it and have impacted its marine ecosystems and water quality (EPIC, 2019). In order to generate effective solutions to managing water quality issues, it is necessary to assess the underlying anthropogenic pressures which impact the water quality in the lagoon, including land use changes and human activity patterns in the area.

It is also important to investigate environmental behavior and perception of St. Maarten's residents. Social science studies have found a relationship between perception, behavior, and awareness of environmental issues and their possible solutions. According to Anderson *et al*., it is crucial to investigate perception and behavior, as these elements have a direct effect on the state of the environment as well as carry the potential to alleviate environmental problems (2007). Some studies have shown that lack of awareness or failure to admit that an environmental problem exists can be associated with one's satisfaction with their immediate condition (Hohm, 1976). In other words, admitting that the issue exists in one's immediate neighborhood can pose a challenge to a person's self-image, therefore causing denial of the issue (Anderson *et al*., 2007). There are numerous theoretical frameworks that have been developed with regards to bridging the gap between environmental awareness and display of pro-environmental behavior (Kollmuss & Agyeman, 2002). Sociological, linear progression, economic and psychological models have been developed, which demonstrates that this relationship is very complex. In particular, specific factors have been determined to have more effect on pro-environmental behavior and include demographic factors, external factors (such as institutional, social, economic, and cultural), and internal factors (such as motivation, environmental knowledge, attitudes, and priorities) (Kollmuss & Agyeman, 2002). Finally, in order to explain the importance and value that St. Maarten's residents assign to the lagoon it is useful to investigate this value through contingent valuation and choice experiment economic valuation techniques. These valuation methods can be used to assign a monetary value to the goods and services provided by the biosphere (Bateman & Turner, 1992). The value of the environment is thus measured by the preferences of the population for the conservation and utilization of these commodities (Bateman & Turner, 1992).

2.2 Conceptual Framework

To incorporate these aspects in a holistic way, this study will use a modified version of the Driver-Pressure-State-Impact-Response (DPSIR) framework. DPSIR framework was developed by the European Environment Agency and is a causal framework for describing the interactions between social, environmental and economic systems. This framework is widely used for various environmental resource applications (Bradley & Yee, 2015). DPSIR framework was modified to include the concept of ecosystem services. In particular, the Impact indicator was modified to include the impact of State Changes on ecosystem services provision, which in turn affects human well-being (Bradley & Yee, 2015).

Ecosystem services (ESS) can be defined as the benefits which humans derive, directly or indirectly, from the properties or processes of ecosystems (Costanza *et al*., 1997). The Millennium Ecosystem Assessment (MEA) classified ecosystem services into four categories: provisioning, regulating, cultural, and supporting (MEA, 2005). Provisioning services refer to tangible material outputs obtained from an ecosystem, such as food, fresh water, and fuel. Regulating services are those obtained from regulation of ecosystem processes, such as climate, flood, and disease regulation. Cultural services are the nonmaterial benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences, such as cultural identity, educational experience, and recreational opportunities related to the environment. Finally, supporting services are defined as those that are necessary for the production of all other ecosystem services and include, for example, nutrient cycling and soil formation (MEA, 2005). The ability of ecosystems to provide ecosystem services in turn affects human well-being, which can be classified into economic, social, and ecologic well-being.

DPSIR has been widely used in academia to analyze complex environmental problems (Kristensen, 2004). This framework is widely used in sustainable water resource management, in particular in relation to the European Water Framework Directive (Borja at al., 2006). It is used to integrate socio-economic approaches with natural science and hydrology (Giupponi, 2002). In the context of this study, it is particularly useful as it allows for the combination of quantitative and qualitative data from both natural and social sciences in one integrated framework. It is suitable for displaying the complexity of the entire system and interactions between its natural and social science components.

Figure 5 portrays the DPSIR framework for this study. The next section explains each element of the framework in more detail. In particular, Drivers are outlined in more detail to provide context for the remainder of the study which addresses Pressures, State Changes, Impacts, and Responses in more detail. In particular, this study pays special attention to the PSI (Pressures, States, and Impacts) portion of the DPSIR.

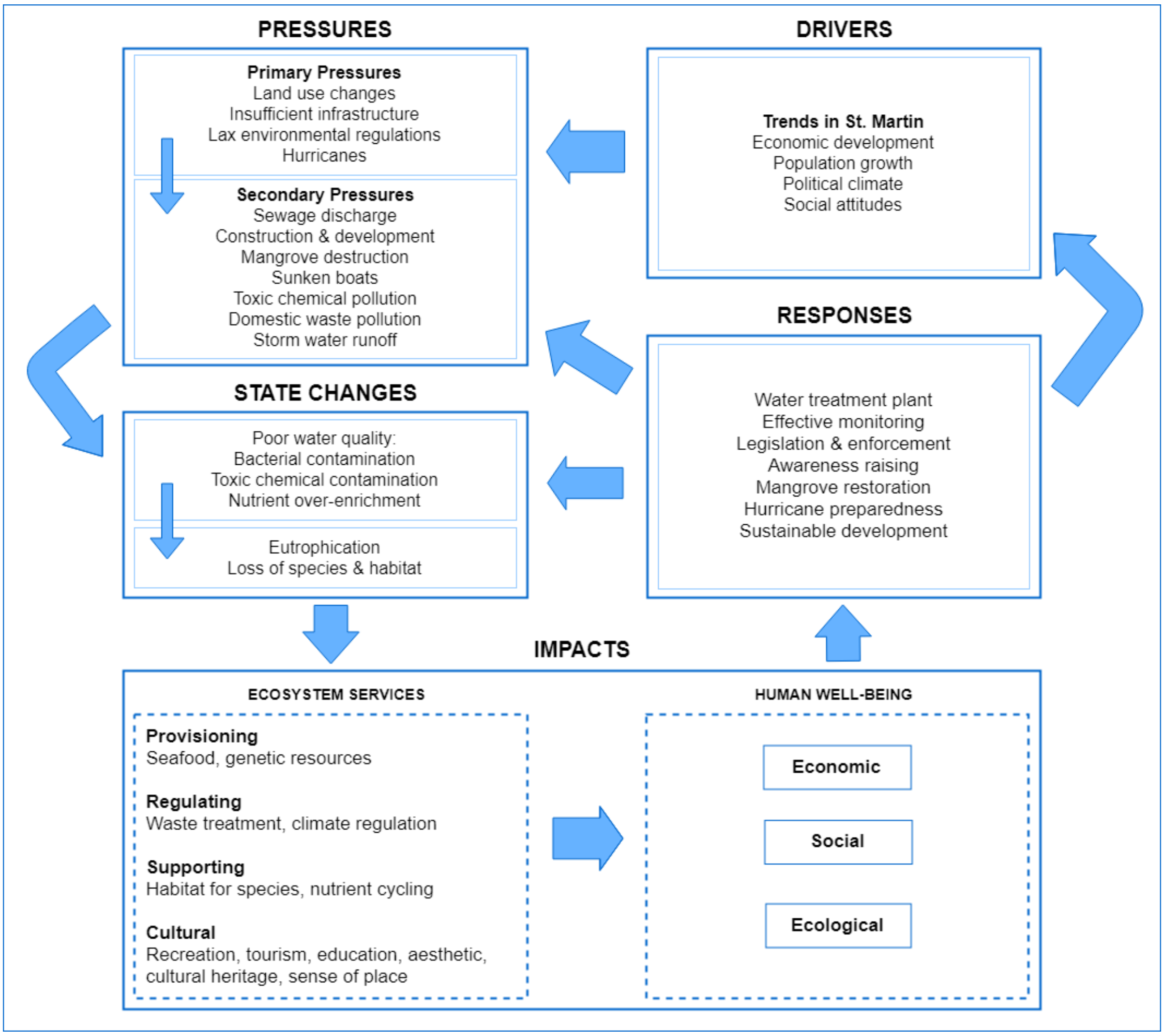

Figure 5. DPSIR framework for this study, focused on water pollution in the Simpson Bay Lagoon.

Drivers

Drivers or Driving forces indicators refer to the underlying causes of environmental change. They describe the social, demographic, and economic developments in societies and the corresponding changes in lifestyles and overall levels of consumption and production patterns (Gabrielsen & Bosch, 2003).

The primary underlying drivers leading to water pollution in Simpson Bay Lagoon are economic, demographic, social, and political. They include economic development of the island, triggered by rapid growth of the tourism sector; population growth, triggered by the economic development of the island; political climate on the island, in particular, the instability of the government of St. Maarten since its independence in 2010; and social attitudes of the residents of St. Martin.

Background: History of St. Martin

Prior to the colonization period of the 16th century, St. Martin was a richly biodiverse island with many endemic species. It contained unique and fragile ecosystems which relied on specific hydrological systems and types of vegetation. During the colonization period, the island was exploited for its resources and experienced rapid deforestation and erosive agricultural practices (Watts, 1993). Salt extraction became an important economic activity and took place at the Salt Ponds which are located in mangrove areas, leading to mangrove destruction (de Albuquerque & McElroy, 1995). In the 18th century, the island's natural ecosystems came under pressure when plantations began to dominate the island. Plantation crops grown on St. Martin included tobacco, indigo, coffee, cotton, lime, and sugar cane (Watts, 1993). Finally, beginning in 1950s, the tourism industry on the island experienced unprecedented growth, which, combined with rapid population growth, put additional pressure on the island's ecosystems (de Albuquerque & McElroy, 1995).

Economic Development

Economic development on the island began during the colonization period in the 16th century, but especially expanded beginning in the 1950s and particularly during the period of 1980-1990s, when the island experienced rapid urbanization and development due to tourism growth (CIA, 2019). During this period the island experienced a staggering 233% increase in tourist visitors, from around 300,000 visitors arriving in 1980 to more than 1,000,000 visitors arriving in 1990 (de Albuquerque & McElroy, 1995).

Currently, tourism accounts for a large portion of St. Maarten's economy, comprising approximately 73% in 2016 (Sint Maarten, 2019a). St. Maarten primarily caters to cruise tourists, with the island's only deep-water port located in Philipsburg. Approximately 90% of the visitors to the island are short-stay cruise tourists that arrive to the port in Philipsburg (INSEE, 2016). Currently, St. Maarten receives an average of 1.7 million cruise passengers each year (Sint Maarten, 2019). With regards to Saint-Martin, the port of Marigot does not have facilities able to accommodate large cruise ships and targets the high-end clientele traveling on smaller vessels of 100 to 360 passengers (INSEE, 2016).

Figure 6 shows the number of visitors arriving on St. Martin from 1970 through 2018. It includes the number of stay-over tourists which are based on the number of arrivals at Princess Juliana Airport and includes visitors destined for Saint-Martin. Additionally, it shows the number of cruise tourists arriving at the Port of St. Maarten in Philipsburg, and the total number of arrivals. This figure does not include additional cruise ship tourists that have arrived at the port of Marigot due to lack of available data. This data demonstrates the growth in tourism since the 1970s: from 1970, when the total number of visitors was about 100,000 people, to the highest total number of visitors in 2012 of 2,857,000 people, St. Martin has seen an increase of 2,857% in the total number of visitors. The estimated total number of visitors in 2018 was approximately 2,062,101 people.

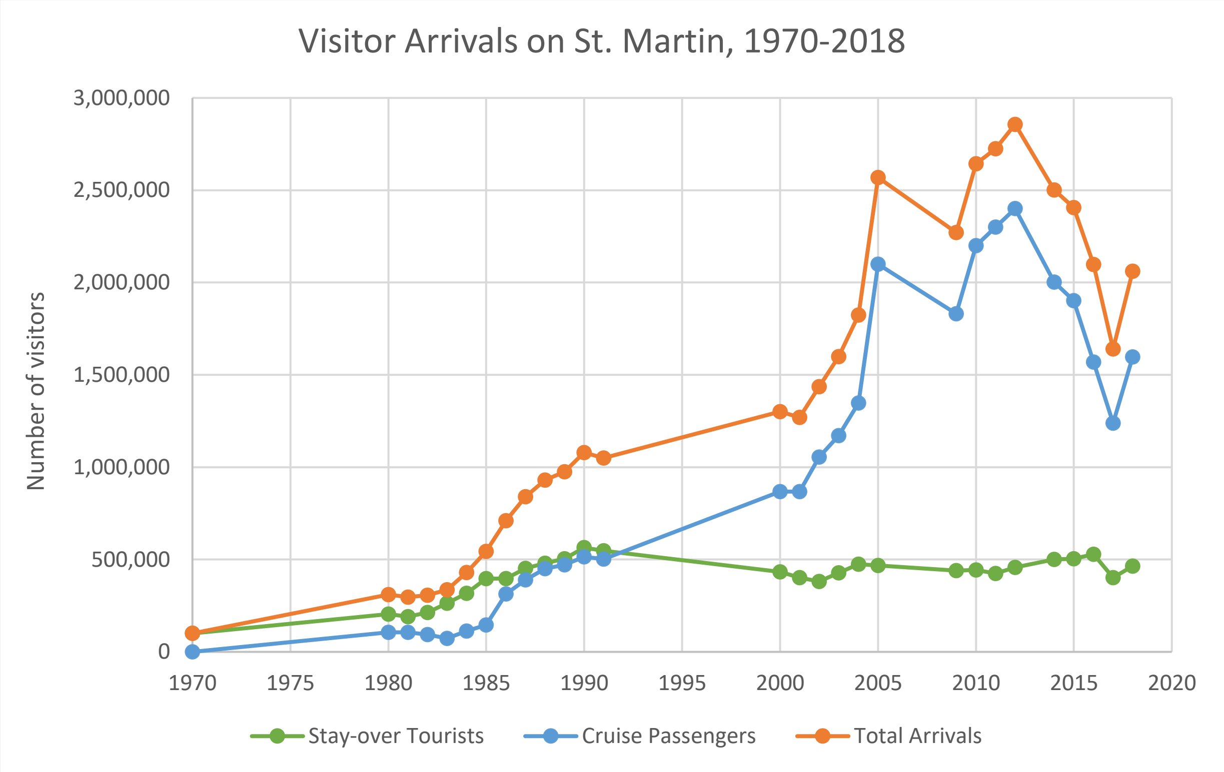

Figure 6. Visitor Arrivals on St. Martin, 1970-2018 (Multiple sources).
Note: Sources include: INSEE, 2016; INSEE, 2018; Department of Statistics Sint Maarten, 2017; de Albuquerque & McElroy, 1995; Department of Statistics Sint Maarten, 2019; IEDOM, 2019.

Population Growth

Another important driver is population growth. Spurred by economic development, the population of the island has been steadily increasing over the past several decades (Figure 7). For the period from 1960 until 2018, population in St. Maarten has increased from only 2,728 people to 40,613 people, comprising an increase of 1,488.78% (Department of Statistics Sint Maarten, 2019). The population more than doubled from 1960 to 1972, and again from 1972 to 1981, and almost tripled from 1981 to 1990. According to World Bank, St. Maarten is currently the most densely populated country in the Caribbean (Sint Maarten, 2019a). The French side of the island has also seen an increase in population growth, particularly, from 1980 until 1990, and a steady increase in population thereafter. From 1967 to 2018, the population on Saint-Martin has grown from 5,000 residents to 35,684, an increase of 713.68%. Total population has increased from approximately only around 5,500 in 1960s to 76,298 in 2018, an increase of 1,398.42%.

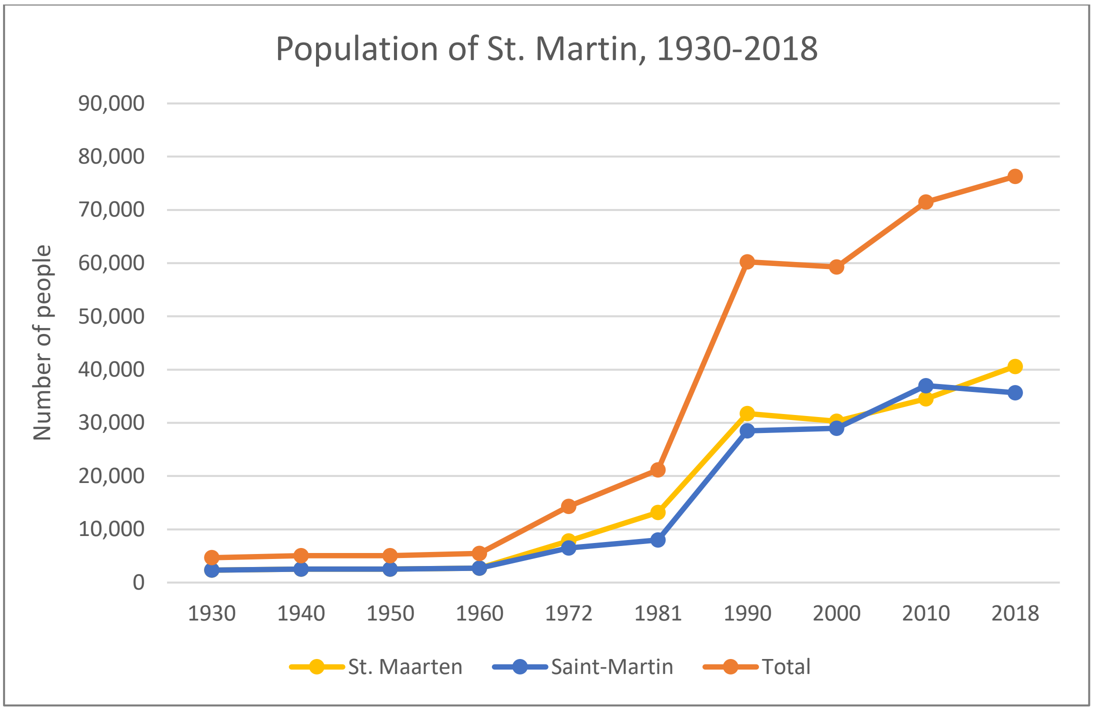

Figure 7. Population of St. Marten, 1930-2018 (Sources: Department of Statistics Sint Maarten, 2019; INSEE, 2018).

Main factors contributing to population growth on the island include births, deaths, emigration, and immigration (Department of Statistics Sint Maarten, 2019). Population continues to increase due to higher birth than death rates, as well as due to immigration from neighboring countries, North America, and Europe (Department of Statistics Sint Maarten, 2019).

Political Climate

Political climate is another important underlying driver. Since 1648, St. Maarten has been a Dutch territory but gained its independence in 2010, becoming a separate constituent country within the Kingdom of the Netherlands. Since then, St. Maarten has had an unstable government, with eight governments replacing each other during the past eight years (K. Gilders, personal communication, September 13, 2018). St. Maarten does not have an established waste-management authority, and waste accumulation on the island has become a large-scale issue that dominates the residents' life and the local landscape. The government is not actively participating in solving environmental problems on the island and suffers from corruption (Gerges at al., 2018).

Lack of cooperation between the two sides is another aspect of the political climate on the island. Each of the countries has a different administrative language and legal system. Due to bureaucratic complexity, cooperation with regards to environmental issues has not been successful (The Government of St. Maarten, 2014).

Social Attitudes

Finally, social attitudes are also an important underlying driver. It is unclear whether the island's residents have a strong desire to protect the lagoon. In fact, the constant deterioration of the natural environment, caused by the pressures of drastic and limitless urbanization and landfill creation may reflect that local society fails to recognize the value of the ecosystems they depend upon.

Pressures

Pressure indicators describe developments in release of substances, physical and biological agents, the use of resources and the use of land by human activities. They refer to human activities which are transported and transformed in a variety of natural processes to manifest themselves in changes in environmental conditions (Gabrielsen & Bosch, 2003).

The primary pressures have been identified as land use changes, insufficient infrastructure, lax environmental regulations, and hurricane damage. These primary pressures in turn trigger additional pressures which directly affect the state of the environment. These dominant sources of pollution include sewage and grey-water discharge from households, businesses, and boats; sunken boats; construction and development which causes mangrove destruction and filling in and dredging of the lagoon; toxic chemical pollution from boatyards and marinas; and domestic waste pollution which is transported into the lagoon with winds and stormwater runoff. There secondary pressures will be investigated in more detail in this study.

State Changes

State changes indicators refer to changes in the state of the environment in response to pressures. Chemical, physical and biological processes interact to affect different ecosystem components, such as chemicals and biological species, that can be measured by their attributes (metrics of quantity or quality) (Bradley & Yee, 2015).

The dominant state change in the lagoon is the deterioration of its water quality. More specifically, lagoon water is suffering from nutrient over-enrichment and resulting eutrophication, bacterial contamination with fecal matter and associated fecal bacteria, as well as possible toxic chemical contamination. These changes in water quality negatively affect marine ecosystems in the lagoon, resulting in dead zones where almost no marine organisms can exist and leading to disappearance species from the lagoon.

Impacts: Ecosystem Services and Human Well-being

Impact indicators are used to describe how changes in the quality and functioning of the ecosystem have an impact on functions of the environment, such as human and ecosystem health, resources availability, losses of manufactured capital, and biodiversity (Gabrielsen & Bosch, 2003). This category incorporates the impact on ecosystem services provision, which in turn affects human well-being (Bradley & Yee, 2015).

The lagoon provides or has a potential to provide a range of ecosystem services to the residents of St. Martin, which in turn affects their economic, social, and environmental well-being. These ecosystem services can be divided into provisional, regulating, supporting and cultural services.

Provisional services include seafood production by the lagoon’s ecosystems and provisioning of potential genetic resources. Water pollution has a negative effect on fish populations as well as on survival of other species in the water and on land near the lagoon. Fishing in the lagoon used to be a major source of food for the surrounding communities in the past, but this is no longer the case since fish populations have been decimated by pollution and may not be safe for human consumption (EPIC, 2019a).

Regulating services include climate regulation by the lagoon water and vegetation, and waste water treatment through the dilution of wastes in the water and subsequent detoxification by microbial communities, which in turn helps to regulate diseases (Molnar *et al*., 2000). The destruction of microorganisms in the lagoon as a result of pollution impairs its waste treatment function.

The lagoon also provides supporting services such as nutrient cycling, as well as performs an important ecological function of being a nursery for fish species which then migrate to coastal waters to mature in coral reef areas. Poor water quality has a negative effect on the state of marine ecosystems inside the lagoon and impairs the ability of the ecosystem to support fish breeding, which has a consequence for fish abundance and fish biodiversity in surrounding coral reef areas and, in turn, for fish availability for human consumption (Nature Foundation, 2013b).

Finally, the lagoon is highly valued for the cultural services that it provides. They include recreational opportunities for activities such as sailing and swimming. Marine industry, which comprises 12.5% of the total economy of St. Maarten, is centered around the lagoon (EPIC, 2019a). Poor water quality may negatively impact the marine industry due to bad odor and unappealing appearance, causing some visitors to choose a different island as their destination. Swimming in most sections of the lagoon is not recommended as it may cause staph infections, which may also negatively impact the tourism sector as well as local residents' well-being (Bervoets, 2019). The lagoon is surrounded by residential neighborhoods that may benefit from the aesthetic enjoyment of the lagoon, while local businesses located near the lagoon can utilize the aesthetic beauty to attract customers. The lagoon also has a high educational and cultural value through its connection to St. Marten's history (Johnson, 2014). Finally, the lagoon contributes to local residents' "sense of place", particularly for communities that live close to the lagoon. Thus, deterioration of lagoon's water quality may have a negative effect on the economic well-being (via the tourism sector and marine industry), the environmental well-being and human health (via regulating and supporting services), and on social well-being (via esthetic, cultural, and recreational values).

Responses

Response indicators refer to responses by groups or individuals in society and government to prevent, compensate, ameliorate or adapt to changes in the state of the environment (Gabrielsen & Bosch, 2003). These actions can be taken at any level of the causal network (Bradley & Yee, 2015).

Responses to poor water quality in the lagoon may include a combination of the following measures: construction of water treatment plant to ameliorate the sewage discharge problem, strict environmental regulations combined with effective monitoring and enforcement, better hurricane preparedness, sustainable development, mangrove restoration, and environmental education and awareness raising.

3. Methodology

3.1 Study Area

The study focuses on both the Dutch and French parts of the lagoon and on land areas immediately neighboring it. Study area was selected by looking at the mountain ridges surrounding the lagoon and only including the areas located on the same side of the ridge as the lagoon. Figure 8 shows the study area.

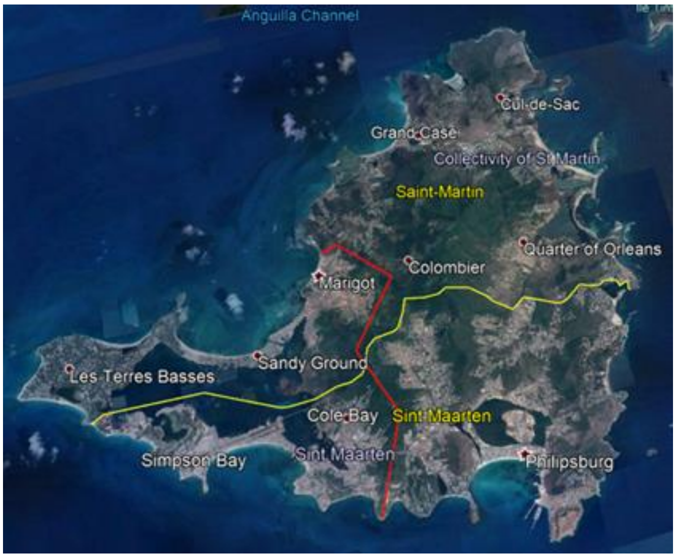

Figure 8. Study area.

3.2 Methodological Framework

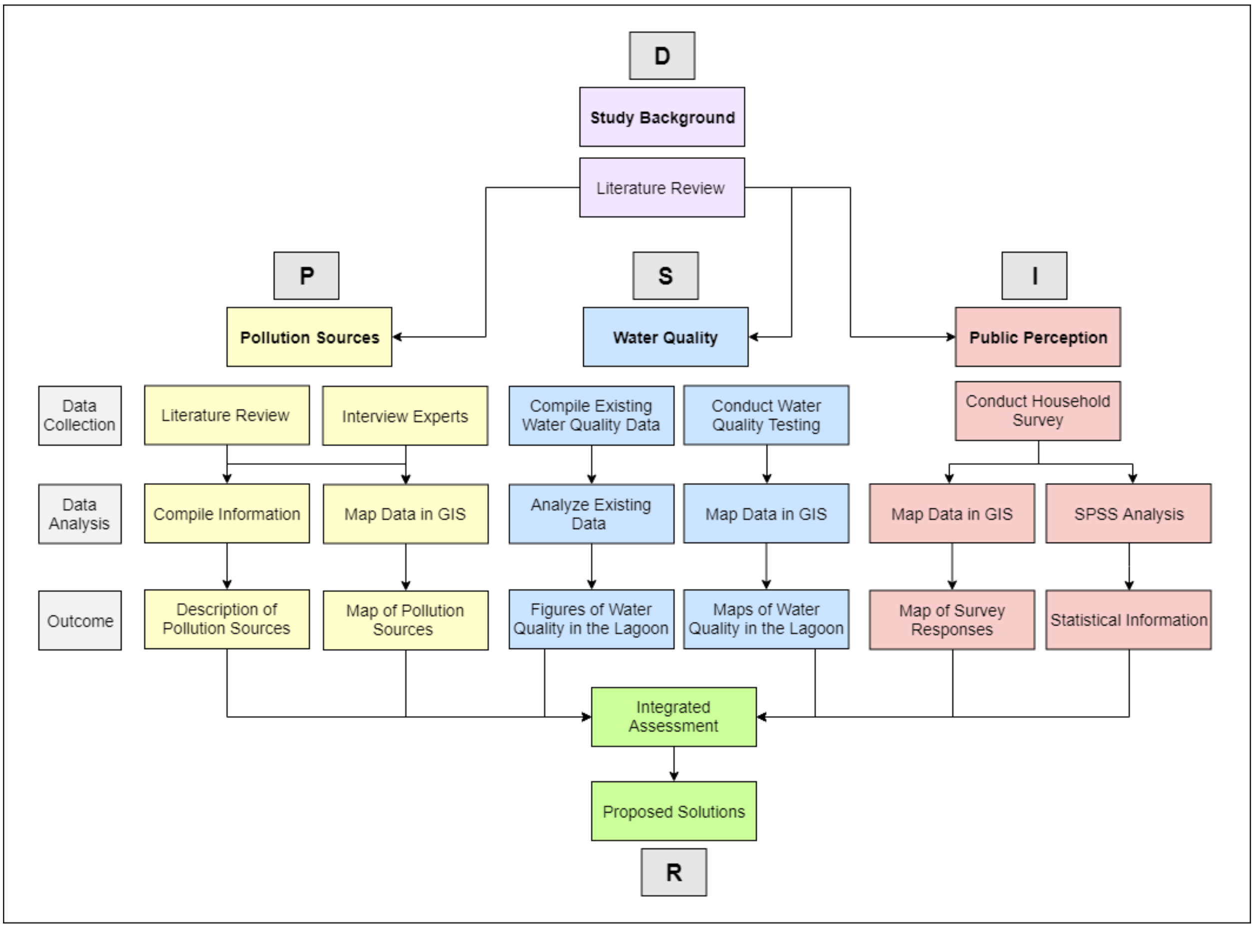

Figure 9. Methodological framework for the study.

Figure 9 shows the methodological framework for this study. A different method was used for each element in the DPSIR framework, followed by a mixed method approach. In particular, literature review and key informant interviews were used to collect information about the Drivers, Pressures and Responses. Furthermore, a more detailed methodology was developed to address the two most important elements of the framework, State changes and Impacts. Finally, a mixed method approach was used to conduct an integrated assessment of the issue. The next section describes the methodological approach for each of the five elements in more detail.

Drivers: Study Background

To obtain information about the drivers of environmental change, a literature review was conducted. The review included scientific publications, scientific studies and reports by EPIC interns, Nature Foundation, VROMI, Reserve Naturelle, and SDAGE, as well as newspaper articles and social media posts. Additionally, data was obtained from open-source online data sources and from employees of VROMI, DEAL Guadaloupe, and Reserve Naturelle.

Pressures: Pollution Sources

To obtain information about the primary and secondary pressures, a literature review and key informant interviews were conducted. Information was then compiled to provide summaries, graphs and maps for this element of the DPSIR.

Literature review included scientific publications, scientific studies and reports by EPIC interns, Nature Foundation, VROMI, Reserve Naturelle, and SDAGE, as well as newspaper articles and social media posts. Additionally, GIS and statistical datasets were obtained from open-source online data sources and employees of VROMI, DEAL Guadaloupe, and Reserve Naturelle.

Key informant interviews were conducted with the relevant experts in the field. Most interviews were unstructured, during which the interviewer took notes. Some interviews directly posed specific questions to the interviewees. The following persons were selected based on their expertise and intimate knowledge of the issue.

1. Rueben Thompson, a board member of EPIC, was interviewed with regards to the following topics: previous EPIC studies, environmental issues facing the island, legislature on St. Maarten, mangrove restoration, cruise tourism and eco-tourism, history of St. Maarten, development, and impact of Hurricane Irma, among others.
2. Tadzio Bervoets, manager of Nature Foundation, was interviewed on the following topics: water quality testing, shipwrecks in the lagoon, impact of Hurricane Irma and pollution on marine ecosystems, sewage pollution and threats to human health, state of the ecosystems in the lagoon, management of the lagoon, sewage treatment plant, plastic pollution, toxic chemical pollution, and government regulations.
3. Kippy Gilders, policy advisor at VROMI, provided her expert opinion with regards to existing environmental regulations, government development plans, and existing sewage treatment infrastructure.
4. Johann Sidial, GIS analyst at VROMI, was consulted with regards to GIS data and geographic information for the Dutch side of the island.
5. Norina Edelman, Brian Deher, Robbie Ferron, and Lorraine Talmi, board members of the Marine Trade Association, were interviewed with regards to primary mission of the Marine Trade Association, shipwrecks in the lagoon, marine industry, government regulations and enforcement with regards to sewage disposal from boats, boat fouling, and boat anti-fouling products.
6. Antoine Lechevalier, GIS analyst at DEAL Guadaloupe, was consulted with regards to sewage treatment facilities on the French side of St. Martin, water quality data and reports, and GIS data and land use changes for the French side of the lagoon.
7. Julien Chalifour, manager of Reserve Naturelle, was consulted with regards to previous studies of the lagoon, ecosystem monitoring on the island, and mangrove destruction.
8. Mark and Jenn Yokoyama, founders of Les Fruits de Mer, were consulted with regards to environmental education, cultural and historic heritage of Saint-Martin, eco-tourism, and endemic species of the island.

State Changes: Water Pollution

Water quality is the primary state change that is addressed in this research. First, existing data were compiled. Second, primary data collection was carried out. Both existing and new data were then analyzed to create water quality maps.

Existing Data Analysis

Existing data for the Dutch side of the lagoon was obtained from studies conducted by Nature Foundation and EPIC. Since 2013, Nature Foundation has conducted regular water quality testing on the island (Nature Foundation, 2013a). Some of these tests were conducted in the lagoon. Often water testing focused on only one specific area of the lagoon or on a specific location, lacking a comprehensive assessment of the entire lagoon. In 2008 and 2009, a master and bachelor thesis reports were written by university students with EPIC supervision and focused on water pollution in the lagoon caused by marine debris and sewage discharge respectively (Vang, 2008; Lips & van Slooten, 2009). In particular, the bachelor thesis which focused on sewage pollution involved water testing conducted next to the largest storm gutters entering the lagoon and included a map of sampling locations (Lips & van Slooten, 2009).

Recent water quality data for the French side of the lagoon was not possible to obtain. After communication with multiple environmental organizations on the French side of the island, it became apparent that most organizations do not possess water quality data for the Simpson Bay Lagoon. Due to the time constraints, it was not possible to continue searching for the data.

Existing data was compiled, georeferenced and imported into GIS to create maps of water pollution. Specific variables such as total and fecal coliforms and nitrates were separated to create separate GIS layers per variable.

New Data Collection

Sample Parameters

Two indicator parameters were measured at each site: nitrate and total coliform.

Nitrate (NH_3)

The test was conducted for the level of nitrate-nitrogen (NH_3) in the water. Nitrate is a form of nitrogen. Nitrogen and phosphorous are nutrients required by all aquatic plants and animals to build protein (USGS, 2019). Nitrogen, in the forms of nitrate, nitrite, or ammonium, is a nutrient needed for plant and algae growth, which in turn provide food and habitat for fish, shellfish, and other aquatic organisms. However, elevated levels of nitrogen cause excessive plant growth in water bodies, leading to increased plant decay and bacterial decomposition (Nutrient Pollution, 2019). This in turn decreases the amount of oxygen available in the water that is crucial for plant and animal survival. This process of eutrophication leads to large growth of algae and causes “dead zones” in water bodies where no plant and animal species can survive (Nutrient Pollution, 2019). Eutrophication in aquatic ecosystems is an ongoing problem for many water bodies around the world (Conley *et al.*, 2009). The main sources of nitrogen added to natural waters are agricultural runoff as well as sewage (USGS, 2019). Elevated nitrogen levels are not only harmful to aquatic life but also have a negative effect on human health and well-being. According to US Environmental Protection Agency, elevated levels of toxins and bacterial growth caused by eutrophication can lead to severe adverse health effects if humans consume polluted fish, come in contact with water, or ingest contaminated water (Nutrient Pollution, 2019).

Total coliform

The term total coliform refers to all bacteria in the coliform group (Lips & van Slooten, 2009). These bacteria can be of fecal origin (fecal coliforms) or of non-fecal origin (Doyle & Erickson, 2006). Fecal coliforms are a subgroup within the total coliform group and originate in the intestinal tract of warm-blooded animals, entering the environment through their waste. Fecal coliform bacteria were used to establish the first microbial water quality criteria (USGS, 2019). Although these bacteria are not harmful themselves, they can serve as an indicator of presence of other pathogenic viruses or bacteria that also occur in human or animal feces (Dufour, 1977). Examples of waterborne pathogenic diseases caused by such bacteria include viral and bacterial gastroenteritis, salmonellosis, staff and ear infections, dysentery, typhoid fever, and hepatitis A (Pandey *et al*., 2014; WHO, 2011). Although some of these pathogens are associated with low or moderately severe outcomes, some of them lead to severe and sometimes life-threatening diseases, particularly in vulnerable populations such as elderly and children (WHO, 2011).

Presence of fecal coliform bacteria in the water serves as a reliable indicator of sewage or fecal contamination of a waterbody (Geldreich & Litsky, 1976). In addition to posing potential human health risks, untreated or minimally treated sewage discharge into aquatic ecosystems contributes to nutrient over-enrichment and can cause eutrophication (Nutrient Pollution, 2019). Although a fecal coliform test would be a more reliable indicator of fecal contamination and possible pathogens in the water, total coliform test was used in this study due to time and monetary constraints.

Sampling Technique

Water samples were collected using sterile standard sampling vials at the depth of approximately 10 cm below water surface. All samples were collected between 10am and 12pm to avoid the time when potential sewage or greywater discharge is high due to residential activities in order to obtain a representative sample of water during the day. Once collected, the samples were tested for two water quality parameters, fecal coliforms and nitrates. GPS coordinates of each test were recorded and stored during the field visit.

Level of nitrates was measured using LaMotte Low Cost Water Monitoring kit (Figure 10). This test is able to indicate the level of nitrates in the water sample in the range from 0 to 40 ppm (indicative color at 5 ppm, 20 ppm, and 40 ppm). The test tubes were filled with a water sample, one tablet of nitrate reagent was added, and the test tube was sealed and immediately stored in a dark container to avoid a reaction from the UV light. Upon returning from the field and within one hour of taking the samples, test tubes were removed from the container indoors and compared to the included color chart. Once the levels were measured, the data was recorded and stored.

Samples were tested for presence or absence of total coliform bacteria using LaMotte Coliform Testing Kit (Figure 10). Total coliform test used in the study detects presence of 20 or more coliform colonies per 100 ml of water. This test detects all coliform bacteria strains, including fecal coliforms. After collection in the field, coliform samples were incubated for 48 hours at room temperature out of direct sunlight. The temperature in the room was kept constant between 22° to 27°C. The samples were not disturbed, handled, or shaken during the incubation period, complying with the manufacturer instructions. Once the levels were measured, the data was recorded and stored. In this study an assumption was made that the higher the amount of gas released during fermentation, the higher is the number of colonies in the sample. This assumption was made for better visual representation of results, but was not based on proven methodologies.

Figure 10. LaMotte Low Cost Water Monitoring kit and LaMotte Coliform Testing kit (Amazon.com, 2019).

Sampling Locations

Water samples were collected on May 24, 2019 at 13 sites: (1) Cole Bay Corner, (2) La Sucriere, (3) Center Cole Bay Lagoon, (4) Bridge Channel (Simpson Bay Bridge Channel), (5) Kim Sha Beach, (6) Airport, (7) Mullet Pond, (8) Porto Cupecoy, (9) Anse aux Cajoux, (10) Nettle Bay, (11) Marina Royale, (12) Center Lagoon (Center Simpson Bay Lagoon), and (13) Causeway (Figure 11). Water testing was done at locations of previous water testing on the Dutch side and in new ones. Locations were evenly distributed around the lagoon. Bridge Channel site where the lagoon enters the ocean, as well as Kim Sha beach, a beach near Bridge Channel, were included to determine whether the lagoon water has any effect on the areas nearby. Photographs were taken at each site (see Appendix).

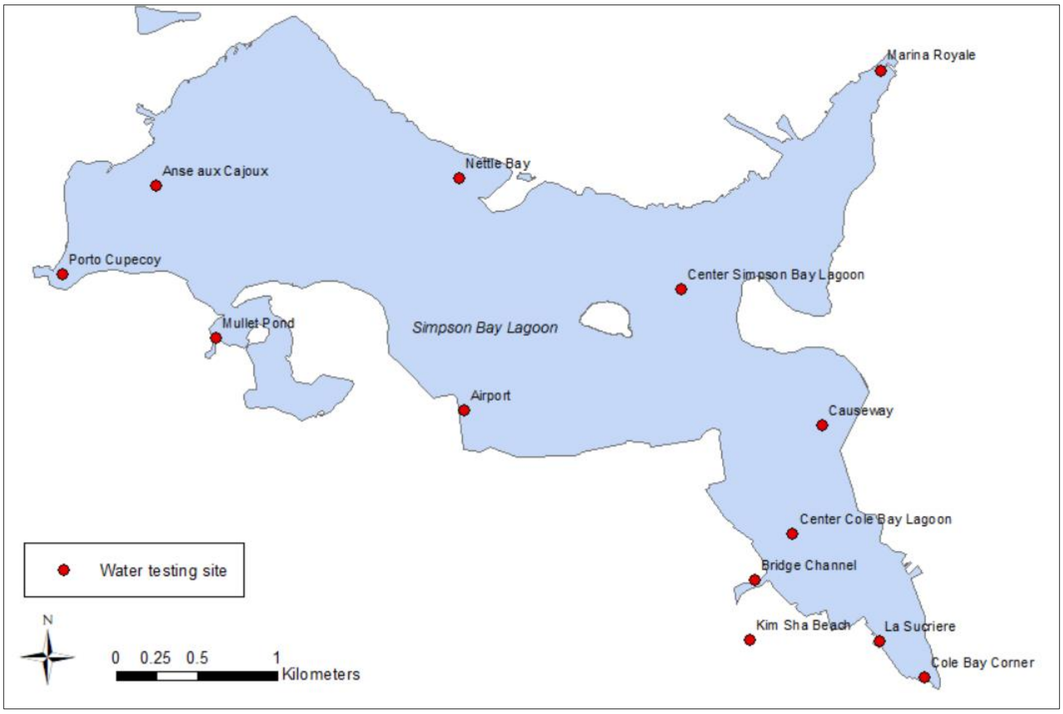

Figure 11. Map of water testing sites.

Data Analysis

New test results were compiled. GPS coordinates were converted from Degrees and Decimal Minutes (DDM) format into Decimal Degree (DD) format. The coordinate system for GIS was chosen as WGS_1984_UTM_Zone_20N, to conform to the projection most frequently used by GIS analysists on the Dutch and French side. Results were then plotted in GIS. Nitrate test results were grouped by the level of nitrate in the sample. Coliform test results were grouped into low, medium, high based on the amount of gas bubbles present in the test tube.

Impacts: Public Perception and Behavior

A household survey was conducted on the island. The survey was designed and carried out by myself and two other ERM master students, Anne Molenaar and Sem Duijndam. The survey consisted of survey questions, a choice experiment, and a contingent valuation sections (see Appendix). Focus groups discussions were held with key informants to obtain feedback regarding survey and choice experiment design prior to implementation. Key informants included EPIC board members, staff of VROMI, Vrije University (VU) PhD researchers, and the VU thesis supervisor.

Choice experiment was used to obtain the residents' WTP (Willingness to Pay) values for each of the attributes. Each of the attributes and their levels were discussed with key informants during focus group discussions. The statistical design of the choice experiment was conducted by Dr. Mark Koetse, a PhD researcher at Vrije University Amsterdam. Dr. Koetse used a d-efficient design with priors based on theoretical expectations with regards to the signs of the coefficients. An efficient design was used instead of an orthogonal design in order to exclude dominant alternatives. This design was generated using the Ngene 1.1.1 software. Each choice experiment was conducted an equal number of times in each neighborhood. Contingent valuation was also used to obtain the residents' individual WTP for environmental management of the lagoon.

A pilot study was carried out in the field on April 22, 2019. It was conducted at 11 households around the lagoon which were chosen at random. Feedback was solicited from respondents after completing the survey with regards to clarity, content, and the length of the questionnaire. During the pilot, it became apparent that the survey was easy to understand and primarily received positive feedback. After the first 2 surveys, no changes were made to the questionnaire. As a result, 9 out of 11 pilot study results were incorporated into the main dataset.

The remainder of the surveys were conducted in the field by three interviewers (myself and the team) for a period of 4 weeks, from April 22 until May 14, 2019. Households were approached from 4:00pm until 7:00pm on weekdays, as well as earlier in the day during holidays and weekends. This time was chosen in order to target the time when most of the household members were at home. Stratified sampling was used to determine the number of surveys necessary for each neighborhood. The number of surveys was determined based on the population of each neighborhood relative to the total population of the study area. The number of surveys in most neighborhoods relative to the total number of surveys is similar to each neighborhood's population relative to the study area population (Table 1). Thus, the number of surveys conducted is representative of the relative size of each neighborhood.

Municipal Area	Number of respondents	Percentage	Population	Percentage
Dutch side				
Cole Bay	89	80.91%	7,194	79.54%
Simpson Bay	13	11.82%	1,142	12.63%
Maho-Low Lands	8	7.27%	708	7.83%
Total	**110**		**9,044**	
French side				
Terres Basses-Baie Nettle-Sandy Ground	43	56.58%	4,627	25.66%
Marigot-Diamant-Bellevue-Concordia-Agrement	33	43.42%	13,405	74.34%
Total	**76**		**18,032**	

Table 1. Population and number of surveys conducted in each neighborhood inside the study area.

Within each neighborhood, the team aimed at simple random sampling by knocking on every third door. When this was not possible due to unapproachable houses, the interviewers relied on convenience sampling by approaching the next available house. In total, 219 surveys were conducted on the island. 131 surveys were conducted on the Dutch side and 88 surveys were conducted on the French side.

Primary sample area was determined to include all towns neighboring the lagoon (Figure 12). Similar to other parts of this study, study area was determined by looking at the mountain ridges surrounding the lagoon and including only households located on the same side of the ridge as the lagoon. This was done in order to target the population living close to the lagoon and benefitting from its ecosystem services. 186 surveys were conducted in the study area, which comprises 84.9% out of the total surveys (Figure 13). Additionally, 33 surveys were conducted outside of the primary sample area which is 15.1% out of the total surveys conducted.

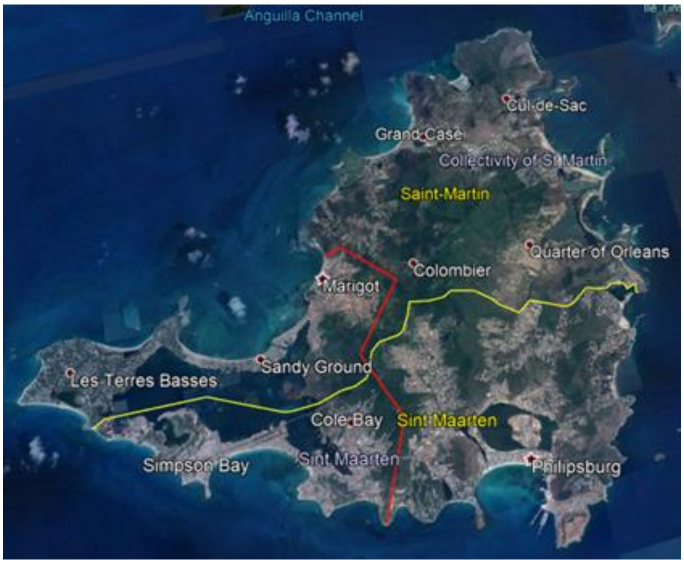

Figure 12. Study area for the household survey.

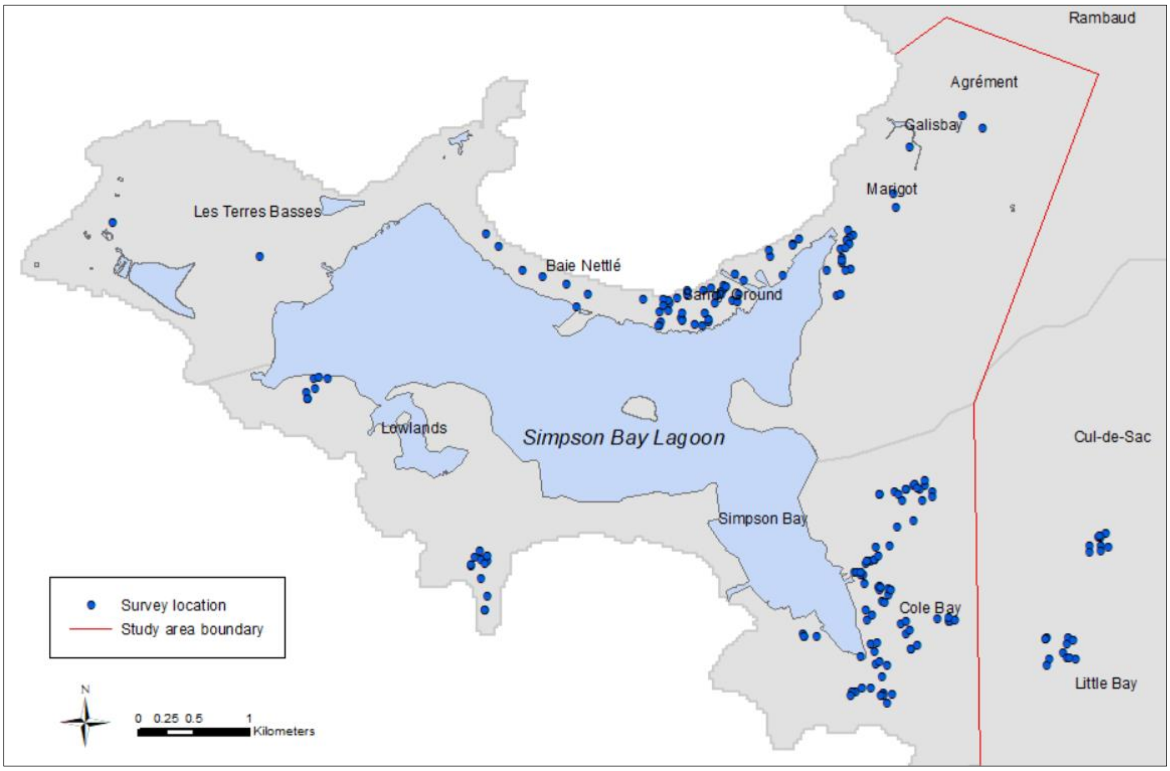

Figure 13. Map of survey locations within the study area.

English and French versions of the survey were created. Three French-speaking interviewers were hired to conduct surveys on the French side of the island and conducted 38 surveys. The survey results were closely monitored for errors by the research team.

Results of this survey were analyzed using SPSS software. The results of the choice experiment were analyzed by the research team and Dr. Mark Koetse in NLOGIT software, using the random parameter logit model with 1000 random draws. Using this model, it is possible to generate the individual WTP estimates for each respondent in the sample. Only those respondents that made at least two choices out of six were included in the model in order to provide more reliable individual estimates. As a result of this analysis, it is possible to calculate the average sample WTP values by calculating the average of the individuals' WTP values.

Responses: Proposed Solutions

The outcome of the investigation into the main pressures, state changes, and impacts was combined in an integrated assessment. An extensive list of responses, based on a literature review, was included in the conceptual framework at the onset of the study; these were investigated in the context of the study findings and only key responses were selected. These responses are the final stage of the DPSIR assessment and form the basis for proposed solutions and policy recommendations.

4. Results and Discussion

4.1 Pressures: Pollution Sources

Sewage Discharge

Domestic sewage pollution

Currently, the main source of pollution in the lagoon is untreated or minimally treated sewage that is discharged directly into the lagoon from land-based point sources, such as households and businesses neighboring the lagoon (Nature Foundation, 2018). Sewage and sanitation services at St. Maarten currently are not available all across the island. There is a sewage treatment plant on the Philipsburg area of St. Maarten, but it only services a small percentage of the population. However, areas surrounding the lagoon, including, Cole Bay, Simpson Bay, Maho, Low Lands, and Cupecoy, do not have an access to an industrial wastewater treatment plant (Quick Scan, 2016). Residents of these areas rely on cluster septic systems which service multiple houses or apartments buildings at the same time.

Septic systems are underground wastewater treatment structures which use a combination of nature and technology to treat wastewater from bathrooms, kitchen drains, and laundry (EPA, 2018). A typical septic system consists of a septic tank and a drainfield, or soil absorption field. The septic tank holds the wastewater long enough to allow solids to settle down to the bottom, while oil and grease floats to the top. Solids, oil, and grease remain in the septic tank. Only the liquid wastewater (effluent) then exists the tank into the drainfiled area (Figure 14). The drainfield is typically an excavation made in soil where the wastewater is discharged and filters through the soil. The soil treats the effluent, naturally removing harmful bacteria, and ultimately discharges the effluent into the groundwater (EPA, 2018). Figure 15 shows a typical cluster septic system which is commonly used to collect wastewater from a group of buildings.

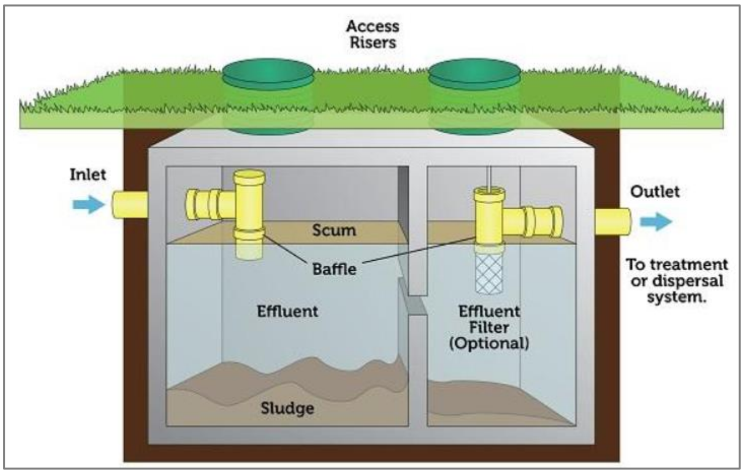

Figure 14. Standard septic tank (EPA, 2018).

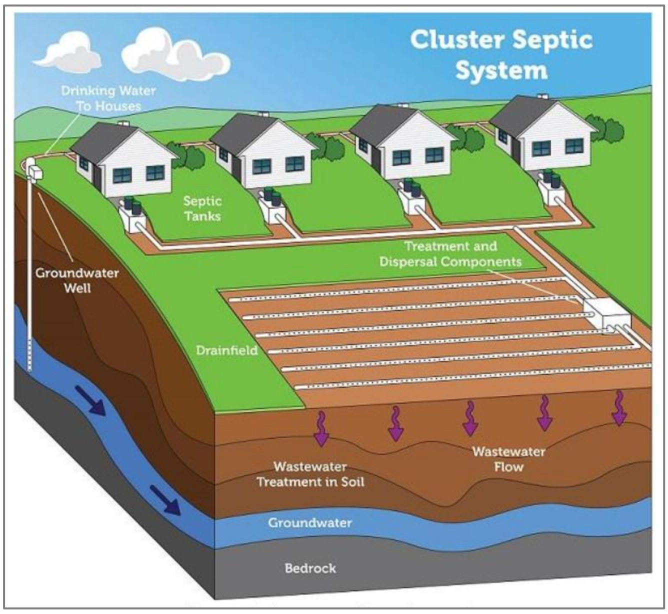

Figure 15. Cluster septic system (EPA, 2018).

If the drainfield receives too much liquid, it can flood, leading to sewage flowing to the ground surface or creating backups in toilets and sinks (EPA, 2018). Additionally, the septic tank itself should be properly maintained and emptied out regularly depending on the household size, volume of waste generated and the size of the septic tank. If the tank is not emptied out on time or is damaged, raw untreated sewage would flow to the ground surface with the effluent.

According to reports by EPIC, Nature Foundation, and St. Maarten's news outlets, and after inspecting storm drains and areas near the houses next to the lagoon, it is evident that septic tanks on the island regularly overflow. A study was conducted in 2009 by EPIC which focused on sewage pollution of the lagoon. In the study, the largest storm drains on the Dutch side were identified and water was tested for fecal coliform bacteria. All sites near residential areas on the Dutch side tested positive for fecal coliform (Lips & van Slooten, 2009). In the current study, an inspection of Cole Bay area in particular yielded similar results. On a dry day with no rain, the storm drains in Cole Bay contained sewage. The water had a constant flow, was of dark color and had the odor of sewage (Figure 16). Additionally, at multiple locations, sewage or greywater was seen flowing directly from behind the house down the slope and into the storm drain leading directly into the lagoon. Refer to Appendix for other photographs of sewage on the island.

On the French side, there is a sewage treatment plant to which most areas are connected. Residents of Marigot, Sandy Ground and Les Terres Bases are connected to water treatment stations, which are linked to the municipal sewage network, leading to the sewage treatment station at Les Terres Bases (Figure 17). However, there is no strict government oversight over the maintenance of water treatment stations and thus there is a possibility that they also don't function properly. According to a report by the French government, the current infrastructure on the French side of the island is on the whole insufficient (The Government of St. Maarten, 2014).

Figure 16. Storm gutter with sewage in Cole Bay, May 2019.

The population, and thus the number of people around the lagoon that need sewage treatment services, is described in Table 2. Based on the latest census, the total population was 9,044 on the Dutch side in 2017 and 18,032 on the French side in 2015 (Department of Statistics Sint Maarten, 2019; INSEE, 2018).

Municipal Area	Population
Dutch	
Cole Bay	7,194
Simpson Bay	1,142
Maho-Low Lands	708
Total	**9,044**
French	
Terres Basses-Baie Nettle-Sandy Ground	4,627
Marigot	3,599
Saint-James-Diamant-Bellevue	2,029
Spring-Concordia	5,613
Galisbay-Agrement	2,164
Total	**18,032**

Table 2. Population of Dutch and French areas around the lagoon (Department of Statistics Sint Maarten, 2019; INSEE, 2018).

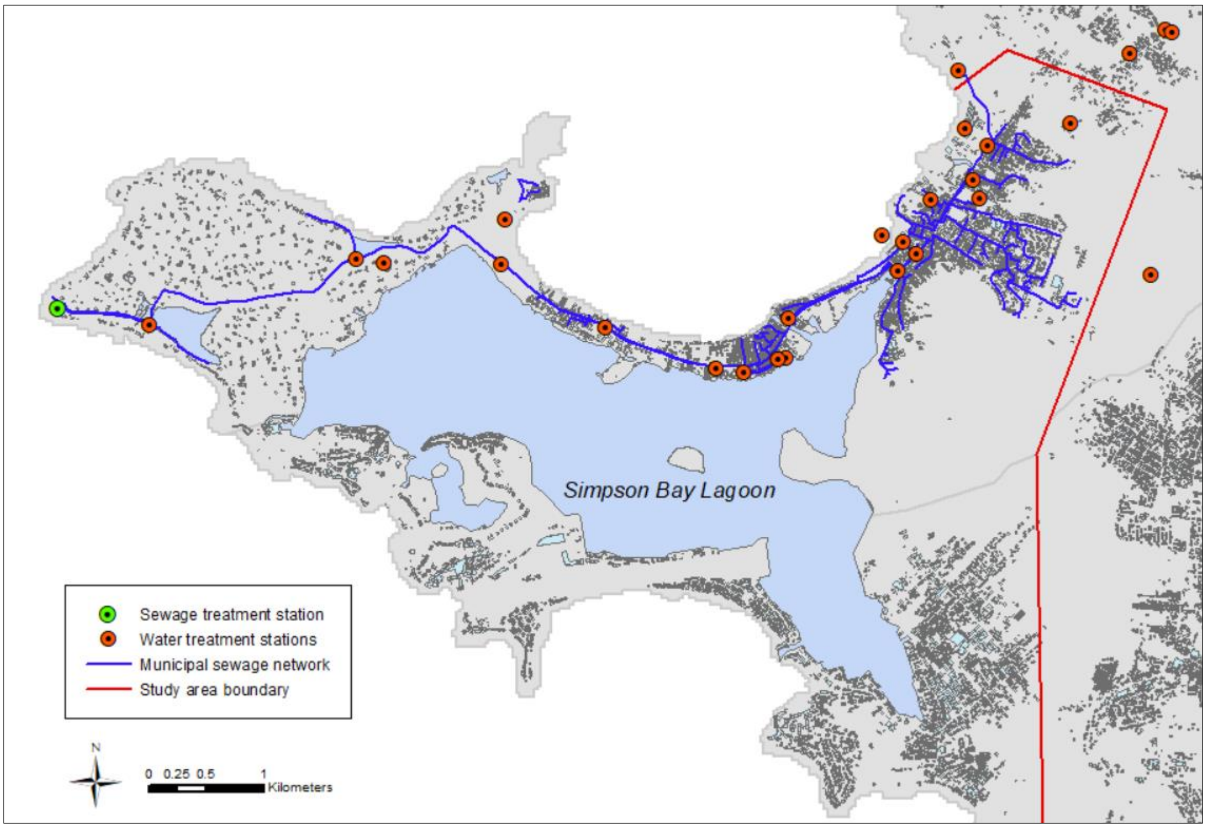

Figure 17. Map of water treatment stations and municipal sewage network, connected to a sewage treatment station on the French side of the lagoon (DEAL, 2019).

With regards to future predictions, the VROMI ministry report have estimated the following figures for the volume of waste. For the Dutch side near the lagoon, the total daily estimated flow was projected to be 3,800 m^3/d by the year 2054. This figure is based on the expected growth rate of the urban population, increase in commercial infrastructure, and hotel stays, and corresponds to a biological pollution load of around 31,000 p.e. (population equivalent) (Quick Scan, 2016). For the French side of the lagoon, the following volume of waste was estimated, based on limited population data or limited data with regards to extension of the existing sewage system. Assuming that the existing sewerage system is not extended and the population growth rate in the area of 0.5% per year, total estimated daily flow of 1,200 m^3/d was estimated by the year 2054, with an estimated capacity need of 9,800 p.e. (Quick Scan, 2016).

Sewage polluted water causes harm to marine ecosystems. In addition to discharging into the lagoon, the sewage-contaminated water poses an additional health risk. There are several freshwater wells on St. Maarten that have brackish water from the lagoon (Bervoets, 2019). Fecal contamination of the lagoon water would lead to contamination of drinking water wells and cause significant health problems. There is evidence of commercial companies using a freshwater well in Cole Bay area, St. Maarten, to supply water to residents not connected to municipal waterline during a drought season (Bervoets, 2019). Such contaminated water poses a significant health risk as well as has a negative effect on coastal water quality that is important for tourism (Sint Maarten National Recovery, 2017).

Sewage from boats

Sewage from boats is another possible source of pollution. Currently, there are no restrictions on the vessels entering the lagoon with regards to their sewage disposal. Environmental laws mandate that boats are not allowed to dispose of any foreign matter in the lagoon (Sint Maarten, 2019c). However, there is no specific clause regarding sewage disposal. Vessels are not required to empty out their septic tank prior to entering, put a coloring agent into their septic tank, or put a lock on their septic tank that would prevent them from emptying it out into the water, as other international laws require (Sint Maarten, 2019c). In addition, there is no sewage pump out service currently provided to the boat owners (Bervoets, 2019). The marine industry is a backbone of St. Maarten's economy, bringing in an approximate 12.5% of the GDP (Deher, 2019). It is an area of high traffic, with the latest figures estimating the number of vessels entering the lagoon to be 3,514 vessels in 2015 and 3,504 vessels in 2016 (SLAC, personal communication, June 27, 2018).

Sewage from hotels and businesses

There are a number of hotels located near the lagoon. Direct sewage and greywater discharge has been an ongoing issue on the Dutch side of the island, with Nature Foundation receiving eyewitness accounts of this issue several times (Nature Foundation, 2018). Similarly, hotels close to Kim Sha Beach have been discharging greywater directly into the ocean (Nature Foundation, 2019a). Particularly on the Dutch side of the lagoon, in Simpson Bay and Cole Bay areas, there is a large number of restaurants, cafés, and other types of businesses. None of these businesses are connected to a wastewater treatment system and rely on septic tanks for their sewage treatment. Waters close businesses located in Cole Bay have tested positive for fecal coliform in the past (EPIC, 2009). According to VROMI report, in some places on the Dutch side, raw sewage is being directly pumped into the lagoon from residences and business alike (Quick Scan, 2016).

Sunken Boats

During Hurricane Irma, approximately 200 boats sank on the Dutch side and 200 on the French. Currently, approximately 150 boats have been salvaged on the Dutch side. Boats were salvaged with government assistance as well as by private owners (Bervoets, 2019). There was a government ban on salvaging the boats by private owners, which significantly delayed their removal and caused irreparable damage, with most boats losing their value as a result. Additionally, the longer the boats remained in the water, the more they were leaking sewage, battery acid, and other chemicals into the lagoon (Hodge, 2018). Approximately 50 boats still remain in the lagoon, contributing to lagoon pollution, with the government still working on removing them (Bervoets, 2019). Exact data on the number of boats is missing for the French side of the lagoon, with the exception of their location. Figure 19 shows the areas where most sunken boats were towed after the hurricane and currently await removal. This figure does not include the sunken boats from previous hurricanes, such as wrecks near Little Key.

Figure 18. Sunken boats in the lagoon.

Figure 19. Location of most sunken boats in the lagoon.

Development & Mangrove Destruction

Mangroves carry out many important ecological functions. Mangrove roots serve as breeding habitat for fish and other marine species, while the branches serve as a habitat for birds and food for pollinators. Additionally, mangroves have an important water purification function, with the plants, sediments, and microbial metabolism able to remove pollutants from the water (Kim *et al*., 2016). As a result, mangroves around the world are studied as a nature-based solution for wastewater treatment (Ouyang & Guo, 2016).

However, on St. Martin, there has been an overall trend of mangrove destruction, with natural areas being replaced with construction and new development. Due to extensive development around the lagoon, 90% of the original mangroves have been destroyed (EPIC, 2019a) (Figure 20). The only remaining areas on the Dutch side are inside Mullet Pond, near the Causeway, and on Little Key. Remaining mangroves on the French side are near Anse aux Cajoux and near the Causeway on a private plot of land.

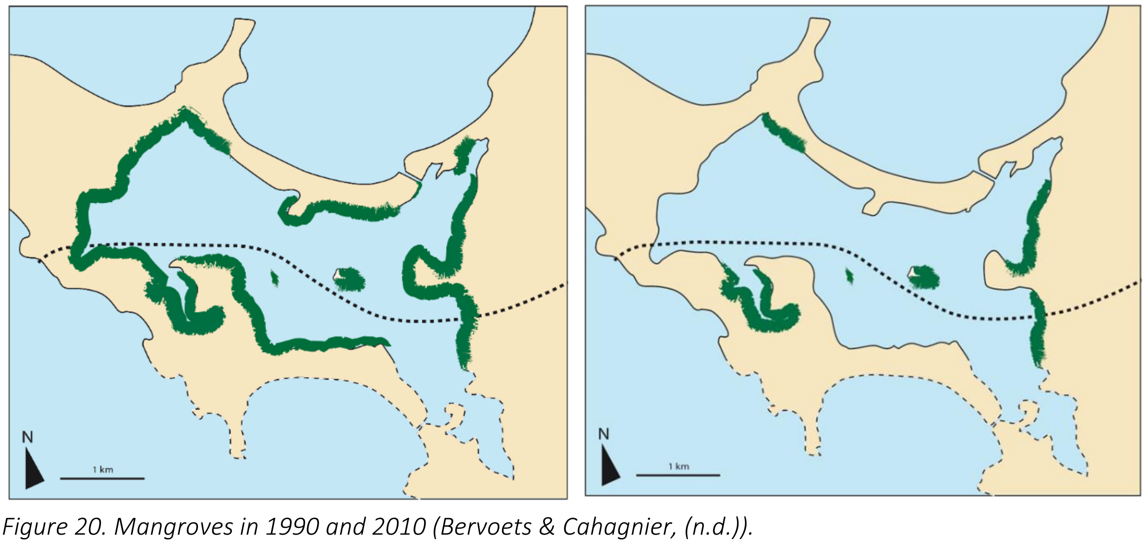

Figure 20. Mangroves in 1990 and 2010 (Bervoets & Cahagnier, (n.d.)).

Construction plans around the lagoon are ongoing and almost never consider the environmental impact. In particular, the Dutch side of the lagoon has been extensively developed, while the French side still has a lot of remaining natural areas, though few remaining mangroves. Figure 21 shows multiple development projects around the lagoon, including already completed construction of the Causeway and filling in near Princess Juliana Airport, and a marina project for Mullet Pond. The French side has plans for creating a "route of friendship" which would lie directly through a natural area, a connecting bridge between Marigot and Sandy Ground, a new passage for the lagoon near Sandy Ground, and a project for a new port in Les Terres Basses/Sandy Ground. All these projects involve destruction of natural habitat, as well as extensive dredging and filling in which damage fragile natural areas and cause water pollution from sedimentation, increased activities, and disruption in the existing aquatic ecosystems. Figure 22 shows the ongoing dredging projects in the lagoon in 2017.

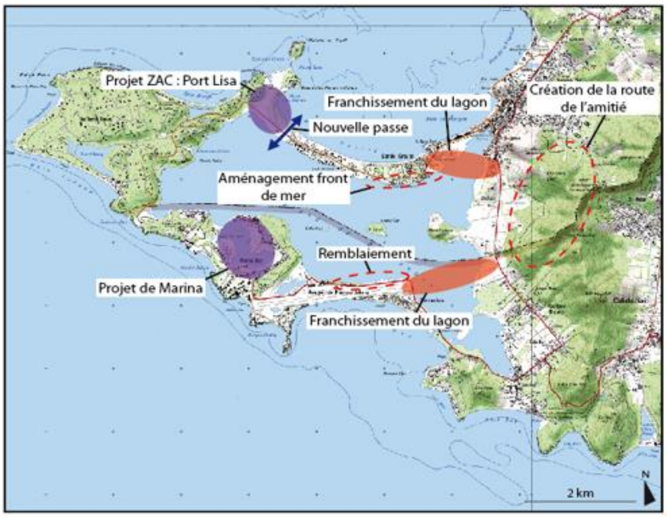

Figure 21. Planned development projects (Bervoets & Cahagnier, (n.d.)).

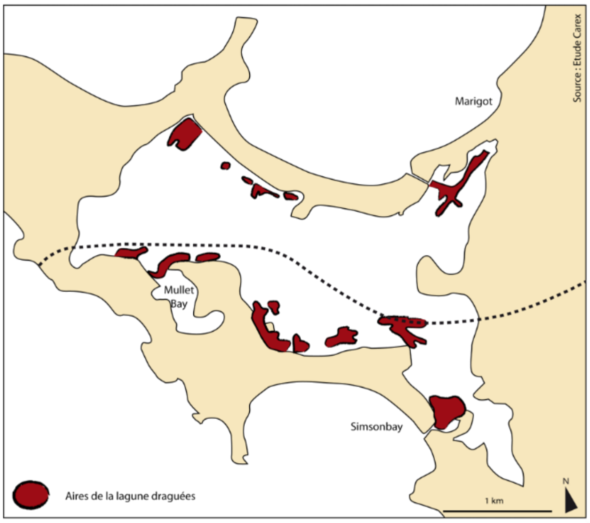

Figure 22. Dredging around the lagoon (Bervoets & Cahagnier, (n.d.)).

Domestic Waste Pollution

Domestic waste pollution is an additional issue for the lagoon. Although it is illegal to litter and leave waste on the side of the road in St. Martin, it is very common as many roads are lined with litter (Sint Maarten, 2019d). An EPIC study addressed this issue in more detail (Vang, 2008). Heavy rains and winds can transport domestic waste towards the water or into the drains which lead into the lagoon. Household litter can include not only biodegradable products, but also plastics, electronics and hazardous chemicals such as oils and paints (Vang, 2008).

Recycling and waste separation on the Dutch side of the island is limited, with the bulk of household waste deposited at the Philipsburg landfill. There are recycling facilities near Philipsburg, but none located near the lagoon. There are small initiatives around the island which can be difficult to locate and have limited recycling capabilities. Proper separation and recycling at those facilities can also be ineffective (Thompson, 2019). On the French side, there are currently two recycling facilities, with one of them located in Marigot close to the lagoon (Que faire de vos déchets? (n.d.).). However, as evident by visual account, littering and debris pollution is still a very pressing problem for this area.

Figure 23. Plastic pollution.

Toxic Chemical Pollution

The lagoon is the center for the boating and yachting industry of St. Maarten, comprising 12.5% of its economy. There are approximately 15 large docks and marinas and 5 boatyard areas situated on the lagoon (Figure 24). These are areas of land where boats are stored, built, and fixed. A lot of the vessels such as megayachts and sailboats come to St. Maarten for repainting and fixing before the high season starts (Bervoets, 2019). There is evidence that instead of using dry docks for painting and other boat repair, boat owners frequently complete this work on the water at the marina or in the lagoon where boats are anchored. On two occasions during this study, boats were seen being painted right on the water. This leads to toxic chemicals such as paints and other products being discharged directly into the water (Nature Foundation, 2019a).

Additionally, on St. Maarten, there is no prohibition on many marine products which are banned in other countries, such as in Europe and the U.S. These products are used for boat protection and cleaning and often contain toxic chemicals which have been proven to be harmful to marine ecosystems and humans. In particular, antifouling self-polishing copolymer (SPC) paints and paints containing copper are still widely sold on St. Maarten. Antifouling paint is a specialized category of coating that is applied to the hull of a boat in order to slow biofouling. Biofouling is the process through which aquatic organisms, such as barnacles and algae, attach themselves to the vessel, slowing down its performance and causing corrosion (Almeida *et al.*, 2007). The self-polishing copolymer paints contain a polymer which dissolves in the water, releasing tributyltin (TBT). TBT destroys the fouling organisms and at the same time makes the surface of the boat smoother. SPC paints were widely used until it was discovered that TBT is toxic to other marine organisms at very low concentrations. Beginning in the late 1970s, several instances of fishery collapse in France and UK have led to research into TBT which concluded that TBT is toxic to a wide range of marine species, ranging from plankton to cetaceans, is a powerful endocrine disruptor, and bioaccumulates in fish species, having implications for human health (Langston, 2006). As a result, SPC paints containing TBT polymer have been banned across the world. The EU banned TBT-based antifouling paints for ships hulls in all EU ports in 2008. The International Convention on the Control of Harmful Antifouling Systems on Ships (AFS Convention) has entered into force in 2008 banning globally both the application and presence on ships hulls of TBT-based antifouling paints (Focus on IMO-Anti-fouling systems, 2013). Although this substance in banned by international organizations, it is still widely used in the Caribbean (see Appendix).

The majority of antifouling paints also contain copper, usually as cuprous oxide (Cu2O). Currently paints containing copper are the main source of copper loading in the marine environment (Valkirs *et al*., 2003). In marine environment, copper leads to a variety of responses associated with heavy metal toxicity (Valkirs *et al*., 2003).

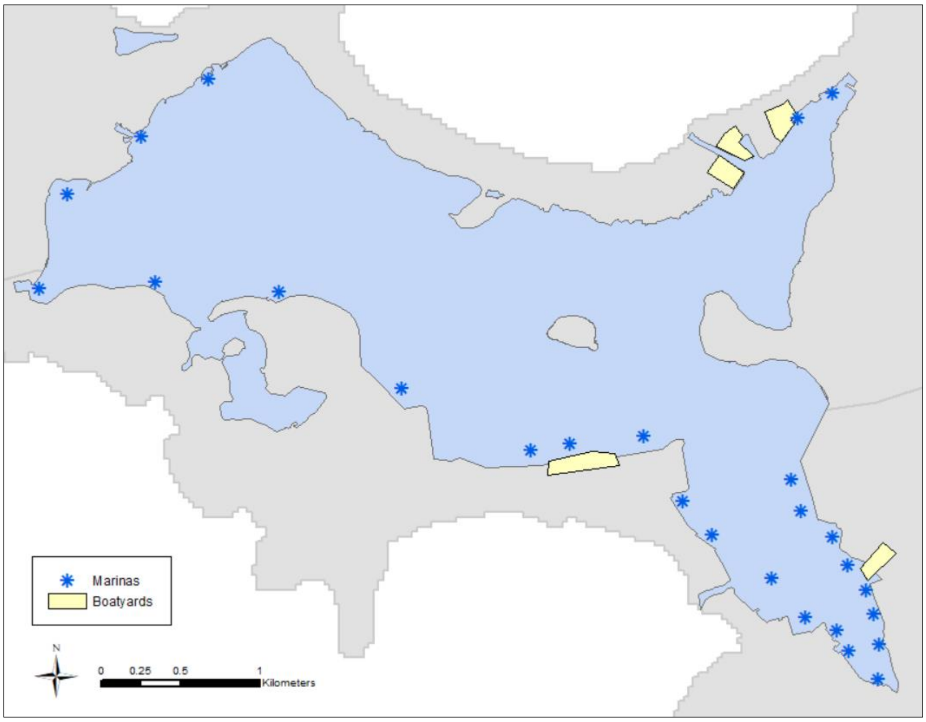

Figure 24. Boatyard and marina locations around the lagoon.

Discussion

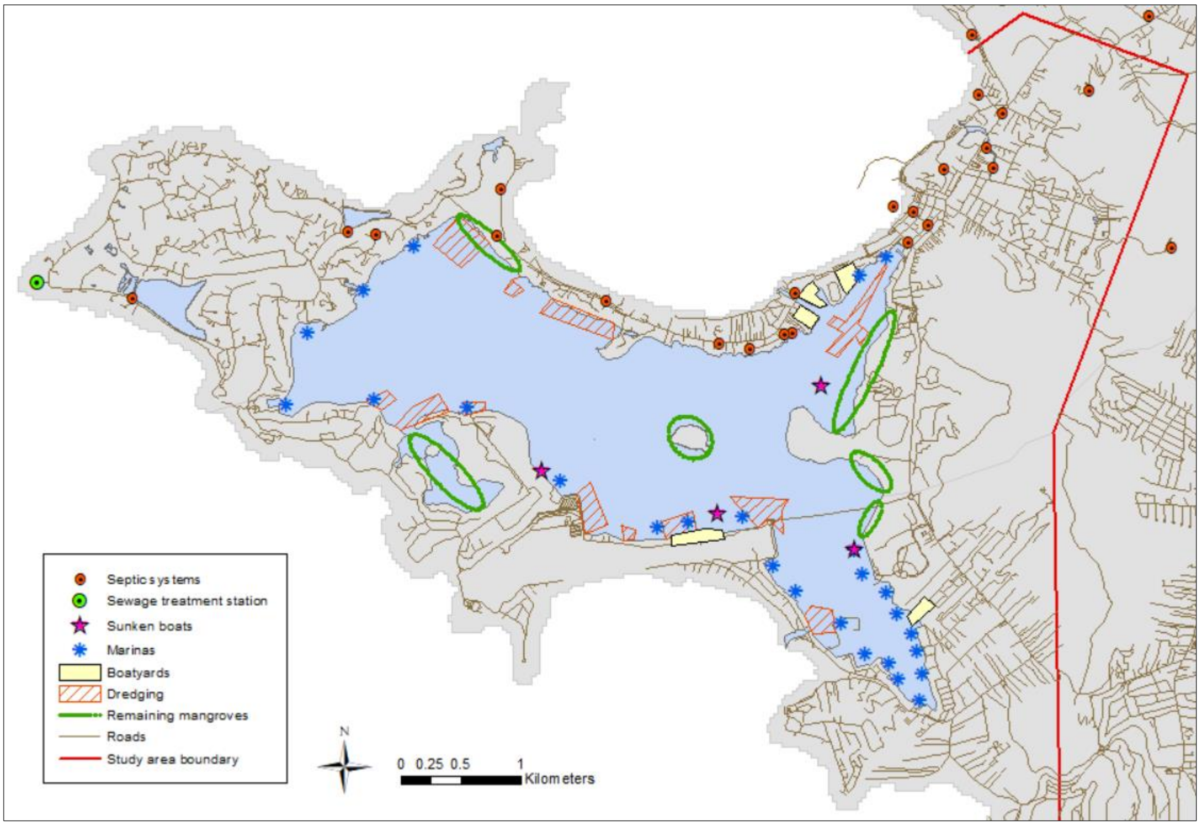

Figure 25. All anthropogenic pressures combined. (Note: Due to limited data, only the septic systems and sewage treatment station on the French side of the lagoon are included.)

All of these anthropogenic pressures combine and interact with each other, having a detrimental effect on water quality in the lagoon and on the aquatic life that inhabits it. Figure 25 shows all of the pressures. With regards to sewage pollution, the figure is showing septic systems and sewage treatment station on the French side, as well as roads as indicators of urban areas on the French and Dutch sides. Furthermore, sunken boats and marinas are depicted which contributed to sewage pollution, as well as to toxic chemical pollution. Locations of boatyards and marinas are shown around the lagoon, as well as areas where dredging is taking place. Roads are included as a proxy for plastic and domestic waste pollution as it primarily aggregates on the sides of the roads and in storm gutters. Finally, areas of remaining mangroves are shown.

From this map, it is evident that most of the areas around the lagoon are under intense pressure from urban and commercial activities. In particular, the area of Cole Bay is one of the most densely populated areas around the lagoon, and directly surrounds the Southern tip of the lagoon. In this area, there are approximately 13 small and medium-sized marinas, a boatyard, dredging, and some sunken boats, but most importantly, it is surrounded by a population of approximately 7,200 people that have no access to the municipal sewage treatment plant. Another area of high pressure is near the airport, where extensive filling in and dredging is taking place, approximately four marinas are located, there are two boatyards, and sunken boats.

With regards to the French side of the island, the area of Marigot and eastern part of Sandy Ground experiences significant pressures. In this area, there are several marinas, three boatyards, extensive dredging, marine traffic from boats exiting and entering the lagoon, as well as sunken boats.

Additionally, water treatment stations are located here as well as the connections to the municipal sewage treatment plant, and an urban population of approximately 12,000 in Marigot and its vicinity.

The only natural areas remaining are on the eastern side of the lagoon, on the French and Dutch side, in Mullet Pond, and near Anse aux Cajoux. These areas, however, are close to sunken boats, marinas, as well as areas being dredged and filled in nearby. This figure shows that there are no natural areas remaining which are completely unaffected by human presence.

4.2 State Changes: Water Pollution

Previous Water Test Results

Nature Foundation

Nitrate-Nitrogen (NH_3) Test Results

Nature Foundation has been monitoring water quality in the lagoon for the past 6 years. In particular, tests of water quality in and around the lagoon were conducted in 2013, 2018 and 2019. Several sites on the Dutch side were monitored for the level of nitrates, phosphates, nitrogen, dissolved oxygen, PH, temperature, and the presence or absence of total coliform bacteria (Nature Foundation, 2013a; 2018a; 2019).

Level of nitrate was tested at four sites in or near the Simpson Bay Lagoon: (1) Cole Bay Lagoon, (2) Kim Sha Beach, (3) Mullet Pond, and (4) Bridge Channel (Simpson Bay Bridge Channel) (Figure 26). All sites exhibited a normal level of nitrate, below 1 mg/l, with only Bridge Channel site showing an elevated level of nitrates of 7 mg/l (Figure 27).

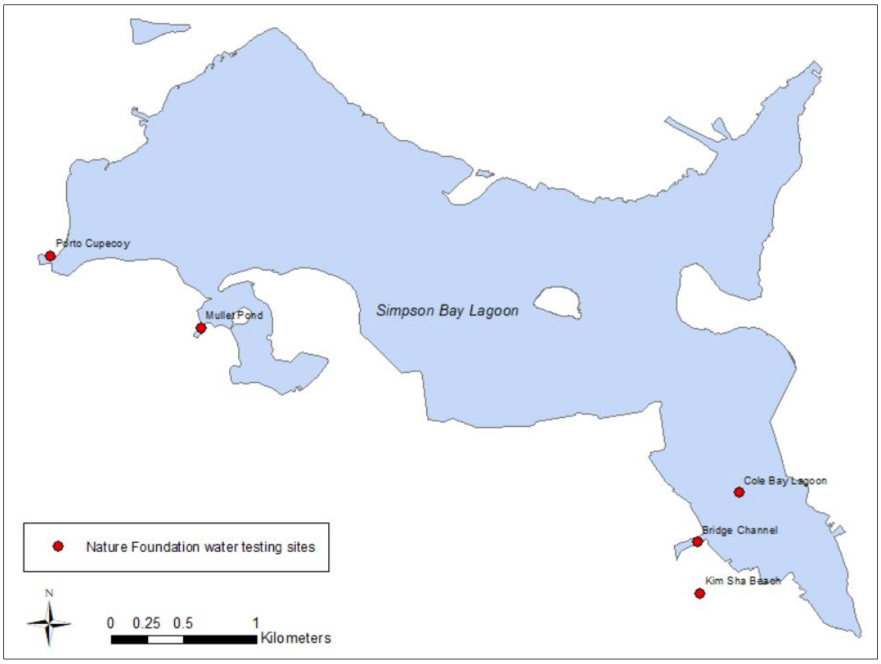

Figure 26. Nitrate and coliform water test locations in and near Simpson Bay Lagoon (Nature Foundation, 2013a; 2018a; 2019).

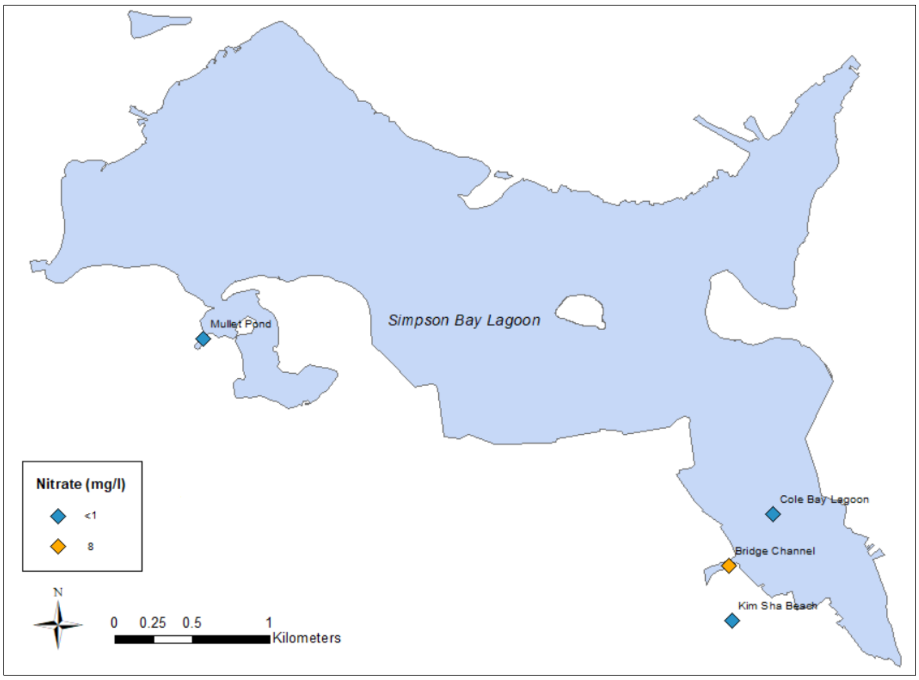

Figure 27. Nitrate test results (Nature Foundation, 2013a; 2018a; 2019). Normal level of nitrate-nitrogen is below 1 mg/l, water is toxic to some fish at 4 mg/l (Nature Foundation, 2013a).

Total Coliform Test Results

Total coliforms were tested in 2013, 2018 and 2019. They were tested at the following sites: (1) Cole Bay Corner, (2) Kim Sha Beach, (3) Mullet Pond, (4) Bridge Channel (Simpson Bay Bridge Channel), and (5) Porto Cupecoy (Figure 26). In 2013, Bridge Channel site tested positive for coliforms. Cole Bay Corner and Kim Sha Beach tested positive for total coliforms in 2018, while Mullet Pond tested negative. In 2019, Porto Cupecoy and Kim Sha Beach tested positive for total coliforms (Figure 28).

An additional site, a drinking well in Cole Bay, has also tested positive for total coliform in 2019. This well receives brackish water from the lagoon. During periods of drought, when cisterns on which approximately 30% of the residents in Cole Bay area rely for drinking water dry out, commercial companies sell drinking water to some residents. In this case, a company was seen pumping the water from this fresh water well. The well water tested positive for total coliform, which means that there is a threat of water contamination with fecal coliform and associated fecal bacteria, which pose a significant health risk to population.

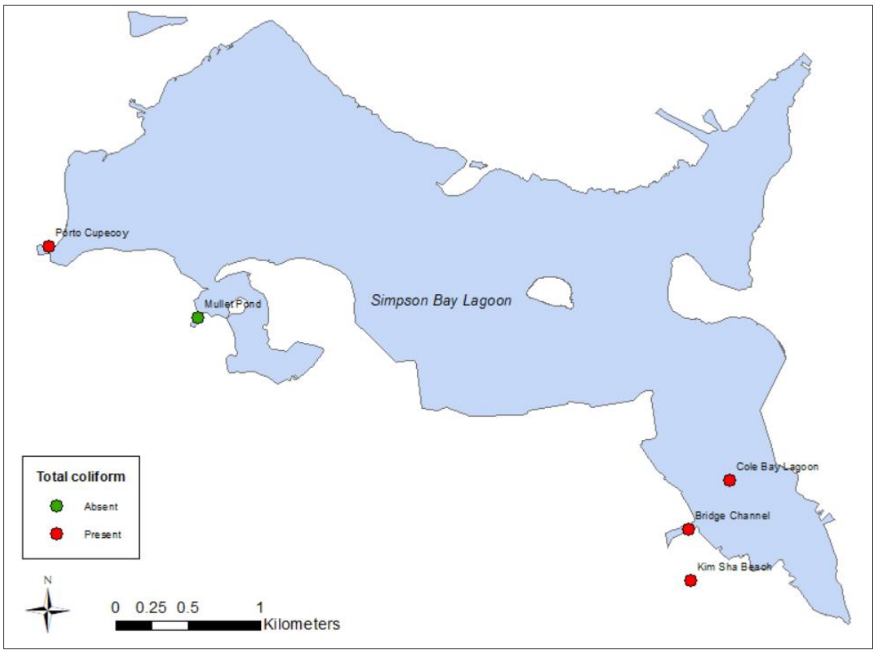

Figure 28. Total coliform test results (Nature Foundation, 2013a; 2018a; 2019).

EPIC Water Quality Tests

A study was conducted by two bachelor students from the Van Hall Larenstein, University of Applied Sciences in conjunction with EPIC in 2009 (Lips & van Slooten, 2009). This study identified the areas with the highest of amount of pollution in the lagoon and used lab testing to measure the level of total coliform, fecal coliform, Enterococci species, Staphylococcus aureus, salinity, temperature, chlorine, nitrate, nitrite, phosphate, and ammonia. For the sake of comparison, in this study only some results were included, in particular, only for total and fecal coliforms and only taken at similar geographic locations in the lagoon as in Nature Foundation tests and in the current study (Figure 29).

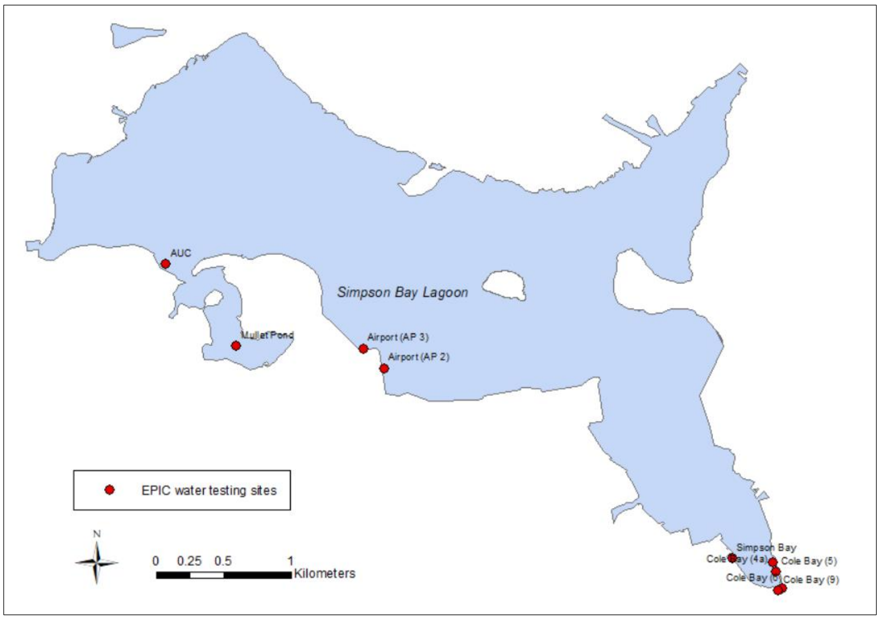

Figure 29. EPIC water testing sites (Lips & van Slooten, 2009).

Total coliform test results

Summary of total coliform and fecal coliform results from 2009 study is as follows. All sites, including Mullet Pond, tested positive for total coliform bacteria (Figure 30). In particular, Cole Bay corner sites exhibited a very high level of total coliform contamination, that of higher than 2,400 colonies per 100mg. Sites at Cole Bay La Sucriere and Airport also had high presence of total coliform bacteria (Figure 30). Two pipes at the Airport (AP 3 and AP 4) showed a medium presence of total coliform bacteria, while Airport site 1 and Mullet Pond exhibited a relatively low level of total coliform (Figure 31).

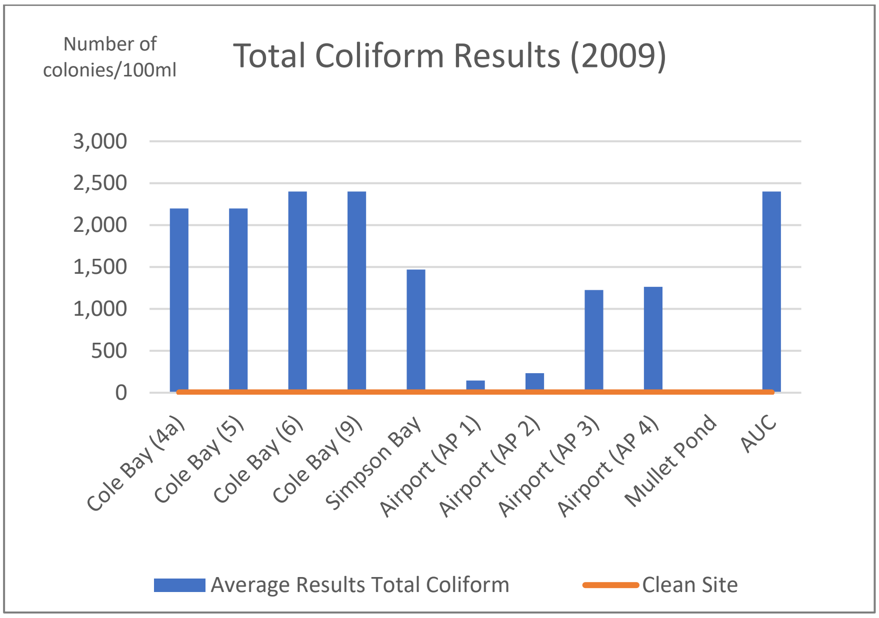

Figure 30. Total coliform results (Lips & van Slooten, 2009).

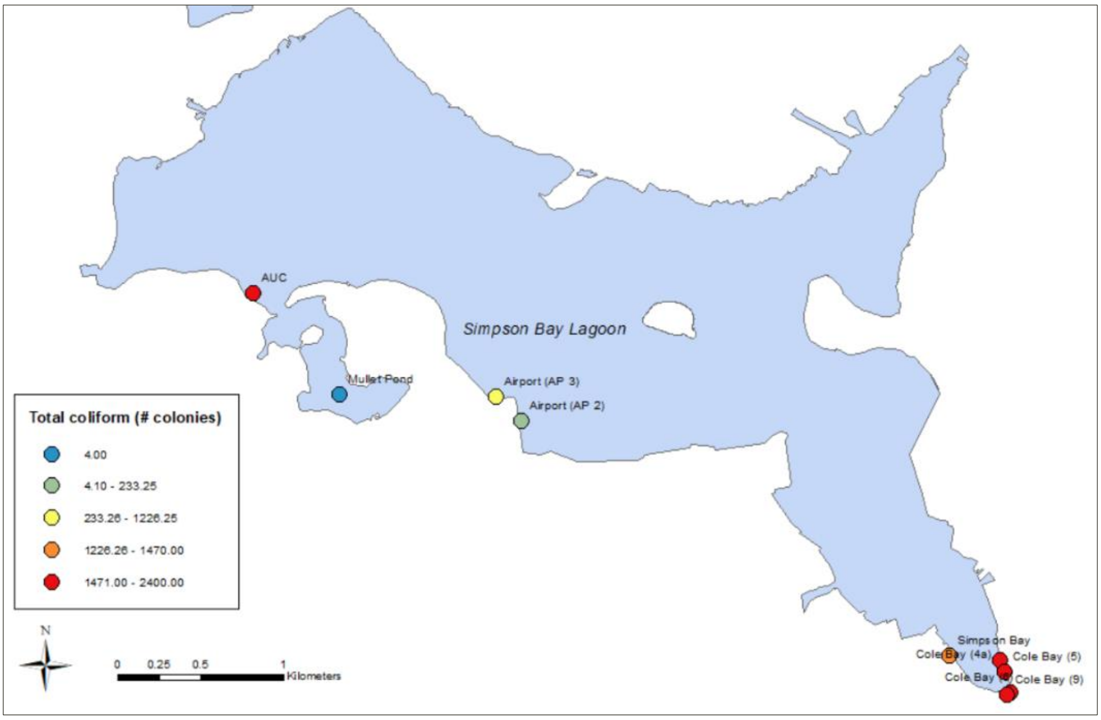

Figure 31. Map of total coliform results (Lips & van Slooten, 2009).

Fecal coliform test results

With regards for fecal coliforms, a better indicator of fecal contamination, only Mullet Pond site showed results lower than the norm set by Ministry of the Netherlands Antilles of 200 colonies per sample (Lips & van Slooten, 2009). All other sites had very high levels of fecal coliform, with some sites having too many colonies to count. In particular, areas in Cole Bay (Cole Bay 4a and 5) exhibited an extremely high level of fecal coliform (Figure 32). Site at Cole Bay 4a had an average count of approximately 110,000 colonies per 100 ml. Site at Cole Bay 5 had a level of coliform equal to approximately 10,000 colonies per 100 ml (Figure 33).

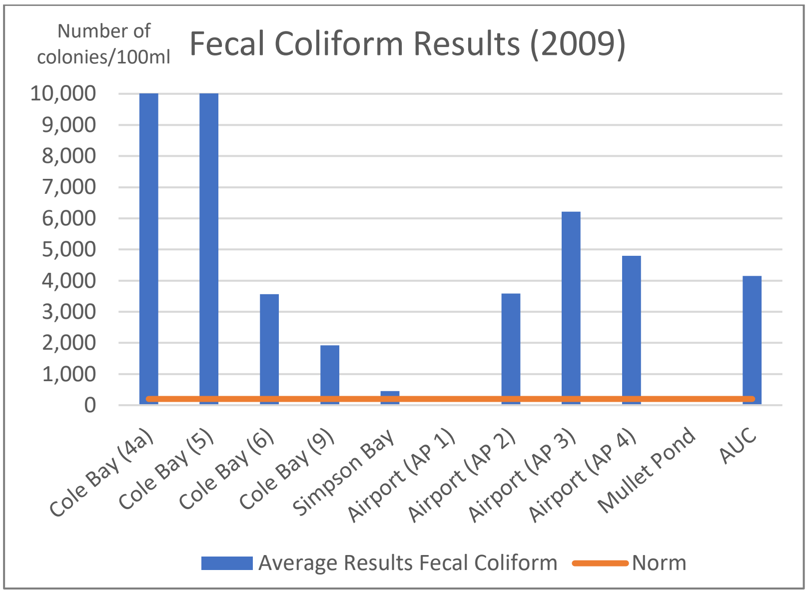

Figure 32. Average results for fecal coliform, capped at 10,000 colonies for better visual representation. Acceptable level of fecal coliform for bathing water is 200 colonies/100mg (Lips & van Slooten, 2009).

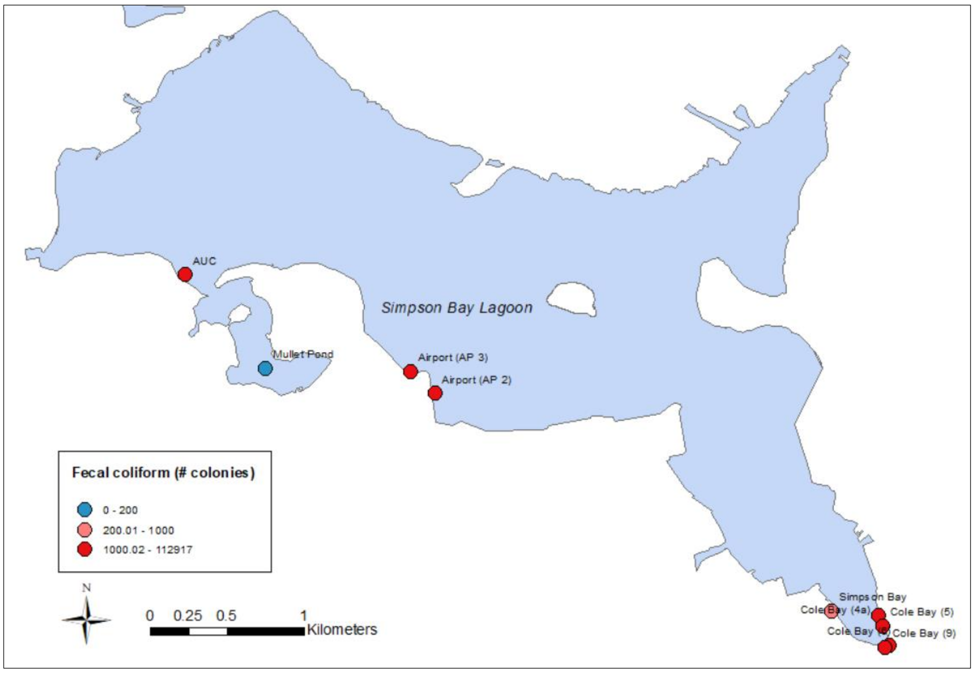

Figure 33. Map of fecal coliform results. Acceptable level of fecal coliform for bathing water is 200 colonies/100mg (Lips & van Slooten, 2009).

New Water Test Results

Total Coliform Test Results

Figure 34 and 35 show coliform and nitrate test results. All sites tested *positive* for total coliform bacteria. A surprising result was the presence of coliform bacteria at the Mullet Pond site. Sites had a different number of bacteria colonies that grew over the 48 hours, with some sites having visibly larger amount of gas bubbles, indicating a larger number of colonies. As a result, results were visually rated on a 3-point scale from low to high based on the amount of gas bubbles and mucus present. Figure 34 shows the coliform test results, rated on a 3-point scale and the variability in coliform test results across the area of the lagoon.

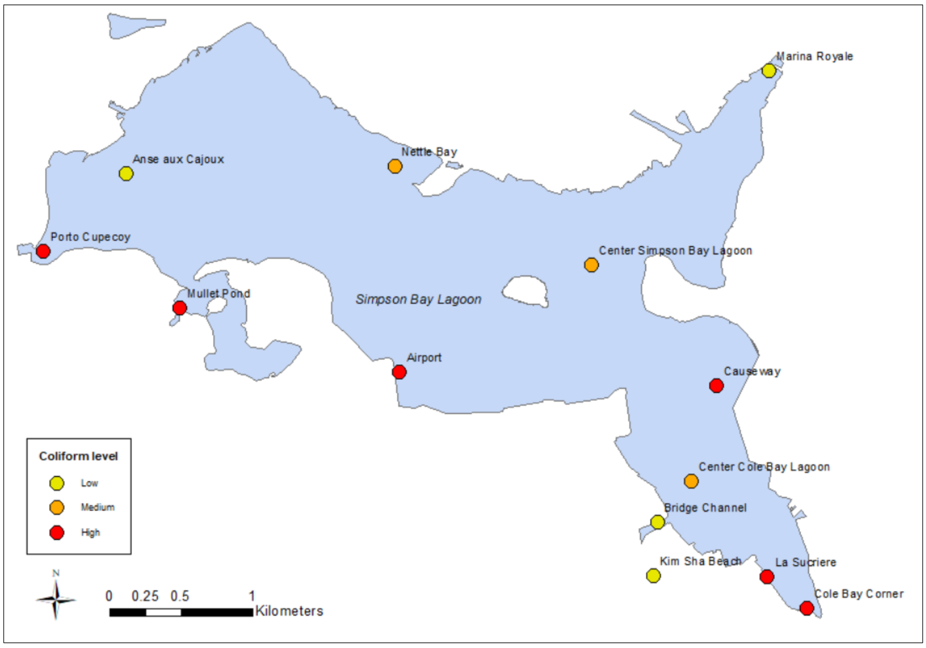

Figure 34. Total coliform test results from this study.

Nitrate Test Results

All sites, with exception of Cole Bay Corner, Cole Bay La Sucrerie, and Bridge Channel showed a level of nitrates lower than 5 mg/l. La Sucriere and Bridge Channel showed a level of approximately 7 mg/l. Cole Bay Corner showed nitrate level of approximately 10 mg/l. Figure 35 shows the level of nitrate at the test sites and shows variability in nitrate test results across the area of the lagoon.

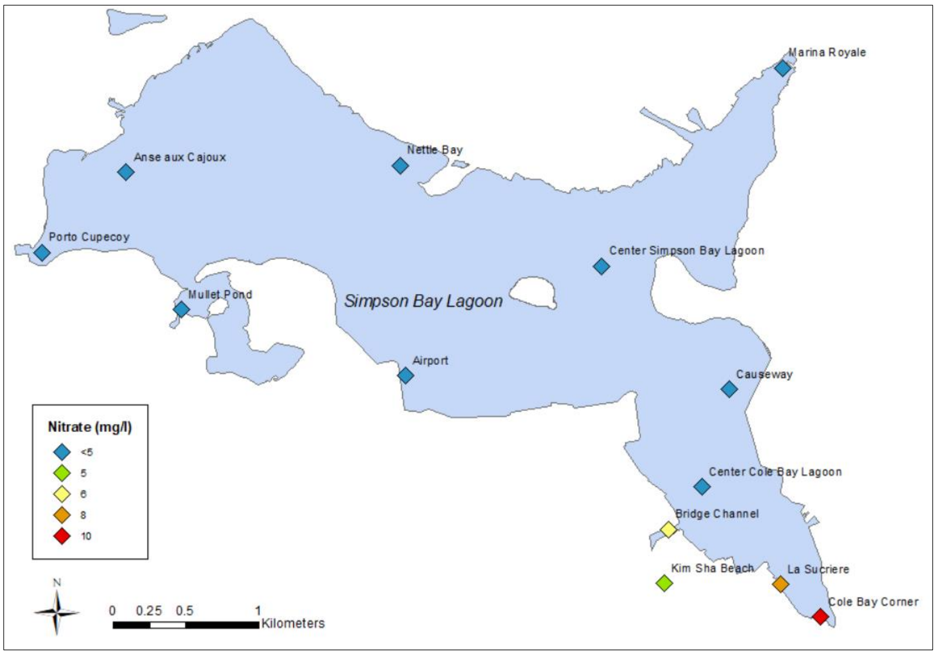

Figure 35. Nitrate test results from this study.

Discussion

Previous water testing and current water testing has confirmed presence of coliform bacteria in 13 different locations over a period of 20 years. Both the extensive coliform colony tests by EPIC and the recent total coliform tests conducted in this study confirm that the contamination with coliform bacteria is extensive. This confirms the existing knowledge that the lagoon is polluted. The current study also adds new knowledge. For example, Mullet Pond area tested positive for total coliform bacteria, which is a new finding as previous tests by EPIC and Nature Foundation found very little or no coliform bacteria in this area. Mullet Pond site had a high number of gas bubbles, similar to a sample from the most polluted area of Cole Bay.

The samples that showed the highest amount of contamination were located in Cole Bay, near the Causeway, in Porto Cupecoy, and in Mullet Pond. Areas that have a good amount of circulation still tested positive for total coliform, which is an alarming finding. Sites such as Center Simpson Bay Lagoon and Causeway exhibited medium to high number of colonies, which is alarming given the strong water circulation in those locations. The sites that showed a low level of contamination were located on the French side, perhaps due to better water treatment facilities located there.

With regards to the nitrate tests, Cole Bay corner showed a very high level of nitrates, indicating sewage pollution and nutrient over-enrichment. This is also consistent with the visual view of the test site, which exhibited algal bloom and unclear water with a bad smell. La Sucriere and the Bridge Channel sites showed medium levels of nitrate, above the norm for clean water (<1 mg/l). The findings for La Sucriere are consistent with the visual account of the site, which exhibited dirty and soapy water, possibly contaminated by laundry detergent discharged from a nearby pipe. The Bridge Channel site is the area where Simpson Bay Lagoon water exists to the ocean, and could serve as an indicator of the overall lagoon water quality, in particular, in Cole Bay and in stagnant areas. Kim Sha Beach site showed a normal level of nitrates, with all other sites exhibiting a level of nitrates below the norm, which indicates clean water with respect to nutrient pollution.

Water Quality and Pollution Sources: An Integrated Analysis

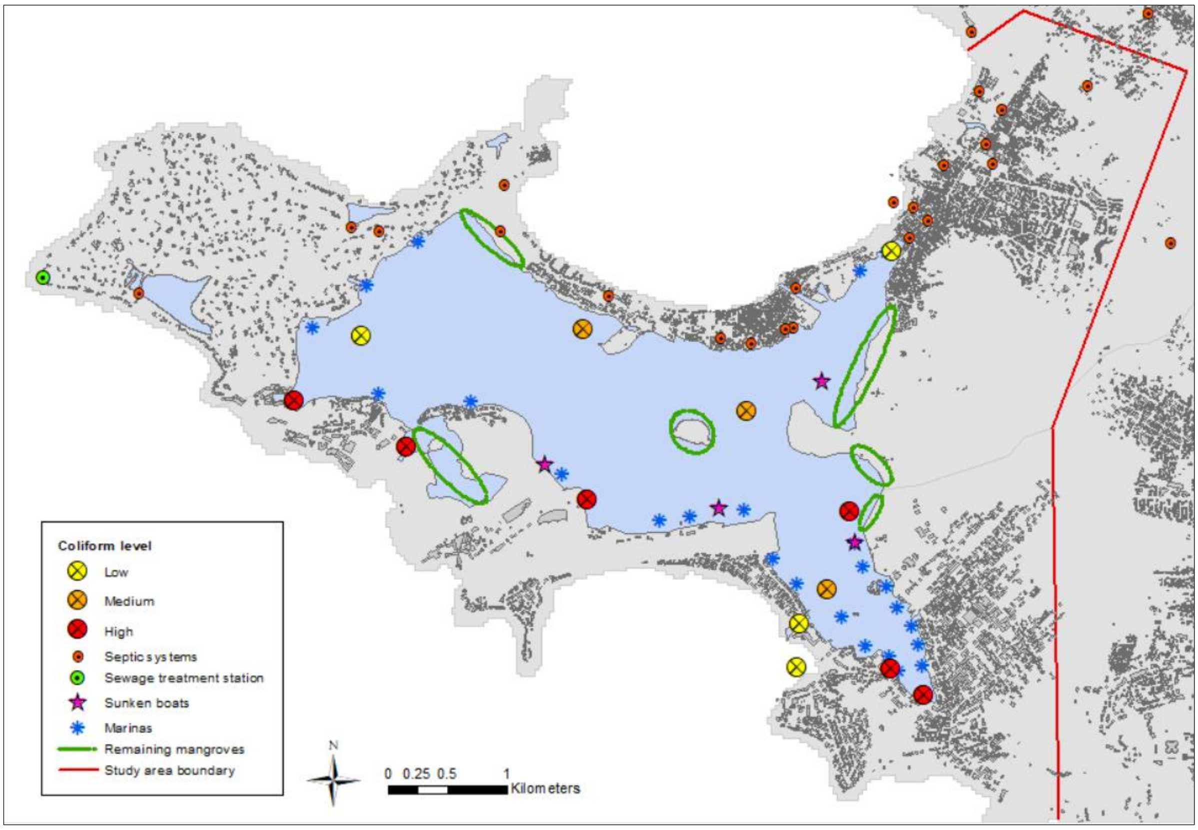

Figure 36. Sewage pollution and pollution sources. (Note: Due to limited data, only the septic systems and sewage treatment station on the French side of the lagoon are included.)

It is possible to combine water test results with related pressures in order to determine a spatial relationship between the two components. In particular, due to water test results being limited to total and fecal coliforms and nitrates, a focus can be made on sewage pollution. In Figure 36, results of two components of the DPSIR, Pressures, and State Changes, are integrated along a common theme of sewage pollution. This figure includes test results from the current study, which show the relative level of total coliform in each location, as well as locations of septic systems and sewage treatment station on the French side, locations of buildings on the French and Dutch side as a proxy for urban sewage pollution, sunken boats that may release sewage into the water, of marinas where sewage may be disposed by boats, and finally, remaining mangroves that may help with water purification.

Some patterns emerge from this assessment. Cole Bay area stands out as experiencing the highest pressures, especially from the sewage discharge, marinas, and sunken boats. It also has very poor water quality, according to the current and previous studies. Locations on the French side show lower levels of coliform, although total coliform is still present. In particular, the area of Marigot appears to have many potential pollution sources, such as densely populated area, large amount of septic systems, marinas, and sunken boats. However, it does not appear to exhibit a high level of total coliform. Areas in the middle of the lagoon on the Dutch and French side are also subjected to possible sewage discharge from boats that are moored in the center but are not visible on these figures, and thus show presence of total coliform bacteria.

With regards to other sources of pollution, such as toxic chemical pollution, plastic pollution, construction and development, and mangrove destruction, it was not possible to establish a relationship to water quality due to limited water quality results which at the moment are limited to sewage-related pollution only.

4.3 Impacts: Public Perception and Behavior

Overview

Scientific literature suggests that environmental awareness and behavior play a crucial role in causing as well as preventing environmental degradation and pollution. The household survey conducted as a part of this study investigated these aspects in more detail. In particular, respondents were asked the following questions to gauge their environmental awareness, behavior, and perception of the issue. The chapters below outline results of the household survey pertaining to each of these questions.

1. Did you notice any changes in the lagoon's environmental condition in the past 10 years or since you arrived on Saint Martin?
2. Which changes have you noticed?
3. How important do you consider the following reasons for the poor environmental condition of the Simpson Bay Lagoon?
4. Who do you think is most responsible for the poor environmental condition of the lagoon?
5. Are you in favor or not in favor of the following management activities to improve the environmental condition of the Simpson Bay Lagoon?
6. How often did you do the following activities in the past year?

Environmental Awareness

According to the survey results, in response to the question "Did you notice any changes in the lagoon's environmental condition in the past 10 years or since you arrived on Saint Martin?", 77.6% of respondents responded that they have indeed noticed a change. This shows a very high level of awareness of the deteriorating environmental condition of the lagoon (Figure 37).

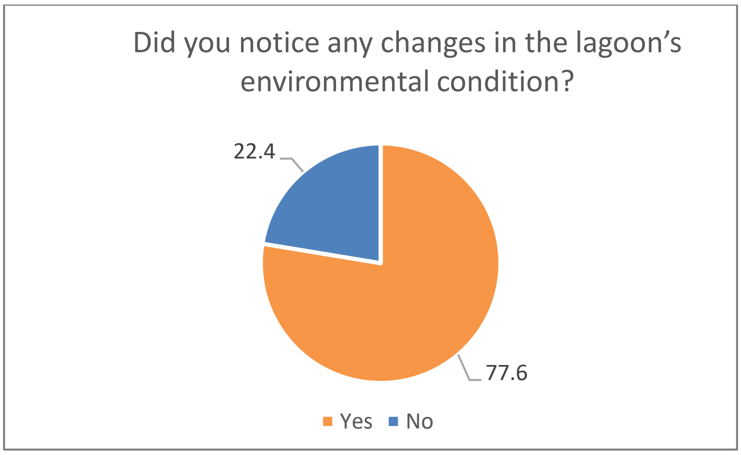

Figure 37. Percentage of respondents who noticed the changes.

In response to the question "Which changes have you noticed?", participants were given four options: bad smell coming from the lagoon, dirty water, trash and plastic pollution in the water/on the shores, less fish in the water, and an option where they could enter their own response (Figure 38).

The highest percentage of respondents, 58.4%, noticed trash and plastic pollution in and around the lagoon; followed by 54.8% that noticed that water in the lagoon is dirty, and 47.5% that noticed a bad smell coming from the lagoon. 32.9% of respondents indicated that they have noticed less fish in the lagoon. 16.4% of respondents indicated that they have also noticed other changes. These changes included: sewage pollution in general, sewage disposal into the lagoon by restaurants, brown seaweed, a large amount of construction, filling in and development that happened very fast around the lagoon, construction without permit, Hurricane Irma damage, ship wrecks throughout the years that leak diesel fuel into the water, algae blooms, massive fish die outs, change in water color from clear blue to muddy, more boat activity on the lagoon, disappearance of star fish species, less mangroves, less iguanas, less birds on the lagoon.

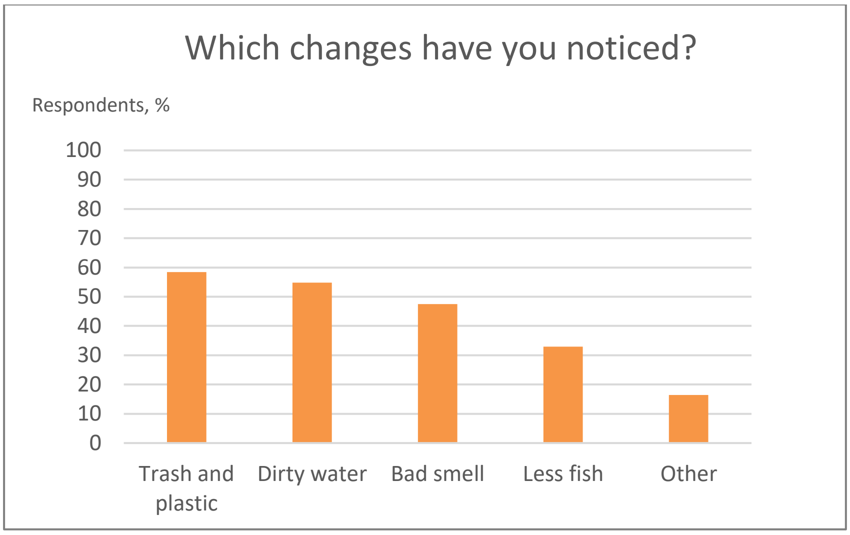

Figure 38. Percentage of respondents who noticed specific changes in the environmental condition of the lagoon.

The next question directly asked the respondents to indicate how important they consider each of the pollution sources to be the reason for poor environmental condition of the lagoon (Figure 39). Respondents were asked to rank the importance of each source of pollution on a Likert scale from 1 (Not Important at all) to 5 (Very important).

Sewage pollution was the highest-ranked source of pollution, with 66.2% of respondents ranking it as "Very important" and 19.6% ranking it as "important". In total, 85.8% ranked sewage pollution as either "Very important" or "Important". Next, garbage pollution was the second highest-ranked source of pollution, with 63.9% of respondents ranking it as "Very important" and 21.5% ranking it as "Important". Shipwrecks were the third highest-ranked source of pollution. 53.9% of respondents ranked shipwrecks as "Very important", and 27.9% ranked them as "Important". 53.9% ranked mangrove destruction as "Very important", 27.9% as "Important" and 27.9% as "Neutral". 35.2% of respondents ranked construction and development as "Very important" and 30.1% as "Important". In total, 14.2% ranked it as either "Not important" or "Not important at All". Compared to the effect of sewage, which 85.8% of respondents ranked as either "Very important" or "Important", only 65.3% of respondents ranked construction and development as "Very important" or "Important". Construction and development has received the highest number of rankings as "Not important" among all six categories (11%).

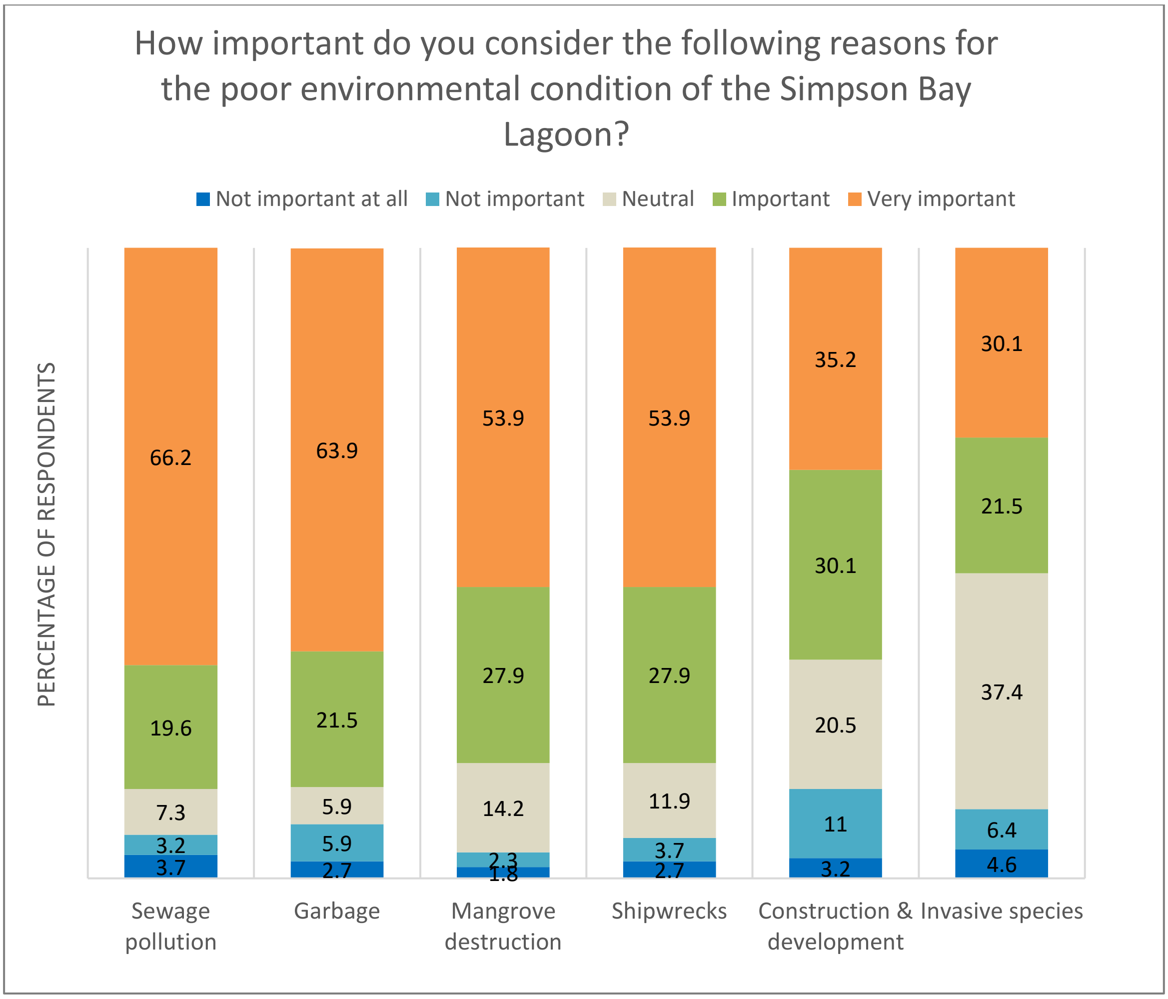

Figure 39. Reasons for poor environmental condition of the lagoon.

Furthermore, respondents were asked the following question: “Who do you think is most responsible for the poor environmental condition of the lagoon?” Respondents could only choose one option, between: government, local residents, businesses, tourists, other, and I don’t know (Figure 40).

It is clear that almost half of respondents (48.9%) believe that it is the government’s fault that the lagoon is experiencing such a level of pollution. However, 21.5% believe that it is the local residents who should be held accountable. Finally, a significant number of respondents, 13.2% are also aware that the businesses near the lagoon are causing the problem. 4.6% of respondents mentioned other actors that are responsible, such as: everyone, Hurricane Irma destruction, local residents and the government, and human activities in general.

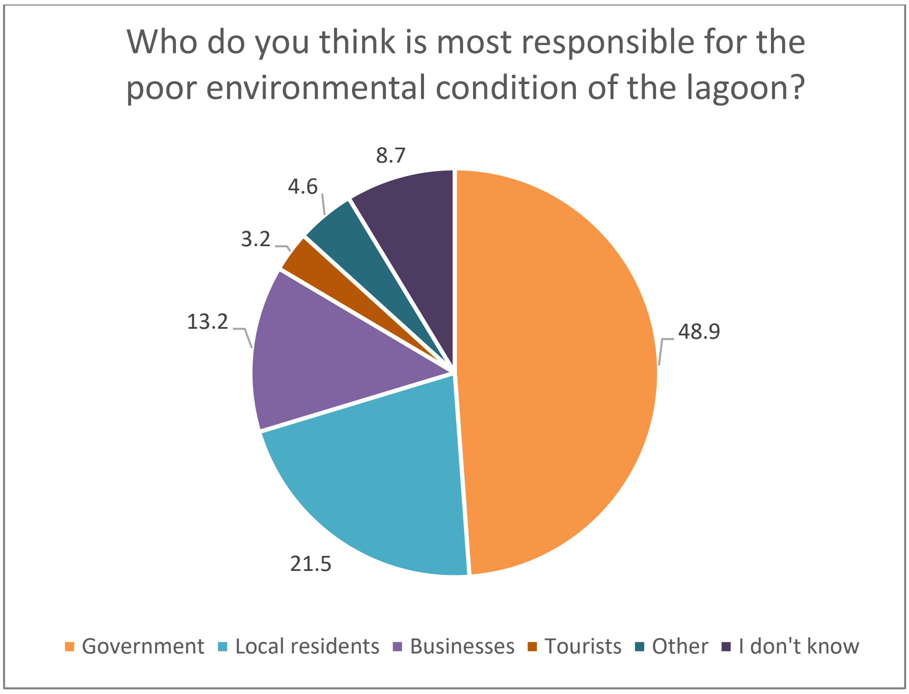

Figure 40. Responsible actor.

Environmental Behavior

In order to gauge environmental behavior of respondents, they were asked to indicate how often they do certain activities (Figure 41). The majority of respondents indicated that they avoid littering very often or often. However, responses to other questions were less enthusiastic. Approximately 45% of respondents walk/bike instead of driving and purchase environmentally friendly products often or very often, but a staggering 45% of respondents do not recycle or recycle rarely. About 56% of respondents never or rarely volunteer for environmental cause, and 76% never or rarely attend public meetings related to the environment.

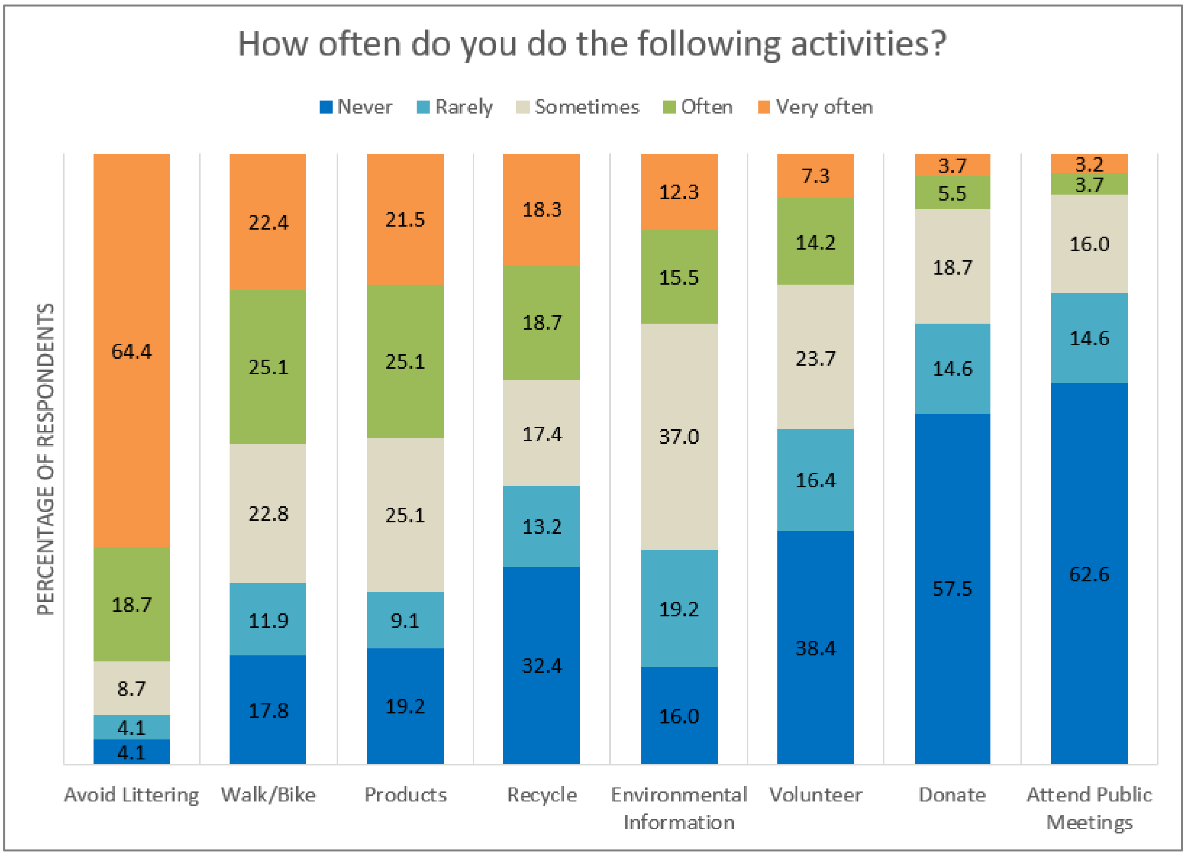

Figure 41. Environmental behavior.

Management Activities

Finally, respondents were asked whether they are in favor of the following management activities to improve the environmental condition of the Simpson Bay Lagoon (Figure 42). Overall, the residents of the study area are in favor of all six of the proposed management activities. The highest amount of support was with regards to raising environmental awareness, where 79% of respondents indicated that they are "Strongly in favor", with 92.7% of respondents being either "In favor" or "Strongly in favor". Improving enforcement of environmental regulations was second highest-ranked alternative, with 67.1% being "Strongly in favor" and additional 22.4% being "In favor". Removing shipwrecks in the lagoon was also strongly supported by 66.2% of respondents, and supported by 20.5% of respondents. Building a sewage treatment plant was strongly supported by 56.6% of respondents, and supported by 26.5% of respondents. Restoration of mangroves was supported by 59.8% of respondents as "Strongly in favor" and 25.1% as "In favor", together adding up to 84.9% of respondents. Finally, restricting development along the lagoon was met with less support than any other option. Only 37.9% of respondents indicated that they are "Strongly in favor" of this option, and 21.9% indicating that they are "In favor". 24.7% of respondents indicated that they are "Neutral" regarding this option, and 8.2% indicated that they are "Not in favor".

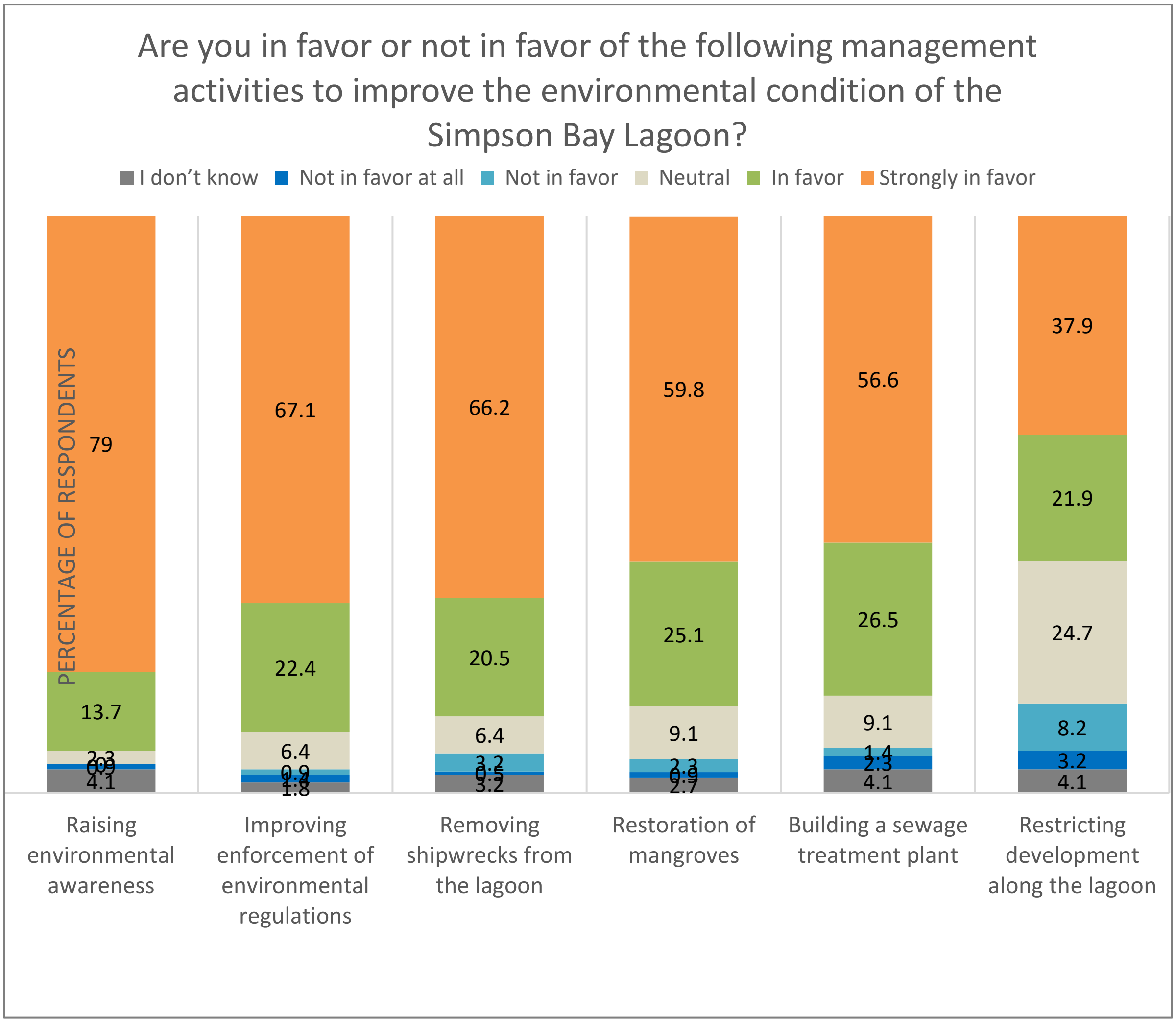

Figure 42. Support for management scenarios.

<u>Contingent Valuation and Choice Experiment</u>

To estimate the monetary value that they attach to good environmental state of the lagoon, respondents were asked the following contingent valuation question: "Are you in principle willing to pay for environmental management of the Simpson Bay Lagoon?". 76.7% of respondents answered Yes to this question. For these respondents, the mean WTP for environmental management of the lagoon was 18.16 ($/month) with the standard deviation of 17.67 ($/month). The lowest value was 2.00 ($/month) and the highest 125.00 ($/month). 79.5% of respondents were willing to pay 20 ($/month) or less; 87.3% were willing to pay 30 ($/month) or less; and 90.4% of respondents were willing to pay 40 ($/month) or less (Figure 43).

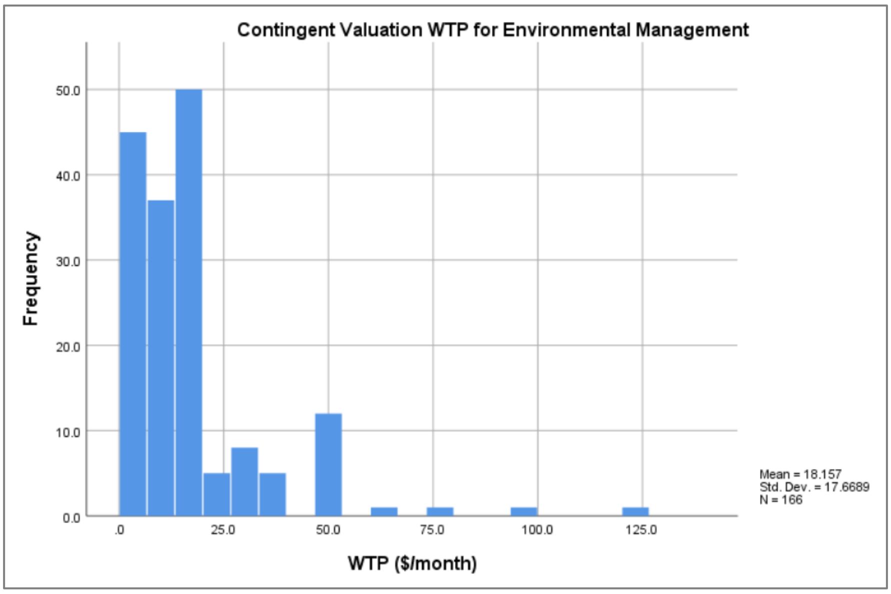

Figure 43. CV - WTP for environmental management.

In regards to the choice experiment (CE), it was determined that four variables were significant: WTP for storm protection, WTP for habitat for species, WTP for moderate water quality, and WTP for high water quality. Current state of the water quality is described in the choice experiment as low. High water quality would mean a significant improvement in the clarity and smell of water. Average WTP for moderate water quality was 25.66 ($/month), with the standard deviation of 5.97 ($/month). The lowest value was 11.45 ($/month) and the highest 33.41 ($/month) (Figure 44).

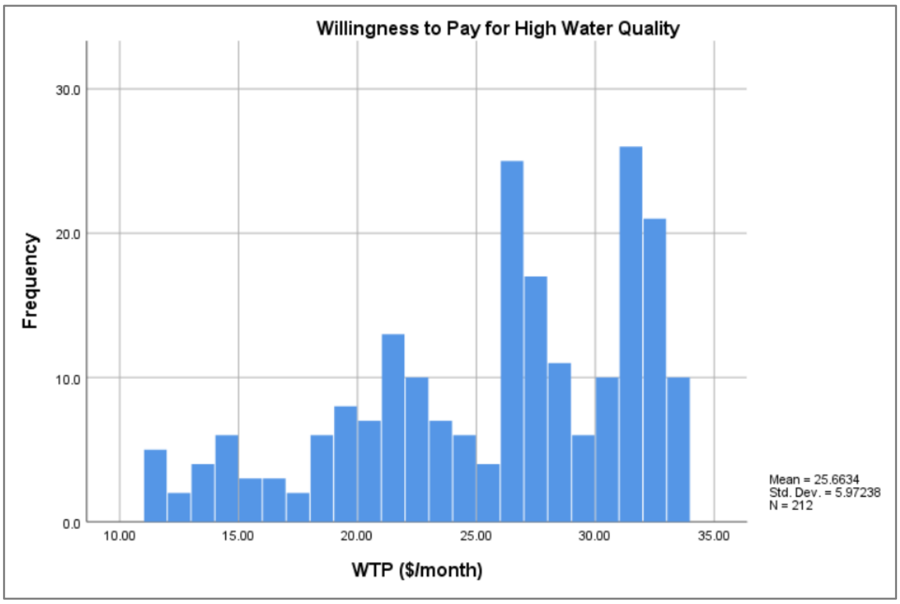

Figure 44. CE - WTP for high water quality.

Total WTP of St. Maarten's residents for the environmental improvement of the lagoon can be estimated by multiplying the average WTP for the contingent valuation (CV) (18.16 $/month) by the number of households on the island. The total WTP for St. Maarten is $252,378 per month and $243,344 per month for Saint-Martin. The total WTP for the island is $497,965 per month. This amounts to approximately $5,975,580 per year.

Total WTP of St. Martin's residents for high water quality can be estimated by multiplying the average WTP for high water quality from the choice experiment (25.66 $/month) by the number of households on the island. The WTP for high water quality is $359,779 per month for St. Maarten and $343,844 per month for Saint-Martin. The total WTP for high water quality is $703,622 per month. This amounts to approximately $8,443,464 per year.

Discussion

Results show a high level of environmental awareness by the survey respondents. In particular, they are very aware of water pollution from garbage and plastic, as well as notice poor water quality, both visibly, as well as in terms of the bad odor coming from the water, and less fish in the water as an indicator of the degraded state of the lagoon's ecosystems. It is also clear that respondents are very aware of the issue of sewage and garbage pollution and its negative effect on the lagoon. During the survey, most of the respondents were not aware that mangroves have water purifying function, as well as that they are important species in the natural ecosystems. However, they did notice the change in the number of mangroves around the lagoon and saw this as part of the poor environmental state of nature. Additionally, most respondents are aware that sunken boats in the lagoon have a negative impact on its condition; although some mentioned that they may be beneficial for organisms that use the boats for habitat and shelter. Respondents were generally not aware of what invasive species were, as well as what they are in particular for the lagoon. Finally, an interesting finding is that respondents were less confident that construction and development has a negative impact on lagoon's ecosystems.

On the other hand, survey results show a very low level of environmental behavior in the population. In particular, recycling, purchasing environmentally friendly products, and knowledge about the environment are particularly low. Although the majority of respondents indicated that they avoid littering, areas near the lagoon are polluted with household litter, thus this may indicate response bias. Finally, involvement in public meetings is the lowest of all categories, indicating lack of participation on behalf of the public with regards to environmental management of the lagoon.

WTP from contingent valuation and the choice experiment generate varied results. WTP from the CV has a lower average than the choice experiment, while also having four potential outliers. This may be due to the fact that in the choice experiment, only four out of six variables tested significant, with high water quality being one of the significant variables. On the other hand, contingent valuation addresses the environmental management of the lagoon in general, which includes all possible variables, including those that did not show significance in the choice experiment. Since the choice experiment is an indirect way of estimating the value, and incorporates multiple tradeoffs, it is a more reliable method of estimating the value. Specifically, in the context of St. Martin, where on average the population is poor, it is more useful to utilize an indirect approach to estimating value. Additionally, the complex statistical design and analysis of choice experiment yields a more accurate estimate. Finally, in relation to estimating the value of water quality specifically, the choice experiment results are more reliable since the choice experiment directly includes water quality as an attribute and results are generated separately for that variable. CV is less reliable since it incorporates all other aspects of the lagoon.

4.4 Responses: Proposed Solutions

When analyzing this complex issue, several main findings became apparent. First, the most critical pressure on water quality in the lagoon is urban and commercial sewage discharge. This is confirmed by comparing previous water tests to new water tests, in particular for fecal and total coliform parameters. Geographic representation of pressures allowed us to demonstrate their extent, in particular, for the densely populated areas of Cole Bay and Marigot whose populations will only continue to grow without access to sufficient sewage infrastructure. Considering the fact that the French counterparts have established a municipal sewage treatment network for the entire population on the French side of the lagoon, it is especially noticeable that the Dutch part has fallen into neglect. For the Dutch side of the island, an agreement was signed in 2013 for financing of a district upgrading project which aims to "eliminate the surface and coastal area pollution for the benefits of inhabitants and tourists" (The Government of St. Maarten, 2014). The project's specific objectives include improving drainage, installing sewage pipes, improving drinking water quality and upgrading road infrastructure (The Government of St. Maarten, 2014). However, at the moment none of these improvements have come to fruition for the areas of Cole Bay, Simpson Bay, and Lowlands. In addition, proposed plans for the wastewater treatment plant shared by the Dutch and French areas near the lagoon halted in 2016 as the two sides couldn't agree on location and legal oversight (Quick Scan, 2016). Based on the survey results, residents of St. Martin appear to be acutely aware of the sewage pollution problem and to be strongly in favor of building a sewage treatment plant for this area. It is crucial that the government takes concrete steps towards establishing municipal sewage treatment infrastructure or conducts an assessment and monitoring of the existing septic systems.

Another theme that has emerged in this study is the dire need for stricter environmental regulations on the island, as well as their effective enforcement. Current regulations on the Dutch side are not sufficient to ensure the health of the ecosystems and residents of the island. In particular, regulations with regards to sewage discharge from businesses and boats, toxic chemical and foreign matter discharge into the lagoon, and sale of certain chemical products, need to be stricter. St. Maarten is widely viewed as a free-for-all place with lax environmental regulations. However, it is essential to protect the health of its natural areas both for its economy as well as for the health and well-being of its residents. Survey results have confirmed that the residents are also aware of the lax environmental regulations and their role in contributing to water pollution.

Finally, an equally important solution to this issue is raising environmental awareness and even more specifically encouraging pro-environmental behavior. Although the residents of St. Martin are aware of environmental issues facing the island as well as have an in-depth knowledge about the lagoon pollution, there is a need to bridge the gap between this passive awareness and active involvement. In particular, recycling or waste-minimizing efforts are very important, especially in the context of this small island. Educational campaigns are needed to inform the residents about toxic chemicals and toxic waste. Environmental education and volunteering events should be further promoted to improve the public's environmental awareness. Valuation results from this study have demonstrated that the residents attach a significant value to Simpson Bay Lagoon. In particular, in the choice experiment, water quality has scored the highest out of the four other variables in terms of the average WTP. The total WTP for high water quality for the entire island is approximately $8,443,464 per year. While caring deeply about the island's natural areas, residents of St. Martin need to feel more empowered to take control of the situation. In the current political climate of ineffective top-down governance, it may be important to explore bottom-up solutions as an alternative. If the residents of St. Martin exhibit more environmentally conscious behavior, this could trigger positive change in society as well as in politics.

On the other hand, the government of St. Maarten in particular needs to shift its focus towards a more holistic perspective on development. It is important to address the three pillars of sustainability, People, Planet, and Profit, as outlined in the UN Sustainable Development Goals (Sustainable Development, (n.d)). As demonstrated in this study, focusing exclusively on Profit often results in the degradation of the environmental state, which negatively affects human the well-being.

4.5 Study Limitations and Further Research

Possible study limitations for the household survey may include interviewer bias since the interviews were conducted in person and non-response bias since the survey was voluntary. With regards to water quality testing, the new water testing was conducted only once, thus there was no possibility to compare new water quality tests over time. Test locations are also very important due to water circulation dynamics in the lagoon and affect the reliability of results.

Further testing is needed with a more detailed lab analysis with regards to fecal coliform in particular, which should be conducted over a longer time frame, at varying locations, and on both sides of the lagoon to achieve comprehensive results which can be comparable to the EPIC study of 2009 (Lips & van Slooten, 2009). Additionally, it would be beneficial if further studies investigate the toxic chemical pollution, plastic pollution, sedimentation in the lagoon, and biological oxygen demand, through more in-depth water quality testing. Due to the prominent marine industry in the lagoon, toxic chemical pollution in particular may yield interesting and unexpected results, and may arise as a new issue that has been overlooked. Additionally, research into microplastics in the lagoon and in coastal areas around St. Martin would prove useful.

Working in a data poor environment also has its limitations. For example, incomplete information may be provided by the interviewees or in existing literature with no alternative sources of information. Due to the administrative division of the island into two countries, data was often only available for one side of the lagoon, as is evident in some maps. Most of the available datasets were disjointed and used different languages and measurements taken at different points in time. Conflicting data was excluded from this report and only reliable sources were incorporated. There is a need to establish a central reliable body of literature that can be referred to for future studies.

Application of the DPSIR

The DPSIR framework proved very useful for this study. It provided a central structure and allowed for the integration of both qualitative and quantitative components. In particular, it provided a backbone in the data scarce environment that connected all components of the issue. This study fits into the DPSIR literature, which underlines its usefulness for similar cases (Giupponi, 2002). DPSIR allowed for a combination of statistically representative data (household survey), a natural science component (water quality testing), and qualitative data from reports and interviews (pollution sources). It shows the complex interactions between natural and social science, and makes an integrated assessment of the issue possible. Further studies could create more quantitative models to investigate these relationships.

5. Conclusion

This study relied on the DPSIR theoretical framework to investigate the causal relationship between water quality in the Simpson Bay Lagoon and the environmental behavior and perception of the residents of St. Martin. The study has determined the current state of water quality in the lagoon, with particular focus on coliform and nitrate parameters. The current state of water pollution was compared to previous water quality tests. It was determined that the state of the water quality in the lagoon has been very poor for the past several decades and remains poor due to several anthropogenic pressures. These dominant sources of pollution include sewage and grey-water discharge from households, businesses, and boats; sunken boats; development which leads to mangrove destruction and filling in and dredging of the lagoon; toxic chemical pollution from boatyards and marinas; and domestic waste pollution which is transported into the lagoon with winds and stormwater runoff. With the help of GIS, the study has established a spatial relationship between sewage pollution in the lagoon and its sources.

Additionally, this study investigated environmental behavior and perception of St. Martin's residents with regards to lagoon water pollution. Contingent valuation and choice experiment results were used to determine the average and total WTP of St. Maarten's residents. Results have shown that residents of St. Maarten are very aware of water pollution in the lagoon and assign significant value to the preservation and restoration of its environmental state and to high water quality. However, they exhibit quite low environmental behavior.

According to household survey results, residents of St. Maarten strongly support the majority of the proposed measures for improving the environmental quality of the lagoon. What is needed is a combination of a top-down and a bottom-up approach to environmental management. Top-down approach should involve significant improvements in existing infrastructure, as well as creation and enforcement of strict environmental regulations. The bottom-up approach should involve environmental awareness campaigns, focused on waste-management and recycling, environmental education, and volunteering.

Finally, application of the DPSIR framework has proven helpful in this study. It is recommended to rely on this framework for similar interdisciplinary research, in particular when tackling complex environmental problems that lie at an intersection of natural and social sciences. It is also very useful in data poor environments as it provides a logical structure that connects all elements of the analysis, allowing for a comprehensive assessment.

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7. Appendix

Table of Contents

7.1 Domestic sewage pollution

Figure 45. Sewage in a storm gutter and flowing from a house in Cole Bay, 2019.

Figure 46. Sewage in storm gutters in Cul-de-Sac and Cole Bay, St. Maarten, 2019.

7.2 Toxic chemical pollution

A search online at the two leading stores offering boat supplies, Budget Marine and Island Waterworld, have revealed the following results. Budget Marine is selling a Micron 99 SPC paint as well as conventional copper-based paints (Budget Marine, 2019). On the other hand, Island Water World is selling only conventional copper-based paints as well as some environmentally-friendly alternatives (Island Water World, 2019).

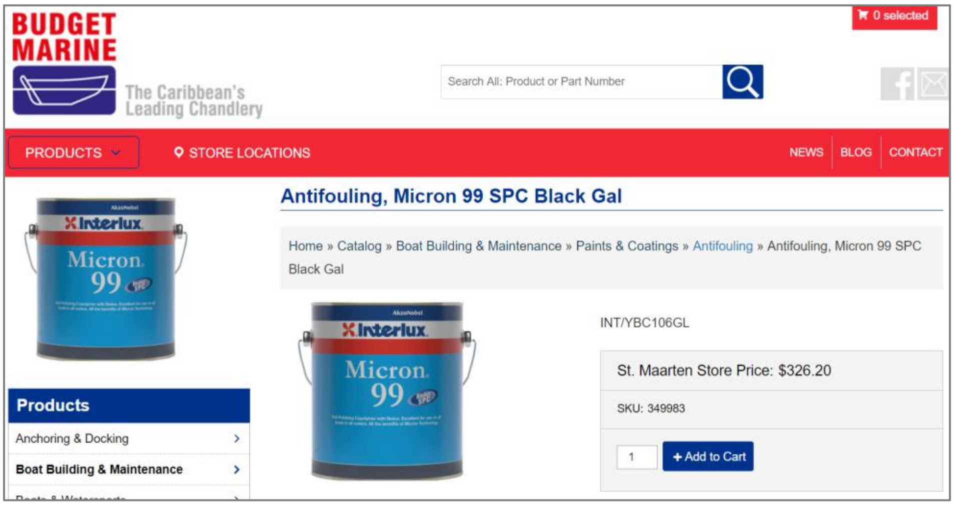

Figure 47. Budget Marine website showing availability of SPC paint.

Figure 48. Island Water World website showing an environmentally-friendly antifouling product.

7.3 Mangrove Destruction

Figure 49. Drone images of remaining mangroves.

7.4 Water Test GPS Coordinates

Site_Name	Y	X
Cole Bay Corner	18.030433	-63.085133
La Sucriere	18.032433	-63.087633
Center Cole Bay Lagoon	18.03845	-63.09245
Bridge Channel	18.03585	-63.094567
Kim Sha Beach	18.032497	-63.094821
Airport	18.0453	-63.1108
Mullet Pond	18.049378	-63.124635
Causeway	18.044467	-63.090817
Porto Cupecoy	18.052917	-63.133233
Anse aux Cajoux	18.05785	-63.128017
Marina Royale	18.0643	-63.087517
Nettle Bay	18.058283	-63.111083
Center Simpson Bay Lagoon	18.052083	-63.098683

Table 3. Water Test GPS Coordinates.

7.5 Water Testing: A Photographic Account

1. Cole Bay Corner

Figure 50. Cole Bay Corner water testing site.

2. La Sucriere

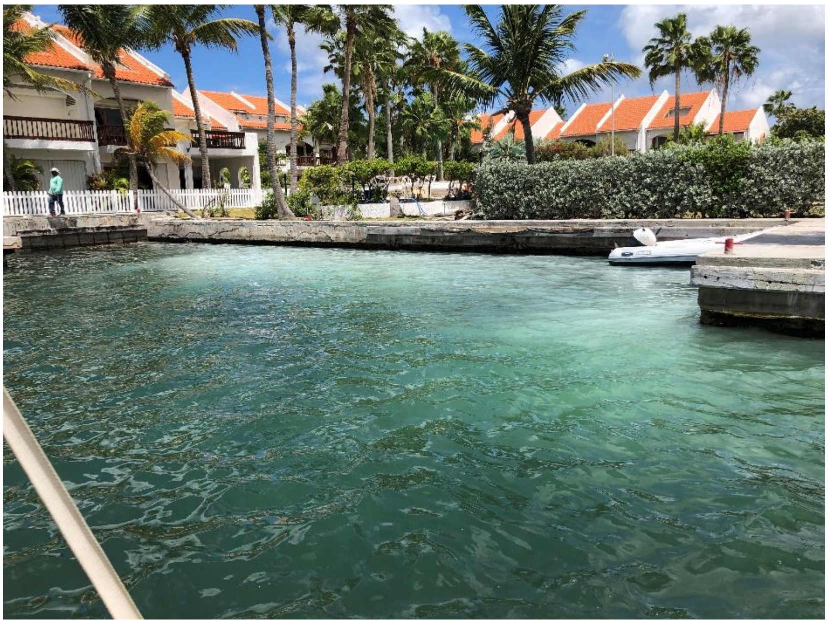

Figure 51. La Sucriere water testing site.

Figure 52. La Sucriere water testing site with the pipe visible on the left side.

3. Center Cole Bay Lagoon

Figure 53. Center Cole Bay Lagoon water testing site.

4. Bridge Channel

Figure 54. Bridge Channel water testing site.

5. Kim Sha Beach

Figure 55. Kim Sha Beach water testing site.

Figure 56. Kim Sha Beach water testing site with a hotel pipe discharging gray-water visible underneath the dock.

6. Airport

Figure 57. Airport water testing site.

7. Mullet Pond

Figure 58. Mullet Pond water testing site.

8. Porto Cupecoy

Figure 59. Porto Cupecoy water testing site.

Figure 60. Algae bloom at the Porto Cupecoy water testing site.

9. Anse aux Cajoux

Figure 61. Anse aux Cajoux water testing site.

10. Nettle Bay

Figure 62. Nettle Bay water testing site.

11. Marina Royale

Figure 63. Marina Royale water testing site.

12. Center Simpson Bay Lagoon

Figure 64. Center Simpson Bay Lagoon water testing site.

13. Causeway

Figure 65. Causeway water testing site.

7.6 Water Test Results

<u>Current Study Results, 2019</u>

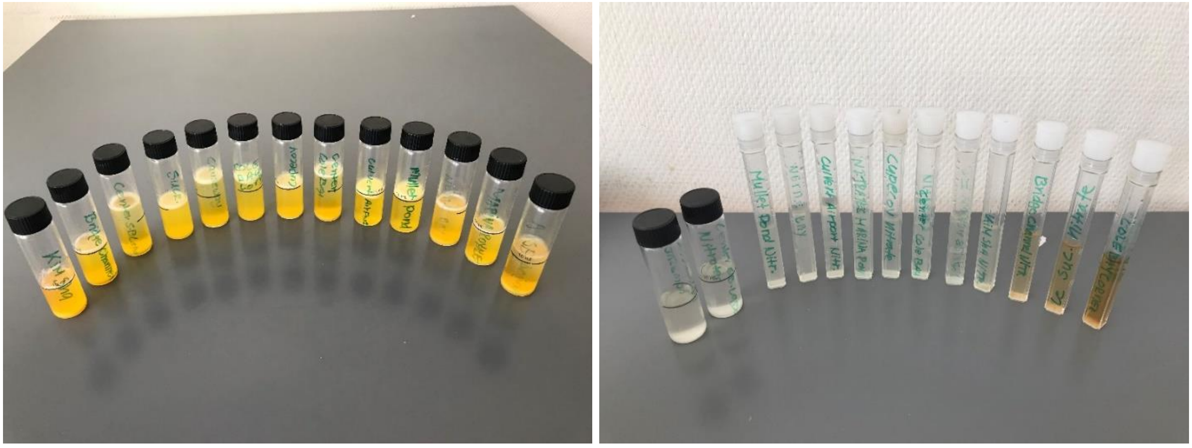

Figure 66. Total coliform and nitrate test results.

Total Coliform Results, 2019

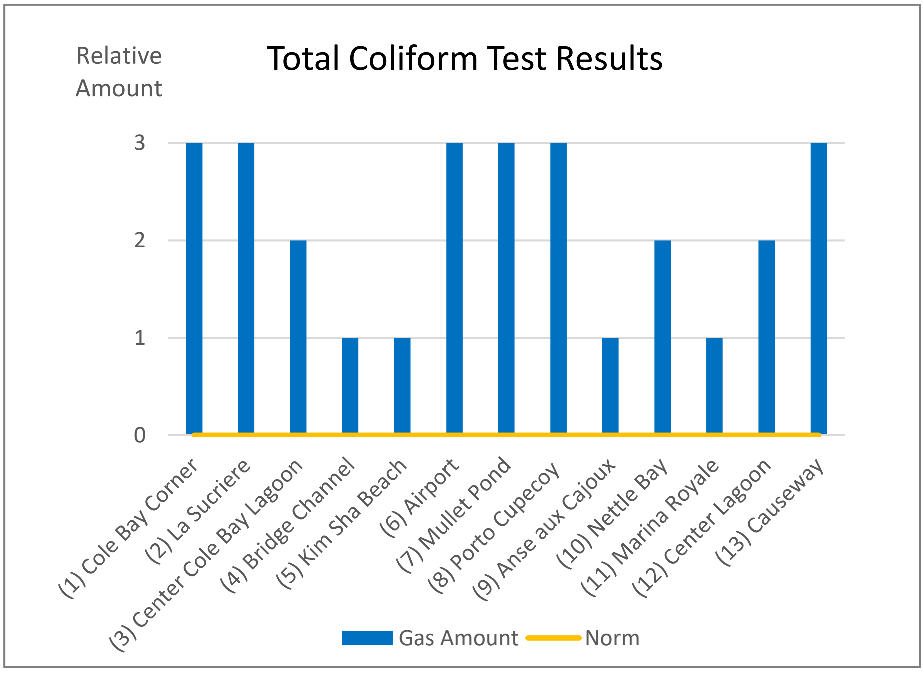

Figure 67. Total coliform test results by amount of gas present.

Nitrate Test Results, 2019

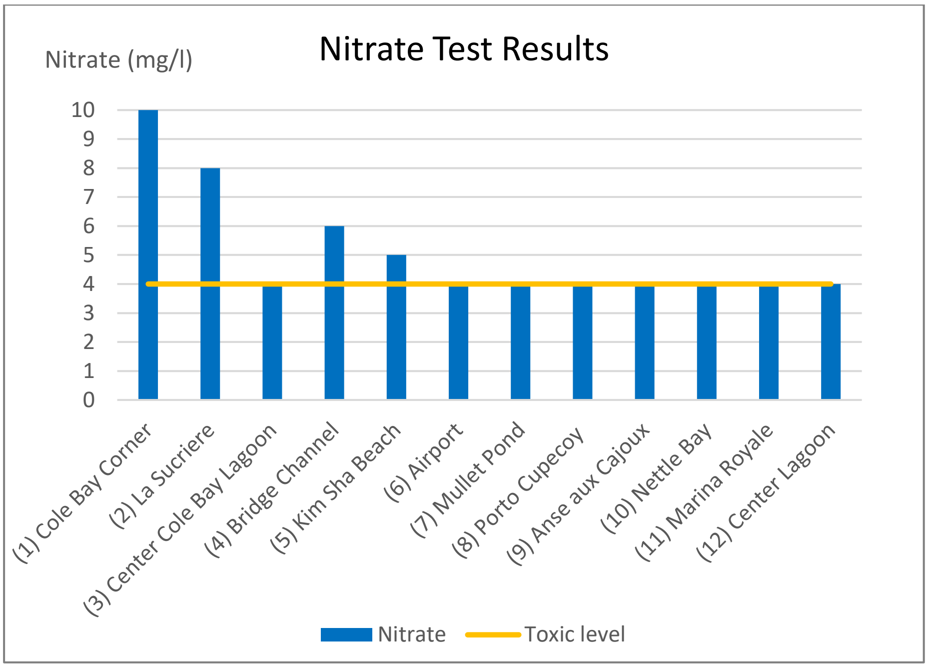

Figure 68. Nitrate test results from this study.