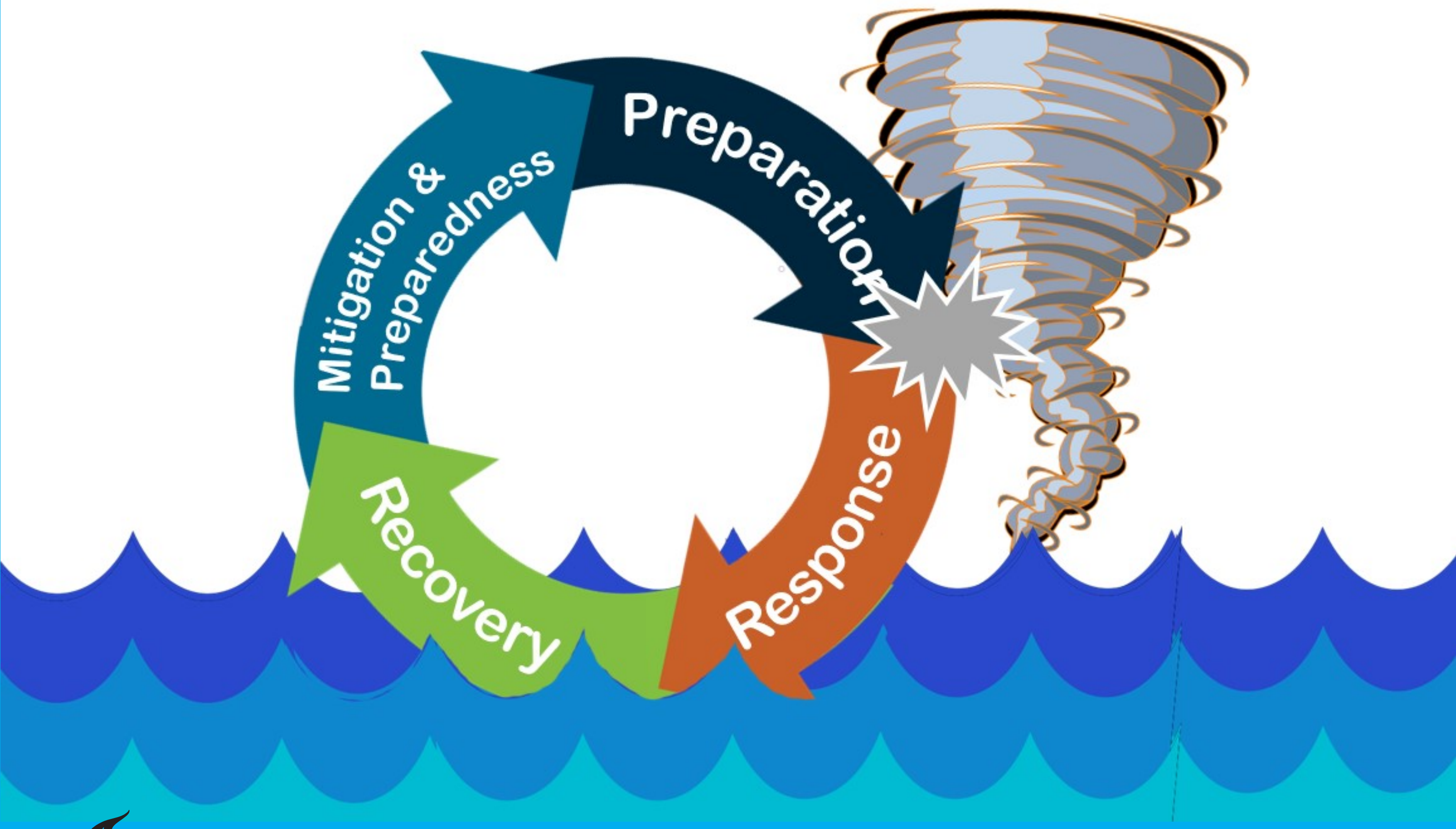
Interaction between a sustainable water management strategy and Build Back Better

Sustainable drinking water management strategy for Grand Bahama Island

L.E. van der Hucht



TU Delft

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by

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Master Thesis
With special thanks to Hans van der Hucht

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Preface

This thesis is written in metric units and this is used throughout this assessment. The gathered information and used sources are sometimes in imperial units or in metric units. The reason for using sometimes both units is for consistency with the individual source documents. When using information from a particular source, the units used in the source are then used in this assessment. In some cases, both units are provided with one unit in parenthesis

Abstract

This thesis examines the role of the concepts of “Build Back Better”, “Disaster Cycle”, and “Sustainability” in water management and the possibility of the interactions between these concepts when designing water management infrastructure. Especially in cases where the disaster cycle is relatively short: 10 to 15 years between disasters. The case study is on the island of Grand Bahama. The island of Grand Bahama depends on the freshwater groundwater lens for its drinking water. Flooding during hurricanes introduces saline water into that groundwater lens. It is therefore highly probable that the current drinking water production method will not be able to meet the demand in the future. An alternative drinking water supply system should therefore be examined. To investigate the interactions between the concepts, they are put into a conceptual design process, which uses the methodology “RenewIsland”, and used to set up some preliminary designs. Three Alternatives were made with the methodology “RenewIsland”. These Alternative designs were then subjected to a Multi-Criteria Analysis (MCA).

This thesis substantiates from the process that the interaction between the concepts is possible and that the inclusion of Build Back Better in the Water management decisions gives more possibilities to make balanced choices. A blueprint has been made for a method to analyze swiftly if an alternative is compatible with the different cycles and phases of a location regarding a disaster and normal circumstances. This thesis also states that the study has to be extended with more research to make it generally applicable.

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Glossary

Disaster condition The Disaster condition is contrary to the Normal condition. The disaster conditions depend on the type, frequency, and intensity of the disaster, and its impact on the water supply system. 54

Evaluation category Evaluation categories are the categories in which the multitude of criteria are simplified in categories. The Evaluation category is Planet, people, and profit. The eventual score of the category is based on the criteria. 38, 40

Multi-Criteria Analysis Multi-Criteria Analysis (MCA) is a framework for ranking or scoring the overall performance of decision options against various objectives. The approach has widespread and growing application in water resource management. Water resource management decisions are typically guided by multiple objectives measured in different units. 34, 49

Normal condition Under normal conditions, there are no extreme weather conditions threatening the water system. During these conditions, there are two water-consuming groups: tourists and inhabitants. 54

Water System Design Alternative A water system design as a solution to the case problem. In this thesis, the case is the salinization of the fresh groundwater source. Water System Design Alternative can be shorted to alternative or design alternative. 57

Weather Scenario The scenarios are based on weather conditions, (normal and disasters) with the disaster divided into tropical storms and hurricanes. In total, there are three weather scenarios against which the performance of the three alternative water systems designs are tested. 51

1

Introduction

This thesis examines the role of the concepts of “Build Back Better”, “Disaster Cycle”, and “Sustainability” in water management and the possibility of the interactions between these concepts when designing water management infrastructure. Especially in cases where the disaster cycle is relatively short: 10 to 15 years between disasters.

The case study is on the island of Grand Bahama, which is the second biggest island economy of the Commonwealth of The Bahamas archipelago [Wilson, 2020]. This island seems an ideal setting for investigating the interaction between society and the environment due to its clear boundary. To avoid an overly abstract approach, the interaction was studied in the context of the following problem. The island of Grand Bahama depends on the freshwater groundwater lens for its drinking water. Flooding during hurricanes introduces saline water into that groundwater lens. It is therefore highly probable that the current drinking water production method will not be able to meet the demand in the future. An alternative drinking water supply system should therefore be examined.

To investigate the interactions between the concepts, the part of each concept that could be relevant to a water management design process is highlighted. These parts are then put into a conceptual design process, which uses the methodology “RenewIsland”, explained in Subsection 2.3.7. This was used to set up some preliminary designs.

These preliminary designs were then subjected to a Multi-Criteria Analysis (MCA) , explained in Subsection 2.3.6. The criteria used were divided into three groups, "People", "Planet", and "Profit", explained in Subsection 2.3.4, and for each criterion, one or more indicators were selected. The indicators were then evaluated for each phase of the existence of the designed solution and for each of the concepts under investigation. The results were analyzed to establish how the concepts interacted with the designs in the case of disaster return periods of 10 to 15 years. The MCA was performed for three different scenarios: normal circumstances, performance during and after a tropical storm, and performance during and after a major hurricane.

Currently, the drinking water infrastructure in Grand Bahama is unintentionally split into two parts. One functions during normal circumstances, the other during disasters. When a disaster is threatening the island another drinking water system starts based on disaster management protocols. These two drinking water infrastructures do not directly interact and are not part of one overall design. These are made using different design models, which are not integrated [van der Hucht et al., 2021]. That makes sense for rare disasters, but hurricanes in the Bahamas are not that rare. When designing water treatment systems it is assumed that the system will complete its full lifecycle, but with devastating storms, this can not be certain.

The question this thesis aims to answer is the following. Do the concepts “Build Back Better”, “Disaster Cycle”, and “Sustainability” influence water management infrastructure design, particularly in cases where the period between disasters is relatively short? These concepts will be explained in Chapter 2.

1.1. Overview of the study

The design of a drinking water supply system for the island of Grand Bahama will used to examine the role of sustainability, frequent disasters, and "Build Back Better" in the design process. The to-be-managed resource in the case study is freshwater availability. The freshwater resource is regularly threatened by disasters. Increases in major hurricane frequency Vecchi et al. [2021] lead to more frequent storm surges that in turn make the fresh groundwater basins brackish. These threats are detailed in Section 2.2

To simulate a normal design process for a water management project a qualitative assessment method, Multi-Criteria analysis (MCA), will be used to assess the performance of the alternatives. These performances and processes will be used to explore the interaction and collaboration between the "disaster cycle", the guidelines of "Build Back Better", and a general desire for "sustainability". An Alternative 0 will be set up as a representation of the current situation. The Alternatives will be compared to Alternative 0 with three scenarios, normal circumstances, and two disaster conditions using an MCA.

1.2. Background and significance of research

Hurricane Dorian hit the small island of Grand Bahama at the beginning of September 2019. Dorian impacted the island much more than other recent hurricanes. In light of increasing economic activity on the island, rising sea levels, and frequent storms, it is not enough to consider building back what there already was with the same methods. The problems arising from climate change, combined with extreme natural cataclysms, are big and complex [van der Hucht et al., 2021].

Furthermore, Grand Bahama does not have a tradition of collective and public plans for safety and infrastructure. Therefore, other than a design for the reconstruction of the island, there needs to be a reflection on the methods, governance approaches, and attitude towards natural disasters. At the moment, the majority of the prevention measures explained and distributed to the people of the Bahamas focus on the individual scale. Meaning that measures taken only have a local or personal effect and no great all-encompassing measures an in place.

The impact of hurricanes has a multitude of consequences and affects the island. The current fresh-groundwater source is unsustainable, it gets saltier with each disaster impact and will in time disappear.

Both President Clinton [Clinton, 2006] and Biden spoke about the need to Build Back Better. Build Back Better states that systems should learn from past events and not just put back what did not work in the previous disaster, which will likely fail in the next disaster [Giovanni and Chelleri, 2019a]. Reflections in the term of disaster management should be taken into account during the design process.

1.3. Problem statement for the case study

Grand Bahama needs fresh drinking water. Grand Bahama has rain-fed groundwater basins which are used as a freshwater source, supplying the whole island with water. After a hurricane, a reoccurring hazard, the island can be flooded with salt water, and the groundwater source becomes brackish and unusable for drinking, as the current drinking water treatment does not desalinate the water. There is a need for a solution to prevent or cope with the salinization of the water source and explore possible alternatives for the production of drinking water.

1.3.1. Research questions

The goal is to assess the performance and interaction of three sustainable water management alternatives, which cope with regular disasters. To form these three alternatives the methodologies and concepts will be used to design and then assess the freshwater resources on a small island, coping with frequent disasters, and the impact of reducing saltwater intrusion. Within a case study, alternatives for a water management strategy will be compared on performance in sustainability in an MCA in two extreme weather scenarios and one normal scenario. The outcome of this research will give an insight into the interaction between the disaster cycle, Build Back Better, and sustainability.

In case of frequent disasters, how could the aspects of the "disaster cycle", the guidelines of "Build Back Better", and a general desire for "sustainability" interact in a water treatment system?

A multitude of existing methodologies, concepts, and tools will be used. These will be used to explore criteria relevant specifically to the different parts of the disaster cycle, Build Back Better, and sustainability for the case study.

Research question: Do the concepts “Build Back Better”, “Disaster Cycle”, and “Sustainability” influence water management infrastructure design, particularly in cases where the period between disasters is relatively short?

Research Subquestions:

- Are there examples of criteria relevant specifically to the different parts of the disaster cycle for the case study?
- Are there examples of criteria relevant specifically to Build Back Better for the case study?
- Are there examples of criteria relevant specifically to sustainability for the case study?

1.3.2. Scope of the research

The thesis aims to explore the interaction of Build Back Better, a water management perspective, and a sustainable design. The focus will be on the storm impacts. The scope of the resource will be only on drinking water. No wastewater flows will be explored, only as environmental criteria. The case study data used will be from before 2019. This is chosen because of the impact of Dorian and the amount of the available data gathered during the workshop [van der Hucht et al., 2021] which was the starting point of this thesis. This thesis will not delve into the realm of seawater rise resilience or climate change.

1.4. Thesis outline

The subject of this thesis is “the interaction of the aspects of the “disaster cycle”, the guidelines of “Build Back Better”, and a general desire for “sustainability” interact in a water treatment system in case of frequent disasters".

Chapter 2 will provide information on the subject of this thesis; the island of Grand Bahama. Most of the information that is used for the case study was gathered during the workshop in 2019, meaning that most information is from before 2019. The theory behind the disaster impacts of a hurricane and tropical storm is explained. In the last section of the chapter Background, the concepts, tools, and methodologies used will be explained.

In Chapter 3 the Methodology there is built on the concepts, methodologies, tools, and background of the case study. The scientific concepts, tools, and methodology which are used in the thesis are; Build Back Better, Disaster Cycle, three-point approach(3PA), Hofstede’s Cultural Dimensions Theory, Three Sustainability Pillars, and Multi-Criteria Analysis. In methodology, the set-up is made for the clear path taken to explore the interaction of the aspects of the “disaster cycle”, the guidelines of “Build Back Better”, and a general desire for “sustainability” to interact in a water treatment system. First, explore the relevance for water treatment plants of aspects of the “disaster cycle”, “Build Back Better”, and “sustainability”. Then set up the way to create alternatives, scenarios, and requirements, then add clear aspects from “disaster cycle”, “Build Back Better”, and “sustainability”.

In Chapter 4 the scenarios for the MCA are described, and these scenarios will be worked out in detail. The scenarios of this thesis are Scenario 1 a tropical storm and Scenario 2 a severe Hurricane.

The design alternatives listed below are developed in Chapter 5.

- Alternative 0 is the representation of the current situation in 2019.
- Alternative 1 is Reverse Osmosis (RO) with grid power using salt water as a water source.
- Alternative 2 is Reverse Osmosis (RO) with solar power using brackish water as a water source.
- Alternative 3 is based on a design made during the workshop. The goal of the workshop was to Build Back Better. The mean solution was based on collective protection by building a levee using the natural landscape. This levee would protect the densely populated area from storm surge flooding.

Chapter 6 presents a summary of the evaluation of the three alternatives.

Finally, the results are discussed in Chapter 7 and Chapter 8 provides suggestions for additional research and states what would have been done differently given the benefit of hindsight.

Appendices A, B, and C present the details of the MCA for alternatives 1, 2, and 3 respectively

2

Background

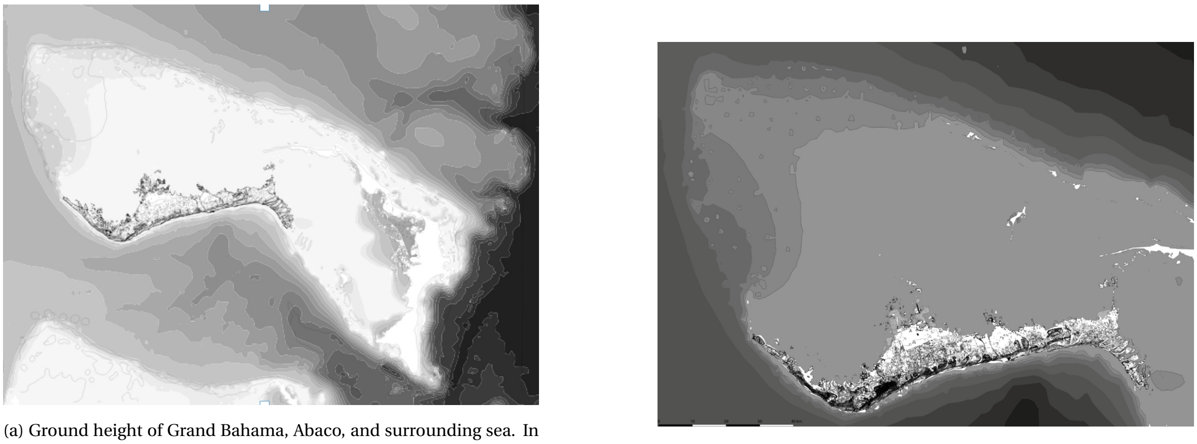
This chapter will inform the reader about the background of the case study of Grand Bahamas and other background topics used in the thesis. The topics are summarised shortly with the relevant aspects highlighted for this thesis. The idea of this thesis and most of the background used for the research comes from a workshop. The workshop focused on Hurricane Dorian. Hurricane Dorian has had a more significant impact on the island than other recent hurricanes and has impacted freshwater availability on the island. In the face of growing economic activity on the island, rising sea levels, and more frequent storms, it is not enough to consider rebuilding what already existed and using the same methods regarding freshwater availability. The workshop provided the inspiration for this thesis and much of the background information on Grand Bahama and Hurricane Dorian.

The workshop started just after Hurricane Dorian hit the tiny island of Grand Bahama in 2019. To analyze this event and the reconstruction that needs to follow, a group of researchers and students of the Technical University of Delft and the University of the Bahamas tasked themselves to explore the vision of Build Back Better. This was done by taking an interdisciplinary approach and connecting engineering to spatial planning and design. The workshop participants proposed a strategy that reduces the risk by taking into account the exposure and vulnerability of the general risk approach. The main objective of the strategy was to create a resilient urban environment in which vital infrastructure like the airport remained functional. This was done by making a collective protection zone of the economic and social city center of Freeport, a zone that also offers shelter. Individual protection and evacuation shelters will be given to residents, buildings, and facilities in the less densely built areas, east and west of the city [van der Hucht et al., 2021].

The conclusions of the workshop were used to propose a solution that involves several aspects: reduced overall risk, increased social cohesion on the island, improved life quality, and reduced costs during reconstruction in the aftermath of a hurricane event. Based on the analysis of the island, the hurricane, and the essential physical processes, two protection methods are proposed based on the location of the isle: collective and individual protection.

In the workshop, the following concepts were used; the Charette model, the Three-point Approach, and the conceptual framework: Build Back Better. The Charette method advises a series of steps where disciplines are twinned in sub-group discussions, and each subgroup's size gradually increases until the final session when one group discussion is held with all disciplines in attendance [Lennertz et al., 2014], [Hooimeijer et al., 2018]. The three-point approach and Build Back Better will be explained later in this chapter.

The Charette model itself is not used in this thesis, the question it raised helped form the research questions. The writer of this thesis represented one of the engineering disciplines, Water management. When combining the disciplines the different views the other disciplines had on Build Back Better as a comparison became apparent. It became obvious, there is considerable room for improvement in the combination of water management and Build Back Better. The workshop's scope made it impossible to go into detail on the water design specifically. In the face of growing economic activity on the island, rising sea levels, and more frequent storms, it is not enough to consider rebuilding what already existed and using the same methods of building regarding water availability.



(a) Ground height of Grand Bahama, Abaco, and surrounding sea. In the north of Grand Bahama, the Little Bahama Bank lay. Note, data from Grand Bahama Port Authority and Office of Coast Survey GBPA, Grand Bahama Port Authority [2017].

(b) Ground height with contour lines of the west side of Little Bahama Bank. Note, data from Grand Bahama Port Authority and Office of Coast Survey.GBPA, Grand Bahama Port Authority [2017]

Figure 2.1: Overview of height around Grand Bahama

2.1. Small island Grand Bahama

Grand Bahama is the most northern island in the Commonwealth of The Bahamas and its second-most populous island. The central city on the Island, Freeport, is regarded as the nation's second-largest city. The pine forest that dominated the island three decades ago made way for a thriving port city with an industrial center and tourist area. This increase came from the Hawksbill Creek Agreement of 1955. The Government of The Bahamas granted 50,000 acres of land with an option of a further 50,000 to American financiers, which created the Grand Bahama Port Authority [Knowles, 2019]. Like the rest of the country, the island of Grand Bahama lies in Hurricane Alley, as seen in Figure 2.8, where many hurricanes are formed [Goudzari, 2006], [APnews, 2019].

2.1.1. The geology, bathymetry, and topography

The bases for the Bahamian islands were formed by the North American and Caribbean plates when the supercontinent Pangea broke apart. Bacteria and sand traveled across the Atlantic Ocean from the Sahara Desert formed on top of these bases forming a rock base. On these rocks, two carbonate banks were formed, now at a depth of five kilometers. The northern bank is called Little Bahama Bank, and the other one is the Great Bahama Bank [Lytle, 2006], [Scarinci, 2016].

On top of these rocks, carbonated sediments were deposited. They consist mainly of limestone but also include Lower Cretaceous dolostone and evaporites, which are sedimentary deposits that result from the

(a) The shore typologies of Grand Bahama. Note, data from Grand Bahama Port Authority and Office of Coast Survey made by P. Grgic

(b) The ecosystems of Grand Bahama. Note, data from Grand Bahama Port Authority and Office of Coast Survey [GBPA, Grand Bahama Port Authority, 2020]

Figure 2.2: Overview of the ecosystems, geology, bathymetry, and topography of Grand Bahama

evaporation of seawater [Lytle, 2006], [Vacher H. L., Quinn T. M., 2004]. On top of this limestone, Coral reefs have grown, shaping the islands today [Scarinci, 2016]. During the last 2000 to 3000 years, the sea level remained stable. This created the environment for coral reef growth. Thereby helping the conditions for sediment transportation, which enhances the growth and stability of the islands [Vacher H. L., Quinn T. M., 2004]. This all influences the shoreline and its material, as seen in Figure 2.2a.

The hydrodynamic conditions highly influence the development of the shape of Grand Bahama. In general, if the flow becomes less energetic, then the flow velocity and wave height will decrease, enhancing sedimentation and growth of the island [Bosboom and Stive, 2015]. The island Abaco in the west, which can be seen on the right in Fig. 2.1a, forms a natural barrier that usually protects Grand Bahama from significant winds and waves—resulting in a low energetic hydrodynamic environment around the island. The consequence is that Grand Bahama is a significantly broad and quiet island, mostly below 5 m above mean sea level. Being on the lee side of Abaco also results in an extensive flatland across the northern part, which is known as the Little Bahama Bank, see Fig. 2.1b. The large island is formed by aeolian processes, wherein the wind creates a high ridge [Vacher H. L., Quinn T. M., 2004]. The contour lines of the topography, from the Grand Bahama Port Authority, and bathymetry, are combined and visible in Figs. 2.1a and 2.1b.

Erosion shouldn't be considered for the design timeline. The exclusion of erosion is because there is no land retreat. Rapid large-scale erosion is the consequence of the relative sea level rise. Based on Google Earth Engine, the island, on a large scale, has been stable since 1984. Except in some locations with some sedimentation, as visible at the breakwater at the Xanadu beach channel [GEE, Google Earth Engine, 2021]. As long as the sea level doesn't rise rapid large-scale erosion won't occur on the Bahamian islands [Vacher H. L., Quinn T. M., 2004].

As mentioned above, Grand Bahama consists mainly of limestone. This is a very porous material and, thus, is easily eroded by rainfall and runoff from the surface, which results in a significant possibility for the formation of caves. The limestone can dissolve on the island's outer edge since there is fresh- and salt water, which also leads to cave formation [Lytle, 2006]. The porosity and permeability of the Limestone on Grand Bahama are highly variable [Ehrenberg et al., 2006]. At 15 to 20 feet above mean sea level, marine deposits are changed from loose sand to an entirely altered rock. This increases the density and reduces the porosity of the soil. Due to groundwater movement, channels can form in this soil, resulting in high conductivity. These channels quickly fill with coarse granular calcite crystals if there is no water movement through these channels [Little et al., 1977].

2.1.2. Ecosystems

The island of Grand Bahama hosts five main ecosystems, and natural habitats based on local observations and data from the Grand Bahama Port Authority and Office of Coast Survey [GBPA, Grand Bahama Port Authority, 2020]. These main ecosystems are Shallow Coral, Pine Forest, Sparse Mangrove, Dense Mangrove Coppice, and Seagrass as can be seen in Figure 2.2b. Only four Bahamian islands have the ecology possible for the special freshwater forest, and Grand Bahama is one of them [Lloyd et al., 2011],[Antalffy et al., 2021].

2.1.3. Population

Grand Bahama had the second-largest intake of Bahamian island migrants. Grand Bahama, however, was one of the top four islands experiencing a net population loss in the period 2000 – 2010; 698 people left [Chief Census Office, 2014]. After a hurricane hits the island, a population decline follows, not only because of the loss of life due to the hurricane and its aftermaths but also due to the loss of work and/or homes. After each hurricane, the cost of maintenance of utilities increases per person due to this population decline. The increase in costs makes it less likely for people to return and rebuild, making the population spiral even further into decline. Grand Bahama's total population in 2010 was 51.368 and consisted of 24.996 males and 26.372 females. The population per square mile is 96.9 [Chief Census Office, 2012].

Religion is a major aspect of the people of the Bahamas. Over 70% of the Commonwealth of the Bahamas is part of the Christian faith. The three largest principal religious denominations are the Baptist, Anglican, and Roman Catholic. Their percentage share of the population in 2010: The Baptist 34.9%, the Anglican 13.7%, and Roman Catholic 12.0%. The amount of religious people increases each year. However, all three major religious groups experienced a decrease in their percentage share of the population. In contrast, the "Other Christian Denomination" category which includes non-denominational churches, increased significantly both numerically and in percentage share in 2010, accounting for 11.7% of the population [Chief Census Office, 2012].

Residents in the more central and southeastern islands are migrating to the urban centers of Freeport due to the lack of water resources, job opportunities, health care, and education in these regions. The population growth and the tourism industry lead to increased water usage for food production and household (or hotel) use, which may intensify water shortages, ultimately leading to economic and social crises [Roebuck and Ortiz, 2004].

2.1.4. Economy

The Bahamas is a stable, developing nation with an economy heavily dependent on tourism. Banking, fishing, agriculture, and manufacturing are other economic contributors. Tourism represents more than 60 percent of the gross domestic product (GDP) and employs about half of the workforce. Steady growth in tourism revenue and a significant increase in new hotel construction, resorts, and residences led to solid GDP growth in recent years until 2002.

Tourism is an industry that global and natural events can quickly have an impact on. The slowdown in the U.S. economy and the attacks of September 11th, 2001, reduced growth in these sectors from late 2001. By February 2002, tourist numbers returned to normal levels [Roebuck and Ortiz, 2004]. Service industry income related to tourism is considered part of export income. The Bahamas leads Latin America and the Caribbean by far in the percentage of total exports attributable to tourism. Tourism accounts for about 75% of total exports. Without exception, the development of the tourism industry is dependent on the proper management of water resources. Pollution of the beaches and associated health risks for tourists and the local population is a tremendous threat to the industry and, therefore, the entire nation's economy [Roebuck and Ortiz, 2004].

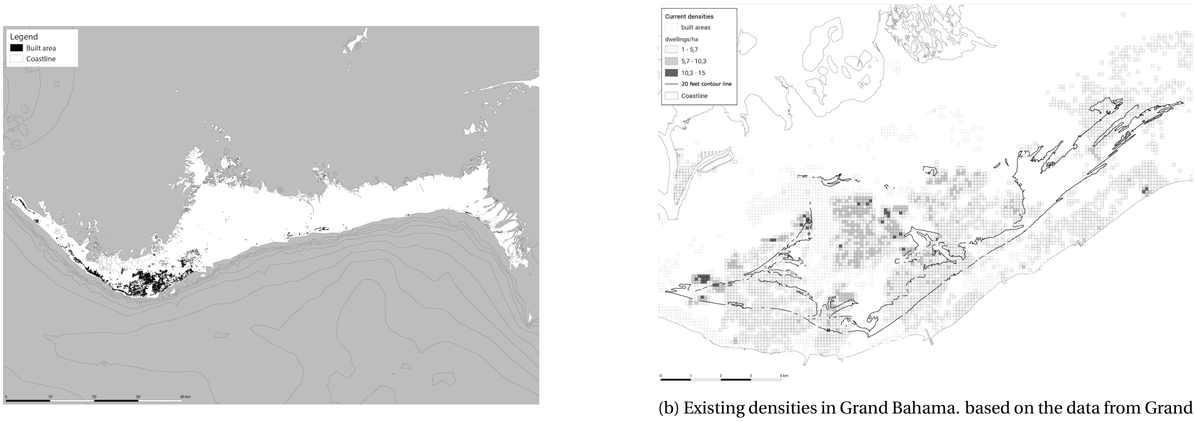
The island of Grand Bahama is the second biggest island economy of the Bahamas. Grand Bahama represented $1.437 billion (14.5%) of Bahama's Gross Domestic Product (GDP) in 2020. Only second to the island New Providence [Wilson, 2020]. Grand Bahama's GDP declined between 2015 to 2020. The contribution of Grand Bahama to the total GDP of The Bahamas - moving from a high of 17% in 2015 to a low of 15% in 2020. The developments were a series of events that impacted the Grand Bahamian economy. [Wilson, 2020]

- 2017, The adverse impact of Hurricane Irma
- 2018, The economy rebounded from Hurricane Irma's devastation
- 2019, A modest fall off as the growth in the first eight months was tempered by the impact of Hurricane Dorian on the Eastern and parts of Central Grand Bahama.
- 2020, Contraction associated with the COVID-19 Pandemic, combined with a temporary halt in the hurricane rebuilding efforts.

2.1.5. Built area

The density of the existing built environment in Grand Bahama is very low. The map 2.3a shows where on Grand Bahama buildings are located. The map 2.3b shows the density of the existing built environment on Grand Bahama calculated in the report van der Hucht et al. [2021]. This map only shows the area of Freeport, where most of the buildings are located. Every building registered in the datasets of the Office of Coast Survey as"residential" was, therefore, counted as a "traditional" Bahamian household that usually hosts one family unit, seen in Fig. D.1. The analysis for the map 2.3b considers each of these buildings as a dwelling. In this way, it is possible to indicate a rough density analysis expressed in dwelling per hectare: dividing the perimeter of Grand Bahama into polygons with a dimension of 100x100m, i.e., one hectare.

The average household size is at 3.4 persons [Chief Census Office, 2012]. Grand Bahama's big city, Freeport, needs cooling for around nine months a year. From March to November, the temperature of the air exceeds 31°C, while the comfort level is 26°C as seen in Fig D.4, [Meteo Blue, 2022], and this situation necessitates solar protection both in the site-scale and the building-scale. Bahamian architecture responds to cultural and climatic aspects.



(a) Location of the built areas. Data from Grand Bahama Port Authority and Office of Coast Survey made by P. Grgic

(b) Existing densities in Grand Bahama. based on the data from Grand Bahama Port Authority and Office of Coast Survey 2020 [GBPA, Grand Bahama Port Authority, 2020]made by P. Grgic

Figure 2.3: Overview of densities of the built areas on Grand Bahama

Value of vehicle	$1,000	$1,500
Tax/fee		
Duty rate = (Value of vehicle) * 65%	$ 650.00	$ 975.00
Processing fee = (Value of vehicle) * 1%	$ 10.00	$15.00
Environment Levy fee for Vehicle	$ 250.00	$ 250.00
Non-tax cost		
Storage Fee ($50 p/w) (only when applicable)	$ 50.00	$50.00
Freight/INS/Other Charges (not a standard fee)	$ 900.00	$ 900.00
Landed charges	$ 100.00	$ 100.00
Security Fees (Vehicles Imported/Exported) (20ft Containers Imported & Exported)	$ 10.00	$ 10.00
Total Landed Cost= non-tax cost+tax/fee	$ 2970	$ 3800
V.A.T.= (Total Landed Cost) * 12%	$ 356.40	$ 456.00
The total amount paid to Bahamas Customs & Excise department = (Tax/fee)+ (V.A.T.)	$ 1316.40	$ 1746
Total added Consumer Cost	$ 2326.4	$ 2756
Total Cost Consumer	$ 3326.40	$ 4256.00

Table 2.1: C-13 entry for a less than 10-year-old vehicle based on a calculation made in "Rates of duty" July 2019 [Moss, 2019]

2.1.6. Transportation

Figure 2.4 shows a map of the most important route lines crossing the island from west to east [van der Hucht et al., 2021]. The majority of them are focused on the area of Freeport. The map 2.4 is based on an analysis by van der Hucht et al. [2021] of the mobility infrastructures on the Grand Bahama island. The report used a space syntax analysis to understand where the traffic concentrates. The space syntax analysis shows the option of choice, therefore measuring how likely it is that a street will be passed through on all shortest routes from all spaces to all other spaces in the entire system or within a predetermined distance from each segment [Hillier et al., 1986]. In this case, the distance that was taken into account was 25km, which corresponds to the distance usually covered by a car ride. All the dark roads indicated on the map are mainly used by car traffic and therefore also designed for it.

The roads of the Bahama are styled like an American layout; Wide roads, large driveways, and big parking spaces with minimal or no green between. American cars have become heavier and wider than most other manufactured cars worldwide [Anderson and Auffhammer, 2014],[Lowrey, 2011]. The roads are designed for American-made cars. However, a possible shift can be observed in the kind of vehicle on the road.

The cars on the road have become smaller due to the increased number of Japanese cars on the road. Some Japanese companies are using the laws around import duty to sell second-hand cars comparatively cheaply to the Bahamas [BCED, The Bahamas Customs & Excise Department, 2020a], [BCED, The Bahamas Customs & Excise Department, 2020b]. This is because the cost of a car is based on the customs duty, which is, in turn, based on the car's value. In Table 2.1 a calculation is made with a car worth $ 1000 and a car valued $ 1500 in Table 2.1. These are both cheap cars, but the small increase in worth makes a big difference in the eventual consumers' cost. The importation of vehicles to Bahama is restricted to vehicles less than ten years old. This means that for any vehicle to be imported above ten years old (from the date of manufacture), special permission must be granted by the Ministry of Finance in advance of the importation [BCED, The Bahamas Customs & Excise Department, 2020a]. Japanese companies sell shipments of used cars less than ten years old cheaply to Bahama. This makes them more affordable than American-made cars. Japanese cars tend to be smaller than American-made cars. Causing the autos on the road to become smaller [AAA Japan Co. Ltd., 2021].

The space that becomes available due to the decrease in car size, can be used for other purposes, such as water management infrastructure.

Figure 2.4: The space syntax analysis shows streets with the highest traffic (the darkest) on the island. Note, data from Grand Bahama Port Authority and Office of Coast Survey

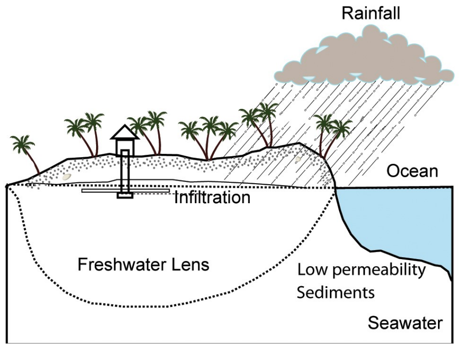


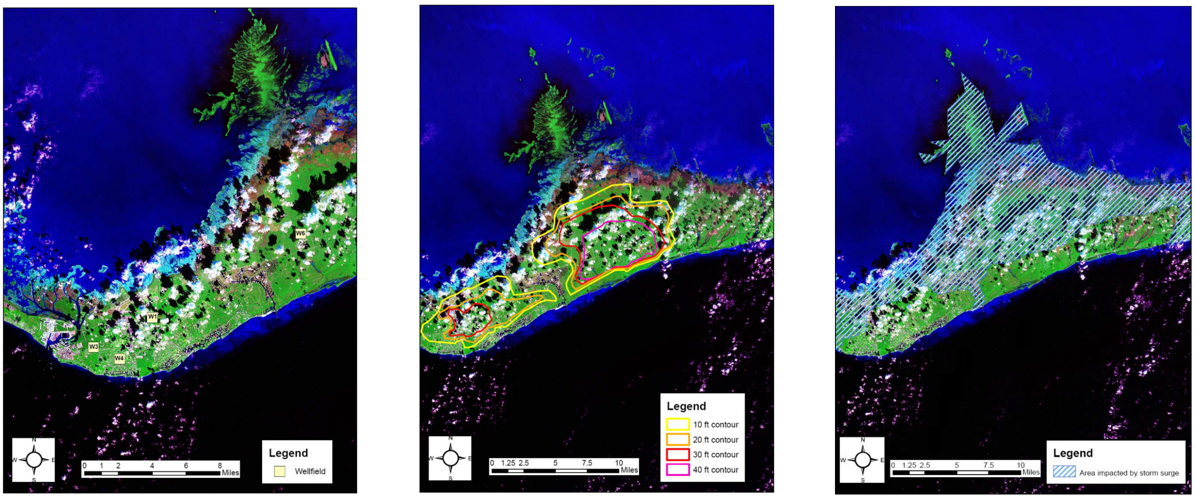
Figure 2.5: Fresh water is lighter than heavier saltwater, which gives a freshwater lens with sufficiently sized islands [Burns, 2002],[Global Change Research Program, 2009], [Cant and Weech, 1986]

2.1.7. Water supply system

Freshwater resources are finite and vulnerable in The Bahamas [Roebuck and Ortiz, 2004]. The lithology of Grand Bahama consists mainly of Limestone as stated in subsection 2.1.1. This is a very porous material and thus is easily eroded by rainfall and runoff from the surface, resulting in a large potential to form caves [Lytle, 2006]. Some of these caves are filled with freshwater basins and are used by the population as a freshwater resource. The extent of freshwater resources is limited to fragile freshwater 'lenses' in the shallow karstic limestone aquifers. The area of the island Grand Bahama is large enough to form a freshwater bubble [Roebuck and Ortiz, 2004].

The 'freshwater' is derived from precipitation, lying underground on top of the shallow saline water as a 'lens.' Fresh surface water is non-existent. The country, therefore, relies on a single source of water, rain. Water availability is so low that it is considered 'scarce,' according to United Nations criteria. Several scenarios for supplying water exist in the various Bahamian islands. The main ones include:

- Ground water provided via water authority on a large scale
- Private water wells
- Ground water barged from one island to another
- Fresh groundwater blended with brackish groundwater
- Ground water piped from one island to another by underwater lines
- Desalination (usually RO)
- Water trucking from one part of the island to another



(a) Location of fresh water wells around Freeport GBUC, Grand Bahama Utility Company Ltd [2008]

(b) Map of the thickness of the groundwater lens GBUC, Grand Bahama Utility Company Ltd [2008]

(c) Extent of storm surge impacting the GBUC wellfields in 2004GBUC, Grand Bahama Utility Company Ltd [2008]

Figure 2.6: Wells on Grand Bahama

- Bottled water for drinking and cooking

Over-abstraction of the limited freshwater reserve can cause saltwater intrusion into the freshwater aquifer, resulting in permanently abandoning well-fields. Sea level rise due to climate change also threatens the availability of freshwater. The aquifers are very shallow and are at significant risk of becoming inundated with saline water, even with a slight rise in sea level. Due to climate change, less precipitation in some islands has also reduced freshwater availability over the years. Contamination also threatens the limited freshwater reserves. The nature of the geology and improper sewage collection and treatment contribute to groundwater contamination. However, natural disasters and severe weather, such as hurricanes, are probably the most threatening to the health of the freshwater reserves.

The water supply of Freeport makes use of this fresh-groundwater reservoir. Wells are installed to capture this water in the area, as shown in Figure 2.6a and 2.6b. If a seawater surge flows over the ground level and the saltwater infiltrates into the ground, a mixing of fresh and saltwater occurs, making the basin brackish and unusable as a freshwater resource. A seawater storm surge occurred in 2004 and the impact on the wellfields is visible in Figure 2.6c. The salt intrusion following Hurricane Dorian ruled out the use of the basin for a long time. Saltwater is heavier than fresh water and will move through the whole bay before reaching the saltwater layer, contaminating the entire basin, , as can be seen in Figure 2.5. Furthermore, once the amount of salt pollution has reached a critical level, remediation is almost impossible. The GBUC, a private company, supplies Freeport with fresh water. Freeport is the second most populous town in the nation. Piped water has been available to residents in Freeport since 1920 [Roebuck and Ortiz, 2004]. Water losses, particularly unaccounted-for water loss, are significant. There is a high percentage of water loss, however, this is typical for Latin America and the Caribbean.

In 2004 the US Army Corps of Engineers Mobile District & Topographic Engineering Center stated that regulating the water resource in Grand Bahama through integrated groundwater management is recommended. Ignoring the over-exploitation and protection will have severe repercussions, such as health issues from water-borne diseases and much higher water costs.

It is also clearly seen in Figure 2.7 that the recently constructed Grand Lucayan Waterway, which supplies tourist accommodations with boat access, cuts the groundwater bubble in half. With the construction of this channel, the groundwater bubble is split in two and no longer one big bubble under the island. This is because the channel polluted the groundwater in that area with seawater.

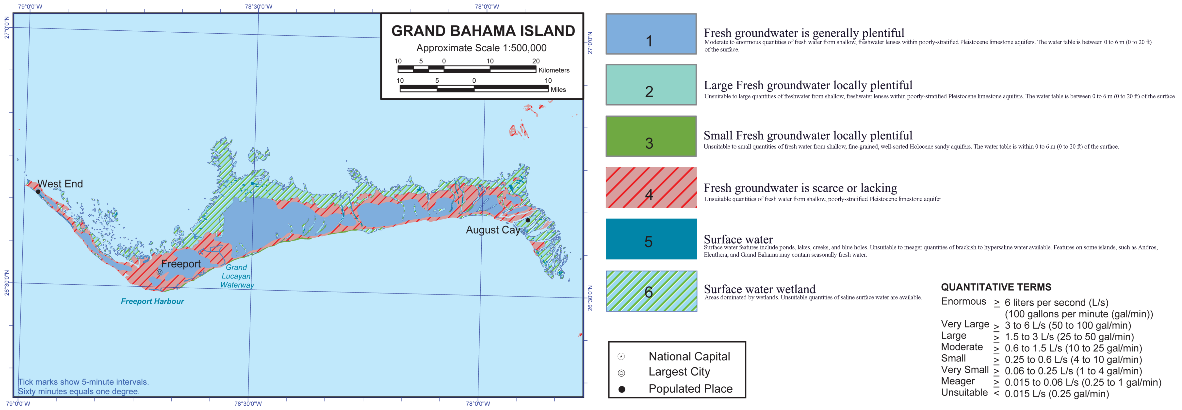


Figure 2.7: Water resources of Grand Bahama [Roebuck and Ortiz, 2004]

2.1.8. Tourism

Tourism brings in about 4 million visitors annually in all of the Commonwealth of Bahama [Roebuck and Ortiz, 2004]. Tourism is the mainstay of The Bahamas' economy. The industry heavily depends on adequate supplies of good quality water for survival. Water is, therefore, a vital economic resource of The Bahamas [Roebuck and Ortiz, 2004]. The minister of the industry has different categories of characterization of Visitor Arrivals. One of the categories is Stopovers. A stopover is anyone who stays at least one night in The Bahamas [BMoT, The Bahamas Ministry of Tourism, 2019]. The number of stopovers can be seen in Table 2.2 and Table 2.3, [Wilson, 2012].

Nassau/Paradise Island received the most stopover visitors. In 2019, approximately 76% of stopover visitors to The Bahamas visited Nassau/Paradise Island, 5% visited Grand Bahama, and 19% visited the Out Islands [Research et al., 2019].

On September 1, 2019, Hurricane Dorian slammed into the islands of Abaco and Grand Bahama as a category 5 Hurricane. In Table 2.4 the decline of visitors beginning in August followed by the hurricane, can be seen.

While being dependent on water availability and quality for the industry to develop and thrive, tourism has devastating consequences for freshwater resources. Tourists use 400 to 1,000 liters of water/visitor/day. Many elements are needed in the tourism industry, but water is the more critical of power, telecommunications, human resources, and the environment. As a result, water is a key economic resource [Roebuck and Ortiz, 2004]. These tourists use an estimated two to five times more potable water than the residents [Roebuck and Ortiz, 2004].

2005	2006	2007	2008	2009	2010	2011
218,722	196,857	178,396	155,131	137,091	160,622	145,442

Table 2.2: Stopover visitors of Grand Bahama 2005 to 2011

2012	2013	2014	2015	2016	2017	2018	2019
146,282	138,601	179,104	205,753	177,188	122,094	125,201	94,979

Table 2.3: Stopover visitors of Grand Bahama 2012 to 2019

2.1.9. Government Grand Bahama

The National Emergency Management Agency (NEMA) is a government agency that operates under the authority of the Cabinet Office. The Cabinet constitutes the executive branch and has general direction and control of the Government of The Bahamas. It comprises at least nine Ministers, inclusive of the Prime Minister and Attorney General. The Cabinet meets at least once per week to consider various issues [The government of the bahamas, 2021], [The goverment of the bahamas, 2021]. The NEMA has the goal of preserving human life in times of crisis. They strive to efficiently and effectively administer the components of the country's

Month	Air Arrivals	Sea Landed	Cruise Arrivals	Total Arrivals
January	5,782	3,506	39,546	48,834
February	6,795	4,298	36,663	47,756
March	7,488	6,465	52,120	66,073
April	6,092	6,007	36,320	48,419
May	5,586	6,409	45,237	57,232
June	5,986	11,290	50,663	67,939
July	5,986	10,485	62,400	78,871
August	4,547	2,891	26,431	33,869
September	486	254	12,175	12,915
October	367	1,323	6,748	8,438
November	700	1,712	18,951	21,363
December	2,053	2,347	29,033	33,433
YTD Jan to Dec	51,868	56,987	416,287	525,142

Table 2.4: Foreign arrivals to Grand Bahamas in 2019

Disaster Management Programme. They do this with the following actions: Mitigation planning, Community preparedness, Public Information, and Recovery coordination [BCED, The Bahamas Customs & Excise Department, 2020c]. The term The House of Assembly which included members of the cabinet has a term of five years the Commonwealth of the Bahamas [2023].

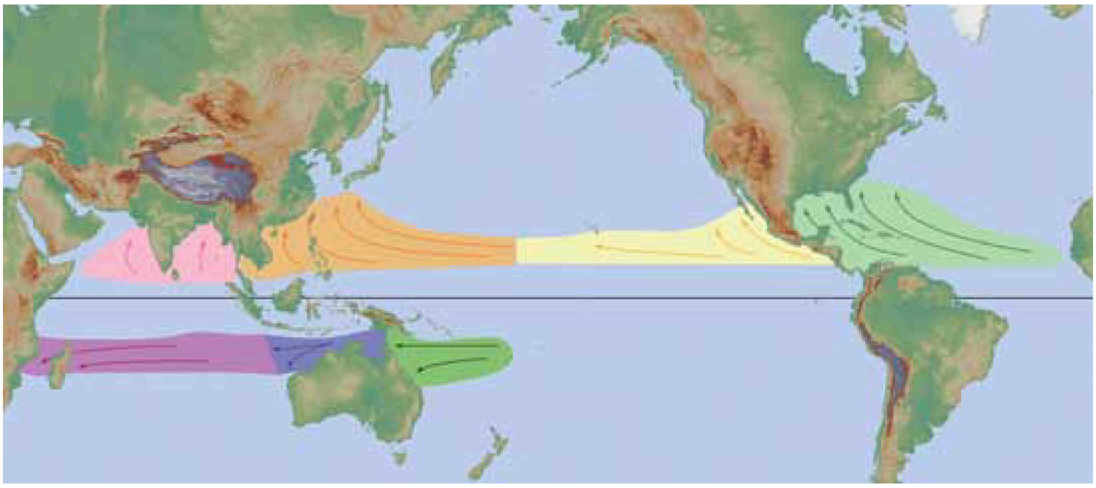


Figure 2.8: Tropical Cyclone formation regions with mean tracks. Grand Bahama is in the green regionNOAA, National Oceanic and Atmospheric Administration [2019]

2.2. Disaster impacts; hurricane and tropical storm

Each location has specific disasters. These paragraphs will explore the recurring disasters that plague the island of Grand Bahama. Based on the analysis of the island, the hurricane, and the important physical processes, an overview and understanding made of the hazards can be made. This hazard overview can optimize a solution, ensuring prosperity on the island Hurricanecity [2021].

Hurricanes are dangerous and can cause significant damage because of storm surges, wind damage, and pluvial flooding. The tropical storms develop over the Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico, terrorizing the U.S. coast or any territory in the Atlantic or Pacific oceans. Storm surge is historically the leading cause of hurricane-related deaths in the United States. All factors of hurricanes are hazardous, such as the rain, wind, and water. Hurricanes are not only a coastal problem but can also impact inland [DHS, U.S. Department of Homeland Security, 2022].

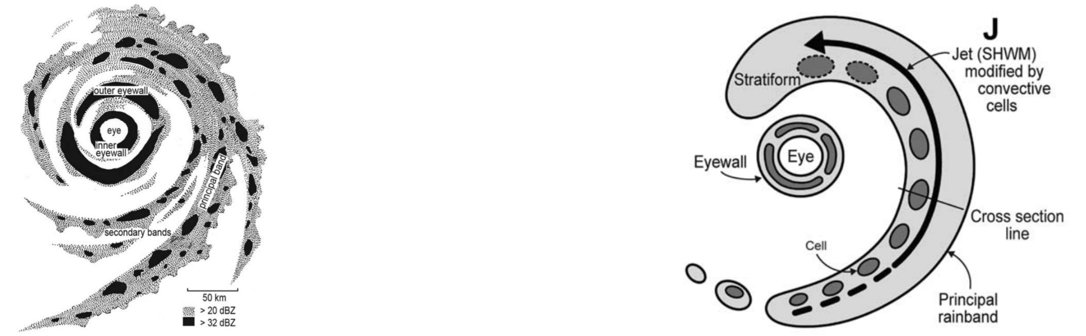
Hurricane season

- Eastern Pacific Hurricane Season: May 15-November 30.
- Atlantic Hurricane Season: June 1-November 30.
- Central Pacific Hurricane Season: June 1-November 30.

The capacity to respond to a hurricane of individual nations can be linked to several factors, such as local and regional economic resources, government organization, and availability of technological, academic, and human resources. However, it is becoming increasingly common that individual nations' resources to respond are insufficient in the face of a large-scale disaster, and outside assistance is needed. Disasters that affect whole regions are not uncommon and require these same international response mechanisms.

"The general consensus is that tropical storms will increase in frequency and intensity with the presence of still warmer tropical waters. That likelihood, combined with rapid development in coastal areas, increases the potential for substantial loss of property and human life. Effective damage prevention and disaster response strategies must be better understood" [Blanco et al., 2009].

There is a direct connection between tropical storms and hurricanes, as can be seen in Figure 2.9 and 2.10. Both are tropical cyclones and a hurricane is always surrounded by tropical storms. The direct hazards of hurricanes and tropical storms are increased precipitation, waves, and flooding due to storm surges. In the case of Dorian, Grand Bahama suffered an intense sea surge, where winds of 295 km/h pushed the water from the shallow northern coast inland, creating great flooding and damage in several locations.



(a) The inner and outer eye wall consist of hurricane condition. The secondary and principal bands are similar to a tropical storm

(b) The eye and eyewall are similar to a hurricane condition. The eye of the hurricane is surrounded by rainbands which are similar to a tropical storm.

Figure 2.9: Overview of multiple schematics of a hurricane and the different intensities in the hurricane Three simple graphs

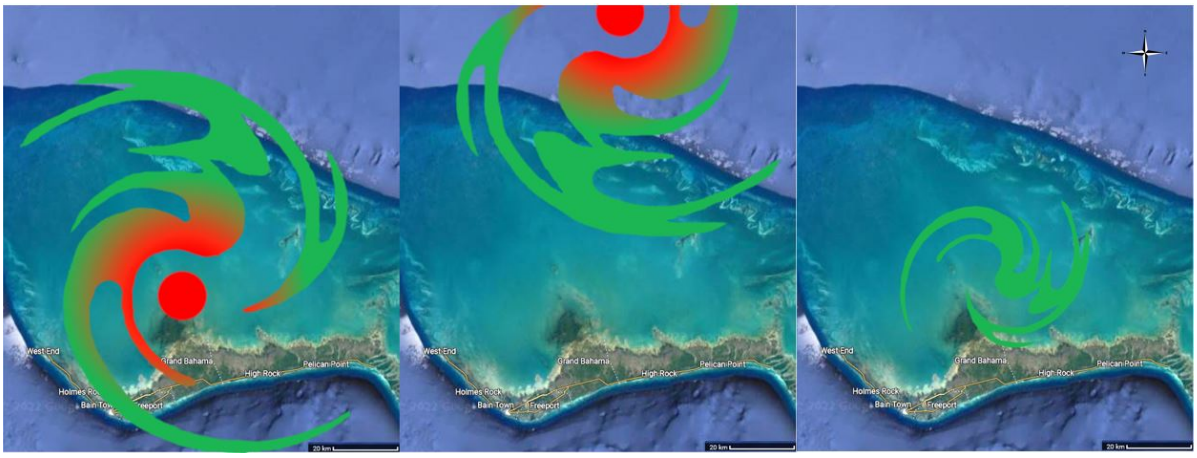


Figure 2.10: The figure shows the connection between hurricanes and tropical storms. The outside of the hurricane eye is always surrounded by a tropical storm. The red shows the hurricane condition and the green is the tropical storm condition. The left is a hurricane on which the eye makes landfall, the island has hurricane conditions. The middle is a brush, not fully to scale, but shows that only the tropical storm condition influences the island. On the right, there is a storm without an eye, so it only has tropical storm conditions and is a storm without a hurricane categoryGoogle [2020].

The categorization of cyclones is NOAA, National Oceanic and Atmospheric Administration [2019];

Tropical Depression: A tropical cyclone with maximum sustained winds of 62 km/h (33 knots) or less.

Tropical Storm: A tropical cyclone with maximum sustained winds of 63 to 117 km/h (34 to 63 knots).

Hurricane: A tropical cyclone with maximum sustained winds of 119 km/h (64 knots) or higher. In the western North Pacific, hurricanes are called typhoons; similar storms in the Indian Ocean and South Pacific Ocean are called cyclones.

Category 1 Very dangerous winds will produce some damage: Well-constructed frame homes could have damage to roofs, shingles, vinyl sidings, and gutters. Large branches of trees will snap and shallowly rooted trees may be toppled. Extensive damage to power lines and poles likely will result in power outages that could last a few to several days NHC, National Hurricane Center [2019].

Category 2 Extremely dangerous winds will cause extensive damage: Well-constructed frame homes could sustain major roof and siding damage. Many shallowly rooted trees will be snapped or uprooted and block numerous roads. Near-total power loss is expected with outages that could last from several days to weeks 119-177 km/h (64-95 kt)[NHC, National Hurricane Center, 2019].

Major Hurricane: A tropical cyclone with maximum sustained winds of 179 km/h (96 knots) or higher, corresponding to a Category 3, 4, or 5 on the Saffir-Simpson Hurricane Wind Scale.

Category 3 Devastating damage will occur: Well-built framed homes may incur major damage or removal of roof decking and gable ends. Many trees will be snapped or uprooted, blocking numerous roads. Electricity and water will be unavailable for several days to weeks after the storm passes 179-208 km/h (96-112 kt)NHC, National Hurricane Center [2019].

Category 4 Catastrophic damage will occur: Well-built framed homes can sustain severe damage with the loss of most of the roof structure and/or some exterior walls. Most trees will be snapped or uprooted and power poles downed. Fallen trees and power poles will isolate residential areas. Power outages will last weeks to possibly months. Most of the area will be uninhabitable for weeks or months 209-251 km/h (113-136 kt)[NHC, National Hurricane Center, 2019].

Category 5 (Dorian) Catastrophic damage will occur: A high percentage of framed homes will be destroyed, with total roof failure and wall collapse. Fallen trees and power poles will isolate residential areas. Power outages will last for weeks to possibly months. Most of the area will be uninhabitable for weeks or months at 253 km/h or higher (137 kt or higher)[NHC, National Hurricane Center, 2019].

2.2.1. Precipitation flooding

Pluvial flooding is a consequence of extreme rain. Extremely heavy downpours can overwhelm drainage systemsSuch heavy precipitation can lead to flooding at ground level.

2.2.2. Wind hazard

A wind hazard is a force that refers to the pressure applied to a structure with the potential to lift it relative to its surroundings. Wind affects all roofs, and it varies depending on factors such as location, terrain, height, size, shape, and exposure. Wind uplift occurs when the air pressure beneath the roof surpasses the air pressure above it. This may be exacerbated during high wind, as air infiltration into the building may increase pressure below the roof, while wind speed above the roof surface may decrease air pressure above it, much like the effect on an aircraft wing. Too high a difference in air pressure will cause roof damage. Nails, as fasteners, are more susceptible to pull-out caused by the dynamic loading of the panels compared to screws. The attachment method should possess sufficient strength to withstand the uplift loads. On the roof add-ons like gutters, the uplift and rotational wind load exerted on the gutter will be transferred to the wall or deck, depending on the bracket design and attachment.

Wind pressure Winds with sufficient speed to damage houses can damage even a well-designed, -constructed, and -maintained facility in an event that exceeds the facility's design criteria. Fortunately, except in the case of tornado damage, it is rare for buildings to experience winds that exceed design levels. Most damage occurs because various building elements have limited wind resistance, resulting from inadequate design, poor installation, or material deterioration.

Wind-Driven Rain Rain or wind-driven rain, and hail damage are not assessed in the same classification as flood damage. Wind-driven interior water damage is a significant loss factor impacting coastal and inland property during hurricanes, severe thunderstorms, and other high wind incidents followed by rain. Many building owners overestimate their buildings' wind and storm-driven rain tolerance and underestimate how much time it will take to restore a destroyed building or build a new one. They also tend to underestimate the impact of disturbance from wind and water on the viability of construction operations. This lack of awareness may prevent building owners from minimizing the weaknesses of their buildings

2.2.3. Storm surge flooding

The storm surge, waves, and tides are the main contributors to coastal flooding, carrying with it secondary – but equally damaging – hazards, such as debris. Coastal areas are subject to flood risks, especially those associated with tropical cyclones. As storms surge and waves propagate onto the coastal area, they can continue to grow and inundate the beaches, buildings, and vegetation, while being dissipated at the same time. In the V Zone, see Figure 2.11 hurricane-induced waves and currents can generate significant hydrodynamic forces to destroy flooded buildings. In Zone A, wave effects are less significant, but buildings can still be flooded.

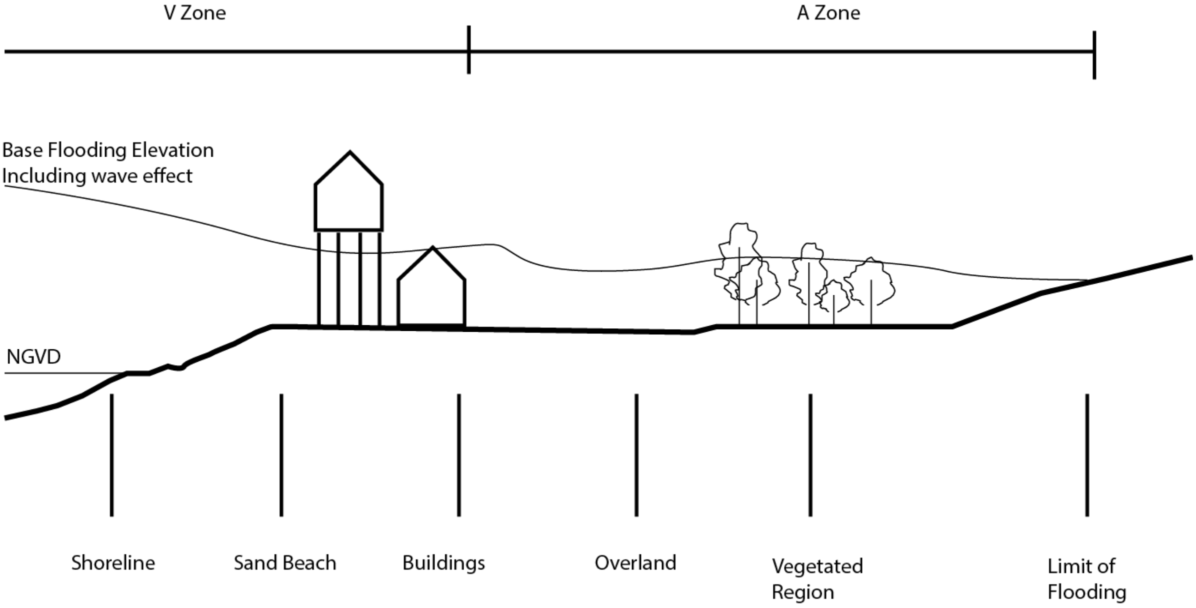


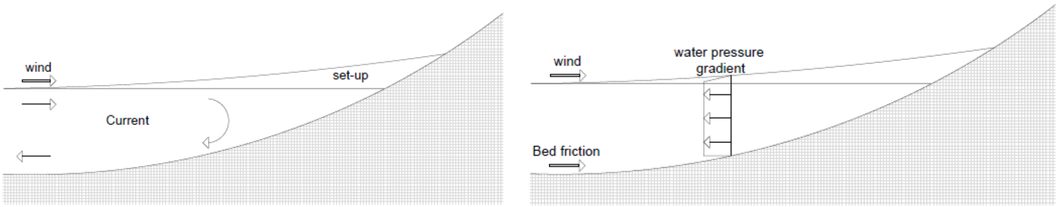
Figure 2.11: An overview of the zone location of the built volumes. data from Grand Bahama Port Authority and Office of Coast Survey

The topographic features and the bathymetry around Grand Bahama play a major role in the storm surge and the waves that reach the island. Grand Bahama is protected from wind and waves that come from the east, due to Abaco an island in the south. The same holds for the West, due to the short distance from the coast of Florida. On the south side, the deep water level can reach up to 2000 m. Just offshore the water depth is already 128 m. As will be explained below, the result is that this side of the island is mainly affected by large waves. While the northern part consists of a very large shoal. This shoal protects the northern side of the island from large waves but significantly increases the extent of a storm surge. In summary, waves can affect the south side of the island and storm surges can affect the north side of the island of Grand Bahama.

However, the shape of the island should be taken into account. Especially in the case of hurricane Dorian. Here the location of the hurricane resulted not only in the north wind over the shallow water, which resulted in a large storm surge on the north side of the island. But also the shape of the island is unfavorable. It acts as a funnel where the wind blows in. As a result, the water can barely flow away.

To give more information on the effect above the storm surge is visible in Figure 2.12a and in Figure 2.12b the wind velocities and the concluding pressures are visible [Bosboom and Stive, 2020].

It is important to conclude that it is not possible that there is a storm surge on both sides of the island. The onshore wind at one location will result in offshore wind on the other side of the island. Due to this offshore wind, the surface water will flow away from the island. This will result in a lowering of the water level. Based on the same reasoning of the storm surge, it can be concluded that this set-down is negligible at the south side of the island due to the large water depth. As a result, the south side of the island can be used as a safe area in case of a severe storm surge from the north.



(a) key concept of a storm surge

(b) Force balance of a water set-up by wind

Figure 2.12: Treats of flooding by seawater

2.2.4. Wave behavior and interactions

When the wind blows over the water's surface, energy is transferred from the air toward the surface waves. There are different mechanisms for this energy transfer but the main result is that this leads to the growth of waves which have different sizes [Miles, 1962]. These waves propagate towards the shore at a certain speed, the phase speed. This velocity is dependent on the water depth. If the water depth is larger, the wave propagates faster. This has multiple effects, for example, if a wave propagates under an angle towards the coast the part that is closer to the shore has a lower water depth. As a result, the more offshore part of the waves travels faster towards the coast. The result is that the waves travel (almost) perpendicular to the coast (shore normal) at the coastline if the coast is relatively flat.

Near a flat coast, when the water depth is slowly decreasing, the shape of the wave itself starts to influence the wave propagation speed. At the wave crest, the water depth is slightly larger than at the wave through. As a result, the wave crest propagates faster than the wave crest and the wave itself starts to deform. The front of the crest becomes steeper as a result of the wave breaking. In this breaking turbulence processes result in energy dissipation [Holthuijsen, 2007]. This dissipation is due to the deformation of the whirls/eddies resulting in smaller rotating motions where viscous shear stresses convert the kinetic energy in thermal heat by viscous shear stresses [Uijttewaal, 2020].

Based on this principle, where the water depth influences the stability of the waves, information about the distribution of the waves can be determined. Since large waves "feel" the bottom earlier, as they start to break at deeper water, the distribution of different wave heights can be determined. So the wave conditions are dominated by the water depth rather than the offshore wave height. This is useful for designing solutions where the significant wave height (Hs) is commonly used. This is the wave height wherein one-third of the waves is higher [Holthuijsen, 2007].

In shallow water, the significant wave height (Hs) is half the water depth (h). There is shallow water if the water depth is 20 times smaller than the wavelength. The wavelength (L) is the length of the crest and trough and can in shallow be determined by the phase velocity (c) and the wave period (T): $L = cT = sqrt(ghT)$ [Holthuijsen, 2007].

If the steepness increases, a larger part of the wave is reflected. The wave can be completely reflected if this wave hits a vertical wall. The reflected wave, which propagates offshore, interacts with the waves that propagate toward the shore. As a result, the water surface level will be elevated even further and the flow velocities will locally increase significantly. This means that a hydraulic intervention interacts with the hydrodynamics around the structure. The resulting condition can lead to erosion, undermining, and eventually, failure of the structure itself [Bosboom and Stive, 2015].

The type of waves, breaking or not breaking, and the corresponding amount of reflection depends on the slope of the bottom. This is usually expressed in the dimensionless Iribarren number. Which is the slope steepness versus the wave steepness [Schiereck and Verhagen, 2019]. This will be relevant for an alternative that includes levees.

2.2.5. Hurricane Dorian

In the early hours of Tuesday, September 3, 2019, Hurricane Dorian was stationary over the island of Grand Bahama for 18 hours, most of the time as a category five hurricane. As seen in Fig 08, the total accumulation of rain over parts of Grand Bahama exceeded 36 inches, according to NASA satellite-based estimates [Reed,

(a) Before Dorian, April 16

(b) During Dorian's September 2

Figure 2.13: Grand Bahama Island before and during Hurricane Dorian. The second image was taken on 2 September 2019 and uses radar to penetrate the cloud cover. Areas that appear nearly black are not flooded [Brumfiel and Hurt, 2019]

2019, August 29]. Hurricanes with comparable rain intensity are expected to occur once every 15 years. This is taken from approximations of the Central Pacific Hurricane Centre concerning occurrence rates of hurricanes on the coast of Florida [NOAA, National Oceanic and Atmospheric Administration, 2020]. Dorian was one of the most powerful Caribbean storms on record, a category-five hurricane with winds up to 297 km/h [News, (2019, September 3]. It stalled over Grand Bahama and Great Abaco islands for 30 hours [Packard, 2019, September 12], becoming the worst recent disaster in the nation's history. Radar pictures of the flooding are indicated in Figure 2.13b. The flooding of the island during Dorian is the result of the high storm tide. The storm tide is the total observed seawater level rise above the mean sea level, which consists of the astronomical tide and the storm surge [Liu, 2019]. The astronomical tide during Dorian was 3 ft. This was, unfortunately, the largest tide of the year, which is called a king tide [Buckingham, 2019].

The storm surge was relatively large due to the onshore winds over shallow water toward Grand Bahama Island [NOAA, National Oceanic and Atmospheric Administration, 2019]. The storm surge was, in general, up to 16 ft above mean sea level and, in some locations, up to 20 ft, according to the Grand Bahama Port Authority. Due to the flooding, Grand Bahama's international airport was under 6ft of water [News, (2019, September 3].

Near the coast, the storm surge was accompanied by large and destructive waves [NOAA, National Oceanic and Atmospheric Administration, 2019]. These waves are offshore generated by the Hurricane and propagate towards the shore. The offshore significant wave heights are approximately 10 to 14 m, with a wave period of circa 13 seconds [Wu et al., 2003]. In a spectrum of varying wave heights, the significant wave height is the one wherein one-third of the waves is higher [Holthuijsen, 2007].

2.3. Concepts, Tools, and Methodologies used

Concepts are understood to be the fundamental building blocks underlying principles, thoughts, and beliefs. This section delves into the concepts used within this thesis. By including these Concepts, Tools, and Methodologies the conclusion and results of this thesis will be more based on existing precedent, and of higher quality. The concepts, Tools, and Methodologies used are Build Back Better, Three points approach, three sustainability P's, Hofstede's Cultural Dimensions Theory, RenewIslands Methodology, MCA, and ACV4e LCA. They can be subdivided in the teachings of water management and Build Back Better, as seen in 2.14.

2.3.1. Build Back Better

> "Reconstruction should dovetail into the next round of mitigation and preparedness work as systems learn from the event by adapting to reduce the likelihood of future events."[Pelling, 2003].

It is not enough to consider building back the structures that were already there while using the same methods, especially in light of increasing economic activity on a tourist island, rising sea levels, and more frequent storms. The problems arising from climate change, combined with extreme natural cataclysms, are big and complex.

The concept of Build Back Better [Clinton, 2006] (also called BBB) understands post-disaster reconstruction not as a mere re-building activity but as a process for rethinking the social and built environment in

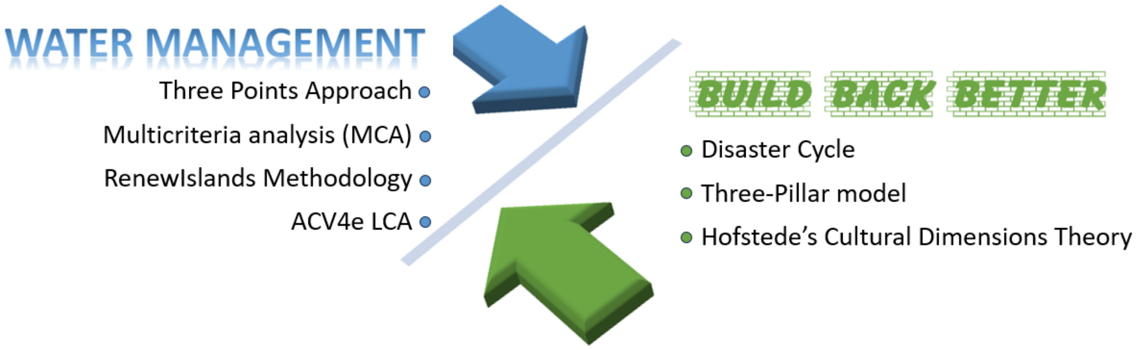


Figure 2.14: Overview of the Concepts, Tools, and Methodologies used.

longer-term scenarios by ambitiously connecting humanitarian relief, reduction of vulnerabilities, and involvement of local communities [Kennedy et al., 2008a], [Kennedy et al., 2008b] of the past and for the future. This introduces the necessity of improving recovery practices in line with longer-term sustainability objectives [Giovanni and Chelleri, 2019a]. The increasing frequency of disaster events has led to a demand for improved post-disaster reconstruction and recovery efforts [Mannakkara and Wilkinson, 2013]. The slogan "Build Back Better" denotes improving the physical, psycho-social, and economic aspects of communities during reconstruction and recovery to induce greater resilience.

Both President J.W. Clinton and President J.R. Biden Jr. have extended policies and reports on the importance of Building Back Better. The “Key Propositions for Building Back Better” by Clinton [Clinton, 2006] was the first official document produced identifying ten propositions to achieve BBB in post-disaster recovery [Mannakkara and Wilkinson, 2013]. This theory has been expanded with concepts like the disaster cycle in Subsection 2.3.2.

BBB principles Key Propositions for Building Back Better by [Clinton, 2006]

1. Governments, donors, and aid agencies must recognize that families and communities drive their own recovery
2. Recovery must promote fairness and equity
3. Governments must enhance preparedness for future disasters
4. Local governments must be empowered to manage recovery efforts, and donors must devote greater resources to strengthening government recovery institutions, especially at the local level
5. Good recovery planning and effective coordination depend on good information
6. The UN, World Bank, and other multilateral agencies must clarify their roles and relationships, especially in addressing the early stage of a recovery process
7. The expanding role of NGOs and the Red Cross/Red Crescent Movement carries greater responsibilities for quality in recovery efforts
8. From the start of recovery operations, governments and aid agencies must create the conditions for entrepreneurs to flourish
9. Beneficiaries deserve the kind of agency partnerships that move beyond rivalry and unhealthy competition
10. Good recovery must leave communities safer by reducing risks and building resilience

The Clinton Principles 1 and 4 address the necessary empowerment of local institutions and communities that emerges as a key element of reconstruction. Principles 3, 5, and 10 share a common focus on long-term risk reduction and enhancement of disaster resilience through the rebuilding process. Principles 6 and 7 highlight the weight of forms of cooperation with NGOs and specialized agencies in post-disaster activities. Finally, principles 2, 8, and 9 stress the promotion of a fair and equitable social and economic relaunch [Giovanni and Chelleri, 2019a].

BBB has been mentioned in several guidelines [Mannakkara and Wilkinson, 2014], and in the Sendai Framework for Disaster Risk Reduction [UNDRR, 2015], [Giovanni and Chelleri, 2019a]. Build Back Better needs to be “Better than before,” affordable and realistic long-term Scenarios addressing previous vulnerability and long-term stresses so that places will not remain “aging and shrinking” [Matanle, 2013]. Restoration and transformation have to be core concepts, highlighting the necessity of redefining priorities, questioning the fragilities of the “pre-existing” status, and the truthful chances of a more solid future.

Disaster-proof communities are infeasible. A more realistic goal is to create communities that can ‘bend’ in a disaster and then bounce back ready to face the next event. Thus resilience affords communities a way to cope with the uncertainties of hazards [Godschalk, 2003],[Blanco et al., 2009]. Resiliency means creating a community that can more readily recover from the next disaster [Burby et al., 1998]. Reconstruction is not a mere re-building activity but a process for rethinking the social and built environment in longer-term scenarios by ambitiously connecting humanitarian relief, reduction of vulnerabilities, and involvement of local communities [Kennedy et al., 2008a], [Kennedy et al., 2008b].

Build Back Better is a concept focused on effective long-term socio-economic strategic implementation [Giovanni and Chelleri, 2019a], as seen in the Clinton principles [Clinton, 2006]. These principles can also be implemented in the lifelines or critical infrastructure systems that support urban activities, such as electric power, natural gas, water, telecommunications, and transportation. In 2004 the Humanitarian Charter made explicit links for minimum standards in disaster response to the defined levels of service delivery in the five core sectors: water supply and sanitation; nutrition; food aid; shelter and site planning; and health services [Khasalamwa, 2009], [Sphere, 2004]. The international NGOs were and still are engaged in these five core sectors in the form of various activities that include shelter, healthcare, education, gender advocacy, food security, and water and sanitation projects, as well as disaster preparedness and mitigation. Many organizations stress their commitment not only to building back what was damaged, but also to responding to gaps in development and disaster preparedness so that the rebuilt communities are safer, more resilient, and better able to respond to future natural hazards [Khasalamwa, 2009].

2.3.2. Disaster cycle

The Disaster Management cycle, or Disaster Cycle for short, features the phases of pre-disaster (Prevention/Mitigation & Preparedness), during-disaster, and post-disaster (Response/Recovery)). Disaster shocks are discrete phenomena with a more or less well-marked beginning and end [Pelling, 2003]. A disaster can be perceived as a sequential event [Mitchell, 1996], [Pelling, 2003]. Often phases of the cycle overlap and the length of each phase highly depends on the severity and scale of the disaster [Khan et al., 2008]. Disaster Management includes the total of all activities, programs, and measures that can be taken up before, during, and after a disaster to avoid a disaster, reduce its impact, or recover from its losses [Khan et al., 2008].

The disaster cycle can help to cope with the number of natural and man-made disasters. Responsible institutions should play an important role but, in general, the disaster management policy responses are influenced by methods and tools for cost-effective and sustainable interventions, which the disaster cycle assists [Khan et al., 2008].

Build Back Better [Clinton, 2006] emerges as a concept bridging the four-stage disaster cycle and a key tension in post-disaster contexts is the time compression between “speed and deliberation,” namely between re-building as quickly as possible the “pre-existing city” and transforming the affected area into an improved territory [Olshansky and Chang, 2009], [Giovanni and Chelleri, 2019b]. This means that a better usage of the disaster cycle will improve the implantation and policies of BBB

Mitigation & Preparedness	Mitigation is the implementation of technologies that will reduce the loss of lives and property in future disasters. Preparedness is the actions that encourage and educate the public in anticipation of disaster events.
Preparation	Actions taken to deal with an upcoming confirmed disaster. The phase starts when alerts are raised.
Response	Actions that react to an ongoing disaster. Provide public notification, warning, evacuation, and situation reports.
Recovery	Activities that continue beyond the emergency period to restore critical community functions and manage stabilization efforts. Getting back to normal.

Mitigation and Preparedness The Phase of Mitigation offers ways to lessen a hazard’s effects. Mitigation is a systematic effort to reduce or eliminate the danger that risks and impacts on people and property. There are

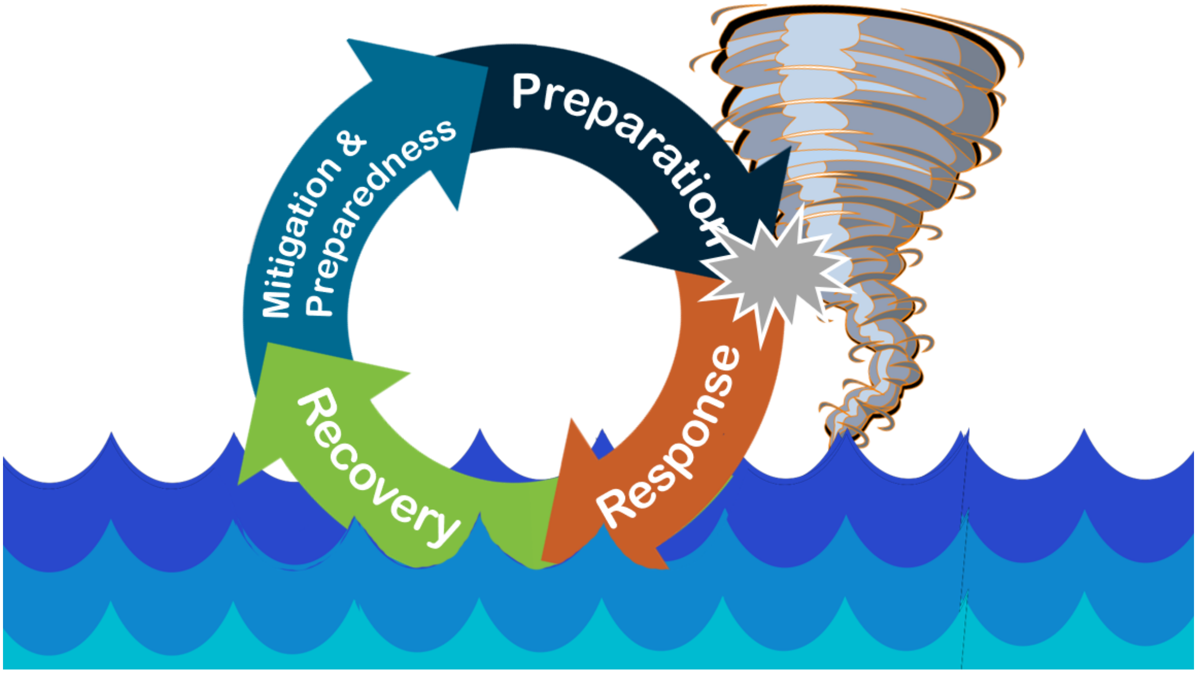


Figure 2.15: Disaster cycle, where the Mitigation & Prepardness are combined based on [Mergel, 2014].

structural and non-structural changes to limit the impact of disasters. Structural mitigation actions change buildings' characteristics or the environment; examples include flood control projects, raising building elevations, and clearing areas around structures. Non-structural mitigation most often entails adopting or changing building codes. Mitigation looks at long-term solutions to reducing risks instead of merely accepting that they will happen and preparing for their consequences [FEMA Federal Emergency Management Agency, 2022].

The impact of the structural mitigation actions is relevant to the design of a water treatment plant. Not all structural changes to buildings' characteristics or the environment can be implemented in every location. There are several factors, including denial of the risk, political will, costs, and lack of funding, which must be taken into account. Despite the best technical knowledge, historical occurrence, public education, and media attention, many individuals don't want to recognize that they or their communities are vulnerable [FEMA Federal Emergency Management Agency, 2022]. Sustainability needs to be tested on the possibility of compatibility with cultural (people), economic (profit), and environmental (planet) factors.

Mitigation is part of the disaster cycle and is not directly connected to a specific disaster. It can however happen that mitigation is still ongoing while a disaster occurs. This is the case if structural mitigation actions are unfinished at the start of a disaster. Examples of this can be; the levee or building is still under construction when a flood or hurricane hits. The overlapping of phases is outside of the scope of this thesis and it will be assumed that mitigation measures are finished at the start of a disaster.

Preparedness within emergency management can best be defined as a state of readiness to respond to a disaster, crisis, or any other type of emergency through planning, training, and exercising. However, preparedness is not only a state of readiness but also a constant theme throughout most aspects of emergency management. Preparedness is a continuous cycle of planning, organizing, training, equipping, exercising, evaluating, and taking corrective actions [FEMA Federal Emergency Management Agency, 2022]. Training and exercise plans are the cornerstones of preparedness, focusing on readiness to respond to all-hazards incidents and emergencies. The better prepared, the more quickly reopening of business and public life can be possible. Preparedness helps minimize the required time for the affected population to return to pre-disaster life.

Preparation In the Mitigation and Preparedness phase, steps are taken to prepare for a hypothetical disaster. While in the Preparation phase, there are actions taken to deal with an upcoming confirmed disaster. The

Preparation phase starts when an official warning is given. The length of the Preparation phase is determined by the rules for the issuing of the alert.

Response The Response phase is a reaction to a disaster or emergency. The response is immediate action to save lives, protect property, and meet basic human needs. Groups that can be in charge of the overall response effort are the first responders, governmental support, and Volunteer Group Response. The search and rescue activities these groups Undertake are out of the scope of the thesis. Meaning that only the activities and needs of the operators of the water system and the end users will be included in this phase.

The overall response effort can be identified in four stages of activities: [Khasalamwa, 2009], [Haas et al., 1977]

1. emergency responses involving debris removal, provision of temporary housing, and search and rescue;
2. restoration of public services (electricity, water, and telephone);
3. initiation of betterment and reconstruction involving economic growth and development of the locale.

To be able to execute all of the above-mentioned points an assessment of the damage needs to be done. Actions and evaluation are key in the Response phase.

Recovery After the emergency period, recovery starts. The Recovery phase begins immediately after the threat to human life has subsided. Recovery consists of restoring critical community functions and managing stabilization efforts. This function often starts in the initial hours and days following a disaster event. Depending on the event's severity, it can continue for months and sometimes even for years [FEMA Federal Emergency Management Agency, 2022].

The goal of the Recovery phase is to bring the affected area back to some degree of normalcy. Recovery involves decisions and actions relative to rebuilding homes, replacing property, resuming employment, restoring businesses, and permanently repairing and rebuilding infrastructure. The recovery process requires balancing the more immediate need to return the community to normalcy with the longer-term goal of reducing future vulnerability. The recovery process can provide individuals and organizations with opportunities to become more economically secure and improve overall safety and quality of life [FEMA Federal Emergency Management Agency, 2022].

2.3.3. Three Points Approach

The three-point approach (3PA) is an essential concept for Building Back Better [Fernandez and Ahmed, 2019], [van de Ven et al., 2021], [O'Callaghan and Murdock, 2021]. 3PA acknowledges that flooding cannot be eliminated and visualizes three essential proactive domains wherein decisions about disaster management are made [Fratini et al., 2012]. 3PA was constructed to scope the fragmentation of stakeholders' interests in urban water flooding. The three points facilitate the possibility of open discussion between different parties. The Three Points Approach is a method to illustrate three impact scenarios on a design under disaster conditions.

The Three Points Approach is a method to help to connect (1) day-to-day operations, (2) operation of the system under loads that are at the limit of its design capacity, and (3) behavior of the system under loads beyond the design capacity [Geldof and Kluck, 2008], [Fratini et al., 2012].

(Point 1) The domain of day-to-day values: where particular attention is given to the way urban space is perceived and used on a daily base by its inhabitants. This domain suggests that projects hold strong day-to-day values when they are able to improve the quality of life within the area in focus. Such considerations are expected to create a solid base for political and public support and thus ask for higher participation in the decision-making process. Social participation is considered important in order to enhance awareness of flood risk and acceptance of the new urban development towards a more resilient city. When the social system is involved in all fields, a strong base for the maintenance of urban infrastructures is further created [Fratini et al., 2012].

(Point 2) The domain of technical optimization: where design standards for sewers and other drainage infrastructures apply. Here professionals discuss technical solutions to deal with defined design in order to prevent damage and meet the service level established politically [Fratini et al., 2012].

(Point 3) The domain of urban resilience and spatial planning: where urban water managers, in order to deal with extreme events, have to interact with urban planners and architects. Here the aim is to mitigate the effect of possible future extreme rains, but also to create the technical basis for adaptation to future changing scenarios. The idea is to make the urban area more resilient to future changes by finding new spaces for water conveyance and storage within the urban area [Fratini et al., 2012].

The word urban in 3PA refers to the complex characterizing of a context where the technical, social, and natural systems interact in an urban area.

This thesis is based on one discipline and the Point three of the 3PA will represent a situation where the protection level is exceeded by applying a lower occurrence rate event: The system fails. The aim of the 3PA is not to calculate the effects of flooding and then perform a cost-benefit analysis, but rather to encourage discussion among stakeholders. Safety is nonlinear in a three-point approach. The magnitude (vertical axis) is expressed in terms of costs, and instead of the frequency, the return period is shown on the horizontal axis [Fratini et al., 2012], [Geldof and Kluck, 2008].

2.3.4. Three-Pillar model

Sustainable development has been adopted by the United Nations as a guiding principle for economic, environmental, and social development that aspires to meet ’the needs of the present without compromising the ability of future generations to meet their own needs ’ and an ’equitable sharing of the environment costs and benefits of economic development between and within countries’ [Hansmann et al., 2012, UN General Assembly, 1987]. These three dimensions have been denoted as pillars of sustainability, which reflect that responsible development requires consideration of natural, human, and economic capital or colloquially speaking the planet, people, and profits Elkington [1997], Hansmann et al. [2012], Kajikawa [2008], Schoolman et al. [2012]. Also known as the ‘tripartite model’, ‘three-legged stool model’, ‘3P model’ (people, planet, profit) and ‘triple bottom line’, and the Three sustainability 3P [Holden et al., 2017]. In this current model, environmental, social, and economic impacts are all given equal weight.

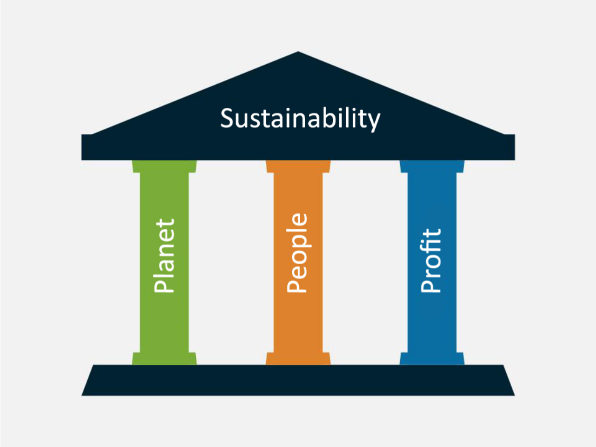


Figure 2.16: An overview of the Three Pillars of Sustainability model

Defining sustainability and measuring sustainability is difficult due to it having different aspects, which this model gives a voice to. There is a competing language of ’sustainability’ and ’sustainable development’, as the two are often so intertwined in the literature that they remain difficult to tease apart Purvis et al. [2019].

Sustainable Development, as defined by the National Society of Professional Engineers(NSPE) Code of Ethics for Engineers, is "the challenge of meeting human needs for natural resources, industrial products, energy, food, transportation, shelter, and effective waste management while conserving and protecting environmental quality and the natural resource base essential for future development.”[NSPE, National Society of Professional Engineers, 2019].

The American Society of Civil Engineers (ASCE) considers sustainability as a future in which human society has the capacity and opportunity to maintain and improve its quality of life indefinitely, without degrading the quantity, quality, or availability of natural, economic, and social resources [Parsons and Denney, 2023]. Under the direction of an ASCE Committee, a report on sustainable procurement was developed as part of providing resources to implement an organization's Sustainability Roadmap [Kralik and Chrzan, 2020].

ISO 20400 is used in used in SDG 1, SDG 2, and SDG 12 of the UN Sustainable Development Goals (SDGs). The definition of Sustainable procurement in the International Organization for Standards (ISO) 20400 is:

> Procurement that has the most positive environmental, social, and economic impacts possible over the entire life cycle. Sustainable procurement involves the sustainability aspects related to the goods or services and to the suppliers along the supply chains. Sustainable procurement contributes to the achievement of organizational sustainability objectives and goals and to sustainable development in general.

Every decision, private or collective, on the micro- or the macro level, for now, or the future, affects others, now and in the future, here and at other places. Following this logic, it is natural to apply a life cycle perspective [Heijungs et al., 2010]. The development of sustainable water management strategies involves the identification of vulnerability and adaptation possibilities, followed by an effective analysis of these adaptation strategies under different possible futures [Haasnoot et al., 2009].

Describing sustainability can be done with the three P's: Planet, Profit, and People. The environmental, social problems and economic issues are equally influential when dealing with an objective to attain a sustainable future [Holden et al., 2017].

The term sustainability has directed policymakers, environmentalists, and industrial decision-makers to a broadening of focus in various directions:

- The assessment of costs and benefits has been expanded from private to societal (People).
- The economic assessment has been expanded to include environmental and social aspects as well (Profit).
- The realization that every actor is embedded in a chain of activities has led to the development of notions such as supply chains, the life cycle, and extended producer responsibility (Planet).

2.3.5. Hofstede's Cultural Dimensions Theory

To support the pillar of people, human and social aspects of the three-pillar model, the Hofstede's Cultural Dimensions Theory will be used.

Geert Hofstede developed the cultural dimensions theory as a framework for cross-cultural communication. This theory explores the influence of a society's culture on its members' values and examines the connection between these values and behavior. By employing factor analysis, this framework provides a structured approach to comprehending these intricate relationships. Hofstede's Cultural Dimensions Theory is a useful tool for understanding differences in cultures across the world is [Hofstede, 1995, Hofstede and Hofstede, 2021]. It provides classifications that give insight into the average pattern of beliefs and values of a culture. Cultures vary amongst five cultural dimensions, these being:

Individualism vs. Collectivism The individualism vs. collectivism dimension considers the degree to which societies are integrated into groups and their perceived obligations and dependence on groups. Individualism indicates that there is a greater importance placed on attaining personal goals. A person's self-image in this category is defined as "I." Collectivism indicates that there is a greater importance placed on the goals and well-being of the group. A person's self-image in this category is defined as "We."

Power Distance Index The power distance index considers the extent to which inequality and power are tolerated. In this dimension, inequality and power are viewed from the viewpoint of the followers – the lower level. A high power distance index indicates that a culture accepts inequity and power differences, encourages bureaucracy, and shows high respect for rank and authority. A low power distance index indicates that a culture encourages flat organizational structures that feature decentralized decision-making responsibility, participative management style, and emphasis on power distribution.

Uncertainty Avoidance Index The uncertainty avoidance index considers the extent to which uncertainty and ambiguity are tolerated. This dimension considers how unknown situations and unexpected events are dealt with. A high uncertainty avoidance index indicates a low tolerance for uncertainty, ambiguity, and risk-taking. The unknown is minimized through strict rules, regulations, etc. A low uncertainty avoidance index indicates a high tolerance for uncertainty, ambiguity, and risk-taking. The unknown is more openly accepted, and there are lax rules, regulations, etc.

Masculinity vs. Femininity The masculinity vs. femininity dimension is also referred to as "tough vs. tender" and considers the preference of society for achievement, attitude toward sexuality equality, behavior, etc. Masculinity comes with the following characteristics: distinct gender roles, assertiveness, concentrated material achievements, and wealth-building. Femininity comes with the following characteristics: fluid gender roles, modesty, nurturing, and concern for the quality of life.

Long-Term Orientation vs. Short-Term Orientation The long-term orientation vs. short-term orientation dimension considers the extent to which society views its time horizon. Long-term orientation shows focus on the future and involves delaying short-term success or gratification to achieve long-term success. Long-term orientation emphasizes persistence, perseverance, and long-term growth. Short-term orientation shows focus on the near future, involves delivering short-term success or gratification, and places a stronger emphasis on the present than the future. Short-term orientation emphasizes quick results and respect for tradition.

Indulgence vs. Restraint The indulgence vs. restraint dimension considers the extent and tendency of a society to fulfill its desires. In other words, this dimension revolves around how societies can control their impulses and desires. Indulgence indicates that society allows relatively free gratification related to enjoying life and having fun. Restraint indicates that society suppresses gratification of needs and regulates it through social norms.

2.3.6. Multi-Criteria Analysis (MCA)

Multi-Criteria Analysis (MCA) tools have been widely used in decision-making situations enabling the exploration of drinking water supply concerning both quantity and quality Gutiérrez et al. [2016].

MCA represents a structured approach to analyzing possible alternatives and preferences and evaluating them under different criteria simultaneously. In the methodology, preferable targets and goals are particularized, and corresponding characteristics and indicators are recognized Department for Communities and Local Government: London [2009]. The MCA brings a systematic approach to ranking adaptation options against multiple decision criteria. These criteria are weighted to reflect their importance relative to other criteria. MCA is a decision-making framework for solving problems with many alternative courses of action Cuofano [2023], Zarghami and Szidarovszky [2011].

The MCA model will be qualitative. An indicator is similar to a criteria but only for yes or no answer options. One of the essential characteristics of MCA is that the assessment of indicators generally hinges on a quantitative analysis of various qualitative impact categories; however, in many cases, the evaluation of indicators is not expressed in monetary terms. In MCA, multiple approaches are used to classify, compare, and select the most appropriate alternatives concerning the given criteria. Each criterion can be evaluated qualitatively based on the chosen method Caravaggio et al. [2019]. MCA acts as a tool and can be effectively applied to the areas and sectors where single criterion–based methodologies are found ineffective and important social and environmental impacts cannot be expressed in terms of monetary value Ren [2021]. Some of the criteria need to be compared with each other and ranked to be able to assist with this qualitative model.

Multi-Criteria analysis is sometimes referred to as multi-attribute analysis. The term attribute is also occasionally used to refer to a measurable criterion Dodgson et al. [2009]. For this thesis, the word criteria will be used rather than an attribute. The six components of a Multi-Criteria Analysis are:

Define Objective Defining the problem, goal, or objective. Try to understand and define the problem as comprehensively as possible Ryan and Nimick [2019].

Define criteria This component is a measure of success and determines the criteria and the constraints. Using a combination of experts' opinions and information from various sources. This could be acquired from discussions with experts in relevant fields, surveying of literature, and analysis of historical data. Dividing a decision or problem into smaller, more understandable parts. It identifies stakeholder interests.

Performance of the Alternative Transform the values onto a relative scale. This allows for comparison between each criterion and represents the judgments and expert knowledge with significant numbers.

Describe the expected performance of each option against the criteria. The performance of the Alternatives are evaluated in Appendices A, B, and C.

Weight of criteria Assign weights for each criterion to reflect their relative importance to the decision. Weight is the importance of each criterion regarding the objective and concerning each other. See under weighting for more information.

Results; Rate options Analyse and then validate the results. The analysis of the result can be found in Chapter 6.

In an MCA, a row describes one of the options that are being considered. Columns correspond to a criterion, or 'performance dimension,' regarded as necessary for comparing the different options. The entries in the matrix body assess how well each option performs concerning each criterion Dodgson et al. [2009]. This thesis uses a rather different layout because (1) there are many criteria and (2) all criteria will be evaluated in the context of several different (sub)scenarios. The (sub)scenario scores will be in the columns and the criteria will be grouped first by scenario, and for each scenario by management

2.3.7. RenewIslands Methodology

The RenewIslands methodology was originally developed for sustainable energy and resource planning for islands. The methodology helps to select energy and resource flow integration based on an island's needs, resources, and applicable technologies [Duić et al., 2008].

The RenewIslands methodology is based on a four steps analysis approach that has to be applied to an island [Duić et al., 2008]: The RenewIslands methodology consists of the following four steps [Duić et al., 2008]:

1. Mapping the island's needs
2. Mapping the island's resources
3. Devising alternatives with technologies that can use available resources to cover the needs
    - Feasibility of technologies
    - Feasibility of storage technologies
    - Feasibility of integration of flows
    - Devising potential scenarios.
4. Modeling.

The "Mapping the island's needs", and "Mapping the island's resources" will be explored in Subsection 3.4.1 and Subsection 3.4.4. Devising potential alternatives will be done at the end of this Section in 5.1. The explanation and the influence of feasibility of "technologies", "storage technologies", and "integration of flows" will be done in Section 5.1. Devising potential scenarios has been done earlier in Chapter 4. Modeling is done in the Appendices A,B,C, and the results are presented in Chapter 6.

Mapping of the island's needs and resources is location-based and not alternative-dependent. Meaning that for all Alternatives the same needs and resources are relevant. The main distinction between the Alternatives regards the fulfillment of those needs and the use of the resources.

RenewIslands focuses on the aspects of the design relevant under normal circumstances. In this thesis, the disaster criteria are added to the RenewIslands methodology to cover design aspects that come into play only under extreme weather conditions.

In line with the Three-Point Approach, explained in Subsection 2.3.3, The Hurricane Dorian conditions will be added to illustrate the failing state of the system. Firstly the design is made applicable to function in normal circumstances setting, then it will be adopted while taking into account the frequent occurrences of tropical storms and hurricanes. Tropical storm and hurricane conditions are the scenarios that challenge the drinking water system with extreme circumstances.

The performance of the alternatives will be tested under different circumstances. These circumstances correspond to the four phases introduced in Subsection 2.3.2.

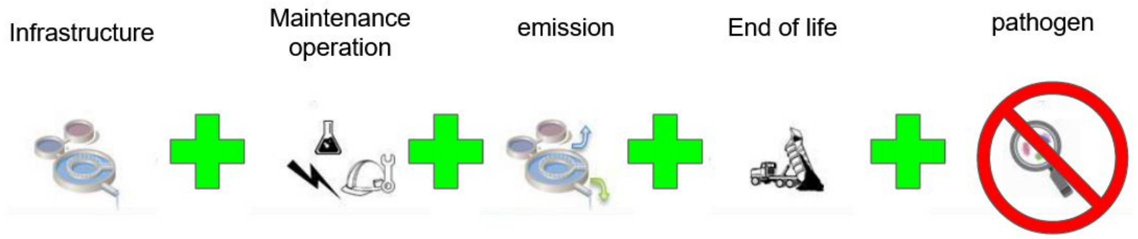


Figure 2.17: An overview of the scope of the ACV4E Tool used

2.3.8. ACV4e LCA

In 2015 in France, a simplified calculator to support investment decisions in the wastewater sector was created. The group behind the ACV4E software strives to spread the Life Cycle Assessment (LCA) among local authorities, facilitating its accessibility for individuals without specialized expertise Guerin-Schneider et al. [2018].

Many studies performing Life Cycle Assessment (LCA) of wastewater treatment plants already exist, but this tool specifically focuses on being a simplified and operational tool usable by non-specialists of LCA to perform LCA of entire wastewater systems. The objective of this work was to develop a simplified software providing objective environmental indicators to be included in the decision-making process along with other criteria [Jolliet et al., 2010], [Guérin-Schneider et al., 2011].

The group behind the ACV4E aims to let non-specialize users, for instance, local authorities, produce the results of the LCA analyses of the scenarios built and parameterized in order to compare these scenarios and then interpret these results to clarify an investment decision Guerin-Schneider et al. [2018].

To be able to assess a water treatment system this tool divides the treatment system up into different categories which all have their own different impacts as seen in Figure 2.17. The intention of using ACV4E is to calculate these impacts;

- Impact of emissions of pollutants into the water and air during treatment
- Impacts of the facilities and installations
- Impacts related to the production of materials, machinery, electricity, diesel, and reagents necessary for the construction and operation of the facilities
- Impacts related to the end of life of materials (infrastructure and machinery)
- Impacts related to the end of life of sludge exported from the treatment plant

ACV4E and the underlying model have been presented in specific scientific articles Risch et al. [2014a, 2015b] and on a website Catel et al. [2018].

3

Methodology

This thesis examines the concepts of “Build Back Better”, “Disaster Cycle”, and “Sustainability” in water management and the possibility of the interactions between these concepts when designing water management infrastructure. Especially in cases where the disaster cycle is relatively short: 10 to 15 years between disasters.

To achieve this objective, a range of established concepts, tools, and methodologies are available to aid in the design and/or reconstruction of water infrastructure on islands. The concepts, tools, and methodologies in the context of this study include RenewIslands [Duić et al., 2008] and Multi-Criteria Analysis (MCA), Build Back Better (BBB), the disaster cycle, Hofstede’s Cultural Dimensions Theory, and the three-point approach. The thesis will evaluate the effectiveness of three sustainable water management alternatives tailored for managing recurrent disasters and the used approaches’ impact on this success while undergoing this process answering the research question. These alternatives will be developed using the aforementioned methodologies and concepts to design and evaluate the freshwater resources on a small island, mitigating the impacts of regular disaster risks and reducing the effects of saltwater intrusion. Alternatives for a water management strategy in a case study will be compared on performance with respect to sustainability in an MCA in two extreme weather scenarios. Sustainability will be measured with the three pillars of Planet, Profit, and People (PPP).

This qualitative research involves collecting and analyzing non-numerical data for both the principles of water management and the disaster cycle. The data and the combination of the two principles will provide information on the problems of freshwater availability on a small island frequently stricken by disaster. The research will use desk research, literature study, and secondary data from third parties.

Data used in this study are based on the research started during a workshop "Grand Bahama after Hurricane Dorian; Interdisciplinary Approach to Build Back Better." The University of the Bahamas and the Technical University of Delft conducted the workshop for groups of students from many disciplines to learn from the disaster recovery in Grand Bahama after 2019 hurricane Dorian. The ideas of the workshop combined with Dutch design principles were applied to the hypothetical reconstruction of the Bahamas, Japanese, and Dutch cities for increased disaster resilience and liveability. This workshop’s approaches and methods aim to create conditions to support Building Back Better. The Delft University of Technology developed this approach during the “living labs” in Tokyo and Tohoku, Japan, which had been subject to storm surges and tsunami hazards. This project incorporated the interdisciplinary design of MSc-level educated civil engineers and spatial designers, focusing on developing a proper understanding of multidisciplinary design and the tools to reach it. It provided a deep comprehension of the regional and urban aspects and the detailing of the building’s architecture. The workshop started with hypothesizing that interdisciplinary design is at the base of Building Back Better [Hooimeijer et al., 2022].

During the workshop, the engineers were more result-oriented compared to the other disciplines which were more process-oriented. This resulted in a few instances where the engineers rejected partial ideas, instead of participating in a process-focused design. When the participants tried to fix this during the workshop it became clear that there was no set process to design with water in a disaster region. There seemed to be a lack of attention to the process found in the literature on the process of water management design, similar to what was encountered by the result-oriented engineers during the workshop.

In the previous Chapter 2 the concepts, tools and methodologies, which are useful for the research question of this thesis are described. In this Chapter, these concepts and methodologies are explained in the light of this thesis and the effect they have when used on the problem, to improve a system that provides sustainable drinking water on the Island of Grand Bahama, an island which is regularly stricken by disasters.

3.1. Build Back Better

Build Back Better wants you to focus on the whole process, not only on the water management result. This became clear during the workshop [van der Hucht et al., 2021]. The parts of the BBB concepts that shall be implemented are the needs of the stakeholders set by Build Back Better and the cyclical nature of disasters. This first part will come back in a later Section 3.2, 3.5, and 3.4.1. For the second point of the cyclical nature of disasters, the Disaster cycle will be used, as seen in Subsection 2.3.2.

Part of the success of BBB is that a system will be suitable to the proposed problem and surroundings. Part of the goal of this thesis is to find possible interactions between BBB and the design process of a water treatment plant.

3.2. Three-Pillar model

As mentioned in Section 3.1, a component that will be implemented is the needs of the stakeholders. The needs of the stakeholders are represented by the criteria People, Planet, and Profit. These criteria are derived from the three-pillar model and will be used to score the alternatives. This thesis will score the alternatives on sustainability. This model combines the social, economic, and environmental angles in order to create a sustainable solution. This will provide valuable understanding regarding how well the Alternative aligns with the economic, environmental, and societal aspects of the case study.

3.2.1. Category People of Grand Bahama

In the Evaluation category people the criteria related to the social aspect are formulated. The focus will be on the acceptance of the alternatives by the people of Grand Bahama. The people of Grand Bahama are defined as the population, tourists, and operators of the water treatment system. Cultural traditions cannot be ignored when trying to solve global water challenges. How water is conceived and valued, understood and managed, used or abused, worshipped or desecrated, is influenced by culture [Schelwald-van der Kley and Reijerkerk, 2009]. In some locations, people sometimes continue to use traditional water systems even when new systems are built [Whittington et al., 1990]. The failure of "imported" solutions has proven, that water resources management will fail if it lacks the full consideration of these cultural implications [IITC, INTERNATIONAL INDIAN TREATY COUNCIL, 2007]. Assessing and better understanding the way various cultures in different parts of the world perceive and manage water may lead to sustainable water management.

Laing [2017] is the most reliable found source using Hofstede's six dimensions of national culture in the Bahamas. This is because Laing is the only local man who focused on the Bahamas, as opposed to others who were later identified as foreigners, with minimal contact or observation of the Caribbean as a whole. Laing however admits to guessing the answers [Laing, 2017]. In Laing's paper, he believes that a professional assessment of the culture might be useful and it goes a long way to provide insights into why some of the political, economic, and social systems work as they do. However, this study came across the same problem as this thesis did while researching this study, that the Bahamas, does not seem to have been examined against Hofstede's six dimensions of culture. Just like other studies, Laing used Jamaica and the United States to do an assessment [Gooden et al., 2004]. Laing guesses that Bahamas culture largely expects unequal power distribution between leaders and followers (65/100); has a preference for masculinity over femininity (50/100); leans in favor of individualism (60/100); marginally tolerates uncertainty and ambiguity (55/100); tends to adhere to longstanding traditions and customs while slow to embrace change (55/100); and is a marginally non-indulgent group (45/100).

To be able to use Hofstede's Cultural Dimensions Theory in a water management project during the study a personal assessment was made. The conclusions are based on observations as a civil engineer during a 3-week visit and available literature [Hofstede, 2009]. These observations will be used to be able to illustrate later points. Further in-depth research is recommended. To be able to use the conclusion of Hofstede's Cultural Dimensions Theory in an MCA, the people assessed are further divided by the water management aspects. In the WM-aspect infrastructure, the wants and needs of the end users are highlighted. The end users include the general population and tourists. In the WM-aspect Maintenance & Operation, the wants and needs of the technicians and operators of the water treatment system are highlighted. These people are the ones who make the water treatment system operate before and after disasters. In the WM-aspect End-off-Life, there are no individuals to evaluate. The time between the start of the water treatment system operation and the end is 30 years, a whole generation of people. This makes it difficult to predict what kind of people will be assessed. To stay within the scope of this thesis no assessment of people will be done in the WM-aspect of End-of-Life. Environmental groups and companies could be assessed within this time frame of 30 years, but their interest is assessed in the sustainable pillars of Profit and Planet. Hofstede's Cultural Dimensions Theory states that attitudes vary along five cultural dimensions, for Grand Bahama the resulting attitudes for each dimension are:

Individualism vs. Collectivism Grand Bahama can be divided into three zones, namely East, West, and the town of Freeport. Freeport is a free trade zone on Grand Bahama Island. The Grand Bahama Port Authority (GBPA) operates the free trade zone, under special powers conferred by the government under the Hawksbill Creek Agreement, which was recently extended until August 3, 2054. The GBPA closely develops the economic and long-term interests of its investment. This area has a higher density of economic activity and buildings. Due to the strong general positive influence of the GBPA, the surrounding area is prone to collectivism.

The national authorities govern the east and west of the island. This area is less dense and prone to individualism among people outside a group, but collectivism inside groups. In the short observation time, the groups seem to be dependent on the situation, there can be family connections, colleagues, or the whole island width. The collectivism inside groups is felt during Junkanoo. Participants spend months preparing for the pageantry of this street parade and there is a clear rivalry between participating groups [Bethel, 2003]. "We can be friends and help each other again after Junkanoo."

Laing says the Bahama leans in favor of individualism, and that assumption seems reasonable if the average of all inhabitants is taken; East, West, and the town of Freeport. Grand Bahama is prone to Individualism.

Power Distance Index An assumption will be that the Bahamas ranks above average on the Power Index dimension, likely influenced by British colonial rule. The countries with high power distance include most Asian countries, Eastern European countries, Latin American countries, Arab countries, African countries, and several Latin European countries. On the other hand, countries with low power distance include German-speaking countries, Nordic countries, and the United States. Interestingly, the power distance in the Netherlands is significantly smaller compared to Belgium, despite their geographical proximity. With this being known Grand Bahama seems to be closer to countries with a high power distance.

On a different note, elections in the Bahamas take place every five years. The two primary political parties are the Progressive Liberal Party and the Free National Movement. Additionally, Grand Bahama, which is part of the islands outside of New Providence, operates under Local Government, allowing for greater citizen involvement in decision-making. This system aims to minimize direct political connections [Hofstede, 1995],[Mooij, 1998].

Laing's assessment is that Bahama has a low power distance index. He has been part of the ministry and makes for this thesis a valid point. The Grand Bahama has a low power distance index indicating that a culture encourages flat organizational structures that feature decentralized decision-making responsibility, participative management style, and emphasis on power distribution.

Uncertainty Avoidance Index An example of low uncertainty avoidance index are the tax laws and the public rules for foreign investors. The government wants their investment without thinking about the long-term consequences of these investments for the Island. Grand Bahama seems to have a low uncertainty avoidance index, indicating a high tolerance for uncertainty, ambiguity, and risk-taking. The unknown is more openly accepted, and there are lax rules and regulations. The writer of this thesis has another view on Laing's assessment, he stated that Grand Bahama marginally tolerates uncertainty and ambiguity, and the writer of this thesis thinks that it has a high tolerance for uncertainty.

Masculinity vs. Femininity Not only resources are minimal on an island, but people are too. This means that a society has fluid gender roles. However, it seems that the preference of society for achievement, attitude toward sexuality equality, and behavior still is masculine. The writer of this thesis agrees with Laing's assessment. The Grand Bahama is prone to Masculinity.

Long-Term Orientation vs. Short-Term Orientation During the workshop a short survey was done by the social department of the University of Grand Bahama. With minimal observation, it became clear the citizens want long-term orientation solutions for their water problem, but they are aware of the political climate which focuses on the Short-Term gratification of the voter. The precise term red ribbon cutter was often used, this means that politicians like projects in which they can cut a red ribbon and pose for a picture. They however are less interested in maintenance, as it provides fewer opportunities for publicity. Liang says that Grand Bahama tends to adhere more to longstanding traditions and customs while slow to embrace change. The writer of this thesis does not agree with Liang. Grand Bahama to me has more of a Short-Term Orientation.

Indulgence vs. Restraint There is only one recycling plant in the commonwealth of the Bahamas [Machinex , Industries Inc., 2016]. Which is located on a different island, Nassau. Islands without recycling plants rely on other methods of waste removal [GBPA, Grand Bahama Port Authority, 2020]. Due to the natural circumstances of an island resources are limited. Traffic between islands is expensive, making the island have a natural tendency to restrain, but there seems to be no social restraint. Restraint indicates that society suppresses gratification of needs and regulates it through social norms. Reusing already imported resources would be a viable option for the decrease in the cost of goods. But this time it does not seem to be possible due to limited technical facilities and available knowledge. The writer of this thesis agrees with Liang that there seems to be a restraint, which indicates that society suppresses gratification of needs and regulates it through social norms, but more out of natural necessity than out of cultural norms.

Summarizing the people of the Grand Bahamas according to Hofstede's cultural dimensions in general according to the writer's view they are individual, low on the power distance, masculine, accepting uncertainty, short-term orientated, and restraint. This will be used in the assessment of the criteria people.

3.2.2. Category Profit

The relative cost of the alternative is taken as a criterion for the Evaluation category Profit. This simplified approach is taken, because profit is not the focus of this thesis. Profit is an important part of decision-making and is expanded upon in a multitude of other studies. Alternatives 1,2, and 3 will be compared to the existing system on a qualitative scale. This means that the cost of an Alternative will not be realized in detail, because there will be a lack of hard figures. A scale will be used that estimates the increase or decrease of the cost compared to the existing system of the case study. The two things that will be considered are personal costs and operational costs.

Personal costs are connected to a willingness to pay. If people are willing to pay for the full costs of a particular service, then it is a clear indication that the service is valued (and therefore will most likely be used and maintained) and that it will be possible to generate the funds required to sustain and even replicate the project. Attempts to incorporate willingness-to-pay considerations into project design have been difficult [Whittington et al., 1990]. Consumers can expect a difference in costs in the alternative compared to the situation in Alternative 0, which will be carefully examined.

Operational costs include construction costs, maintenance costs, and demolition costs. These costs can include the cost of material consumed (chemicals, filters, fuel), depreciation period, and construction material. As stated earlier these costs will not be detailed, but simplified. Which one of these costs is highlighted depends on the water-management criteria assets and scores.

With the simplification of the cost and the profit the question that remains to answer is: Will a glass of drinking water be more expensive due to the implementation of the Alternative?

3.2.3. Category Planet

Evaluation category Planet includes criteria that describe the environmental impact of the effects of the Alternative. In line with and in favor of holistic interests for the survival of life on the planet a good Environmental view is by healthy ecosystems and sustainable, responsible consumption. Water is abundant on our planet, but only a mere 2.5 % is fresh water, and most of this is "trapped" in glacial ice and the polar caps. Less than 1 % of fresh water exists in lakes, streams, rivers, and shallow underground reservoirs that can be used as drinking water, industrial water, or as irrigation water for food production [Schelwald-van der Kley and Reijerkerk, 2009]. Taking good care of resources, including water, is essential for maintaining the status quo and other scenarios. Assessing this category is done by looking at the impact of consuming non-renewable resources, during construction and normal use, emissions, and discharge. The importance and hence respect many indigenous people attach to water, and their practical knowledge of the relationship between humans and the natural world, may prove valuable for a new water ethic and sustainable management practice in the interest of human survival on this planet.

An example of Environmental effects can be the increase in the use of consuming non-renewable resources.Other Environmental effects can be the ecological impact of the construction or damaging by-products of processes. A positive Environmental effect is the change of use to a sustainable water source and decrease of impact of the Alternative on the ecosystem.

3.3. Disaster cycle

> "Disasters are expected but unpredictable. This uncertainty makes it impossible to pinpoint in detail what is required to manage crises that will occur [Borell and Eriksson, 2013]."

As mentioned in Section 3.1, the cyclical nature of disasters is represented by the Disaster cycle in this thesis. The disaster cycle helps display the needs and function of each phase before during and after a disaster. This separation into stages would make it easier to analyze the effectiveness of a design in each stage.

The disaster cycle will inform the development of disaster sub-scenarios, which assist the research question. As a result, effectiveness per times phase is displayed making it possible to test the alternatives in each phase.

The sub-scenarios will be derived from the time-sensitive nature of disaster management within the disaster cycle framework. The disaster sub-scenarios are based on the disaster cycle's four phases: Mitigation & Preparedness phase, Preparation phase, Recovery phase, and Response phase. To use Build Back Better and the Disaster cycle in a water management system Mitigation and Preparedness are combined, these two phases occur simultaneously for a water management system. More emphasis is put on the preparation phase, which is time-sensitive and crucial for the success of most alternatives for a water management system. The normal circumstances are added as a separate phase to also have a clear sub-scenario visualizing the regular usage of the system and the scoring of this system. Overall these sub-scenarios are time-related. Sub-scenarios are grouped by phase and scored by the earlier mentioned People-Planet-Profit in Subsection 3.2. These grouped criteria for Disaster, listed below, will be implemented in assessing the performance of the three alternatives presented in Appendix A, Appendix B, and Appendix C.

Normal circumstances	The regular usage of the system
Mitigation & Preparedness	Mitigation is the implementation of technologies that will reduce the loss of lives and property in future disasters. Preparedness is the actions that encourage and educate the public in anticipation of disaster events.
Preparation	Actions taken to deal with an upcoming confirmed disaster. The phase starts when alerts are raised.
Response	Actions that react to an ongoing disaster. Provide public notification, warning, evacuation, and situation reports.
Recovery	Activities that continue beyond the emergency period to restore critical community functions and manage stabilization efforts. Getting back to normal.

3.3.1. Mitigation and Preparedness

This phase is very close to the normal circumstances. It represents the period between the end of the recovery from the previous disaster up to the first official action related to the imminent arrival of the next disaster, and most likely won't cope with the impacts of previous disasters. During the scoring of the criteria people, profit, and planet in this phase, the focus will be on the parts of the design that are specifically intended to mitigate the effects of a disaster.

3.3.2. Preparation

In the Bahamas, there is a multitude of advisories and warnings of impending danger from severe weather [NEMA, National Emergency Management Agency, 2006], as seen in the table 3.1 below. The inhabitants are asked to prepare for the hurricane and tropical storm conditions if this warning is given. There is an important difference between alert, watch, and warning. With the alert and watch, it means that there is a possibility of extreme winds affecting the area. A warning is more serious. It means extreme winds are expected in a stated area [CDC, Centers for Disease Control and Prevention, 2019]. From the alert to the hit or brush of the disaster takes in this case study 48 hours. Based on this table 3.1, the length of the Preparation phase is 48 hours in the case study. meaning all the goals set in this phase need to be completed within this time frame, preferably earlier.

Tropical storm Alert	Within 48 hours, a tropical storm (55-117 km/h) is likely to hit.
Tropical storm Watch	Within 36 hours, a tropical storm (55-117 km/h) is likely to hit.
Tropical storm Warning	Within 24 hours, a tropical storm (55-117 km/h) is likely to hit
Tropical storm All clear	The storm has left the area, but caution should prevail.
Hurricane Alert	Within 48 hours, a hurricane (winds over 117 km/h) is likely to hit.
Hurricane Watch	Within 36 hours, a hurricane (winds over 117 km/h) is likely to hit.
Hurricane Warning	Within 24 hours, a hurricane (winds over 117 km/h) is likely to hit.

Table 3.1: Overview of the Alert, Watch, and Warning for Storm on Grand Bahama

3.3.3. Response

Actions and evaluation are key in the Response phase. For this thesis, the Response doesn't have a direct action. Search and rescue activities are not within the scope, even though some alternatives can have an impact on those aspects. This phase becomes more of an evaluation of what is there and what should be done. This is mainly due to the shortness of the disaster impact and hit. The response has the most impact on the criteria profit.

3.3.4. Recovery

After the emergency period, recovery starts. The Recovery phase begins immediately after the threat to human life has subsided. A hurricane or tropical storm is a short disaster, compared to a public health crisis like the coronavirus, making it a point disaster. Due to the case study being a point disaster with a short response period, the Recovery phase starts at the end of the response period without any overlap with the previous Response phase. In the Bahamas, regarding water precautions, the National Emergency Management Agency (NEMA) suggests you save water in containers. These clean containers will be acceptable for 2 – 3 weeks [NEMA, National Emergency Management Agency, 2006]. Some alternatives will rely on these 2 - 3 weeks of self-sufficiency. This period of self-sufficiency is followed by a period in which a temporary solution is needed. The people of Grand Bahama are individual, low on the power distance, masculine, accepting uncertainty, short-term orientated, and restrained, this means that if an Alternative relies on this self-sufficiency it will be assumed weaker compared to the one with other solutions.

3.4. RenewIslands Methodology

There will be three design alternatives made, based on the RenewIslands methodology. These designs will be compared and ranked in a tablebased on how they fit the research question, case study, and model group criteria. To create this table a Multi-Criteria Analysis (MCA) will be used. MCA is chosen due to its use in similar case studies [Singh et al., 2017], [Lai et al., 2008], [Aubert et al., 2018] and the possibility of comparing Alternatives. The RenewIslands methodology was originally developed for sustainable energy and resource planning for islands. The methodology helps to select energy and resource flow integration based on an island's needs, resources, and applicable technologies [Duić et al., 2008].

The RenewIslands methodology is based on a four-step analysis approach that has to be applied to an island [Duić et al., 2008]. It consists of the following four steps:

1. Mapping the island's needs.
2. Mapping the island's resources.
3. Devising scenarios with technologies that can use available resources to cover the needs.
    (a) Feasibility of technologies (energy conversion, water supply, waste treatment, wastewater technology treatment).
    (b) Feasibility of technologies for energy, water, waste, and wastewater storage.
    (c) Feasibility of integration of flows (cogeneration, trigeneration, polygeneration, etc.).
    (d) Devising potential Scenarios.
4. Modelling the scenarios.

Mapping the island's needs will be explored in subsections 3.4.1, 3.4.2, and 3.4.3. Mapping the island's resources is the subject of Subsection 3.4.4. Devising potential alternatives will be done at the end of Section 5.1. The influence of feasibility of "technologies", "storage technologies", and "integration of flows" will be done in Section 5.1. Devising potential scenarios will be done in Chapter 4. Modeling is done in the Appendices A,B,C, and the results are presented in Chapter 6.

Mapping of the island's needs and resources is location-based and not alternative-dependent. Meaning that for all Alternatives the same needs and resources are relevant. The main distinction between the Alternatives regards the fulfillment of those needs and the use of the resources.

RenewIslands focuses on the aspects of the design relevant under normal circumstances. In this thesis, the disaster criteria are added to the RenewIslands methodology to cover design aspects that come into play only under extreme weather conditions.

The alternatives will be worked out at the conceptual design level. Concept design is the stage of the design process that is not meant to be implemented as commercial products, at least not without major additional design work. Conceptualization describes the manipulation and combination of ideas. Thus, concepts must be designed, drawn, and described so that others can understand and build on them [Keinonen and Takala, 2006],[Andreasen et al., 2015]. The design of the alternatives will not be set out in detail.

The alternatives will be designed for normal-, and tropical storm conditions. In line with the Three-Point Approach, explained in Subsection 2.3.3, The Hurricane Dorian conditions will be added to illustrate the failing state of the system. Firstly the design is made applicable to function in normal circumstances setting, then it will be adopted while taking into account the frequent occurrences of tropical storms and hurricanes. Tropical storm and hurricane conditions are the scenarios that challenge the drinking water system with extreme circumstances.

The performance of the model will be tested under different circumstances. These circumstances correspond to the four phases introduced in Subsection 2.3.2.

Due to the focus of the thesis, the scope of the Alternative will not include the production of electricity on an external site. Meaning that the environmental impact of the production of grid power will not be included. The effect this production has on the site like an absence of electricity will be included. The alternatives will be worked out at the conceptual design level. Concept design is the stage of the design process that is not meant to be implemented as commercial products, at least not without major additional design work. Conceptualization describes the manipulation and combination of ideas. Thus concepts have to be designed, drawn, and described so that others can understand and build on them [Keinonen and Takala, 2006],[Andreasen et al., 2015]. The design of the alternatives will not be set out in detail.

3.4.1. Mapping the island's needs

The basic needs of the island are a requirement for the design. The term requirement pertains to those criteria wherein the design not only fulfills the people, profit, and planet standard but also carries the potential for outright rejection based solely on that individual requirement. As mentioned in Section 3.1, the implementation of the needs as the drinking water production the design process.

The needs correspond to commodities and services the local community requires for proper functioning. Services like energy (electricity, heat, cold, transport fuel, et cetera), but also refer to all other commodities or utilities that might or might not depend on energy supply, like water, waste treatment, wastewater treatment, and so on [Duić et al., 2008]. What the needs exactly for each commodity and service are, has to be defined locally. The alternatives must fulfill the program of requirements [Andreasen et al., 2015].

This thesis introduces the subsequent section to the process of Mapping the island's needs. The needs are fundamental to defining the requirement [Andreasen et al., 2015]. The definition of the needs to be considered in this design process and the requirement to be included in MCA will be relevant to designing the drinking water treatment plan and the resources required to achieve clean drinking water. Due to the different needs in the different phases, the drinking water needs are defined per phase. For drinking water, the needs are expressed in terms of both quantity and timing. Moreover, the needs depend on the phase the system is in.

3.4.2. Normal condition needs

Under normal conditions, there are two water-consuming groups: tourists and inhabitants.

Tourists can be divided into classes depending on the duration and nature of their stay. The class determines water consumption. One of the classes is stopover visitors. Stopover visitors are tourists who stay more than 24 hours, meaning they have stayed on the island for at least one night.

In Alternative 0 of the case study, there is a warning moment of 3 days before impact and an after-effect of more than a year. The alternatives want to decrease this after impact to 10 months, before the next hurricane season. Due to the nature of the impact, this thesis will only consider stopover visitors. Including only tourists that sleep on the island, excluding cruise-ship tourism and the other two classes Transits and Day visitors. The average taken over the period from 2005 to 2018 will be used. The year 2019 will be excluded because of the impact of Hurricane Dorian in that year. The average number of stopover visitors over this period is 163 320 per year. 163320*7/365=3132 gives the average number of tourists present on the island every day. Tourists use $400\,\mathrm{L\,d^{-1}}$ to $1000\,\mathrm{L\,d^{-1}}$This thesis will use $700\,\mathrm{L\,d^{-1}}$ per visitor. So 3132*700= $2.2\times10^{6}\,\mathrm{L\,d^{-1}}$ is needed for tourism. The bunkering of cruise ships is not included in the calculation, due to the exclusion of Transits and Day visitors. Bunkering is a maritime term for supplying logistics to a ship. In this context, it refers to replenishing the ship's fresh water supply from a local source [Lisica, 2021].

Inhabitants use less water than tourists per day but are larger in number. Tourists use an estimated two to five times more potable water than the residents [Roebuck and Ortiz, 2004]. Residents use $200\,\mathrm{L\,d^{-1}}$ per inhabitant in the normal condition. 50 000 inhabitants multiplied with $200\,\mathrm{L\,d^{-1}}$ = $10\times10^{6}\,\mathrm{L\,d^{-1}}$ [Roebuck and Ortiz, 2004]. Total $12\times10^{6}\,\mathrm{L\,d^{-1}}$

3.4.3. Definition of needs under disaster conditions; quantity and time sensitivity

The four phases of the disaster cycle will serve as a starting point to establish the needs during a disaster. In addition to the quantity needed for drinking water, there is a need to go back to normal conditions as quickly as possible. The water demand (L/d) and duration will be discussed per phase. A human being can survive three days without water. However, in the design such extremes are excluded. This three-day fact does illustrate that water supply is subject to constraints on time of delivery as well as quality and quantity. Next to the absolute "minimum water requirement" for humans, defined by the survival minimum, there is also the need for drinking water in households and industries. The needs that are required before or after a disaster differ based on the specific phase.

Mitigation and Preparedness The quantity needed in this phase is similar to the normal condition of $12.2\times10^{6}\,\mathrm{L\,d^{-1}}$. Because this phase occurs during normal conditions, it is less time-critical than the subsequent phases, which are directly linked to a disaster.

Preparation In the Mitigation and Preparedness phase, steps are taken to prepare for a hypothetical disaster. While in the Preparation phase, there are actions taken to deal with an upcoming confirmed disaster. There is a decrease in tourism before a hurricane or tropical storm hits the island. It will be assumed that there will no longer be any tourism during the preparation and the next phases. The total water needed without tourism for the residence in this phase is $10.0\times10^{6}\,\mathrm{L\,d^{-1}}$. The Preparation phase starts when an official warning is given that a hurricane or tropical storm will occur in the area. The length of the Preparation phase is determined by the rules for the issuing of the alert. From the alert to the hit or brush of the disaster takes in this case study 48 hours. The length of the Preparation phase is 48 hours, see the overview in Subsection 2.3.2.

Response The hurricane or tropical storm hits and communication and transportation are complicated. People accept that there is a disaster situation and adjust their water consumption.

The 200 L/d/inhabitant decreases to 120 L/d/inhabitant and might even go as low as 90 L/d/inhabitant. The 90 L/d/inhabitant estimates will be used for the Response phase. At the beginning of the disaster, prepared inhabitants will most likely have personal storage. Also, personal resilience is assumed, meaning they are willing and prepared to use less water due to the disaster. 50 000 inhabitants multiplied with $90\,\mathrm{L\,d^{-1}} = 4.5{\times}10^6\,\mathrm{L\,d^{-1}}$. This phase begins at the start of the hit or brush of a hurricane or tropical storm. In the case of Hurricane Dorian, this phase lasted for 36 hours.

Recovery 120 L/d/inhabitant will be needed during the recovery phase. In this phase, it will be assumed that the tourists have not yet returned and other recovery activities linked to services and commodities outside the scope of this thesis are underway. Still, the inhabitants will have resumed their normal activities, and the normal needs of the inhabitants will have returned. 50 000 inhabitants multiplied with $120\,\mathrm{L\,d^{-1}} = 6.0{\times}10^6\,\mathrm{L\,d^{-1}}$. A year after Hurricane Dorian the water system of Grand Bahama was still not back to normal condition. This is assumed unacceptable for this design. The set recovery time for the thesis will be 10 months. With a set recovery time of 10 months, the condition will be normal again before the next hurricane season. [Rivero, 2020].

3.4.4. Mapping the island’s resources

Mapping the resources means taking stock of local resources or supplies, like wind, sun, geothermal energy, ocean energy, hydro potential, and water resources, but also imported ones like grid electricity, piped or shipped natural gas, oil derivatives or oil, water shipped, the possibility to dump waste and wastewater, and so on. [Duić et al., 2008].

To map the resources for the design, a list of relevant resources is needed. The quality and usefulness of a resource depend on the particular technology. The described methodology is general and can be applied to systems other than islands. The islands’ specificity comes into play when characterizing the needs and resources and assessing the system’s feasibility. Classifying the different options will be based on the island’s condition. When designing for an island, the cost of resources is a relevant factor. Conventional energy costs are higher on islands due to their isolation. Endogenous resources that would not be competitive in other regions may become competitive compared to the difficulties and costs of imported resources on islands. It is possible to select potential energy carriers based upon area needs and resources [Duić et al., 2008].

The relevant resources for the upcoming alternatives are water resources, groundwater storage, grid electricity, water shipping capability, and sun- and oil availability. There are three water resources in the case study;

Rainwater can be gathered by direct catchment or surface runoff. Gathering rainwater is to induce, collect, store, and conserve local surface runoff [Boers and Ben-Asher, 1982]

Brackish ground water can be withdrawn by wells. Brackish water is a mixture of salt and fresh water. Brackish water is easier to desalinate than seawater [Muñoz and Fernández-Alba, 2008], [Volker, 1961].

Sea water abstracting salt water from the ocean [Seckler, 1996].

3.4.5. Feasibility of technologies

The feasibility of technologies in the RenewIslands methodology generally depends on a particular demand and the availability of particular resources. Its economic viability depends on the status of technology, commercial, emerging, in development, on the quality of resources, but also on the matching of demand and resource. Also, the environmental viability, as well as the social viability of technologies, can be pondered. This will later be tested by the three-pillar model, but will already now be used to think of the feasible technologies. While conjuring technologies that will be used for this case study the aspects of a disaster are already thought of, like the unavailability of resources. The RenewIslands already presents a case, where a technology may be viable, but not available at all times. RenewIslands researchers use the examples of wind energy and solar energy. Solar energy can not be generated at night, so it is supplemented by energy made by wind turbines. Looking at this example from a disaster management viewpoint raises the following question; If the main technology is not operational, what will take its place? Disaster control measures need to be part of the design, this will be worked out in Subsection 3.4.9. With the salination of the water source two feasible technologies are chosen; Reverse osmosis and protecting the status quo with a dike. Reverse osmosis is a well-used technology to desalinate water, and the dike is of interest to the topic of this thesis, due to it also having protecting elements during disasters.

3.4.6. Feasibility of storage technologies

The feasibility of technologies for storage is part of the scope of this thesis about energy and water storage. In the case of Grand Bahama, there is no connection to the mainland, it is generally necessary to have storage. The topic of the feasibility of storage in the RenewIslands methodology includes an electricity storage system, heat storage, fuel, water, waste, and wastewater. The scope of this thesis will only include the electricity system, fuel, and water storage, but excludes heat storage, fuel, waste, and wastewater storage.

Water storage will generally be part of the water supply system, even in the case of a water pipeline, where it is needed to keep the pressure constant. Most islands will have storage of oil derivatives, covering all other energy needs, like transport fuels and electricity generation. Those with hydro potential will sometimes have water reservoirs. Electricity is difficult to store. The most economically efficient way to store the excess electricity is reversible hydro, pumping water to the upper reservoir when there is excess electricity and reversing the process when there is a lack.

In the case of Grand Bahama, the storage capability is minimal. Grand Bahama is a flat island and close to sea level, which makes large-scale gravity-based alternatives impossible. The island of Grand Bahama consists mainly of limestone. Limestone is a very porous material. Caves and caverns are easily made by nature and man. This opens and closes possibilities of storage. Space can easily be made, but the porous material is not watertight. If water is stored in the limestone caves, the water will still interact freely with the outside environment.

3.4.7. Feasibility of integration of flows

In the RenewIslands methodology, the feasibility of integrating flows is exploring the possibility of efficiently using and combining flows of the different needs and criteria. Some flows of resources and commodities may be integrated to increase the system's efficiency. The examples used in the RenewIslands methodology are cogeneration, trigeneration, and polygeneration. This paper only considers the energy and water flows, which can assist each other, but also limits the possibilities set in RenewIslands methodology.

An example to illustrate the possibilities of this step might be useful. In Corvo Island, a case study of the RenewIslands methodology, the water supply system integrates with electricity generation by using water as a mechanism for ironing demand. The Corvo Islands water supply system is well suited for integrating energy storage systems such as reversible hydro. The same reservoirs could be used for both purposes, which would significantly increase the viability of such a scheme and the penetration of renewable energy. The main barrier to the wider application of such integration lies in the traditional separateness of water and power utilities, as well as the need for similar time dependence or seasonal corporation [Rei et al., 2002]. This is unfortunately inapplicable on Grand Bahama, but for later use of this method important to mention the possibilities of this specific step.

Since complicated, strongly coupled flows depend on the timing of resources, demands, etc., the only practical way to check the viability of the scenarios is to model them in detail. After the technical viability of scenarios is thus checked, many potential ones are dropped due to not being acceptable or viable; the economic viability should be checked, even when it is clear demonstration activity.

3.4.8. Devising potential scenarios

Potential scenarios have been devised in the previous chapter. The two Scenarios are the Normal condition and the Disaster condition, with the two options for the disaster condition being tropical storm condition and hurricane condition. These conditions have their own needs and consequences. The needs are the same for all the alternatives. The effects of a disaster on the Alternative differ.

3.4.9. Disaster control measures

Disaster control measures are added to the alternative to cope with the impact and uncertainty of a disaster. Next to the original design being implementable at other locations, specific design measures need to be taken to be able to deal with the specific disaster at the location. To design in the uniquely constrained environment caused by disaster, one first needs to understand the to-be-managed institutions and planning processes to operate effectively. In particular, development management and planning processes must be sensitive to the tension between speed and deliberation and the stresses citizens, organizations, and governments feel in post-disaster time frames [Blanco et al., 2009].

Adding disaster to the design is particularly important in integrating insights from the emerging literature on institutions, planning processes, and management approaches in disaster management. Disaster control measures will complement the existing design and balance with the existing institutions and planning processes to operate effectively in a uniquely constrained disaster environment. Disaster control measure is added to adjust the design to deal with disaster.

Disaster control measures are designed together with the whole Water management system but will be scored in different parts of the sub-scenarios. This is because the Disaster control measures are active or productive in other or specific phases of the disaster cycle.

3.5. ACV4e LCA

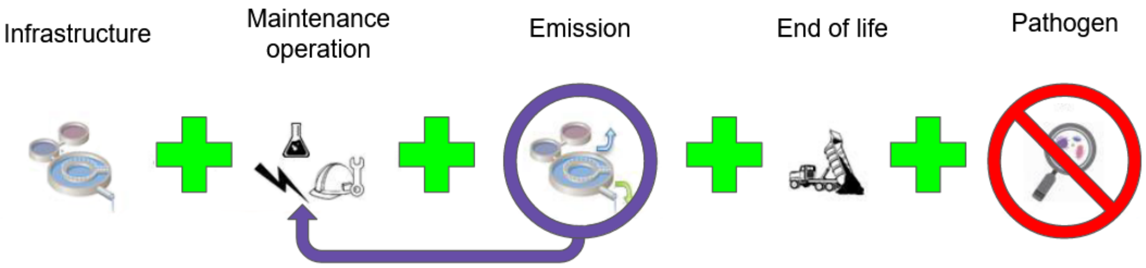


Figure 3.1: The Water Management aspects are based on ACV4e LCA. Because of the negligible influence, the emissions are categorized under Maintenance & Operation in this thesis. The Pathogen is out of scope of this thesis [Risch et al., 2014b][Catel et al., 2018][Loubet et al., 2014], [Risch et al., 2015a].

As mentioned in Section 3.1, the implementation of the needs of the water treatment plant as a stakeholder will be implemented into the process. ACV4e was used to do a similar analysis of a water treatment plant that this thesis would like to accomplish, though the disaster elements will be added. The process ACV4e starts with an alternative resulting in an impact overview. The results of the ACV4e impact overview have the same purpose as the results of the MCA will have for this thesis, providing a way to compare the alternatives on the criteria. Due to the usage of MCA instead of LCA, the conclusion of this thesis will not be as detailed. The research behind ACV4e will be used to create assessment aspects for the water management components in the MCA.

The aspects grouped under "Water management" correspond to normal operation and are based on a model used in the software package ACV4e [Catel et al., 2018]. ACV4e considers the effects of construction, consumption of resources and emissions during operation, and various End-of-Life impacts. ACV4e also considers pathogens, but this is outside of the scope of this thesis.

ACV4E can produce the results of the LCA analyses of the scenarios built and parameterized in order for users to compare these scenarios and then interpret these results to clarify an investment decision Guerin-Schneider et al. [2018]. To be able to assess a water treatment system this tool divided the treatment system up into different steps which all had their own different impacts as seen in Figure 2.17. They want to include the following with these impacts;

Infrastructure : The term "Infrastructure" represents the "hardware" of the system, such as building material used in the construction. To integrate BBB and water management it is necessary to judge the infrastructure not only based on normal operation "Water management", but also under "Disaster management".

Maintenance & Operation : "Maintenance" groups impacts related to replacement parts and periodic repairs and also includes emissions of greenhouse gas and discharge of polluting material.

End-of-Life : "End-of-Life" includes reuse, redistribution, recycling, and environmental effects of demolition.

The terms “Infrastructure” and “Maintenance & Operation” have their boundaries set clear. “Infrastructure” mainly focuses on the building phase and its impacts. The infrastructure components will be the fundamental facilities and systems set out during the building of the Alternative. People that are relevant to infrastructure will be the end users. “Maintenance & Operation” covers the time between building and collapse, meaning normal operation. The Maintenance components will be the ones that need to be replaced due to normal operation. People that are relevant to ‘Maintenance & Operation” will be the technicians and operators. The end-of-life is slightly more complicated and needs more explanation, which will be given in Subsection 3.5.1.

To be able to assess compatibility with people, their needs first to be defined. For this Hofstede’s Cultural Dimensions Theory is used

3.5.1. End-of-Life

The term End-of-Life (EoL) is used here to refer to the end of the lifespan of a system or one of its components.

The WM aspect of "End-of-Life" includes reuse, redistribution, recycling, and the environmental effects of demolition. For long-lived products, like a water system, the impact of EoL processes such as demolition and disposal will occur in the distant future. For construction materials, EoL processes are often estimated to occur within 50 to 100 yearsFrijia et al. [2012],Sandin et al. [2014]. A non-disaster-stricken Water treatment system has a lifespan of 50 years. These longer time frames cause technological uncertainty, meaning new technology could be developed for disposal and the type of substituted technology can change. Straight-line depreciation times of 100 years do exist in financial accounting for long-lived assets. The use of straight-line depreciation is difficult to justify if a disaster can rapidly decrease the value of the system to zero. A hurricane disrupts the process of depreciation, meaning that implementation of a straight-declining line is impractical. The nature of EoL processes is highly uncertain, even without disasters, as seen in Figure 3.2. This time-dependent uncertainty has previously been acknowledged as a challenge for life cycle assessments (LCA) in the construction industry [Singh et al., 2011], [Verbeeck and Hens, 2007], [Sandin et al., 2014]. EoL particularly focuses on uncertainties regarding the means of disposal, the expected technology development of disposal processes, and the type of substituted technology. Despite its significance, the element of uncertainty is frequently overlooked in the LCA of constructions and construction materials. Decision makers suffer from this blind spot even when the objective is to inform decisions regarding long-lasting constructions[Bribián et al., 2011],[Habert et al., 2012],[Lundie et al., 2004],[Persson et al., 2006], [Sandin et al., 2014]. Until now, there has been insufficient consideration of EoL uncertainties of long-lived products, which may hamper sound decision-making for sustainable development [Sandin et al., 2014].

A scenario can be used to cope with this uncertainty surrounding EoL. Setting up scenarios to account for different possible futures of EoL has been done before Bouhaya et al. [2009]. When modeling future disposal processes several fundamentally different scenarios are needed according to Mathiesen et al. [2009]. The construction of a complete model of EoL is out of the scope of this thesis. Sandin et al. [2014] recommend cornerstone scenarios to capture the range of possible outcomes of temporally more dynamic impact assessments. These Cornerstone scenarios are similar to the scenarios suggested by the Three-Point Approach used in the thesis. Combining the need for EoL scenarios with the scenarios in this thesis will boil down to Normal circumstances, tropical storms, and hurricanes. The Normal circumstances will assume that the whole 50 years of the water system lifespan will be utilized. Making a comparison of the alternative with Alternative 0 in the case no disaster will strike in that time frame. In the disaster phases, (Mitigation & Preparedness, Preparation, Recovery, and Response) the degradation in the system value by the disaster will be compared and scored, this will be scenario-dependent.

In the case study, regular transportation is equivalent to international shipping. Transportation has a higher impact on an island. Normally transportation and supply-chain processes would be of lower importance when contrasted to demolition [Sandin et al., 2014].

Promoting transportation to have an environmental effect will be a significant element in the EoL. Another element of EoL is the emissions and waste which occur during EoL processes. Waste is an unavoidable by-product of most human activity. The term “waste” refers to any product or substance that is no longer suited for its intended use [Balwan et al., 2022]. In the case of the WM aspects of End-of-Life, no score can be given for the sustainability category people. For the scope of this thesis, it is impossible to assess the category of people 30 years in the future. The interests of environmental groups and companies could be assessed within this time frame of 30 years, but the aspects they are interested in are also covered by the sustainable pillars of Profit and the Planet. Because of this, on the criterion people, all Alternatives will receive a neutral score for EoL.

In the case of the WM aspect of End-of-Life, no score can be given for the sustainable category People. For the scope of this thesis, it is impossible to assess the category of people 30 years in the future. Environmental groups and companies will be assessed within this time frame of 30 years, but their interest is assessed in the sustainable pillars of Profit and the Planet. Because of this, the criterion people will be given no score.

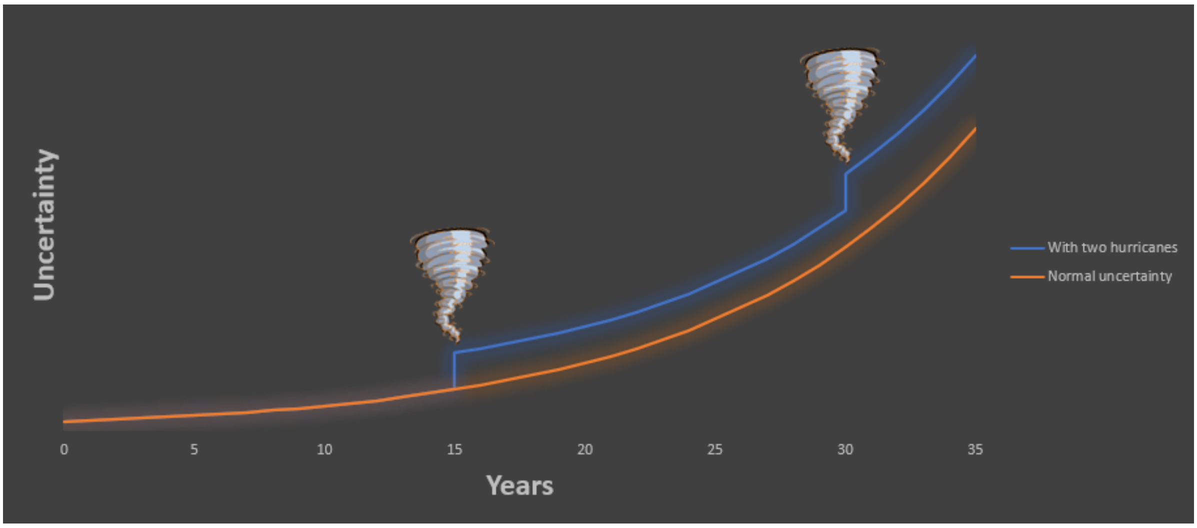


Figure 3.2: Depiction of uncertainty regarding EOL overtime. The regular uncertainty is depicted in orange and the added uncertainty by hurricanes with an interval of 15 years is depicted in blue. The uncertainty increases during a disaster due to the unpredictability of the effect and impact such an event has.

3.6. Multi-Criteria Analysis (MCA)

Multi-Criteria analysis is a typical method to aid in selecting one solution from a set of possible solutions. Multi-Criteria Analysis (MCA) tools have been widely used in decision-making situations to ensure a drinking water supply in terms of quantity and quality Gutiérrez et al. [2016].

The goal is to design a sustainable water management strategy, including disaster management for the growth of freshwater resources on a small island, coping with regular disaster risks, and reducing saltwater intrusion's impact. In an MCA, a row describes one of the options that are being considered. Columns correspond to a criterion, or 'performance dimension,' regarded as necessary for comparing the different options. The entries in the matrix body assess how well each option performs concerning each criterion Dodgson et al. [2009]. The Alternatives will be tested with multiple criteria of usability in normal conditions and disaster conditions. First, the Alternative must fulfill its purpose of providing its service in the normal circumstances scenario. This is followed by defining and setting criteria for evaluating sustainable design and usability in the phases of the Disaster Cycle. The sustainability of the Disaster Cycle phases will be evaluated on the indicators.

The components of a Multi-Criteria Analysis are:

Define Objective The objective of the MCA is to enable a structured and transparent comparison of alternatives, allowing decision-makers to understand trade-offs and potential synergies.

Define criteria This thesis uses a modified table, where multiple scenarios, aspects, and criteria will be set in a matrix. The criteria scored will be the three sustainability pillars, People, Profit, and Planet. The Alternatives will be split into three Management aspects which will be set against scenarios normal, tropical storm, and hurricane, with sub-scenarios of the disaster cycle phases. Each of these intersection will be scored on the criteria People, Profit, and Planet

Performance of the Alternative The performance of the alternative is based on the criteria. The focus of the literature study was to combine the different criteria from the disaster cycle and the needs of a general water treatment design. The criteria have been determined with a combination of experts' opinions and information from various sources. Dividing a decision or problem into smaller, more understandable parts. This makes it possible to compare each criterion and describe the expected performance of each option against the criteria. This process is repeated with three Alternatives. The performance of the Alternatives is evaluated in Appendices A, B, and C.

Scoring: The Scoring is the expected consequence of each option and is assigned a score on the strength of preference scale for each criterion. More preferred options score higher on the scale, and fewer select options score lower. In this thesis a scale of 5 points is used; bad, inadequate, neutral, adequate, and good. This 5-point scale will be set in a visual scale from - - till ++, as shown in Table 3.2. This way of scoring is comparable to an Ordinal scale – where each alternative is rated on how well it satisfies a particular interest. If one alternative ranks higher than another, a higher score will be given to this alternative. The approach is called the compensatory MCA, technique since high scores on another may compensate for low scores on one criterion [Dodgson et al., 2009].

Weighting: The most common way to combine scores on criteria, and relevant weights between criteria, is to calculate a simple weighted average of scores. Using such weighted averages depends on the assumption of mutual independence of preferences. For each criterion, numerical weights are assigned to define the relative valuations of a shift between the top and bottom of the chosen scale. Due to the nature and minimal interaction with stakeholders, the weight of all criteria will be set to 1. In future models, this can be changed by the wishes and needs of the stakeholders.

Results Analyse and then validate the results, which can then be discussed. The analysis of the result can be found in Chapter 6.

Meaning behind the score	Bad	Inadequate	Neutral	Adequate	Good
Model input	1	2	3	4	5
Visual representation of the score	- -	-	0	+	+ +

Table 3.2: The scoring system for the criteria is a 5-point scale. The visual score will be used for this thesis. The score is interchangeable.

These key parts of the BBB will be seen as similar to the interactions stakeholders have in the design process. A weighting system specific to the needs of a particular stakeholder group is often introduced by providing weights for individual variables, which then gives this specific variable more impact in the final decision Scholz et al. [2013]. It can however be explored if these stakeholders will interact earlier in the design and be better integrated into the design of a water management system.

The model will be semi-quantitative. For a criterion there are indicators, the values of an indicator can be binary (yes/no), discrete (black water, grey water, potable water) or continuous (cost, acidity, etc.), but due to the scope of the thesis is this not always possible.

The goal is to design a sustainable water management strategy, including disaster management for the growth of freshwater resources on a small island, coping with regular disaster risks, and reducing saltwater intrusion's impact.

The Alternatives will be tested with multiple criteria of usability in normal conditions and disaster conditions. First, the Alternative must fulfill its purpose of providing its service in the normal circumstances scenario. This is followed by defining and setting criteria for evaluating sustainable design and usability in the phases of the Disaster Cycle. Both sustainability and the phases of the Disaster Cycle will be evaluated on the indicators, which are then ranked.

3.7. Three Points Approach

The three-point Approach will be used to support three scenarios. The Weather Scenario used in this research will be based on current weather conditions in the case study area. Long-term water management studies have adopted scenario analysis as adequate instruments to explore uncertain aspects of the future, the potential implications of future global change, and possible strategies [Haasnoot et al., 2009], [Grundy, 2003]. Scenarios can be used to explore a range of plausible future states and their challenges.

The division of weather conditions will be based on two categories: normal and disastrous. The weather conditions are composed of a series of events in time (storylines) of a natural event (e.g., floods, droughts). There is a difference in duration between the time series or the storyline of a natural event and the timeline or lifespan of a water system. Water systems are built to be in use for 50 years or longer [Latva et al., 2016]. A natural disaster will disrupt the water system's lifespan, particularly in vulnerable locations. The difference in time scale between a natural event and a water system makes it difficult to combine them in one design. Scenarios can be used to explore a range of plausible future disaster states, and their challenges [Parson et al., 2007]. The most significant difference in the weather scenarios is the frequency and intensity of the disaster events.

3.8. Reporting of the thesis

For the literature study, the concept brought forward by Build Back Better was checked. Scientific articles were also searched in Google Scholar and Springer about, Sustainability and the Disaster cycle from the water management perspective. America heavenly influences the Commonwealth of the Bahamas. Due to this, the study focused on American as well as Dutch literature, with a general focus on American principles.

For the case study data, only data from before September 2019 were used, due to the start of the MDP [van der Hucht et al., 2021], which began in 2020. Furthermore, a literature study was conducted. Sources that are observed as reliable or relevant were used, for example, journals and local newspapers. The focus of the literature study was to combine the different criteria from the disaster cycle and the needs of a general water treatment system. The technologies of the alternative will be in use for ten years, this is to ensure that the techniques are not only theoretically suitable but also practically.

This thesis examines ways to include the performance of a water management system in the context of disaster management in the initial phase of the design process of a drinking water supply system for the island of Grand Bahama. The scoring of the performance of a regular drinking water treatment alternative combined with the disaster cycle. Build Back Better is a concept that delivers insight into the ideas and approaches towards the specific case of Grand Bahama.

Papers have been collected through Google Scholar discussing the concepts and the influence of the Disaster cycle on a water management design to gain insight into the criteria for the relationship between water management design and the Disaster cycle. The following concepts have been explored;

- Build Back Better (BBB)
- Water Management perspective on BBB
- Sustainability in a civil engineering perspective
- Disaster Cycle
- Multi-Criteria analyses
- RenewIslands methodology
- Three-point approach

These concepts will be implemented in a case-study design process. Detailed investigation of one specific case of a small touristic island's freshwater availability during the different phases of a hurricane disaster. The case study will include three Alternatives that will be tested on scenarios.

3.9. Data analysis, model

After formulating a problem statement and research questions and describing which theories, ideas, and models about the subject, it is now possible to choose a framework and set up the model. The aim is to collect rich data to better understand a theoretical framework's specific contexts, phenomena, or behaviors. The choice of particular models and definitions also gives the research direction. The model will answer the research questions and get the consequence of the criteria of the condition and express the different Scenarios. A model that is used in comparing the performance to aid decision-making is the Multi-Criteria Analysis (MCA).

4

Devising potential Scenarios

In a Three-point approach designed in the Netherlands, the return periods for the three points are 0.1, 2, and 100 years. Such a timescale is not relevant for Grand Bahama due to the extreme events happening within 15 years instead of 100 years. The three points used for Grand Bahama are Normal, tropical storm, and hurricane. The first point of 3PA is the scenario of Normal Circumstances with a return period of 0.1 per year. This is done because 0.1 is a mathematically convenient low number. The second point of 3PA is the scenario tropical storm with a 2-year return period, based on the return period of a tropical storm. The third point of the 3PA is Hurricane 5, based on Dorian with a 15-year return period. The weather conditions of these three points will be detailed in the following paragraphs and seen in Figure 4.1. The three points are 0.1, 2, and 15 years for the event return period [Bak, 1996]. This creates three scenarios, one normal and two disasters.

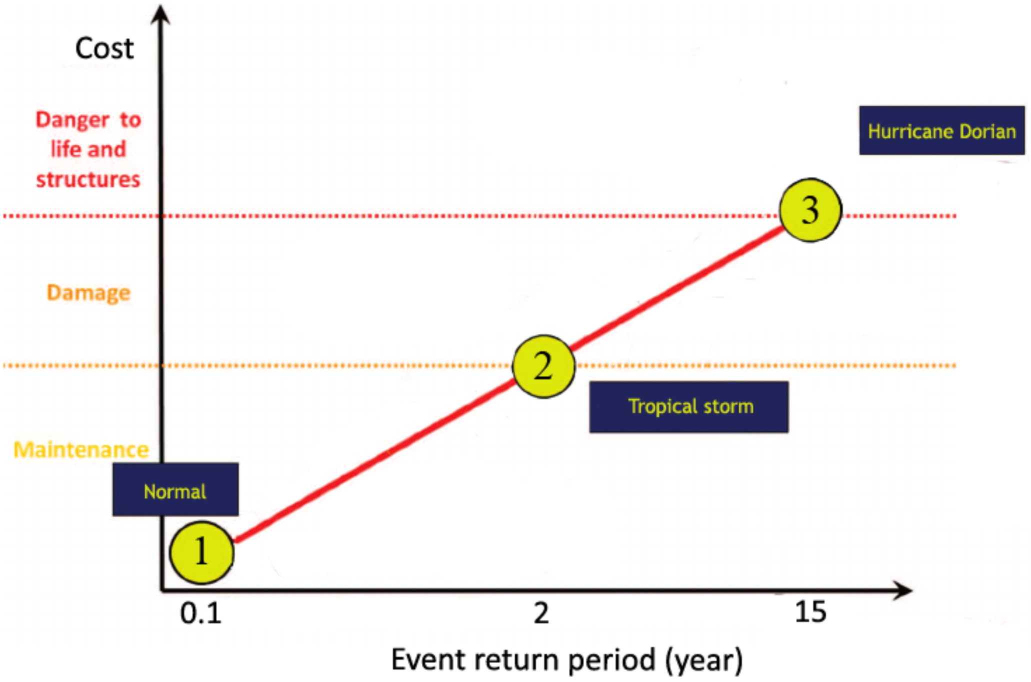


Figure 4.1: 3PA is the scenario of Normal Circumstances with a return period of 0.1 per year. The second point of 3PA is the scenario tropical storm with a 2-year return period. The third point of the 3PA is Hurricane Dorian with a 15-year return period.

The weather conditions, normal and disaster were chosen as scenarios. The disaster condition is divided further into two scenarios Hurricane and Tropical Storm. A disaster is followed by the need to go back to normal, which then cycles back to a following disaster threatening the normal. A three-point approach can plot the three weather conditions on a graph, which then illustrates intensity and frequency.

Scenarios describe possible future conditions and are generally developed to inform decision-making in situations of uncertainty. Scenarios can be used to explore a range of plausible future states and their challenges [Parson et al., 2007]. The most significant difference in the weather scenarios is the return period and intensity of the disaster events.

Based on the analysis of the island, the hurricane, and the essential physical processes, an overview, and understanding of the hazards can be made.

4.1. Normal condition; Normal circumstances

The first point of 3PA is the scenario of Normal Circumstances with a return period of 0.1 per year. The first point illustrates the Normal circumstances values of the case study. The label "Normal circumstances" represents the everyday situation. Here, it is taken into account that everything proceeds favorably and trouble-free operation. Instead of being a hindrance, disaster control measures will provide added value to society. Multi-functionality of the protection measures is beneficial. In addition to flood prevention, the required construction efforts for flood protection should be merged with other essential social or economic tasks or services in a living community.

During Normal condition, rainfall in Grand Bahama is minimal compared to the rain during a hurricane. The Bahamas are famous for their blue sky, which is reflected in the minimal number of downpours. The required water needs of the people in this time phase are described in Subsection 3.4.2.

4.2. Disaster condition; Tropical storm

The Disaster condition of a tropical storm is the second point of the three-point approach (3PA) with a 2-year return period. The second point is initiated by designing a facility that protects against a storm event in extreme conditions within the design scope. This means that the facility will be able to handle a scenario described by the second point and will break when the condition becomes worse. In 3PA, point 2 is a middle ground between optimistic and pessimistic forecasts, a mean between normal circumstances and system failure extremes. Point 2 is the domain of technical optimization. Professionals discuss technical solutions to deal with the defined design storms to prevent damage and meet the service level established politically [Fratini et al., 2012].

A tropical storm can be part of a hurricane or a storm on its own. Every two years, Grand Bahama interacts with a tropical storm.

A tropical Storm is a tropical cyclone that doesn't yet appear on the Saffir-Simpson Hurricane Wind Scale. The maximum sustained winds of a tropical storm are 63-117 km/h (34 to 63 knots). The dangerous winds will produce some damage: Well-constructed frame homes could damage roofs, shingles, vinyl siding, and gutters. Medium branches of trees will snap, and shallowly rooted trees may be toppled. If extensive damage to power lines and poles occurs, it will likely result in power outages that will last a few to several days [NHC, National Hurricane Center, 2019].

This means minimal damage to a drinking-water treatment system if the system is out of the V zone and A zone, as seen in Figure 2.11. The system will, however, become an isolated system. This means that it will become difficult to connect to the grid power, damage the external water transport system, and challenging to reach the treatment plant with vehicles if the roads are damaged. The required water needs of the people in this time phase are described in Subsection 3.4.3.

4.3. Disaster condition; Hurricane

Hurricane Dorian is the third point of the three-point approach (3PA) with a 15-year return period. Point three of the 3PA represents a situation where the protection level is exceeded by a threat with a high return period: The protection system fails. This point emphasizes the need for a design to minimize the damage to that failing system by maximizing its coping and recovery capacity. The third point represents an unfavorable condition in the lifespan of a project. It illustrates an instance where all potential elements manifest unfavorably.

The Frequency is based on the return period of a category 5 Hurricane for Grand Bahama. Hurricane Dorian will be used for the hurricane condition intensity, and impact. Hurricane Dorian portrays a situation where every conceivable factor takes a negative turn and is not representative of an average category 5 Hurricane. Hurricane Dorian stayed above the Grand Bahama and coexisted with a king tide.

In the early hours of Tuesday, September 3, 2019, Hurricane Dorian was stationary over the island of

Grand Bahama for 18 hours, most of the time as a category five hurricane. Dorian was one of the most potent Caribbean storms, a category five hurricane with winds up to 298 km/h [News, (2019, September 3]. It stalled over the islands Grand Bahama and Great Abaco for 30 hours [Packard, 2019, September 12], becoming the worst recent disaster in the nation's history. Hurricane Dorian had two major disaster impacts; hurricane wind and flooding due to the combination of a storm surge and the king tide.

The impact of Hurricane Wind is more extensive than that of a tropical storm. During Hurricane Dorian, many framed homes were destroyed, with total roof failures and wall collapses [NHC, National Hurricane Center, 2019]. During a Category 5 hurricane, fallen trees and power poles can isolate residential areas, but Grand Bahama has minimal tree growth. It can still be assumed that during a storm similar to Dorian, the power outages will last for weeks to possibly months. The surrounding area will be uninhabitable for weeks or months. According to NASA satellite-based estimates, the total accumulation of rains over parts of Grand Bahama exceeded 36 inches [Reed, 2019, August 29]. Hurricanes with comparable rain intensity are expected to occur once every 15 years. This is taken from approximations of the Central Pacific Hurricane Centre concerning occurrence rates of hurricanes on the coast of Florida [NOAA, National Oceanic and Atmospheric Administration, 2020].

The impact of the combined storm surge and king tide caused significant flooding on Grand Bahama during Dorian. The flooded area can be seen in Figure 2.13b. The king tide is the largest astronomical tide of the year and was 0.915 meters during Dorian [Buckingham, 2019]. The storm surge was relatively large due to the consistent onshore winds over shallow water towards Grand Bahama Island [NOAA, National Oceanic and Atmospheric Administration, 2019]. The hurricane stood stationary for 30 hours at a very unfavorable location, resulting in the onshore wind blowing over shallow water, raising the water level to 4.88 meters above mean sea level and in some locations up to 6.1 meters according to the Grand Bahama Port Authority. The storm tide is the total observed seawater level rise above mean sea level, which consists of the astronomical tide and the storm surge [Liu, 2019], which was extreme during Dorian.

Destructive and large waves near the coast accompanied the storm surge [NOAA, National Oceanic and Atmospheric Administration, 2019]. These waves are generated offshore by the Hurricane and propagate towards the shore.

The surge of salt water that flooded the island infiltrated this freshwater resource. Tainting fresh groundwater with salt causes lasting ecological and economic damage, according to the Bahama National Trust (BHT).

5

Design Alternatives

The Water System Design Alternatives were formulated using the RenewIslands methodology [Duić et al., 2008]. RenewIslands focuses on the aspects of the design relevant under normal circumstances. In this thesis, the disaster criteria are added to the RenewIslands methodology to cover design aspects that come into play under extreme weather conditions. The RenewIslands methodology was originally developed for sustainable energy and resource planning for islands. The methodology helps to select energy and resource flow integration based on an island's needs, resources, and applicable technologies [Duić et al., 2008].

The alternatives will be worked out at the conceptual design level Purdue OWL; College of Liberal Arts, Purdue Online Writing Lab [2023]. Concept design is the stage of the design process that is not meant to be implemented as commercial products, at least not without major additional design work. Conceptualization describes the manipulation and combination of ideas. Thus concepts have to be designed, drawn, and described so that others can understand and build on them [Keinonen and Takala, 2006],[Andreasen et al., 2015]. The design of the alternatives will not be set out in detail.

The alternatives will be designed and put in different scenarios with normal, tropical storm, and hurricane conditions. Firstly the design is made to function in normal circumstances setting, then it will be adopted while taking into account the frequent occurrences of tropical storms and hurricanes. Tropical storm and hurricane conditions are the scenarios that challenge the drinking water system with extreme circumstances.

The performance of the model will be tested under different sub-scenarios. These sub-scenarios correspond to the four phases introduced in Section 3.3.

The RenewIslands methodology consists of the four steps [Duić et al., 2008]. The "Mapping the island's needs", and "Mapping the island's resources" have been explored in Subsection 3.4.1 and Subsection 3.4.4. Devising potential alternatives will be done in this Chapter. The explanation and the influence of feasibility of "technologies" has been done in Subsection 3.4.5, "storage technologies" in Subsection 3.4.6, and "integration of flows" has been done in Subsection 3.4.7. Devising potential scenarios has been done earlier in Chapter 4. Modeling is done in the Appendices A,B,C, and the results are presented in Chapter 6.

Mapping of the island's needs and resources is location-based and not alternative-dependent. Meaning that for all Alternatives the same needs and resources are relevant. The main distinction between the Alternatives regards the fulfillment of those needs and the use of the resources.

5.1. Devising Alternatives with technologies

This chapter will be about devising Alternatives with technologies that can use available resources to cover needs. The aim of each alternative is to satisfy the needs by using available resources and satisfying preset criteria. The RenewIslands methodology focuses on sustainable energy and resource planning for islands. When designing with RenewIslands, local sources of energy and water will be given priority due to security of supply reasons. Then, cheaper technologies will be given priority. Technologies will have to be assessed from a local and global environmental point of view. Due to global warming and falling reserves, and sometimes the security of supply problems, fossil fuels should generally be used as the option of last resort in setting scenarios, even though they will often provide the most economically viable solution with the current price levels. Where possible priority should be given to the use of locally available renewable resources.

The needs are worked out in Subsection 3.4.1. The available water resources in Grand Bahama are rainwater, brackish groundwater, and seawater. The technology used in the alternatives is a variation of the desalination method of reverse osmosis(RO) and protection of the current water resource. Due to the scope of this study, only conventional technologies that have been used for multiple years were considered.

Alternatives can now be devised using technologies that utilize available resources to cover the needs. Alternative 1 uses RO with grid power and salt water. An introduction will be in Subsection 5.1.2. It will be in detail scored in Appendix A. Alternative 2 uses Solar Powered RO source and brackish water. An introduction will be in Subsection 5.1.3. It will be in detail scored in Appendix B. In Alternative 3 the current groundwater source will be protected with a levee. An introduction will be in Subsection 5.1.4. It will be in detail scored in Appendix C.

5.1.1. Alternative 0 the current system

Alternative 0 is the Alternative the other systems will be compared to. Alternative 0 is the current system in 2019. This system is unsustainable and needs to be replaced due to the threat of saltwater in the drinking water. In 2019 the drinking water system was straightforward. Out of a multitude of wells, fresh groundwater is pumped up and treated with chlorine at the water treatment plants. Chlorine has been successfully used for the control of water-borne infectious disease for nearly a centuryBull et al. [1995]. There are a multitude of wells as seen in Figure 2.6a. The drinking water cleaning is done by Grand Bahama Utility Company (GBUC). Multiple water treatment plants are located within the city limits of Freeport. At the water treatment plants water is disinfected via chlorination (Gas), pumped into storage tanks, and ultimately into the distribution system and tested for quality daily. There are miles of water lines supplied from different pumping stations and wells throughout Grand Bahama Island. [GBUC, Grand Bahama Utility Company, 2020], [van der Hucht et al., 2021]. The chlorination of this alternative has slightly impacted the environment and the people for years. As stated by other studies Freuze et al. [2005], Harshfield et al. [2012], this effect is long-term. This means that choosing another alternative or continuing this one with these effects in mind won't increase or decrease the impact this "old" contamination has.

Production capacity of drinking water The full scale of the possible capacity of the drinking water treatment plant of 2019 is unknown. What is known is the needs of the inhabitants, worked out earlier in Subsection 3.4.2. For this thesis, it will be assumed that the water treatment plants operate at 75 % capacity. This is because if one water treatment plant needs repair or faces other obstacles the full capacity of the others could temporarily compensate for the absence. The total normal needs are $12{\times}10^6\,\mathrm{L\,d^{-1}}$, meaning that the total capacity of the Alternative 0 is $16{\times}10^6\,\mathrm{L\,d^{-1}}$. These liters are divided by water treatment plant so the maximum capacity for the production of drinking water per water treatment plant is $4{\times}10^6\,\mathrm{L\,d^{-1}}$.

5.1.2. Alternative 1 RO with grid power using salt water

Alternative 1 cleans salt water with Reverse Osmosis (RO). RO is a technology that needs electricity to function. The electricity is used to power pumps that create a pressure difference, which pushes water through a membrane. This membrane only lets water molecules through, extracting the salt and other particles, and cleaning the water. The part of the inflow that does not pass through the membrane should be considered as a waste flow and needs to be disposed of. Because Grand Bahama is an island, the ocean is the most logical location for this wastewater flow.

The water intake source is saltwater from the ocean, an unlimited source for Grand Bahama. However, the location of the intake point should be chosen with care. It should not be close to pollution sources and protected from physical damage by shipping or tourist activity on the water. Due to geometry, there is a substantial difference between conditions near the north and south shores. As stated in Chapter 2 the north is warm with shallow sea and the south has deep waters with more industry.

Production capacity of drinking water Alternative 1 will meet the same requirement set by Alternative 0. The water treatment plants will operate at 75 % capacity and there will be four built. This is because if one water treatment plant needs repair or faces other obstacles the full capacity of the others could temporarily compensate for the absence. The total normal needs are $12{\times}10^6\,\mathrm{L\,d^{-1}}$, meaning that the total capacity of the Alternative 1 is $16{\times}10^6\,\mathrm{L\,d^{-1}}$. These liters are divided by water treatment plant so the maximum capacity for the production of drinking water per water treatment plant is $4{\times}10^6\,\mathrm{L\,d^{-1}}$. The location of the water treatment plants will be different from Alternative 0. This is to ensure safety precautions for a disaster and easier access to the intake of saltwater. $4{\times}10^6\,\mathrm{L\,d^{-1}}$ is a very feasible size for the island. The capacity is similar to a mid-size Reverse Osmosis plant. Sea Water Reverse Osmosis (SWRO), like the one on Sal Island Cape Verde, operates with a capacity of $1{\times}10^6\,\mathrm{L\,d^{-1}}$[Peñate and García-Rodríguez, 2012]. Just on the other side of the ocean on the island Fuerteventura (Canary Islands) there is at least five reverse osmosis with the same capacity of $4{\times}10^6\,\mathrm{L\,d^{-1}}$ [Feo-García et al., 2016]. Even if you would combine the full capacity in one facility that would be possible. The largest desalination hybrid plant Fujairah produced has a water production of $170{\times}10^6\,\mathrm{L\,d^{-1}}$ from seawater reverse osmosis[Sanza et al., 2007], which is 10 times more than the needed total capacity.

The infrastructure is the hardware of the system of the Alternative. For Alternative 1, the main infrastructure components are [Kucera, 2015];

- Intake pump (Saltwater)
- Pre-filtration equipment
- Reverse osmosis equipment
- Energy recovery equipment
- Post-treatment equipment
- Freshwater storage
- Saltwater storage
- Piping
- (Remote) monitoring and control equipment
- Building
- Connection to Grid power

Maintenance for this alternative is more frequently required due to saltwater usage compared to a brackish or freshwater source. Maintenance is important to ensure that infrastructure stays operational during the lifetime of the water plant. Regularly and properly maintaining the system prolongs the lifespan and condition of a water filtration system. A properly maintained water filtration system will better protect from harmful toxins found in unfiltered water. Additionally, proper maintenance will help prevent taking on costly repairs from malfunctions. Saltwater corrodes pipe systems more than freshwater and brackish water. A case study has been done on the operation and maintenance of a $2000\,\mathrm{m^3\,d^{-1}}$ desalination plant erected in 1995 in Eqypt. The results were obtained over 6 years of operation. The plant consists of four units with a capacity of $500\,\mathrm{m^3\,d^{-1}}$ each [Abou Rayan and Khaled, 2003]. The maintenance during this period of operation highlighted the following items as needing intervention and in most cases complete replacement.

Seawater pump In the case study of the plant in Eqypt [Abou Rayan and Khaled, 2003] the corrosive nature of saline water led to damage to the pumps. The pumps were eroded shortly after starting the operation. During the 6 years of operation, the total number of working pumps was 8. Four have been replaced with new pumps and the other four have been completely overhauled. Another case study [Hicks et al., 1989], says a typical expected useful life for top-of-the-line pumps, operating continuously and with regular maintenance, is 4-7 years. For this thesis, the lifetime of the seawater pump will be 6 years.

Multi-media filters Each filter unit consists of 2 filters made from Glass-fiber Reinforced Polymer (GRP) the first filter for sand and the other for activated carbon. The two filters are in series. Multimedia filtration (MMF) can be clogged. To prevent this clogging, backwashing is used, which needs to be done daily or weekly, depending on the size of the tank and the pollution of the water. The advantages of MMF are that it has a high throughput and long lifetime. The media has a lifetime of several years [Mehner, 2010]. For this study, an average operation of 3 years per pump is assumed, based on the lifetime usage of activated carbon which is 3 years [Weschler et al., 1994], [Van der Hoek et al., 1999].

Cartridge filters Cartridge filters ensure that particles larger than 5 microns, carried over from the MMF, will not enter the membranes. The core of the cartridge filter will be changed regularly every 3 months [Abou Rayan and Khaled, 2003].

Membrane The frequency of filter maintenance depends on the type of pre-filtration. Pre-filtration can avoid frequent membrane replacement. Another interesting maintenance activity for Reverse osmosis is flushing. To avoid frequent replacement, the membranes should be flushed with fresh water at every shut-down. Meaning that clean water is pushed in the opposite direction to clean the filters. This increases the functional lifespan of the filters [Ezzeghni, 2016]. According to the literature, saltwater RO membrane has a functional lifespan of 3-5 years, and brackish RO membrane has a functional lifespan of 5-10 years. In the case studies that were consulted for this thesis, it was assumed that replacement occurred every 5 years on average, disregarding the water source. To better illustrate the difference between the alternatives, extremes of both will be included in the MCA [Ruiz-García and Ruiz-Saavedra, 2015] [Afonso et al., 2004], [Al Suleimani and Nair, 2000], [Kassis et al., 2023]. The membrane's economic lifetime was considered 5 years, based on the previous info.

Besides ensuring the upkeep of these infrastructure items, a dependable power source (specifically, electricity) is essential.

The waste produced at the End-of-Life (EoL) of Reverse Osmosis (RO) is similar to that of maintenance of RO. At the end of the life cycle of a RO system, nearly all components will have been replaced. The pump, membranes, and filters will already have been replaced 4 times after 50 years of RO operation [Senán-Salinas et al., 2019],[Raluy et al., 2005]. The only components which in normal circumstances would not be replaced are infrastructure components such as; freshwater storage, saltwater storage, piping, building, and (Remote) monitoring and control. EoL is an important part of an LCA. Other papers [Senán-Salinas et al., 2019], [Raluy et al., 2005] performing an LCA and EoL have difficulty differentiating between maintenance and EoL, because RO membranes have a short service life of 5 years, generating tonnes annually of membrane waste that is put into landfills worldwide [Senán-Salinas et al., 2019]. This paper will use an MCA as its assessment, which means that it also needs to simplify the EoL as just the impact of the part that is left at the end of the life-cycle. RO generates continuous waste during operation, like concentrated salt water and replacement infrastructure. In conclusion, RO doesn't face specific waste management problems at the end of its life cycle.

Disaster control measures are added to the design to be the fallback if the main drinking water supply systems fail. It is assumed that the grid power will be temporarily unavailable. This could have a multitude of reasons; the water treatment system got disconnected from the power grid, or it is not possible to generate power in the power plant. Whatever the reason is it can be assumed that the water treatment system needs to temporarily generate its power. This alternative will be done by using diesel generators. Emergency Diesel Generators (EDGs) provide onsite emergency ac power if all offsite power sources are lost.

The infrastructure for the diesel generators consists of the generator itself, storage for the generator when not needed, fuel storage, and connection possibilities to the water treatment plant. The maintenance is to ensure the proper functioning of the EDG before every hurricane season while also striving to prevent any potential failures during usage. The EDG's failure to start could be due to: undetected failure before the demand during the standby period, a failure caused by the demand, EDG unavailability due to ongoing maintenance, and EDG unavailability due to testing [Samanta et al., 1994].

Before using the EDG, it will be assumed that the water treatment plant is contaminated. This contamination can also have a multitude of reasons, for example when there is no flow. In times of disaster, it is necessary to halt production, and idle water can get contaminated. Another reason can be leakages, even minor storms can cause disturbances such as moving pipes, and breaking connections and resulting in leaks. A check of the facilities needs to be done before temporary production can start.

Feasibility Technology Storage and integration of flow For this alternative, all storage included in the scope is important. Due to the scope of this thesis, the electricity system, fuel, and water storage will be included. All the connecting flows are seen in figure A.2. Freshwater storage and saltwater buffer are water storage for this alternative. The energy storage is done in the form of fuel during disaster conditions and out of the scope of the alternative, at the energy power generation plant in normal conditions.

Impact of the scenario on the alternative Based on the scenarios devised in Chapter 4, the impact of the scenarios on the alternative will be given in this section. Scenarios are devised as an impact on the normal system. The alternative includes disaster control measures, which make the system more resilient to the effects of the scenario. The impact on the system by the disaster depends on the severity of the disaster, in this case, a tropical storm or hurricane. Damages can't be completely prevented, especially in the case of hurricanes. In both cases, the system will be contaminated and partially collapsed. The impact will be different in the scenarios.

In the case of this alternative, it will be assumed that the grid power will be unusable after a storm hits. The grid power supply is assumed disrupted after a disaster event.

Disaster Tropical storm condition The condition of the infrastructure after a tropical storm is presumed to be as follows; Pre-filtration (no impact), Reverse osmosis (no impact), Energy recovery (no impact), Post-treatment (no impact), Freshwater storage (possible contaminated), Saltwater storage (contaminated), Piping (contaminated), Remote monitoring and control (no impact), Building (no impact) and grid power (disconnected).

The condition of the maintenance components is presumed to be as follows; Seawater pumps (maintenance needed), Multi-media filter (contaminated), and Membrane (contaminated, backwash needed).

A comprehensive and meticulous inspection of the system needs to take place after a disaster impacts. The possibility of contamination is high. Most of the system did not “break” but did “bend” by only being contaminated. The biggest impact of the tropical storm is the grid power disconnection.

Disaster Hurricane condition The condition of the infrastructure after a hurricane is presumed to be as follows; Pre-filtration (contaminated), Reverse osmosis (contaminated), Energy Recovery (contaminated), Post-treatment (contaminated), Freshwater storage (collapsed), Saltwater storage (collapsed), Piping (contaminated) (Remote) monitoring and control (disrupted), Building (mild damage), grid power (disconnected).

The condition of the maintenance components is presumed to be as follows; Seawater pumps (shorting of lifespan), Multi-media filter (contaminated), and Membrane (contaminated).

All filters need to be replaced or cleaned. It is more probable to replace the filters given the limited resources available on the island. Most parts can be reused, but are contaminated. Contamination of the system; fresh and saltwater tanks, pipes, and filters. The storages are the most likely to be impacted by the disaster as they are outside the concrete building.

5.1.3. Alternative 2 Solar Powered RO source; brackish

Alternative 2 is similar to Alternative 1. To prevent repeating information the aspects that the two alternatives have in common will be not repeated here. Alternative 2 cleans water with Reverse Osmosis (RO). RO is a technology that needs electricity to function. The wastewater of this process will be disposed of as in Alternative 1.

The differences between Alternative 1 and 2 concern the sources of water and energy. Alternative 2 will clean brackish groundwater with Reverse Osmosis(RO) instead of salty seawater. The island’s size and local rain determine the maximum size of the groundwater bubble. The brackish groundwater is a finite resource and could be used up. The brackish groundwater bubble can be polluted by salt water and other pollutants. Another threat can be that the bubble “pops” due to overconsumption. This means that the bubble becomes unstable resulting from its size being too small.

The positive side of using brackish water is that it is easier to clean than salt water. Which is easier cleaned by the membranes, as seen in Figure D.3. Saltwater has higher concentrations of salt/ions that need higher pressure to clean out of the water Matin et al. [2011]. Brackish water can be cleaned at a lower pressure, which means it will use less electricity per liter of water produced. This will result in lower energy use per liter.

The energy source that will be used for this alternative is solar-powered. Island development problems are mostly related to imported fossil fuel energy dependence, associated with transportation and other problems [Chen et al., 2007]. Locally produced solar energy could help make energy production more sustainable.

Production capacity of drinking water Alternative 2 will meet the same requirement set by Alternative 0 and 1. The water treatment plants will operate at 75 % capacity and will be modified from the previous four locations used by Alternative 0. This is because if one water treatment plant needs repair or faces other obstacles the full capacity of the others could temporarily compensate for the absence. The total normal needs are $12{\times}10^6\,\mathrm{L\,d^{-1}}$, meaning that the total capacity of the Alternative 2 is $16{\times}10^6\,\mathrm{L\,d^{-1}}$. These liters are divided by water treatment plant so the maximum capacity for the production of drinking water per water treatment plant is $4{\times}10^6\,\mathrm{L\,d^{-1}}$. The location of the water treatment plants will be the same as Alternative 0. The source will be different, changing from fresh to brackish water.

The infrastructure is the hardware of the system of the alternative. For Alternative 2, the main infrastructure components are [Kucera, 2015];

- Intake pump (brackish)
- Pre-filtration equipment
- Reverse osmosis equipment
- Energy recovery equipment
- Post-treatment equipment
- Freshwater storage
- Saltwater storage
- Piping
- (Remote) monitoring and control equipment
- Building
- Solar panels
- Solar frame
- Storage Building for solar panels
- Battery buffer

Maintenance prolongs the lifespan of a system, as stated in Alternative 1. Maintenance for Alternative 2 is less frequently required, due to brackish-water usage as compared to a saltwater source. In Alternative 1 a clear case study was available to base the alternative on. In Alternative 2 a long-time case study with relevance and data for the study which did not use any assumptions could not be found. Enough studies compared different water sources for RO, which will be used to construct a comparative maintenance plan for a similar plant as in Alternative 1.

Important materials which need maintenance are Brackish water pumps, Batteries, Multi-media filters, Cartridge filters, and Membranes. These Maintenance components are expended upon below.

Brackish water pump Renewable energy sources may be less reliable and may therefore cause frequent system shutdowns or successive On/Off cycling of motor pumps. Generally, this may increase the potential wear on motor pumps and reduce their lifetime. Renewable energy forecasts can be a viable solution to predict renewable power generation to help with the time intervals. This enables significant improvement of energy management performance by reducing the number of pumps-switching On/Off events [Ben Ali et al., 2020]. There are pumps used in a case study similar to Alternative 2. This case study deals with the same constraints of solar energy and application in remote communities [Richards and Schäfer, 2002]. The pumps, in this case-study, have an expected pump life of up to 20 years and a replacement period for wearing parts of 5-l0 years [Richards and Schäfer, 2002].

Batteries Without batteries the system would only run in the daytime and would not disturb people at night; the short lifetime of the battery, typically 5-8 years, depending on how the battery is treated. The increased maintenance of the system and a separate battery housing are worth the buffer that a battery provides. The buffer gives the high-pressure membrane a more constant flow to avoid fluctuations in water productivity. Losses on the order of 20% have to be reckoned with when current is directed into and out of the battery [Richards and Schäfer, 2002].

Multi-media filters Multimedia filtration (MMF) can be clogged. To prevent this clogging, backwashing is used, which needs to be done daily or weekly, depending on the size of the tank and the pollution of the water. The advantages of MMF are that it has a high throughput and a long lifetime. The media has a lifetime of several years [Mehner, 2010]. For this study, an average operation between maintenance of 3 years per filter is assumed. This 3 years is based on the lifetime usage of activated carbon [Weschler et al., 1994], [Van der Hoek et al., 1999]. Meaning after 3 years the carbon in the filter isn't active anymore and no longer extracts particles out of the water.

Cartridge filters The core of the cartridge filter will be changed regularly every 3 months.

Membrane Brackish RO membranes function with a lifespan of 5-10 years. The membrane lifetime was considered 10 years [Afonso et al., 2004, Al Suleimani and Nair, 2000, Ruiz-García and Ruiz-Saavedra, 2015]

The End-of-Life (EoL) impact of Reverse Osmosis (RO) is similar to that of maintenance of RO just as in Alternative 1. At the end of the life cycle of a RO system, nearly all components will have been replaced. The only components which in normal circumstances would not be replaced are infrastructure components such as; freshwater storage, saltwater storage, piping, building, and (Remote) monitoring and control. RO generates continuous waste during operation, like concentrated water and replacement infrastructure. RO doesn't face specific waste management problems at the end of its life cycle.

Disaster control measures are added to the design to provide a fallback option if the main drinking water supply systems fail. It is assumed that a large volume of water will be shipped to the Grand Bahamas. The bags, tanks, or bottles will be produced in Florida or another location unaffected by the hurricane. This method has been used after Hurricane Dorian [Rivero, 2020].

Feasibility Technology Storage and integration of flow For this Alternative, all storage included in the scope of this thesis is important. The storage includes the electricity system, fuel, and water storage. All the connecting flows are seen in figure B.1. In this Alternative, there is no direct fuel consumption, not in the normal condition and also not in the disaster condition. The electricity is made in the scope of the design with the sun as a source. Electricity is made during the day and stored in batteries for night availability. Given the large scale of production, a cautious stance is adopted: when batteries are incorporated, merely fifty percent of the overall electricity capacity is allotted for operations.

The freshwater storage and brackish-water buffer are the storage of water for this alternative.

Energy could be stored with gravity, by creating water pressure by storing water at a higher altitude, while energy is available. This can be difficult in Grand Bahama due to the minimum height difference in the area.

Impact of the scenario on the alternative Based on the scenarios devised in Chapter 4, the impact of the scenarios on the alternative will be given in this section. Scenarios are devised as an impact on the normal system. The alternative includes disaster control measures, which make the system more resilient to the effects of the scenario. The impact on the system by the disaster depends on the severity of the disaster, in this case, a tropical storm or hurricane. Damages can't be completely prevented, especially in the case of hurricanes. In both cases, the system will be contaminated and partially collapsed. The impact will be different in the scenarios. In the case of this alternative, it will be assumed that solar panels will be unavailable directly after a storm hits.

This is because the solar-energy racking permits panels to be removed and stored in advance of a storm's arrival as well as reinstallation after the storm passes [Krantz, 2020],[Jacoby and Greenfader, 2021]. There has been an idea of a PV (solar photovoltaics) racking system that would permit the safe removal, storage, and return of solar panels by unskilled community members without the assistance of professional PV electricians after the initial installation. For this thesis removal of the number of solar panels that power a drinking water treatment plant is assumed. Removal of solar panels cannot yet be done by unskilled community members and for this process, skilled labor is needed.

Disaster Tropical storm condition The condition of the infrastructure after a tropical storm is presumed to be as follows; Pre-filtration (no impact), Reverse osmosis (no impact), Energy recovery (no impact), Post-treatment (no impact), Freshwater storage (contaminated), Saltwater storage (contaminated), Piping (contaminated), (Remote) monitoring and control (no impact), Building (no impact), Solar panels, (disconnected), Solar frame (no impact), and Storage space for solar panels (No impact)

The maintenance components of Alternative 2 are Batteries (contaminated), Multi-media filters (contaminated), Cartridge filters (contaminated), Membrane (contaminated), and Brackish water pump (contaminated)

A comprehensive and meticulous inspection of the system needs to take place after a disaster impacts. The possibility of contamination is high. Build back better ask a question about systems bending (repairs needed before resuming usages) or breaking (in need of replacement). Most parts of the system did not break as a consequence of the hurricane but were bent by only being contaminated. The biggest impact of the tropical storm is the disconnection of the solar panels, which was done to prevent further damage.

Disaster Hurricane condition The condition of the infrastructure after a hurricane is presumed to be as follows; Pre-filtration (contaminated), Reverse osmosis (contaminated), Energy Recovery (contaminated), Post-treatment (contaminated), Freshwater storage (collapsed), Saltwater storage (collapsed), Piping (contaminated), (Remote) monitoring and control(disrupted), Building (mild damage), Solar panels (disconnected), Solar frame (damaged) and Storage space for solar panels (mild damage).

The condition of the maintenance components is presumed to be as follows; Batteries (contaminated), Multi-media filters (contaminated), Cartridge filters (contaminated), Membrane (contaminated), and Brackish water pump (contaminated)

All filters need to be replaced or cleaned. With the resources on the island is likelier to replace them. Most parts can be reused, but are contaminated. The parts that are likely to be contaminated are; fresh and saltwater tanks, pipes, and filters. The water storages and Solar panel frames are the most likely damaged by the disaster as they are outside the concrete building.

5.1.4. Alternative 3 Protect the current groundwater source with a levee

Alternative 3 is based on a comprehensive protection strategy for the current situation (Alternative 0) of Grand Bahama. The main goal of the design is to protect the economic center of Grand Bahama and not to secure the freshwater availability. This Alternative is based on the results of the MDP "Grand Bahama after Hurricane Dorian; Interdisciplinary approach to Build Back Better"[van der Hucht et al., 2021]. To increase resilience, the strategy is to collectively protect the most densely populated part of the island. This core with critical infrastructure will serve as safe ground for the rest of the island, where individual protection measures and improvement of evacuation must reduce the vulnerability of other parts of the island. The two distinct flood protection methods, collective protection, and individual protection are applied to deal with the flood risk that threatens the island in the case of a storm surge during a hurricane. The individual protection area (shown in stripes) and the naturally elevated, industrial, and densely populated collective protection area (shown in black) of the city of Freeport are visible in Figure 5.1.

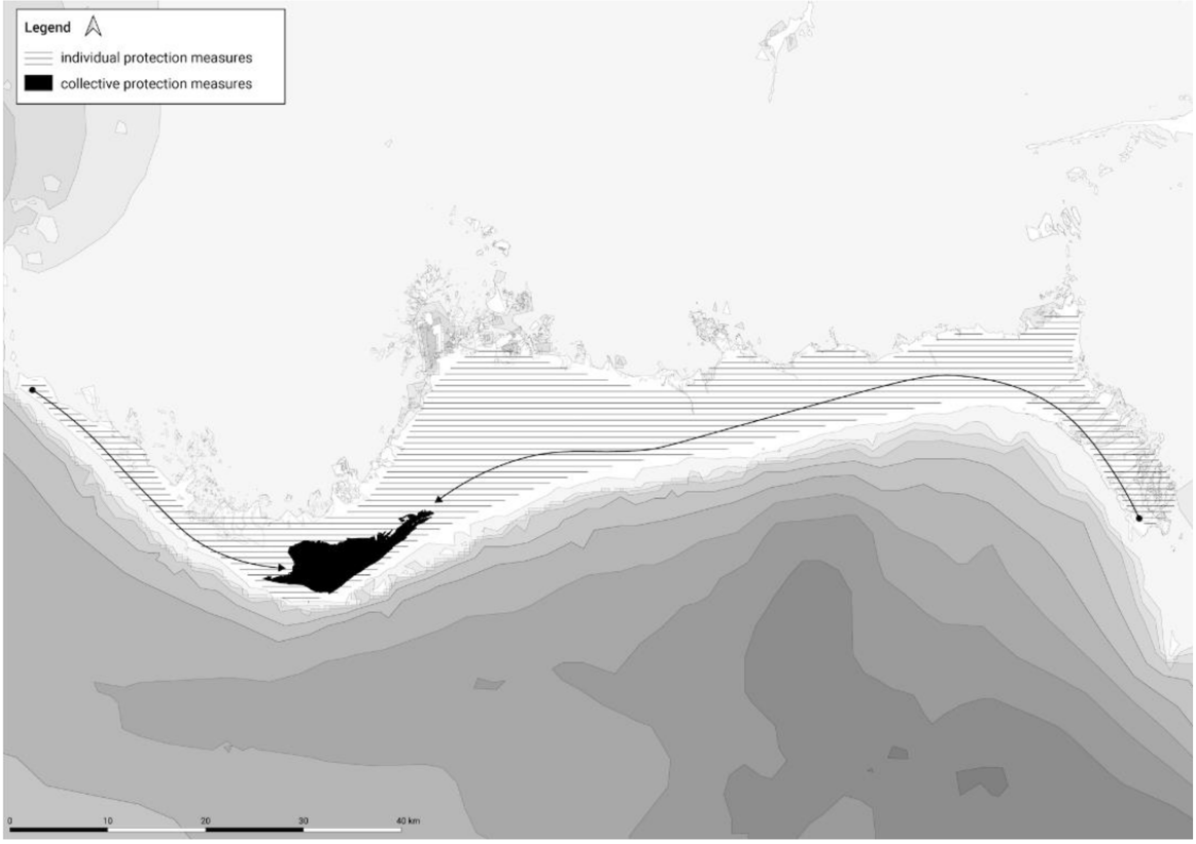


Figure 5.1: The design of the MDP "Grand Bahama after Hurricane Dorian; Interdisciplinary approach to Build Back Better". Location of the two macro areas of intervention; individual protection area and collective protection area. With black arrows the connection between the area and evacuation routes are depicted[van der Hucht et al., 2021].

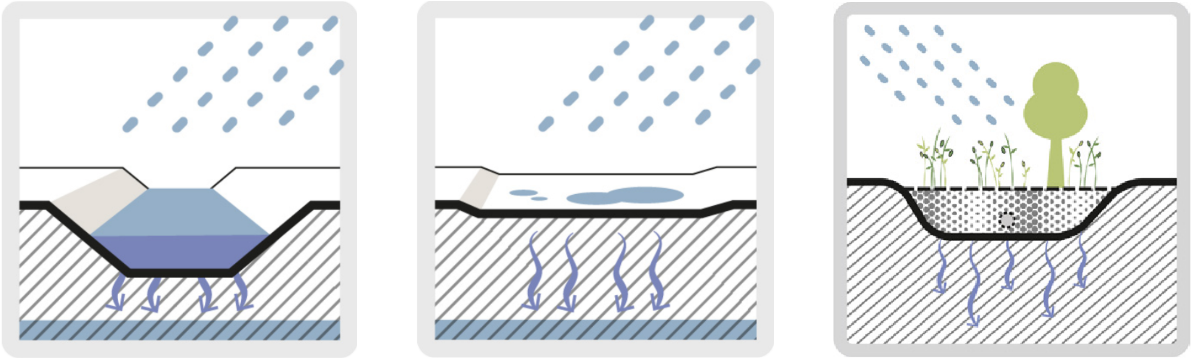
Figure 5.2: The design of the MDP “Grand Bahama after Hurricane Dorian; Interdisciplinary approach to Build Back Better”. Levees with their corresponding number and the 20 feet contours, surround the proposed collective protected area of Freeport which is divided in the industrial and urban areas [van der Hucht et al., 2021].

Collective protection protects an area against flooding and is not focused on a single structure. This protected area does not apply only to buildings, but also to critical infrastructure, economic structures, and environmentally significant areas. Collective protection tends to have a bigger impact on the surrounding areas. If the cost of this implementation is divided by the protected population it can be less costly than individual protection. In the MDP, Freeport is chosen to become protected with a collective protection system. Freeport is a densely populated area that lies on top of a ridge; this central site hosts the majority of economic and social functions. Hence the area can sustain significant economic damage during a hurricane. Protecting the residents of this area and their surroundings by a collective protection system ensures safe and stable living in the area.

The placements of 5 levees, also known as dikes, are the main collective protection for Freeport, a “ring” was designed by the MDP as an assembly of natural heights and levees, as seen in Figure 5.2. With a height of 20 ft applied for the levees, storm surge water can no longer enter the inner-city area and eastern area if a Dorian-like storm surge occurs. Increasing the height of the levee will reduce the overtopping but will increase the construction costs and the effects on society.

The by-effect of placing a levee on the given location is that it protects parts of the current drinking water treatment system. Under Freeport, there is currently a freshwater bubble. If Freeport is protected from a storm surge of saltwater so is the freshwater bubble. The water bubble that is saved is only a third of the total groundwater lens of Grand Bahama, as seen in Figure 2.6b. Protecting the fresh groundwater in this way will not cover the full needs of the Grand Bahama in normal conditions, as stated in Subsection 3.4.2. But this thesis wants to assume that it could be enough, in order to be able to compare collective protection-focused alternatives with a stand-alone water treatment alternative. Thus, giving an option to compare the different alternatives.

The levees protect the current drinking water system. By protecting the fresh groundwater and containing the threat of desalinating the current water source, the current drinking water treatment system can continue to operate. The current drinking water cleaning is done by Grand Bahama Utility Company (GBUC). Water treatment plants that are strategically located within the city limits of Freeport At the water treatment plants



(a) **Ditch or infiltration-strip** A ditch is a small channel that facilitates temporary rainwater retention, transportation, and infiltration. A ditch can contain water or can stand dry. Ditches can be integrated into green verges or the roadside.

(b) **Infiltration field** Field that temporarily stores runoff water from roads and roofs. Adding fields next to paved surfaces is a simple way to allow water to infiltrate. The size of the field that is needed is determined by the permeability of the ground and the volume of precipitation that needs buffering.

(c) **Gravel layers** A gravel layer is a subsurface facility packed with gravel for infiltration of runoff. Runoff is carried above or below the surface and led into the layer or shaft. Such systems are used next to paved surfaces or unpaved surfaces that do not offer sufficient room for infiltration ditches or where the ground has an insufficient permeability factor.

Figure 5.3: Rain infiltration method, which can replenish the fresh groundwater bubbleDeltares [2019]

water is disinfected via chlorination (Gas), pumped into storage tanks, and ultimately into the distribution system and tested for quality daily. There are miles of water lines, which are supplied from different pumping stations throughout Grand Bahama Island. Some of these pumping stations will be outside the protected area, but this thesis will assume they are sufficiently protected from salt contamination [GBUC, Grand Bahama Utility Company, 2020], [van der Hucht et al., 2021].

Dutch polders are drained by the famous windmills or by more modern pumping systems. This is to prevent pluvial flooding and handle seepage through and under the levee. The levees in the Netherlands are handling more constant differences in water level height. The levee of this alternative needs to protect from storm surges which only occur once every 15 years for a total of 3 days. This minimizes the possible seepage to only 3 days in 15 years. It might be sufficient in this case to focus on the pluvial flooding only and increase the rain infiltration inside the polder. Rain is fresh water and increased infiltration will also help stabilize the existing fresh groundwater bubble. No pumping system will be needed for this polder.

To increase the rain infiltration inside the polder there are a multitude of methods, for example, the ones shown in Figure 5.3. In the Bahamas, there seems to be enough place for these implementations, but it might go against the willingness to do so. Because most spaces are used by infrastructure for cars or green slopes, which are there for tourism.

Production capacity of drinking water Alternative 3 will meet the similar to Alternative 0. The water treatment plants will operate at 75 % capacity and there will be four built. This is because if one water treatment plant needs repair or faces other obstacles the full capacity of the others could temporarily compensate for the absence. The total normal needs are $12{\times}10^{6}\,\mathrm{L\,d^{-1}}$, meaning that the total capacity of the Alternative 3 is $16{\times}10^{6}\,\mathrm{L\,d^{-1}}$. These liters are divided by water treatment plant so the maximum capacity for the production of drinking water per water treatment plant is $4{\times}10^{6}\,\mathrm{L\,d^{-1}}$. The location of the water treatment plants will be the same as Alternative 0. This is possible because the chlorination is maintained by the positive impact of the levee.

The infrastructure is the hardware of the system of the alternative and consists of:

- 5 levees/dikes
- Wells
- Rain infiltration system
- Original water treatment plant(chlorination) equipment
- Freshwater storage
- Piping

- Building
- Connection to Grid power

Maintenance prolongs the lifespan of a system. Maintenance of a levee system is of a larger scale than just that of a water treatment plant. The cost is also higher compared to that of Alternative 1 And 2. For Alternative 3 the important materials that need maintenance are Levees, Rain infiltration systems, and Freshwater pumps. These Maintenance components are expended upon below.

Levees/dikes Due to a combination of settlement, subsoil consolidation, and relative sea-level rise (denoted by crest-level decline), the levees slowly sink “away into the sea” and should therefore be heightened and strengthened regularly [Speijker et al., 2000]. In the Netherlands, levees are maintained based on 5-yearly inspections, as laid down in the Dutch Flood Protection Act [Speijker et al., 2000]. Five times a year a person will check along the whole length of the levee. This is condition-based preventive maintenance rather than time-based preventive maintenance carried out at predetermined repair times. If during one of the inspections, the levee is damaged or too low, the levee will be repaired on that specific location, within a month [Speijker et al., 2000].

In a case study on the Dutch Oostmolendijk, the mean time between two levee heightenings was 38 years for linear decline and 51 years for the non-linear decline, similar to the 50 years of life expectancy of the present levee design in the Netherlands [Speijker et al., 2000]. Each heightening brings the levee section back into its “as good as new state”.

Outside the Netherlands, communities report that they have to protect themselves with low-cost repair work done on their own initiative [Naz and Buisson, 2015]. The role of individual community members becomes all the more crucial in emergencies. Whereas formal and centralized levels need time to mobilize resources, the informal community level has more flexibility. Moreover, while households may have difficulties in valuing their interest in contributing to maintenance regularly, emergencies bring clear and short-term incentives.

For example, in the Bagachra-Badurgacha sub-project most households own land and it is therefore understood that they have to work voluntarily toward maintenance of the infrastructure to protect their land. For example, local farmers build bamboo pilings to prevent damage or to repair damaged parts of the embankments [Naz and Buisson, 2015]. This sort of collaboration is also the basis of how this started in the Netherlands, with landowners coming together to fight against the water.

Whoever will check and repair the levee. It needs to be checked at least once before and twice during the hurricane season. After a disaster happens it should be checked again. If damage is found it should be repaired before it has a consequence.

Rain infiltration system The intensity of maintenance that is needed is dependent on the infiltration system. In all cases, the rain infiltration needs to be clean enough that permeability is still higher than the needed capacity. What clean means and how to maintain it differs per method. Sometimes heavy machines are used to clean once a year [Dierkes et al., 2002]. However, maintenance of the methods suggested in Figure 5.3 is to stay free from bigger debris and to maintain the landscape and gardens properly. The bigger debris lowers the capacity of the infiltration [Deltares, 2019]. It can be assumed that rain infiltration will fall under regular gardening activities. Gardening in the Bahamas’ is not season-specific, so this thesis it is assumed to take place once a month. The Rain infiltration system looks natural in the landscape but will take up space.

Fresh water pump Fresh water pumps are in better operating condition than the pumps in Alternative 1 and 2. In this alternative, there are no renewable energy sources, which might cause frequent system shutdowns or successive On/Off cycling of motor pumps. Also, there is no Salt water which can increase the potential wear on motor pumps and reduce their lifetime. The pumps, in this alternative, are assumed to have an expected pump life of up to 25 years and a replacement period for wearing parts of 10 years.

Disaster control measures are interesting for this alternative because the main function of the levee is to be a disaster control measure. So instead of a disaster measure being added to the alternative, the alternative starts with a disaster control measure, in which a drinking water system is added. The levee prevents storm surge which occurs during a hurricane scenario. It doesn’t protect from wind damage, but buildings and structures could be temporarily secured for this kind of impact. Also, grid power will be again unavailable after a storm, similar to Alternative 1.

Feasibility Technology Storage and integration of flow For this Alternative, all storage included in the scope of this thesis is important. The storage includes the electricity system, fuel, and water storage.

Alternative 3 is based on the findings of the workshop mentioned in the introduction. In this workshop, the protection with levees on Grand Bahama was explored and the feasible placement was designed. It happens that this design protects part of the freshwater lens. Meaning that it can be assumed that part of the freshwater lens could be protected from salt water and prevented from becoming brackish. However, the part of the freshwater lens that would be protected is not sufficient to meet the water needs of the design. Nonetheless, it gives a perspective on the protection of the status quo and the effort this would take.

The water storage in the status quo is the fresh groundwater basin and the treated freshwater basin. The production of electricity is not included in the scope of this alternative. Electricity production is done elsewhere on the island and is transported to the water treatment location, with grid power.

Impact of the scenario on the alternative Based on the scenarios devised in Chapter 4, the impact of the scenarios on the alternative will be given in this section. Scenarios are devised as an impact on the normal system. The alternative includes disaster control measures, which make the system more resilient to the effects of the scenario. The impact on the system by the disaster depends on the severity of the disaster, in this case, a tropical storm or hurricane. Damages can't be completely prevented, especially in the case of hurricanes. In both cases, the system will be contaminated and partially collapsed. The impact will be different in the scenarios. In the case of this alternative, the reliability of the levee is key to the success of this alternative.

Disaster Tropical storm condition The condition of the infrastructure after a Tropical storm is presumed to be as follows: 5 levees (in need of inspection), Wells (no impact), Rain infiltration system (in need of cleaning), Original chlorination water treatment plant (no impact), Freshwater storage (contaminated), Piping (contaminated), Building(no impact) and Grid power (disconnected).

The maintenance components of Alternative 3 are Levees (in need of inspection), Rain infiltration system(in need of cleaning), and freshwater pump(contaminated)

A comprehensive and meticulous inspection of the system needs to take place after a disaster impact. The possibility of contamination is high. Build back better ask a question about systems bending (repairs needed before resuming usages) or breaking (in need of replacement). Most parts of the system did not break as a consequence of the hurricane but were bent by only being contaminated. The biggest impact of the tropical storm is the disconnection of the grid power.

Disaster Hurricane condition The condition of the infrastructure after a hurricane is presumed to be as follows:

5 levees (in need of repair), Wells (in need of repair), Rain infiltration system (in need of cleaning and repair), Original chlorination water treatment plant(contaminated), Freshwater storage (collapsed), Piping (contaminated), Building (mild damage), and Grid power (disconnected).

The maintenance components of Alternative 3 are Levees (in need of repair), Rain infiltration system(in need of cleaning and repair), and freshwater pump(contaminated)

This alternative prevents flooding, which the other alternatives do not. Most parts can be reused, but are contaminated. The parts that are likely contaminated are; fresh tanks, and pipes as they are outside the concrete building. During the hurricane, a lot of rainwater has fallen which will replenish the freshwater bubble. The hurricane also impacts the rain infiltration system, which needs to be cleaned and repaired. Due to the function of the infiltration system, the cleaning does not need to be done immediately, but to ensure proper handling of runoff in the future event needs to be done as soon as possible.

The prevention of flooding also impacts the whole area that is protected by the levee. Only aspects that are relevant to drinking water production will be inside the scope. Alternative 3 is also beneficial for economic and social value retention due to saving infrastructure and lives, but these aspects will fall outside of the scope. However, this alternative would not be considered if it did not have any other functions next to protecting freshwater.

6

Results

The results section presents and describes the analytical output and findings from the study. In the appendix, the performance and the score of the three Alternatives are worked out. The performance and the scoring are done with an MCA. The interaction of the concepts “Build Back Better”, “Disaster Cycle”, and “Sustainability” and how they could influence water management infrastructure design is the focus of this thesis and the MCA is used to explore this.

The Alternatives are rated for each course of action in terms of how it satisfies each criterion, using background information, and consultation. This however can not result in a detailed quantitative score. This means that the way the MCA is presented can be used as an exploratory method to determine the need for further detailed research.

The three Alternatives are evaluated on their performance in the context of Scenarios. The main weather scenarios are normal conditions, a tropical storm, and a hurricane. The two disaster conditions scenarios, a tropical storm, and a hurricane, have sub-scenarios based on the disaster cycle, Mitigation & Preparedness, Preparation, Response, and Recovery. The alternative is divided into water management aspects: Infrastructure, Maintenance & Operation, and End-of-Life. In each cell of the matrix, the alternatives are primarily scored on sustainability, which will be based on the PPP pillars (People, Profit, Planet).

Alternative 1 uses Reverse Osmosis (RO) with grid power using salt water as a water source with a disaster measure in the form of a backup generator. Alternative 2 is Reverse Osmosis (RO) with solar power using brackish water as a water source with the disaster measure being a transported waterbag used after the disaster. Alternative 3 is based on a design made during the workshop van der Hucht et al. [2021]. The mean solution was based on collective protection by building a levee using the natural landscape. This levee would protect the densely populated area from storm surge flooding, making it easier to bounce back with the economic center of the island intact. A side effect of the levee is that it also protects the current water supply from salination. In the Alternative 3 case, the disaster measure secures the possibility of the original water supply systems.

Previously, PPP, BBB, the disaster cycle, and the background of the case study were presented. These concepts, tools, and methodologies have been used to construct the scenarios, aspects, and criteria to give a first impression on the possible choice of a water system. This allows the elimination of the less viable alternatives. The viable alternatives can then be examined in more detail. Given below is the table which is the conclusion of the performance and the scores of the three Alternatives in the Appendix A, B, and C.

The interpretation of the results of the alternatives will be given in Chapter 7. Examining the role of the concepts of “Build Back Better”, “Disaster Cycle”, and “Sustainability” in water management and the possibility of the interactions between these concepts when designing water management infrastructure. Especially in cases where the disaster cycle is relatively short: 10 to 15 years between disasters. The results of the interactions are between the concepts, tools, and methodologies and can be used for further research to explore new approaches and solutions in water management.

An initial summary of the results is provided in table form below, with greater detail provided later in the discussion section as well as Appendices A, B, and C.

Water management criteria	Infrastructure		Maintenance		End of life	
Scenario	Tropical storm	Dorian hurricane	Tropical storm	Dorian hurricane	Tropical storm	Dorian hurricane
Disaster criteria						
Normal circumstances	+		- -		+ +	
M & P phase	-	-	+	+	0	0
Preparation phase	+	+	-	-	0	0
Response phase	0	0	0	-	0	0
Recovery phase	0	-	+	-	0	0

Table 6.1: MCA scores for Alternative 1

Water management criteria	Infrastructure		Maintenance		End of life	
Scenario	Tropical storm	Dorian hurricane	Tropical storm	Dorian hurricane	Tropical storm	Dorian hurricane
Disaster criteria						
Normal circumstances	0		-		0	
M & P phase	-	-	+	+	0	0
Preparation phase	-	-	-	-	0	0
Response phase	0	0	0	-	0	0
Recovery phase	-	-	0	-	0	0

Table 6.2: MCA scores for Alternative 2

Water management criteria	Infrastructure		Maintenance		End of life	
Scenario	Tropical storm	Dorian hurricane	Tropical storm	Dorian hurricane	Tropical storm	Dorian hurricane
Disaster criteria						
Normal circumstances	0		0		0	
M & P phase	-	-	-	-	0	0
Preparation phase	0	0	+	+	0	0
Response phase	0	+ +	0	-	0	0
Recovery phase	0	0	0	0	0	0

Table 6.3: MCA scores for Alternative 3

Scenario Aspects		Normal	Tropical storm				Hurricane			
			M & P	Prep	Resp	Recov	M & P	Prep	Resp	Recov
	PPP									
Infra	People	++	-	0	0	0	-	0	0	-
	Profit	0	0	+	0	0	0	+	0	0
	Planet	-	0	0	0	0	0	0	0	0
M & O	People	-	+	-	0	0	+	-	0	0
	Profit	- -	0	0	0	+	0	0	-	0
	Planet	-	0	0	0	0	0	0	0	-
EoL	People	x	x	x	x	x	x	x	x	x
	Profit	+	0	0	0	0	0	0	0	0
	Planet	-	0	0	0	0	0	0	0	0

Table 6.4: MCA scores for Infrastructure Alternative 1

Scenario Aspects		Normal	Tropical storm				Hurricane			
			M & P	Prep	Resp	Recov	M & P	Prep	Resp	Recov
	PPP									
Infra	People	++	-	-	0	0	-	-	0	0
	Profit	-	0	0	0	-	0	0	0	-
	Planet	-	0	0	0	0	0	0	0	0
M & O	People	-	++	-	0	0	++	-	0	0
	Profit	-	-	0	0	+	-	0	-	0
	Planet	+	0	0	0	-	0	0	0	-
EoL	People	x	x	x	x	x	x	x	x	x
	Profit	0	0	0	0	0	0	0	0	0
	Planet	0	0	0	0	0	0	0	0	0

Table 6.5: MCA scores for Infrastructure Alternative 2

Scenario Aspects		Normal	Tropical storm				Hurricane			
			M & P	Prep	Resp	Recov	M & P	Prep	Resp	Recov
	PPP									
Infra	People	0	-	0	0	0	-	0	+	0
	Profit	- -	- -	0	0	0	- -	0	++	0
	Planet	++	++	0	0	0	++	0	0	0
M & O	People	0	-	+	0	0	-	+	0	0
	Profit	0	+	+	0	0	+	0	-	0
	Planet	0	-	0	0	0	-	0	0	0
EoL	People	x	x	x	x	x	x	x	x	x
	Profit	0	0	0	0	0	0	0	0	0
	Planet	0	0	0	0	0	0	0	0	0

Table 6.6: MCA scores for Infrastructure Alternative 3

7

Discussion

The examination of possible interactions between the concepts of "Build Back Better", "Disaster Cycle", and "Sustainability" is the main product. The MCA of the alternatives is a byproduct of this thesis. The focus of this chapter will be to analyze the outcomes of the Multi-Criteria Analyses (MCA) and how the interactions are shown in the MCA model's outcome.

The following process has been undertaken, which concluded in the results. There was a simple design made for alternatives that accommodated the need for fresh drinking water availability on the island of the case study. Then the thesis explored the disaster cycle and combined it with the perspective of the water-management. The exploration of both the standpoint of water management and the concept of the disaster cycle resulted in the creation of water management aspects and disaster-management sub-scenarios. These aspects and sub-scenarios were put into a Multi-Criteria Analysis. The MCA was used to compare the interaction and performances of three alternatives with the current situation (Alternative 0). This Alternative 0 can not perform sufficiently according to the water needs of the island, due to saltwater intrusion, as discussed in Subsection 5.1.1. The conclusion of the MCA makes it possible to explore the impact of the inclusion of disaster criteria on a design decision for water-management systems/questions.

As a preparation for the discussion, recall that there were some limitations to the study. A specific case study is used, which has clear boundaries. It is not an attempt to define a universal criteria/methodology. Therefore clear conclusions about its universality or validity cannot be drawn, which highlights the need for further research.

Alternative 1 and Alternative 2 were purposely made similar in their design. This sets the stage for using these alternatives to carefully gauge the small differences that show up in the results. They score differently in Normal Circumstances, compared to each other and to the basis which is set by the Alternative 0. These results mirror the approach that a typical water design would employ through Multi-Criteria Analysis (MCA), without the disaster criteria. When looking at the results of the disaster criteria the unique aspects emerge.

Alternative 3 was based on the design of the workshop [van der Hucht et al., 2021]. This design was more focused on securing the safety of the residents than on the drinking water supply. The resulting solution was to build a levee. The side effect of this levee is that it secures parts of the fresh groundwater. This Levee makes it unlikely for saltwater to infiltrate, due to storm-surge flooding. It was assumed that enough fresh groundwater would be secured to answer the needs of the case study. Normally the production of the wells that are still outside the protected area should be replaced by other methods, it is assumed that the levee protects all fresh groundwater.

The focus of the thesis is on analyzing the interactions and possibilities of "Build Back Better", "Disaster Cycle", and "Sustainability" on alternatives and understanding the connection between them. The following are unique findings that emerged from the process of this thesis.

7.1. Criteria relevant to the different phases of the disaster cycle

The sub-research question asked about criteria, but it seemed not possible to integrate criteria specifically into the different phases of the disaster cycle. The different phases of the disaster cycle are time-dependent and it was easier to implement them as sub-scenarios. Next to the weather scenarios, these sub-scenarios could be used for a timeline or time story within the extreme weather scenarios. With this solution, the RenewIslands methodology could still be used in the modeling of scenarios. In "the mapping of the needs" in the RenewIslands methodology, the specific needs requirement and needs per disaster phase were added. Due to the scope of the thesis, it was not possible to go into detail on this point, but it illustrates the possibility of meeting the needs of the case study per phase.

To add the disaster elements in the design the disaster measure was added, coming from disaster management. The Disaster measure of Alternative 1 was the backup generator providing power after grid power became unavailable. The Disaster measure of Alternative 2 was a water supply in the form of a waterbag, which provided a water buffer between disaster and normal production of drinking water. The Disaster measure of Alternative 3 is the levee. The choice of a disaster measure had a significant influence on the score of Alternative 2. Disaster measure was first secondary for the design, but in the results, the relevance of the choice of measure was significant in the results. Most differences in the disaster sub-scenarios are with the WM-aspects infrastructure in the Preparation phase. The criterion people in Infrastructure focus on the general population, the end-users. Both Alternatives have the increased importance of self-reliability regarding personal water gathering during this phase. The centralized system of Alternative 1 can run longer and is more reliable. This stability makes Alternative 1 score higher in the criteria people for Infrastructure in the Preparation phase. Alternative 2 can not provide clean drinking water as long as Alternative 1, due to the needed storage of Solar panels during the preparation phase. This is also the reason why the Recovery after Tropical Storm Alternative 2 gives a lesser score. Some damage is assumed to the solar panels.

7.2. Criteria relevant specifically to sustainability

All three pillar criteria are based on the "sustainability" concept. Meaning that all results have a connection to this concept. The ratings of the criteria can be better used during further discussion.

End-of-Life The most strained connection seems to be with End-of-Life. The End-of-Life differences in the disaster phases between Alternative 1 and Alternative 2 are non-existent. The scale of time of 30 years and the minimal exploration of the scenarios make no difference in the score. More detailed EoL scenarios might give a more specific score, but that is out of the scope of the Thesis.

Maintenance In Maintenance the differences between Alternative 1 and 2 in the disaster criteria are minimal. The scored maintenance components and the perspective of the operators are similar compared to Alternative 0 in both alternatives.

In the Recovery, there is a difference in the tropical storm scenario. The value-neutral is assigned to all criteria grouped under People in both Alternatives. The estimated work for the operators in the Recovery phase and the precise difference compared to Alternative 0 is negligible. This thesis can not estimate the precise difference in work, the timescale difference is weeks and days and will fall within the 10-month maximum recovery time. This makes the People in Recovery for both Alternative 1 and Alternative 2 Neutral. The profit of maintenance in the recovery is also similar for the alternatives between the scenarios. The difference in Recovery comes from the criteria Planet. Studies show that the impact on solar panels is not dependent on the severity of the storm, but more on the angle at which the intense wind is blowing. Meaning that even though a tropical storm is a less intense storm than a hurricane, the angle of wind can have the same effect. The possibility of an unfortunate wind direction is a heavy aspect in the Recovery of the Maintenance.

7.3. Criteria relevant specifically to Build Back Better

The parts of the BBB concepts that were implemented are the needs of the stakeholders set by Build Back Better and the cyclical nature of disasters.

Needs of the stakeholder The needs of the stakeholders were set in Section and Subsection 3.2, 3.5, 3.4.1, 3.4.2 and, 3.4.3. The criteria set by the three sustainability pillars assess the compatibility of the alternative with the people and environment. The Water management aspects divided the water treatment system in a way that was easier to asses on different points. The three Water management aspects have different timelines. Infrastructure has an economic and social impact at the beginning of construction, which is a linear storyline. Maintenance & Operation is a combination of multiple repeating smaller cycles. Some cycles got broken by the disaster and the impact is shown in the profit of the response under Maintenance & Operation. When zoomed in on these broken cycles it becomes possible to choose a less impact-full alternative fitting the scenarios of the location. Water management aspects End-of-life can be a cycle or linear. This model had difficulty scoring EoL, due to the larger timescale of EoL.

The last step of the MCA can be seen as weak due to it being normal for various stakeholders to compare the scores. In this thesis, there are no multiple stakeholders or a weight set per criteria. The scores and weight are based on the literature and personal experience of the author. The implemented of the needs of the stakeholders can be done better in follow-up studies.

Cyclical nature of disaster As read earlier in this section the cycles were added earlier in different parts. The cyclical nature of disasters specifically comes forward in the use of the Disaster cycle, as seen in Section 3.3. The integration of disaster management with disaster measures in the design is an example of criteria relevant specifically to the "Build Back Better" concept. Examples of criteria relevant specifically to the "Build Back Better" concept can be identified within the case study. However, some of them seem to be obscured. An example of this seems the comparison between alternatives 1 and 2. The Disaster measure of Alternative 2 gives a high score in the recovery phase, canceling out the consequence of the destruction the solar panels endured during the Response phase. The profit loss, of the solar panels is compensated by a positive in the criteria people, which is provided by the disaster measure.

The demands of the “disaster cycle” and the guidelines of “Build Back Better” forced to design with the stages in the lifetime in mind. The separation of all the components of the design and the influence of each phase on these fulfilled the general desire for “sustainability”. These interactions were scored with PPP pillars. It gives through the performance of the MCA model an interaction that can be discussed.

The best-performing Alternative between 1 & 2 is still dependent on the normal circumstances, and the needs of the day-to-day. However, integration by adding disaster measures and the usage of scenarios will give a better overview of the decision-making process of which disaster measures can be added to the alternative. The scope of the thesis is relevant to the performance of Alternative 3. If the levee is already built, meaning that it has no impact on this alternative, then the profit is neutral or positive. Only the positive qualities of the levee are then taken into the Alternative. The positive qualities are faster recovery of the system surrounding the water supply and decreased impact on the Ecosystem (planet). Negative qualities like high repairing, maintenance, or building costs are then not relevant for Alternative 3. The scope of the levee can also be expanded to the saved assets now outside the scope of the thesis.

With the impact of the disaster sub-scenarios on alternatives visible due to the MCA it can be seen how the disaster cycle paves the way for new approaches and solutions in water management. The concluding table in Chapter 6 with the disaster sub-scenarios and Water management aspect can be used for further research to explore new approaches and solutions in water management, maybe even a universal usable theory or model.

7.4. Conclusion

The research question was; Do the concepts “Build Back Better”, “Disaster Cycle”, and “Sustainability” influence water management infrastructure design, particularly in cases where the period between disasters is relatively short?

The parts of the BBB concepts that were tried to be implemented are the needs of the stakeholders set by Build Back Better and the cyclical nature of disasters. As stated in Section 7.3 the implementation of the cyclical nature of disasters is numeral and interesting. Some cycles of the water treatment system were broken by the disaster and the impact is shown in the scores of the MCA. The results of the MCA make it possible to choose a less impact-full alternative fitting the scenarios of the location.

The interaction between the concepts of “build back better”, the “disaster cycle”, and “sustainability” show that Alternative 1 scores better due to a more centralized design compared to Alternative 0. Alternative 2 scored worse due to the concepts of “build back better”, and the “disaster cycle”, which show that Solar panels can be a weakening link, but scored better due to its Disaster measure of the water bag, which gives the design the "bend" it needs to be sustainable. Alternative 3 scores better due to the interaction with “build back better”, and the “disaster cycle”. The comparison of Alternative 3 with Alternative 0 gives mostly neutral scores, due to Alternative 3 maintaining the status quo. The other alternatives have more negative results. Therefore Alternative 3 scores better, but not positive.

It is logical to continue on the path of having the concepts “Build Back Better”, “Disaster Cycle”, and “Sustainability” interact with water management infrastructure design, particularly in cases where the period between disasters is relatively short. The concepts “Build Back Better” and “Disaster Cycle” assist with setting up a more realistic scenario within the extreme weather conditions. If used in scenarios-based design this interaction will give a better overview of the requirements and needs before, after, and during a disaster. It gives a better view of the possibilities of mitigation and preparedness being combined with external systems. In this thesis the scope is small, but this way of thinking could be expanded upon to include a whole island and not just the drinking water system. Solutions for alternatives can be made everywhere in the world, but the implementation in a specific location should still be tested on compatibility. “Build Back Better”, and “Sustainability” help with asses the compatibility.

8

Recommendation

After carefully analyzing the available data, I would like to make a recommendation regarding the current study. While the findings are promising and shed light on certain aspects of creating enough sustainable drinking water in Grand Bahama regarding periodic disasters, additional research is needed on several key points to strengthen the validity and generalizability of the results.

Additional research would not only provide a more comprehensive understanding of the topic but also ensure that any conclusions drawn are based on robust evidence.

Upon reviewing the methodology employed in this study, I could not help but think that I would have approached it differently.

8.1. Foresight of sustainability

One of the notable strengths of this study lies in the possibility of "quickly" determining sustainability, thereby simplifying the intricacies associated with this concept. Future exploration of sustainability should be prioritized to address the intricacy of the topic. With the escalating threats posed by climate change, resource depletion, and ecological degradation, it is necessary to engage in comprehensive research aimed at understanding and mitigating these challenges.

Expending the complexity of the design and criteria For the criteria People, only residents, and operators were used in this research. It is recommended to add other "people" and stakeholders to give a better insight into the acceptance of a technology. There are critiques on the origin and applicability of Hofstede cultural dimensions theory [Fang, 2003],[Signorini et al., 2009]. For water management, it would be nice if people's sustainability could be set on a quantitative scale, without these critiques, but this is a topic for other disciplines.

For the criteria Profit, cost of operation, and the eventual cost of the per liter water production were used. The thesis compared the additional cost of the scenarios for all Alternatives 0, 1, 2, and 3. Inevitable sustainability will cost in the first instance more funding than Alternative 0. Nevertheless, it is necessary to explore this line, because of the future extra cost. The island water management authorities should reform with sustainable drinking water measures. In the long run, this is cheaper than maintaining the situation described in Alternative 0. However, this future insight is out of the scope of the thesis concerning profit and needs further research. Only the manageable consequences are measured. In this thesis with Profit, I only took the consequences of obvious costs into account, which were based on estimations and comparison, and not on hard figures. Further and deeper analysis of the exact cost is recommended for the promising Alternatives [Blanco et al., 2009], [Friesema, 1979], [Gordon et al., 1995].

For the criterion Planet, the usage of the resources was set central. Cascading effects and long-term consequences have not been measured. Just like the criterion Profit only the manageable consequences were measured. It is inevitable that especially for an island like the Grand Bahama sustainability is very important. Further studies on water management on this island should take sustainability as a major research point.

Adding additional flows The focal point of the thesis revolved around drinking water treatment. To broaden the scope, additional flows can be incorporated into the Alternatives. This is already possible with the usage of RenewIslands methodology. The first flow I would recommend adding is a wastewater flow. Nowadays, sustainability has become a core issue of wastewater management [Massoud et al., 2009]. As highlighted by Andersson et al. [2016], few areas of investment possess as much potential to contribute to the global shift toward sustainable development as sanitation and wastewater management. The role of wastewater management in a sustainable society is to act as an instrument to minimize environmental burdens, preserve human health, and create business opportunities. Actually, the importance of wastewater for sustainability involves not only the traditional function of pollutant emission reduction but also the development of resource recovery practices [Coelho et al., 2018].

8.2. Using another evaluation model

This thesis used the MCA. There is a multitude of possibilities of other models which might give another perspective on the explored subject.

One of the models was SMART (Sustainable Management of Scarce Resources in the Coastal Zone) and OPTIMA (Optimization for Sustainable Water Resources Management) projects funded respectively by the 5th and 6th Framework Programmes of the European Union [Harmancioglu et al., 2012]. These might be of interest for further exploration. The overall aim of OPTIMA is to develop, implement, test, critically evaluate, and exploit an innovative, scientifically rigorous yet practical approach to water resources management intended to increase efficiencies and reconcile conflicting demands. Based on the European Water Framework Directive (2000/60/EC) the approach equally considers economic efficiency, environmental compatibility, and social equity as the pillars of sustainable development [Yilmaz and Harmancioglu, 2010].

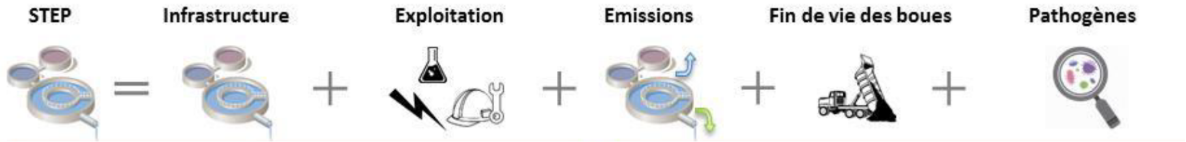


Figure 8.1: Original picture of the overview of the scope of the ACV4E Tool

The main recommendation for the usage of another model would be to use a Life cycle assessment (LCA) because this thesis is based on the LCA the WM aspects, which would make it easier to explore this further in this model.

Life cycle assessment (LCA) Life cycle assessment (LCA) is a tool already widely used worldwide in analyzing water management systems because it allows a project's negative and positive impacts to be quantified by a scientific methodology. Indeed, LCA has been proven to be a suitable instrument to assess the environmental effects of WTP in both the design and operation phases [Zang et al., 2015]. LCA provides a better understanding of the environmental impacts generated by water treatment systems, and minimizes adverse effects contributing to environmental protection [Limphitakphong et al., 2016], [Coelho et al., 2018], [Barjoveanu et al., 2014], [Hernández-Padilla et al., 2017]. A complete LCA might fit this subject better, especially with the added negative lifespan of the categories due to disaster[Heijungs et al., 2010].

Add emmision back In the LCA which was the basis of the WM-criteria the emission was a separate category. This was excluded from this research because there was no emission next to concentrated water, which was put under the Maintenance & Operations criteria. If other Water Treatment Alternatives are added, that use UV, nuclear energy, or other dangerous chemicals, adding the category back might be smart.

The long-lasting effect of these items could not be put under normal operations and would be needed to be assessed separately.

8.3. Scenarios

As stated before there are only two disaster conditions flowing in a cycle of normal conditions followed by disaster in this thesis. In later research, it might be possible to expand on the two scenarios. When expanding please think about time series scenarios that include both natural and socio-economic events (e.g., floods, droughts; economic crisis), trends (e.g., climate change; changing public perception of safety or nature), interactions between the water system and society (e.g., social flood impacts; flood mitigation measures) [Haasnoot et al., 2009] and economic factors (e.g., population decline and growth, industrial water needs).

Scenarios can be expanded upon in future research. Recent scenario studies on water management were mainly 'what-if' assessments in one or two future situations. The future is, however, more complex and dynamic. It involves general trends and unexpected events in the water and social systems [Haasnoot et al., 2009]. Scenarios can be uncertain due to natural, social, and technological factors [Haasnoot et al., 2009].

I would recommend a workshop that will give a better idea of possible scenarios for a case study. All possible aspects of a scenario can be represented as parameters, qualitative or quantitative. A scenario is thus described by a set of parameters and their hypothetical values. The guidelines for a workshop regarding an application of scenarios can be as follows[Borell and Eriksson, 2013]:

1. Choose aspects of reality considered probable to be important in future instances of crisis management. (often prepared before the workshop)
2. Describe some relevant aspects of reality in a scenario, using the parameter to model
3. Discuss and alter the parameter representation, which possibly establishes shared mental models
4. Provide the opportunity for the individual stakeholders to express feedback

The specific possible scenarios I would recommend exploring are the following paragraphs

Tourism For this thesis, we assumed a constant amount of tourism and that they would all leave during a disaster event. The overall growth prospects for the Bahamian economy depend most on the tourism industry, at least in the short run. The World Tourism Organization has forecast tourism, over the next ten years, to increase by more than 40%. To continue the country's stronghold on the tourism industry, economic planning must include the protection and management of the natural and cultural resources of the country, including the water resources [Roebuck and Ortiz, 2004]. Fluctuation in scenarios for this factor could be of interest in further studies. Compared to the inhabitants, the amount of tourism and their water consumption is significant. It can be interesting to explore the requirements and criteria coming from this difference in the amount of people and their consumption.

Sea level rise Sea level rise is a disaster that has not been taken into the scenarios of this thesis. Sea level rise which could affect the capacity of freshwater aquifers and the quality of groundwater in the future, and temperature increase which could increase evaporation and evapotranspiration (both predicted effects of global warming from greenhouse gas emissions); [Roebuck and Ortiz, 2004].

Population Just like tourism Population is taken more constant than it is now in the scenarios. Especially with the population moving out with an increased threat level by disasters. People only want to live somewhere where they can feel it is livable. Disasters cause a 1% per year decline in population, due to deaths or immigration, because houses are made unlivable. There is an influx of people from other islands, which seek the more stable bigger islands for better facilities [Klessens et al., 2022]. These population flows can be of interest to further studies.

End-of-Life Scenarios When it came to unraveling the intricate web of EoL, there was little to say in this study. Other studies, it has been shown that assumptions on EoL modeling can be of great importance for the life cycle impact of construction materials (Ardente et al. 2008). So there are strong reasons to improve the modeling of EoL processes in LCAs of construction materials. This can contribute to more robust decision-making in the construction sector, for example, in the development of new construction materials and policies [Sandin et al., 2014].

In this thesis there have been simple assumptions made where there were no larger nontoxic components at the end of the life cycle of the system, one last cycle of maintenance components, and all the infrastructure components. This is a simplification of EoL and could be expanded upon.

8.4. Validity and reliability

It is essential to recognize both the strengths and weaknesses of this study. The case study is on an island, which has clear boundaries. These boundaries make it easy to dismiss certain aspects, which will not be the case in most situations. However, these boundaries weren't always set clear. In the case of the levee in Alternative 3, the building and the maintenance of the levee are included in the assessment, but not the other benefits a levee as the disaster measure could have. Where exactly the boundaries were set influenced the conclusions made in this thesis.

Furthermore, this research started as part of an interdisciplinary project and became a mono-disciplinary project. The BBB states that disaster management should be an interdisciplinary approach and this thesis focuses only on the water management perspective. Further, the data are from 2019 due to Corona's restrictions. The decisions were made by the researcher which normally would be done by stakeholders.

Using the framework of this researcher, backed by available research and data, but still having this one perspective the thesis could cause simplification, by reducing complex concepts. I have used the available material, but it might not be enough to give the full picture.

8.5. The different phases of the disaster cycle

If the focus of the follow-up studies would be more on the economic or sociology route it might be smart to disconnect the Mitigation & Preparedness phase. This was combined in this study due to the way a water treatment plant interacts with these factors, which is similar to normal circumstances.

8.6. Missing beneficial information

If I could choose the pieces of information available for this study, I would have liked to have the exact amount of the flows available for Alternative 0. I estimated the well extraction, the production of drinking water, and the daily usage of Grand Bahama. If these details are available, there could be more realistic assumptions made in Subsection 3.4.3. With these realistic assumptions, the production per Disaster Cycle phase could be checked and a requirement can be made for the minimum production per phase. With these requirements per phase, the capability of the alternative can be checked. This brings me to another piece of information I would have liked, the exact production possibility of a Reverse Osmosis and Water chlorination plant under disaster conditions, applicable in Chapter 5. For this study, this is less relevant, due to the incomplete information mentioned before. However, in further studies, the production of the alternative under distress can be crucial to assess the impact of the cyclical nature of a disaster. I have now assumed that a drinking water plant can now function at half capacity, but details of the performance are essential for further studies. For instance, it might be possible to do full production with flooding on the location, because of the higher elevation of the equipment and the correct preparation. On the other hand, the plant could be fully out of commission if the intake pump is completely damaged. I don't know how a hurricane or tropical storm could impact water production, but I would like to know this information for further studies.

8.7. Conclusion

The findings of the current study are promising and shed light on certain aspects of creating enough sustainable drinking water in Grand Bahama regarding periodic disasters, additional research is needed on several key points to strengthen the validity and generalizability of the results.

For the criterion People, only residents, and operators were used in this research. it is recommended to add other people and stakeholders to give a better insight in the acceptance of a technology. In this thesis with Profit, only the consequences of obvious costs were taken into account, which were based on estimations and comparison, and not on hard figures. Further and deeper analysis of the exact cost is recommended for the promising Alternatives. For the criterion Planet focuses on Cascading effects and long-term environmental impact are recommended as a major research point.

Other flows, like the use of wastewater, could be added to the Alternatives. A recommendation for the usage of another model would be to use a Life cycle assessment (LCA).

If the Alternatives and the needs of the case study are worked out in more detail, it is possible to see per phase if the alternatives will meet the requirements of the case study. Because of the details per phase, the interaction between Build Back Better and the Alternatives is clearer. In this way, the expectations and requirements of BBB can be met easier. The result of the combination of other more detailed needs per phase and the capacity for production by the alternative will give insight into all requirements, restrictions, and needs.

The concepts “Build Back Better”, “Disaster Cycle”, and “Sustainability” can influence water management infrastructure design, particularly in cases where the period between disasters is relatively short because they help to frame the disaster usable for a design. However, exploration of this thesis is not sufficient to be able to implement the results generalized. It is recommended to explore general implementation.

A

Performance Alternative 1

In this chapter, the performance of Alternative 1 will be worked out. This is the first of 3 Alternatives dealing with three Scenarios; Normal conditions, a Tropical Storm, and a Hurricane. There are three water management aspects assessed; Infrastructure, Maintenance & Operation, and End-of-Life. These assessments are crossed with five disaster sub scenarios; Normal Circumstances, Mitigation & Preparedness, Preparation, Response, and Recovery. The categories are scored on sustainability, which will be based on PPP pillars (People, Profit, Planet).

Alternative 1 is Reverse Osmosis (RO) with grid power using salt water as a water source. The alternative is similar to any other Reverse Osmosis-based water treatment. There are some differences because of the need to deal with hazards from a hurricane. One of the differences is the adaptation to prevent flooding. All the equipment should be on a higher elevation to prevent flood damage. The height of the flood-safe placement of all the infrastructure should be measured from the mean sea level to ensure the placement above the expected storm surge level. Pluvial flooding is also possible, meaning that precipitation causes the flooding instead. Pluvial flooding is less severe than storm surges but needs to be considered. During Dorian, there was 400mm of rain on Grand Bahama between 31 August and 5 September 2019. If an RO plant is safe from a storm surge but not from pluvial flooding, then extreme precipitation that falls in the surrounding area may still cause damage. Water likes to follow the path of least resistance. Flood models made during the workshop showed some places that were safe locations during a storm surge but were still subject to severe flooding from rainwater with depths of up to 5 meters. The pluvial flooding happened because rainwater from the surrounding area gathered at the site due to its geographical location. Another risk associated with a hurricane is wind damage. The wind mainly affects the building that surrounds the RO installation. Minimal use of windows and a robust wind resistance design of the building are therefore essential. There is less force behind air than water, but wind speed is higher. This means that the debris thrown against the building is the most severe concern regarding wind damage. The building in which the RO is situated should be made hurricane-proof. After a hurricane, it is assumed that the initial energy production will be done by diesel generators.

A.1. Infrastructure

The infrastructure is the hardware of the system of the alternative. For Alternative 1, the main infrastructure components are an Intake pump (Saltwater), Pre-filtration, Reverse Osmosis, Energy recovery, Post-treatment, Freshwater storage, Saltwater storage, Piping, (Remote) monitoring and control, Building and Grid power, as stated in Subsection 5.1.2

A.1.1. Normal circumstances

In normal circumstances, the water treatment plant functions as any other reverse osmosis-based water treatment. The difference is that all the equipment is placed at a height that is assumed to be flood-proof, and the building is designed to withstand hurricane conditions. There is a location for the backup generator.

The overall score of Alternative 1 Normal circumstances infrastructure is Adequate (+2+0-1)=1. This is based on the following partial scores.

People The emphasis will be on the general public when it comes to scoring the category of people for infrastructure. Technicians and operators are more relevant in the maintenance and operation and will be scored there. As observed by this researcher, the citizens of Grand Bahama are very knowledgeable about the need for change in the drinking water system. The RO is a technology used on the surrounding island, with which Grand Bahamas citizens have a close relationship. RO aligns with the political need for short-term gratification because it can be built in a year [Water dept, 2021]. Cost is a big part of the acceptance of technology, this is included in the profit criterion, seen below. RO is a costly and technology-heavy water treatment method. RO could be accepted as a general water treatment technology by the people. Tourist yachts[REVERSE OSMOSIS, International Division, 1991], more remote residents on the island, and families of residence on other islands have already used personal RO machines, private and commercial for years. Compared to Alternative 0 which pumps up water from the disappearing fresh groundwater followed by only a chlorination treatment, this alternative will produce safer and more sustainable water. RO fits with political short-term gratification, better than Alternative 0, because it promises something new. The criterion People for Infrastructure in Normal circumstances is Good(++).

Profit For the criterion Profit for infrastructure in normal circumstances, the cost is compared to Alternative 0 of Grand Bahama in 2019. Electricity usage falls under maintenance, due to it being part of the operation costs in normal circumstances. This is the same for the cost of membranes, which also falls under Maintenance and operation. Due to these exclusions for infrastructure, there is no extreme deviation in the cost of the main infrastructure components when compared to the in Alternative 0 described drinking water treatment systems. The criterion for Profit for infrastructure in Normal circumstances is Neutral(0).

Planet The building of this alternative uses resources. Some natural resources, in the form of land, and building material resources are used. None of the existing infrastructure components can be used in this alternative. Most are general building materials, which needed to be imported from the mainland. The resource itself does not have a specific Environmental effect. The ecological impact due to the construction is taking space away from the original environment with buildings and other infrastructure. This space is not more significant than the in Alternative 0 described drinking water systems, only slightly bigger than the existing infrastructure, due to added generators. The conclusion is that there is an increase in impact due to import and a slight increase in ecological impact, compared to Alternative 0. The criterion Planet for infrastructure in Normal circumstances is Inadequate (-).

A.1.2. Mitigation & Preparedness

Mitigation refers to the structural and non-structural changes that limit the impact of disasters. Preparedness is a state of readiness, a continuous cycle of planning, organizing, training, equipping, exercising, evaluating, and taking corrective action [FEMA Federal Emergency Management Agency, 2022]. Mitigation & Preparedness for Alternative 1 is the upkeep and placement of locations and facilities that prevent damage by a storm and the spreading of knowledge needed for this.

The Alternative will have more building costs and needs more planning than a non-disaster-proof RO-plant would have. The changes only serve to limit the impact of disasters. The long-term structural changes can be built together with the average components of the building and facilities of the whole structure which need to be completed between two hurricane seasons. If this is not possible, overlap between phases will occur. This means that the Infrastructure needs to be constructed within 10 months. All infrastructure components are needed for the alternative to function.

The overall score of Alternative 1 Mitigation & Preparedness infrastructure is Inadequate -1+0+0=-1 This is based on the following partial scores.

People In this phase, the people's relationship to the Mitigation and Preparedness components is scored, compared to Alternative 0. In Alternative, there is no mitigation measure, only Preparedness regarding the drinking water system. In this phase of the Alternative, there is something difficult to accept: power generators have to be available in a safe storage area along with fuel for the next phases, which in this phase should not be used or tampered with. If resources or equipment are not in daily use, people tend to move them or use them without replacing them. Equipment that is not in daily use needs to be checked before it is needed for a disaster, to ensure it is still operational. With the tendency to individualism, the low uncertainty avoidance index, and the draw of "better" usage of the equipment while waiting for the disaster, it can not be sure that the equipment will be available in the next stage of Preparation [PDC, Pacific Disaster Center, 2022]. The state of readiness includes informing the stakeholders to be able to plan, organize and train. So social aspects are less applicable, but not irrelevant. The collectivism and the Uncertainty Avoidance index cancel each other out and make it neutral, due to it being similar to Alternative 0. To conclude the combination of Preparedness, the technical knowledge needed and the readiness to learn, and the desire to touch the Mitigation infrastructure. The criterion People for infrastructure in Mitigation & Preparedness is Inadequate(-).

Profit For Profit in this phase, the extra costs due to hurricane-proofing are scored. Extra costs will be made, due to hurricane precaution measures, compared to a non-hurricane-stricken RO. The results of these precautions are helping to reduce damage and impact in the next phases. The significant impact during the construction is due to normal construction, the additional costs due to hurricane prevention are minimal. Compared to Alternative 0 there are no significant extra costs. The criterion Profit for infrastructure in Mitigation & Preparedness is Neutral(0).

Planet For the planet the most impact during this phase in the construction is more due to normal construction and import of these materials, the added impact due to hurricane prevention is minimal. With the minimal size increase the same ship transport could be used. Compared to Alternative 0 there is no significant increase or decrease in impact. The criterion Planet for infrastructure in Mitigation & Preparedness is Neutral(0).

A.1.3. Preparation

As stated before, the preparation phase only has at most 48 hours to complete its goals. For this alternative, in these hours a water buffer can be created using the freshwater storage tank. This fresh drinking water can be used during the recovery phase if the storage tank is not contaminated during the disaster event/recovery phase. For this Alternative, it is recommended to always have a water buffer available in normal circumstances. This means that the filling up of the freshwater aquifer is an ongoing precaution during the previous phases. However, filling it completely during this phase prevents damage during a storm. Increased water weight lessens the impact of wind damage, due to components not blowing away. See also Figure A.1 for an example of wind damage. Furthermore, an increase in water pressure reduces the possibility of contamination. To complete the precautions for the disaster skilled manpower is needed. In order to prevent hurricane damage, it is necessary to secure the RO facility. An example of securing can be by setting up hurricane-proof windows. The backup generators need to be checked and assessed for functionality. The backup generators ensure the availability of electricity in the phases after the hurricane. All these activities need manpower. The availability of manpower is crucial.

The overall score of Alternative 1 Preparation infrastructure is Adequate 0+1+0=1 This is based on the following partial scores.

People For the criterion of people of infrastructure, the focus will be on the general population. According to the alternative, the population should focus on personal preparation in this phase. As stated in Subsection 2.3.2, FEMA and NEMA recommend storage of drinking water for at least three weeks. This means two liters or more per person per day in the household to store in clean containers. The infrastructure stays active to provide drinking water for these people till the moment of the shutdown of the system. The Uncertainty Avoidance and Power Distance index of Grand Bahama makes it uncertain that all inhabitants take this precaution. This problem is similar to the one in Alternative 0, Hurricane Dorian and other disasters have shown it is not a reliable assumption. The situation has changed compared to Alternative 0. Meaning that the importance of this need for self-reliability regarding water during a disaster has increased. The criterion People for infrastructure in Preparation is Neutral(0) relative to Alternative 0.

Profit In this phase, the wells of Alternative 0 are being locked up and the distribution of freshwater is halted. RO is a more central system meaning lockdown can occur more immediately than a system where the wells are distributed all over the island. There is no increase in cost due to the lockdown compared to Alternative 0. Longer production and distribution of water could be possible compared to Alternative 0. It can be assumed that this is better for the end users due to the reliability and certainty of the RO operation. The criterion Profit for infrastructure in Preparation is Adequate (+).

Planet For the planet, there is no increase in resources used compared to Alternative 0. Meaning there are no natural resources or material resources used, in Alternative 0 or Alternative 1. The criterion Planet for infrastructure in Preparation is Neutral (0).

Figure A.1: The Power of Hurricane Force Winds. The penetration of a palmtree in Saipan,CNMI.

A.1.4. Response

The Response phase is a reaction to a disaster or emergency. It is assumed that the water treatment plant will not be operating during the disaster. During the previous phase, the Preparation phase, the facilitates are prepared for the disaster. It is assumed there will be no human or other external change made to the facilities except directly by the storm. Search and rescue activities are not within the scope of the alternative.

The overall score of Alternative 1 Response Infrastructure Scenario 1 is neutral 0+0+0=0. The overall score of Alternative 1 Response Infrastructure Scenario 2 is neutral 0+0+0=0. First, the expected effects of the two Scenarios are given, and then the overall derived scores above are given in the paragraph People, Profit, and

Planet.

Scenario 1 Tropical storm The tropical storm is the second point of the three-point approach(3PA) with a 2-year return period. The second point is initiated by designing a facility that protects against a storm event in predictive conditions. Meaning that the facility should be able to handle a scenario described by the second point of 3PA and will break when the condition becomes worse.

The expected damage to the system after a tornado or a brush with a hurricane is similar and has maximum sustained winds of 63 to 117 km/h. Everything left outside the hurricane-proof building should be assumed to have been moved, lost, or slightly damaged. There will be damage to the connecting infrastructure, external piping, and electricity. With this design, no flooding is assumed at the location. A system is more vulnerable to pathogens when flooded. Still, pathogens might have infiltrated the system. Pipes need to be cleaned before usage in the next phase, but no future restoration might be needed. The typical process for clearing water systems of contaminants is a chlorination process similar to what you would do with a swimming pool. Chlorine sits in the system for about 24 hours. This seems to work well with current contaminants, but bacteria or chemicals from industrial facilities might be the source of an unknown threat [Schembri, 2018]. The system bend and did not break.

Scenario 2 Hurricane The Hurricane Dorian scenario is the third point of the three-point approach (3PA) with a 15-year return period. Point three of the 3PA represents a situation where the protection level is exceeded by applying a lower occurrence rate event: The system fails. The importance of minimizing damage to a failing system and maximizing its ability to cope and recover is emphasized by point three of 3PA.

The damage to the system after a hurricane is expected to be significant. Everything left outside the hurricane-proof building should be assumed to have been moved, lost, or damaged. There will be damage to the building despite the hurricane-proofing. The water storage tanks might be unusable in the immediate future. Also, there will be significant damage to the external infrastructure, which will need weeks to repair. With this design, no flooding is assumed at the location. A system is more vulnerable to pathogens when flooded. Still, pathogens might have infiltrated the system. The pipes that remain need to be cleaned before use. The typical process for clearing water systems of contaminants is a chlorination process similar to what you would do with a swimming pool. Chlorine stays in the system for about 24 hours. This seems to work well with current contaminants, but bacteria or chemicals from industrial facilities might cause an unknown threat [Schembri, 2018]. Restoration or replacement of the pipes that are lost might be needed.

People For people, there is no direct interaction between the population and the water treatment plan in this phase. During the preparation phase, the population is asked to fill clean water containers with drinking water. Also to prevent the impact in case of losing the water supply to the residence it is recommended to fill up the sinks and bathtubs with water for washing [CDC, Centers for Disease Control and Prevention, 2019], usable for the household. The population is asked to stay inside for the duration of the storm, which can be a few hours to a few days. There is limited interaction with the water treatment during this phase and similar action compared to Alternative 0. The criterion People for infrastructure in Response is Neutral(0).

Profit The water system decreases in value due to damage to the system.

After a tropical storm, as described in Subsection 5.1.2, the condition of the infrastructure is presumed to be as follows; Pre-filtration (no impact), Reverse osmosis (no impact), Energy recovery (no impact), Post-treatment(no impact), Freshwater storage (possible contaminated), Saltwater storage (possible contaminated), Piping (possible contaminated), Remote monitoring and control (no impact), Building (no impact) and grid power (disconnected). Contamination is possible during scenario 1. Most of the system did not “break” but did “bend” by only being possibly contaminated. The biggest impact of the tropical storm is the grid power disconnection. Compared to Alternative 0 this is a similar loss in infrastructure for Scenario 1. The criterion Profit for infrastructure in Response in Scenario 1 is Neutral(0).

After a hurricane, as described in Subsection 5.1.2, the condition of the infrastructure is presumed to be as follows; Pre-filtration (contaminated), Reverse osmosis (contaminated), Energy Recovery (contaminated), Post-treatment (contaminated), Freshwater storage (collapsed), Saltwater storage (collapsed), Piping (contaminated) (Remote) monitoring and control(disrupted), Building (mild damage), grid power (disconnected). All filters need to be replaced or cleaned. It is more likely to replace the filters given the limited resources available on the island. Most parts can be reused, but are contaminated. The parts of the system that are contaminated are; fresh and saltwater tanks, pipes, and filters. The water storages are the most likely to be impacted by the disaster as they are outside the concrete building. Compared to Alternative 0 this is a similar loss in infrastructure as in Scenario 2. The criterion Profit for infrastructure in Response in Scenario 2 is Neutral(0).

Planet For the planet, within the scope of the case study, there are no resources used. Meaning there are no natural resources or material resources used, by Alternative 0 or Alternative 1. This is the same for both Scenarios 1&2. The criteria Planet for infrastructure in Response is neutral(0).

A.1.5. Recovery

For the Recovery phase of this alternative, the biggest issue is the need for grid power. The difference in impact depends on the intensity of the disaster. The specifics of the intensity of the disaster are elaborated on in the paragraphs below. After the disaster, the operation of the RO needs to be started as quickly as possible. Recovery has 3 stages of temporary water production. The functionality of these stages is depending on the available infrastructure. To determine which stage is applicable assessment and cleaning of the system is crucial.

In Stage 1 the goal is to start producing water as quickly as possible. To be able to produce water with RO the facilities themselves need to be operational. These RO facilities are the infrastructure components mentioned earlier. To be able to produce on-site electricity diesel generators and fuel need to be available after the disaster. In Stage 1, the water can not yet be distributed or produced. Locals are dependent on their personal storage of drinking water. The first stage is the repairing stage and the residents are dependent on their own water storage.

In Stage 2 production of drinking water with RO starts with on-site electricity production, the generators. This water will go no further than the reservoir and will not yet be distributed over the island. Water will be produced with RO with on-site electricity production. In the second stage connecting the water treatment plant to the grid network and the water network is vital to get it back to normalcy.

In Stage 3 production of drinking water starts with RO into the reservoir and distribution over the island with power from the electricity network. Stage 3 is the full normal stage and is no difference compared to the normal situation.

During all these stages it might be possible to have the water treatment plant operate at half capacity. The reason to do this might be contamination, damaged material, lack of electricity, lack of pressure, etc. The RO has parallel watertracks and it could be possible to produce on a lower capacity. Crucial infrastructural components need to be still operational. Components also still would need to be cleaned before use.

The overall score of Alternative 1 Recovery infrastructure Scenario 1 is Neutral 0+0+0=0. The overall score of Alternative 1 Recovery infrastructure Scenario 2 is Inadequate -1+0+0=-1. First, the expected effects of the two Scenarios are given, and then the overall derived scores above are given in the paragraph People, Profit, and Planet.

Scenario 1 Tropical Storm A contaminated water supply is to be expected in the case of a tropical storm [Incorporated, 2018]. Contamination of the water distribution network and disconnection from the grid power is to be expected. However, contamination in the drinking water treatment plant will be minimal, due to the low impact a tropical storm has on a hurricane-proof building. Meaning that Stage 2 is in effect immediately. To the user, in Scenario 1 the fact there is no direct distribution of water is the most inconvenient. The whole infrastructure between the user and the water treatment plant needs to be checked for contamination.

Scenario 2 Hurricane A hurricane does a lot of damage, more than a tropical storm. Hurricanes are known to topple water towers, ravage homes and let toilets spew raw sewerage. A compromised water supply is to be expected in the case of such a strong storm and creates a lingering crisis for drinking water supplies. The biggest difference between tropical storms and hurricanes is the possibility of industrial contamination of the drinking-water supply chain [Incorporated, 2018].

After Hurricane Dorian, Grand Bahama's Freeport city, relief actors report near-normal functioning of ports, restaurants, road traffic, and shops, and NEMA reports that some public schools and several government departments, including the Department of Labor and Road Traffic Department, have resumed or plan to resume operations in Grand Bahama after 20 days. The Grand Bahama Power Company had restored power to nearly 50 percent of its customer base after 15 days according to media, and technical teams continue to work to fully restore power across the island.

All phases are relevant and must be completed. For this thesis, Stage 2 the fixing of the contamination and connection of the drinking water supply chain is out of the scope. The water source for the alternative is seawater. The water can not be distributed by the existing pipes, due to possible industrial contamination down the distribution line. More tests need to be done to safely asses the water resource to begin Stage 1. Additional tests are required to start Stage 2 to ensure safe distribution by a pipe system.

People In Alternative 0, Stage 1 of the Recovery is similar to Alternative 1. Both alternatives assume that residents have their own water available. This water is collected by the residents in earlier phases. The difference between Alternative 0 and Alternative 1 is that people in Alternative 1 can not rely on personal wells anymore. Which just like the wells in the Alternative 0 will contain undrinkable due to salt. In Alternative 1 it is important that individuals are responsible for their own water in Stage 1 of the recovery. This results in a difference in scores for Scenarios 1 and 2. In Scenario 1 the importance of the successful previous phase is less crucial. In Scenario 2 it is important that individuals have a water buffer available, but also more likely that even if they had a water buffer they lost it during the disaster. This also has been seen as inadequate in Alternative 0

The criterion People for infrastructure in Recovery in Scenario 1 is Neutral (0). The criterion People for infrastructure in Recovery in Scenario 2 is Inadequate (-1).

Profit The significant cost made, meaning the recovery of the grid and water distribution network, is out of the scope of this MCA. No infrastructure components are assumed to be in need of replacement, only maintenance components, and the membranes. Membranes will be assessed in maintenance. Compared to Alternative 0 there is no increase or decrease in profit. The criterion Profit for infrastructure in Recovery is Neutral(0).

Planet For the planet, there are no resources used. Meaning there are no natural resources or material resources used, by Alternative 0 or Alternative 1. Compared to Alternative 0 there is no increase or decrease in planet. The criterion Planet for infrastructure in Recovery is Neutral(0).

A.2. Maintenance & Operation

As stated in the previous Section 5.1, the term maintenance includes replacement and care for operational purposes in normal circumstances as part of the evaluation of the alternatives. "Maintenance" groups impacts related to replacement parts and periodic repairs and also includes emissions of greenhouse gas and discharge of polluting material.

Maintenance for Alternative 1 is more frequently required due to saltwater usage, compared to the current freshwater source. Saltwater corrodes pipe systems more than freshwater and brackish water. The maintenance during this period of operation highlighted the following items as needing intervention and in most cases complete replacement. The maintenance components are the following;

Seawater pump The lifetime of the seawater pump will be 6 years.

Multi-media filters For this study, an average operation of 3 years per pump is assumed, based on the lifetime usage of activated carbon.

Cartridge filters The core of the cartridge filter will be changed regularly every 3 months.

Membrane The membrane's economic lifetime is assumed to be 5 years.

A.2.1. Normal circumstances

In normal circumstances, the water treatment plant functions as any other reverse osmosis-based water treatment. The difference is that all the equipment is placed at a height that is assumed to be flood-proof, and the building is designed to withstand hurricane conditions. There is a storage that has a backup generator . During normal operation, there are no emissions of greenhouse gas. With the current grid power plant, gasses like carbon dioxide are produced during electricity production. The production of grid power is out of scope in the Normal circumstance.

In normal circumstances, there is a discharge of concentrated salt water. When a RO is operated not all water goes through the system to become clean freshwater. Some water remains, which contains everything that was in the original water. This means everything that was "bad" is now concentrated in the water that is discharged.

The overall score of Alternative 1 Normal circumstances Maintenance is Bad -1-2-1=-4 This is based on the following partial scores.

People For people in the maintenance technician and operators are the stakeholders that are highlighted here. RO is a more technology-heavy Water treatment system than the in Alternative 0 described system. It might be difficult to always have staff available on the island with the right skills to operate the water treatment plant at the right times. Grand Bahama does better economically than most of the other islands in the Bahamas, but still, has difficulty retaining skilled labor. Compared to Alternative 0, which is less technology-heavy, it might be more difficult to find the people to properly operate and maintain the water system. The criterion for People for Maintenance & Operation in Normal circumstances is Inadequate(-).

Profit The maintenance components of Alternative 1 are a Seawater pump, Multi-media filters, Cartridge filters, and a Membrane. This is an increase in maintenance components compared to Alternative 0. The RO is costly compared to other drinking water treatment methods, especially if the source is seawater. RO needs pressure to function, which consumes energy. Electricity consumption is part of the operation. In Alternative 0, energy is used to pump up water from the ground aquifer, this energy consumption of transporting water from the source is similar to Alternative 1. Compared to Alternative 0 the cost per freshwater liter will increase due to added energy usage for the high-pressure process of RO. The criterion Profit for Maintenance & Operation in Normal circumstances is Bad (–).

Planet For the planet, the water source that is used is seawater in Alternative 1. Seawater can be assumed to be an endless resource. An endless resource means that it can not be depleted and can be increased without risk to the environment. Usage of an endless resource means that the island's water resources are not impacted. The impact on the planet of this Alternative 1 is mainly with the usage of the grid power, which is diesel fuel powered. The electricity needs to be generated on the island due to the minimal possibility of shipping or transporting electricity to Grand Bahama. Grand Bahama has long used electricity, generated from imported oil. There have been initiatives like biofuel production to curb the usage of imported diesel [The Bahamas investor, 2015]. This was, however, not widely implemented on the island as of 2019. In the future, it might be possible for grid power to be generated by alternative green energy. For this study, it is assumed that the grid power is fueled by diesel. An increase in the usage of this dirty electricity could increase the impact on the environment. As stated before, the production of this electricity is out of the scope of this thesis. Alternative 0 also uses grid power to operate the pumps of the wells. The energy consumption of Alternative 0 is lower than that of Alternative 1 but is similar in the energy source. The discharge of concentrated seawater is impacting the environment through high local salt concentrations and higher concentrations of any other pollutants that were in the seawater before in lower concentrations. The discharge of concentrated water makes Alternative 1 less friendly to the environment than Alternative 0 is. The criterion Planet for Maintenance & Operation in Normal circumstances is Inadequate(-).

A.2.2. Mitigation & Preparedness

Mitigation refers to the structural and non-structural changes that limit the impact of disasters. Preparedness is a state of readiness, a continuous cycle of planning, organizing, training, equipping, exercising, evaluating, and taking corrective action [FEMA Federal Emergency Management Agency, 2022]. Mitigation & Preparedness for Alternative 1 is the upkeep and placement of locations and facilities that prevent damage by a storm and the spreading of knowledge needed for this. The upkeep of the Mitigation & Preparedness is part of the Maintenance & Operation. Most of the mitigation aspects are scored in the WM aspect infrastructure. Maintenance & Operation focuses on keeping the infrastructure in a state which is needed for the next phases. Mitigation & Preparedness also focus on that people have the knowledge, the required material, and resources to prepare for a disaster. The overall score of Alternative 1 Mitigation & Preparedness maintenance is adequate 1+0+0=1. This is based on the following partial scores.

People For the people aspect of maintenance technicians and operators are the stakeholders that are highlighted here. RO is a more technology-heavy Water treatment system than Alternative 0. The state of readiness is informing the stakeholders to be able to plan, organize and train. The compatibility of the planning, organizing, and training with the stakeholders is more difficult for Alternative 1 than in Alternative 0. Alternative 0 has been in use for years and it is also a less technology-heavy system compared to Alternative 1. Just like in normal circumstances it might be difficult to find skilled labor to implement the measures needed to make Alternative 1 successful. Short-Term gratification also reduces the willingness to focus on maintenance. However, the writer of this thesis sees possibilities to improve the compatibility of operators with Mitigation & Preparedness measures. But It needs to be packaged in a way with is compatible with the political climate. During her stay in the Bahamas, the writer of this research came across the term red ribbon cutter. The term was used often and means that politicians like projects in which they can cut a red ribbon and pose for a picture. The workshop which this researcher took part in was on national news. If it might be possible to present maintenance like an event worthy of a "red ribbon", then it increases the compatibility of this Alternative with the operators. The operators become more willing to do the maintenance needed for Mitigation & Preparedness with this added incentive. For instance, the bi-annual workshop, needed for preparedness, could be presented like a monument day in the Netherlands[Nederland Monumentenland, openmonumentendag, 2023]. This workshop could make it more like an event and less like a meeting. It could be televised and important figures could pose in front of the visually impressive RO equipment, but the center should be the distribution of information and showing the readiness of the equipment. If maintenance of the Mitigation & Preparedness can be made a national news event Alternative 1 is slightly better than Alternative 0 in handling Mitigation & Preparedness. The criterion People for Maintenance & Operation in Mitigation & Preparedness is Adequate (+).

Profit The maintenance components are a Seawater pump (6 years), Multi-media filters (3 years), Cartridge filters (3 months), and a Membrane (5 years). Hurricanes with comparable rain intensity like Dorian are expected to occur once every 15 years and Grand Bahama interacts with a tropical storm every two years. The probable duration of 15 years between the extreme hurricane can be nicely divided by the Multi-media filters (3 years), Cartridge filters (3 months), and a Membrane (5 years).

The seawater pump has a lifespan of 6 years. Theoretically, the third pump will only be used for 3 years if the lifetime of three pumps is put consequently. Meaning you lose half the lifespan of 1 in 3 pumps per hurricane cycle. A tropical storm frequency of 2 years is incompatible with the lifespan of most maintenance components, but the intensity and impact of a tropical storm ensure minimal damage to those maintenance components. The lifespan of a seawater pump or a Multi-media filter or a Membrane is longer than the mean interval between tropical storms. However, a tropical storm does not impact these maintenance components, due to them being underwater or inside a hurricane-proof structure.

Because there is only a loss of half of the lifespan of the third pump per hurricane cycle, this makes it comparable to Alternative 0 which also deals with pumps of the wells in a similar manner. The criterion Profit for Maintenance & Operation in Mitigation & Preparedness is Neutral (0).

Planet For the planet, there are no resources used specifically for the use of mitigation or Preparedness for Maintenance & Operation. Meaning there are no natural resources used or material resources used, by Alternative 0 or Alternative 1. Compared to Alternative 0 there is no increase or decrease in planet. The criterion Planet for Maintenance & Operation in Mitigation & Preparedness is Neutral(0).

A.2.3. Preparation

As stated before, the Preparation phase only has a maximum of 48 hours to meet its goals. The goal of Maintenance & Operation in the Preparation phase is to ensure that planned precautions and actions are taken in this small window of time. The water system should be shut down and disconnected from external water and pollution sources. Before this shutdown, the water buffer should be created using the freshwater storage tank and according to the normal operating procedure. This fresh drinking water can be used during the next phase of recovery if the storage tank is not contaminated during the disaster event/recovery phase.

To complete the precautions for the disaster skilled manpower is needed. In order to prevent hurricane damage, it is necessary to secure the RO facility. An example of securing can be by setting up hurricane-proof windows. The backup generators need to be checked and assessed for functionality.The backup generators ensure the availability of electricity in the phases after the hurricane. All these activities need manpower. The availability of manpower is crucial. The maintenance components of Alternative 1 are a Seawater pump, Multi-media filters, Cartridge filters, and a Membrane.

The overall score of Alternative 1 Preparation maintenance is Inadequate -1+0+0=-1. This is based on the following partial scores.

People For people in the maintenance technician and operators are the stakeholders that are highlighted here. In the Preparation phase, there is the factor of manpower. This means that multiple people need to put the needs of the collective, securing the water treatment plant above their individual needs of looking up their private residence or moving to another island.

Despite the fact that it falls within their job responsibilities, there is a personal sacrifice involved. With the stated Individualism vs. Collectivism of Grand Bahama, it is plausible that such a task might not be carried out. This is comparable to Alternative 0, where the willingness of putting job responsibilities above individual and private affairs in a crisis situation. For Alternative 1 it is more crucial that goals of the securing the water treatment plant are met, due to the central location, compared to the scattered location of the wells in Alternative 0. There is no fallback on an external second parallel system. Due to the increase in risk, Alternative 1 is slightly worse compared to Alternative 0.

The criterion People for Maintenance & Operation in Preparation is Inadequate (-).

Profit There is no increase in cost due to the lockdown compared to Alternative 0. Next to some additional manpower, there are no costs made or gained compared to Alternative 0. The criterion Profit for Maintenance & Operation in Preparation is Neutral (0).

Planet For the planet, there is no increase in resource utilization compared to Alternative 0. This implies that neither natural resources nor material resources are being consumed in either Alternative 0 or Alternative 1. The criterion Planet for Maintenance & Operation in Preparation is Neutral(0).

A.2.4. Response

The Response phase is a reaction to a disaster or emergency. It is assumed that the water treatment plant will not be operating during the disaster. During the previous phase, the Preparation phase, the facilitates are prepared for the disaster. It is assumed there will be no human or other external change made to the facilities except directly by the hurricane. Search and rescue activities are not within the scope of the alternative.

The overall score of Alternative 1 Response Maintenance & Operation Scenario 1 is Neutral 0+0+0=0. The overall score of Alternative 1 Response Maintenance & Operation Scenario 2 is Inadequate 0-1+0=-1. This is based on the following partial scores.

People In this phase, the search and rescue is assumed to be out of scope. There have been stories shared during the workshop of operators trying to prevent further damage when the 3-day hurricane Dorian hit the island, but again this is out of the scope of this thesis. For people, there is no direct planned interaction between the operators and the water treatment plan in this phase, similar to Alternative 0. The criterion People for Maintenance & Operation in Response is Neutral (0).

Profit The water system decreases in value due to damage to the system components. In this criterion, only maintenance components will be scored. The infrastructure components are scored under infrastructure.

After a tropical storm, as described in Subsection 5.1.2, the condition of the maintenance components is presumed to be as follows; Seawater pumps (maintenance needed), Multi-media filter (contaminated), and Membrane (contaminated, backwash needed). The possibility of contamination is there, but due to the placement of the filter and membrane in the case of a tropical storm, it is minimal. Compared to Alternative 0 this is a similar loss as in the case of Scenario 1. The criterion Profit for Maintenance & Operation in Response in Scenario 1 is Neutral(0).

After a hurricane, as described in Subsection 5.1.2, the condition of the maintenance components is presumed to be as follows; Seawater pumps (shorting of lifespan), Multi-media filter (contaminated), and Membrane (contaminated). All filters need to be replaced or cleaned. It is more likely to replace the filters given the limited resources available on the island. Most parts can be reused, but are contaminated, this does not include the membrane. Which are costly aspects of maintenance. Compared to Alternative 0 this is a bigger loss in the case of Scenario 2. The criterion Profit for Maintenance & Operation in Response in Scenario 2 is Inadequate(-).

Planet For the planet, within the scope of the case study, there are no resources used. Meaning there are no natural resources and material resources used, by Alternative 0 or Alternative 1. This is the same for both Scenarios 1&2. The criterion Planet for Maintenance & Operation in Response is Neutral(0).

A.2.5. Recovery

For the recovery phase of this alternative, the biggest issue is the need for grid power. The difference in impact depends on the intensity of the disaster. The specifics of the intensity of the disaster are elaborated on in the paragraphs below. After the disaster, the operation of the RO needs to be started as quickly as possible. It has 3 stages of temporary water production. The functionality of these stages is depending on the available infrastructure. To determine which stage is applicable assessment and cleaning of the system is crucial.

In Stage 1 the goal is to start producing water as quickly as possible. To be able to produce water with RO the facilities themselves need to be operational. These RO facilities are the infrastructure components mentioned earlier. To be able to produce on-site electricity diesel generators and fuel need to be available after the disaster. In Stage 1, the water can not yet be distributed or produced. Locals are dependent on their personal storage of drinking water. The first stage is the repairing stage.

In Stage 2 production of drinking water with RO starts with on-site electricity production, the generators. This water will go no further than the reservoir and will not yet be distributed over the island. In the second stage connecting the water treatment plant to the water distribution is vital to get it back to normalcy.

In Stage 3 production of drinking water starts with RO into the reservoir and distribution over the island with power from the electricity network. Stage 3 is the full normal stage and has no difference compared to the normal situation.

During all these stages it might be possible to have the water treatment plant operate at half capacity. The reason to do this might be contamination, damaged material, lack of electricity, lack of pressure, etc. The RO has parallel watertracks and it could be possible to produce on a lower capacity. Crucial infrastructural components need to be still operational. Components also still would need to be cleaned.

The overall score of Alternative 1 recovery Maintenance & Operation Scenario 1 is Adequate 0+1-0=1. The overall score of Alternative 1 recovery Maintenance & Operation Scenario 2 is Inadequate 0+0-1=-1.

This is based on the following partial scores.

People For the operators, this phase is a very busy time. The impact of the storms and hurricane needs to be fixed, replaced, or cleaned. The precise difference in work cannot be estimated by this thesis, but on the scale on which the phases are viewed, it is comparable and the difference is negligible. Therefore for the operators, the scoring is similar to Alternative 0 in both Scenarios.

The criterion People for Maintenance & Operation in Recovery is Neutral (0).

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Profit During this phase, operators need to work hard to detect and fix problems in the system, similar to Alternative 0. This is easier, due to the central placement of Alternative 1 compared to Alternative 0. This positive aspect is hindered if replacement components need to be shipped, which takes more time. Due to the quicker possible start-up because of the centralization the criterion Profit for Maintenance & Operation in Recovery in Scenario 1 is Adequate (+). In the case of Scenario 2 replacement of the membrane is assumed, which adds time and cost, compared to Alternative 0, but is still a centralized system. The criterion Profit for Maintenance & Operation in Recovery in Scenario 2 is Neutral(0).

Planet For the planet, in the case of Scenario 1, there are no resources used, similar to Alternative 0. Meaning there are no natural resources or material resources used. For Scenario 2 there are material resources used, and membranes need to be shipped from the mainland, which is on increased use of resources compared to Alternative 0. The criterion Planet for Maintenance & Operation in Recovery in Scenario 1 is Neutral (0). The criterion Planet for Maintenance & Operation in Recovery in Scenario 2 is Inadequate (-1).

A.3. End-of-Life

The term End-of-Life (EoL) is used here to refer to the end of the lifespan of a system or one of its components.

The WM criteria grouped under "End-of-Life" include reuse, redistribution, recycling, and the environmental effects of demolition. For long-lived products, like a water system, the impact of EoL processes such as demolition and disposal will occur in the distant future. For construction materials, EoL processes are often estimated to occur within 50 to 100 years[Frijia et al., 2012], [Sandin et al., 2014]. A non-disaster-stricken Water treatment system has a lifespan of 50-year. These longer time frames cause technological uncertainty, meaning new technology could be developed for disposal and the type of substituted technology can change. Straight-line depreciation times of 100 years do exist in financial accounting for long-lived assets. The use of straight-line depreciation is difficult to justify if a disaster can rapidly decrease the value of the system to zero. A hurricane disrupts the process of depreciation, meaning that straight-line depreciation is impractical. The nature of EoL processes is highly uncertain, even without disasters. This time-dependent uncertainty has previously been acknowledged as a challenge for life cycle assessments (LCA) in the construction industry [Singh et al., 2011], [Verbeeck and Hens, 2007], [Sandin et al., 2014]. EoL particularly focuses on uncertainties regarding the means of disposal, the expected technology development of disposal processes, and the type of substituted technology. Despite its significance, the element of uncertainty is frequently overlooked in the LCA of constructions and construction materials. This oversight persists even when the objective is to inform decisions regarding long-lasting constructions [Bribián et al., 2011], [Habert et al., 2012], [Lundie et al., 2004], [Persson et al., 2006], [Sandin et al., 2014]. Until now, there has been insufficient consideration of EoL uncertainties of long-lived products, which may hamper sound decision-making for sustainable development [Sandin et al., 2014].

A scenario can be used to cope with this uncertainty surrounding EoL. Setting up scenarios to account for different possible futures of EoL has been done before [Bouhaya et al., 2009]. When modeling future disposal processes several fundamentally different scenarios are needed according to [Mathiesen et al., 2009]. The construction of a complete model of EoL is out of the scope of this thesis. [Sandin et al., 2014] recommend cornerstone scenarios to capture the range of possible outcomes of temporally more dynamic impact assessments. These Cornerstone scenarios are similar to the scenarios suggested by the Three-Point Approach used in the thesis. Combining the need for EoL scenarios with the scenarios in this thesis will boil down to Normal circumstances, tropical storms, and hurricanes. The Normal circumstances will assume that the whole 50 years of the water system lifespan will be utilized. Making a comparison of the alternative with Alternative 0 the current situation in the case no disaster will strike in that time frame. In the disaster phases, (Mitigation & Preparedness, Preparation, Recovery, and Response) the degradation in the system value by the disaster will be compared and scored, this will be scenario dependent.

In the case-study regular transportation is equivalent to international shipping. Transportation has a higher impact on an island. Normally transportation and supply-chain processes would be of lower importance when contrasted to demolition [Sandin et al., 2014].

Promoting transportation to have an environmental effect will be a significant element in the EoL. Another element of EoL is the emissions and waste which occur during EoL processes. Waste is an unavoidable by-product of most human activity. The term “waste” refers to any product or substance which is no longer suited for its intended use [Balwan et al., 2022].

For Alternative 1, the End-of-Life (EoL) impact of Reverse Osmosis (RO) is similar to that of maintenance of RO. At the end of the life cycle of a RO system, nearly all components will have been replaced. The only components which in normal circumstances would not be replaced are infrastructure components such as; freshwater storage, saltwater storage, piping, building, and (Remote) monitoring and control. RO generates continuous waste during operation, like concentrated water and replacement infrastructure. RO does not face specific waste management problems at the end of its life cycle.

A.3.1. Normal circumstances

In Normal circumstances, it is expected that the entire 50-year lifespan of the water system will be utilized. Making a comparison of the alternative with Alternative 0 in the case no disaster will strike in that time frame.

For Alternative 1, at the end of the whole life cycle of a RO system, nearly all components will have been replaced. The pump, membranes, and filters will already have been replaced 4 times after 50 years of RO operation. The only components that would not be replaced in Normal circumstances are infrastructure components such as; freshwater storage, saltwater storage, piping, building, and (Remote) monitoring and control. RO generates continuous waste during operation, like concentrated salt water and replacement infrastructure, membrane, and filters. RO does not face specific hazardous waste management problems at the end of its life cycle.

The overall score of Alternative 1 Normal circumstance End of Life is Good x+1+1=2 This is based on the following partial scores.

People For the criterion people there is no score given because it does not apply, see Subsection 3.2.1 for more details.

Profit All infrastructure components are above ground, making fewer demolition costs compared to Alternative 0 multitude of wells which are underground systems. The depreciation period is similar to that of the current situation, though the use of salt water might increase degradation in some parts of the system. The criterion Profit for End-of-Life in Normal circumstances is Adequate (+).

Planet The infrastructure could reuse and recycle to be used in other infrastructure projects on the island, which might be easier than Alternative 0 due to all components being above ground. Alternative 1 is on ground level, which makes demolition's environmental effect less compared to Alternative 0 , which has underground components. The criterion Planet for End-of-Life in Normal circumstances is Adequate(+).

A.3.2. Mitigation & Preparedness

The length of the Mitigation & Preparedness phase is too short for the EoL depreciation time frame in the case of Scenario 1, 2 years. The length of the Mitigation & Preparedness phase in Scenario 2 is just long enough to have some EoL depreciation, it is equivalent to more than a third of the time frame, 15 years. The goal of the Mitigation & Preparedness phase is to anticipate the next phases of the disaster cycle, which consumes material but does not produce waste. The overall score of Alternative 1 Mitigation & Preparedness End-of-Life is for both Scenario 1 and Scenario 2 Neutral x+0+0=0 This is based on the following partial scores.

People For the criterion people there is no score given because it does not apply, see Subsection 3.2.1 for more details.

Profit In the time frame of this disaster phase depreciation occurs, especially in Scenario 2. However, this is similar to the depreciation of Alternative 0 . The criterion Profit for End-of-Life in Mitigation & Preparedness is in both Scenario 1 and Scenario 2 Neutral (0).

Planet No waste is produced during this phase and no future environmental effects of demolition occur. This is comparable to Alternative 0 in this phase. The criterion Planet for End-of-Life in Mitigation & Preparedness is in both Scenario 1 and Scenario 2 Neutral (0).

A.3.3. Preparation

As stated before, the Preparation phase only has a maximum of 48 hours to complete its goals. The length of the Preparation phase is too short for the EoL depreciation time frame. The goal of the Preparation phase is to prepare for the disaster, which consumes material and manpower but doesn't produce waste. The overall score of Alternative 1 Preparation End-of-Life is Neutral x+0+0=0 This is based on the following partial scores.

People For the criterion people there is no score given because it does not apply, see Subsection 3.2.1 for more details.

Profit In this time frame of this disaster phase, no depreciation occurs. This is similar to the depreciation of Alternative 0 . The criterion Profit for End-of-Life in Preparation is Neutral (0).

Planet No waste is produced during this phase and no future environmental effects of demolition occur. This is comparable to Alternative 0 in this phase. The criterion Planet for End-of-Life in Preparation is Neutral (0).

A.3.4. Response

The length of the Response phase is too short for the EoL depreciation time frame, but it is shortened by the disaster. During the Response phase waste is produced, with components that can no longer operate in their original function. Also, rapid degradation takes place due to the disaster event.

The overall score of Alternative 1 Response End-of-Life is Neutral x+0+0=0. This is based on the following partial scores.

People For the criterion people there is no score given because it does not apply, see Subsection 3.2.1 for more details.

Profit In this time frame of this disaster phase, depreciation occurs, due to the disaster and not due to time passing. This is similar to the depreciation of Alternative 0 . The criterion Profit for End-of-Life in Response is Neutral (0).

Planet Waste is produced during this phase and environmental effects of demolition occur. These are however linked to the disaster event and not to the water system. This is comparable to Alternative 0 in this phase. The criterion Planet for End-of-Life in Response is Neutral(0).

A.3.5. Recovery

The goal of the Recovery phase is to bring the affected area back to some degree of normalcy. Recovery involves decisions and actions relative to rebuilding homes, replacing property, resuming employment, restoring businesses, and permanently repairing and rebuilding infrastructure. Recovery activity produces waste to be able to get back to normal.

The overall score of Alternative 1 Recovery End-of-Life is Neutral x+0+0=0. This is based on the following partial scores.

People For the criterion people there is no score given because it does not apply, see Subsection 3.2.1 for more details.

Profit In this time frame of this disaster phase, no depreciation occurs. This is similar to the depreciation of Alternative 0 . The criterion Profit for End-of-Life in Recovery is Neutral (0).

Planet Waste is produced during this phase and environmental effects of demolition occur. These are however linked to the disaster event and not to the water system. This is comparable to Alternative 0 in this phase. The criterion Planet for End-of-Life in Recovery is Neutral (0).

Water management criteria	Infrastructure		Maintenance		End of life	
Scenario	Tropical storm	Dorian hurricane	Tropical storm	Dorian hurricane	Tropical storm	Dorian hurricane
Disaster criteria						
Normal circumstances	+		- -		+ +	
M & P phase	-	-	+	+	0	0
Preparation phase	+	+	-	-	0	0
Response phase	0	0	0	-	0	0
Recovery phase	0	-	+	-	0	0

Table A.1: MCA scores for Alternative 1

A.4. Overview infrastructure

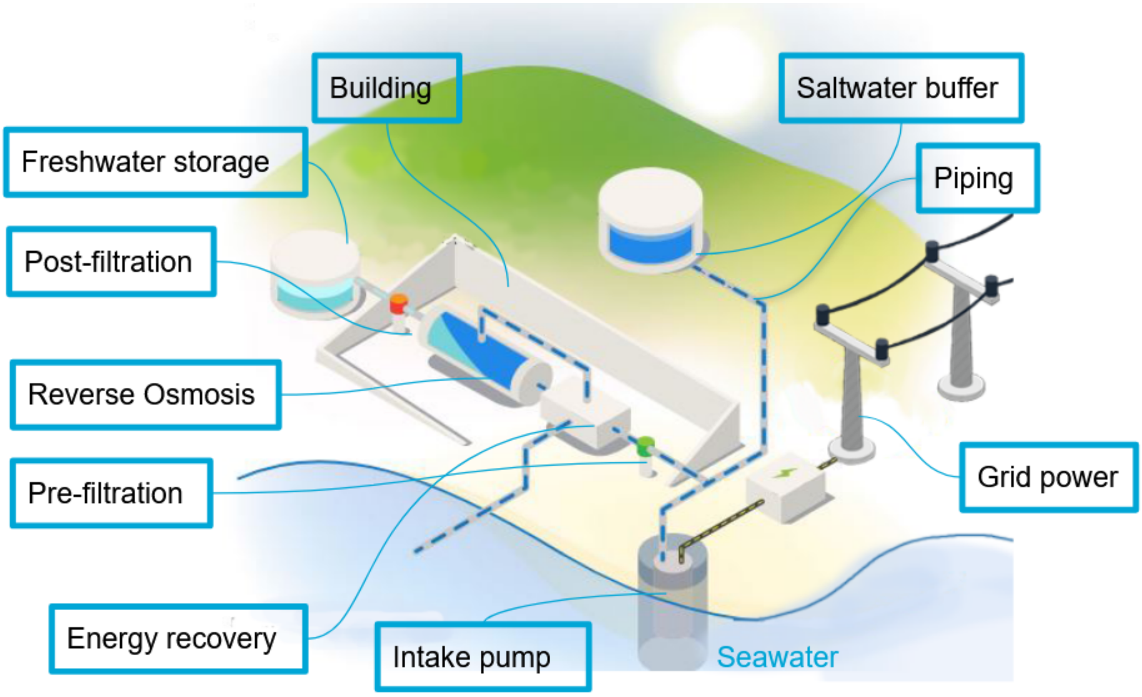


Figure A.2: An overview of design Alternative 1. Infrastructure and flows of grid-powered reverse osmosis drinking water facility with seawater as the source. The freshwater storage at the plant serves as central drinking water storage for the island. This is the normal condition of Alternative 1

Figure A.3: **[Disaster measure]**; Backup Diesel generator. The Backup Diesel generator will provide electricity in the Recovery phase. Depicted is a diesel generator for a water treatment facility in Texas Worldwide Power Products [2023].

(a) **[Intake pump]** is where the water enters the pump intake system. The pressure provided by the pump distributes the water in the system. Most pumps have to be replaced yearly when used for salt water.

(b) **[Pre-filtration]** will prevent larger polluting particles to enter the RO, which is an easily clogged membrane. To avoid frequent membrane replacement, the pre-treatment will be designed for your site-specific situation. This can involve sand filtration, cartridge filtration, and more

(c) **[Reverse osmosis]** is a membrane that rejects solutes and other particles while at the same time having a throughput (flux) of water. The high pressure used for this process is made by pumps which run on electricity.

(d) **[Energy recovery]** enables re-using of the brine pressure. The already high pressure present in the runoff water makes it possible to reuse that same energy again. Energy recovery helps recover some of the energy typically lost from the pumps and membrane system. The primary objective is to recover much of the energy held in the pressurized RO concentrate stream. Before continuing to disposal or treatment, the concentrate is sent through an energy recovery device, and the recovered energy is used to partially power the pumps.Greenlee et al. [2009]

(e) **[Post-treatment]** is possible specific applications that can add fresh water treatment steps to the system, for example, remineralization, UV treatment before end use, or preservation dosing to make it suitable for longer-term storage.

(f) **[Salt water-buffer tank]** & **[Fresh water-buffer tank]** are buffer tanks of concrete, build as a basin to ensure stable pressure in the system. The saltwater tank is elevated to ensure constant pressure. The freshwater tank is a location in which the produced fresh water is stored. This ensures pressure in the system and helps the availability of freshwater for the users.

(g) **[Piping]** is used for long-distance transportation of liquid. Pipe sections should withstand high pressures, and salt water, offer flexibility to be placed in bends, and withstands forces from outside.

(h) **[(Remote) monitoring control]** This included all electronics equipment to maintain the system. The units are equipped with internet-based monitoring for remote control and alarm messaging. This is to check in on the water supply from anywhere

Figure A.4: All components for Alternative 1 reverse osmosis powered on grid energy

B

Performance Alternative 2

In this chapter, the performance of Alternative 2 will be worked out. This is the second of 3 Alternatives dealing with three Scenarios; Normal conditions, a Tropical Storm, and a Hurricane. There are three water management aspects assessed; Infrastructure, Maintenance & Operation, and End-of-Life. These assessments are crossed with five disaster sub scenarios; Normal Circumstances, Mitigation & Preparedness, Preparation, Response, and Recovery. The categories are scored on sustainability, which will be based on PPP pillars (People, Profit, Planet).

Alternative 2 is Reverse Osmosis (RO) with solar power using brackish water as a water source. The Alternative is similar to any other Reverse Osmosis-based water treatment, just like Alternative 1. Compared to Alternative 1 the difference is the energy source and the water source. In these alternatives, there are components added to deal with hazards from a hurricane.

Solar power is only available during the day, making direct production during the night impossible.

During daylight hours, solar energy can be harnessed to pump water into a storage tank at an elevated position above the surrounding landscape. This elevated placement generates the required pressure for water movement through the membranes. By leveraging the height difference water to the reverse osmosis (RO) setup, pressure is sustained throughout the night, allowing production to proceed even during hours of darkness. Batteries help store energy during the day which ten can be used in the night and sunless hours.

There are added measures for the hurricane hazard. All the equipment is placed at a height that is assumed floodproof (storm surge and pluvial) and the building is assumed hurricane-proof, similar to Alternative 1. After a hurricane, it is assumed a water-bag and other shipped water resources will be used during the post-disaster period.

B.1. Infrastructure

The infrastructure is the hardware of the system of the alternative. For Alternative 2, the main infrastructure components are an Intake pump (brackish), Pre-filtration, Reverse osmosis, Energy recovery, Post-treatment, Freshwater storage, Saltwater storage, Piping, (Remote) monitoring and control, Building, Solar panels, Solar frame, Storage space for solar panels and a Battery buffer, as stated in Subsection 5.1.3

B.1.1. Normal circumstances

Under normal circumstances, the water treatment plant functions as any other reverse osmosis-based water treatment with solar power. The difference is that all the equipment is placed at a height that is assumed to be flood-proof, and the building is designed to withstand hurricane conditions. There is a location for the storage of solar panels in case of a hurricane.

The overall score of Alternative 2 normal circumstances infrastructure is Neutral 2-1-1=0 This is based on the following partial scores.

People The emphasis will be on the general public when it comes to scoring the category of people for infrastructure. Technicians and operators are more relevant in the normal circumstances of maintenance and operation. As observed by this researcher, the citizens of Grand Bahama are very knowledgeable about the need for change in the drinking water system, as discussed in Alternative 1. RO aligns with the political need for short-term gratification because it can be built in a year [Water dept, 2021]. The installation of the solar panels can be done in a year as well, but have a buffer of temporary using the grid power during construction. Cost is a big part of the acceptance of technology, more than in Alternative 1, due to the inclusion of power generating inside the scope of this alternative. This assessment of the cost is included in the profit criterion. RO fits with the political short-term gratification and the fact that it is a known water treatment method. Solar panels waterI need to add something of geert. The combination with solar is still new but not unheard of. So even though it is a technology-heavy water treatment method, people could accept it. A significant benefit is the attraction of eco-tourism with solar panels. Solar panels may contribute to a more eco-friendly image of resorts, which can be appealing to tourists. Compared to Alternative 0, in which water from the disappearing fresh groundwater is pumped up followed by only a chlorination treatment, Alternative 2 will produce safer and more sustainable water, with an eco-friendly image. The criterion People for Infrastructure in normal circumstances is Good (++)

Profit For profit, the RO is costly compared to Alternative 0, in which water from the disappearing fresh groundwater is pumped up followed by only a chlorination treatment. Electricity usage falls under maintenance, due to it being part of the operation costs in normal circumstances. Due to electricity being excluded from infrastructure, the only deviation in the cost of the main infrastructure components when compared to the in Alternative 0 described drinking water systems, are the Solar panels, Solar frame, Storage space for solar panels, and Battery. These components increase the cost and give it a lower score than Alternative 1. The criterion Profit for infrastructure in normal circumstances is Inadequate (-).

Planet The building of this alternative uses resources. Some natural resources are used, in the form of land and there are building material resources used. None of the existing infrastructure components can be used in this alternative. Most are general building materials, which needed to be imported from the mainland. The resource itself does not have a specific Environmental effect. The ecological impact due to the construction is taking space away from the original environment with buildings and other infrastructure. This space is not more significant than the in Alternative 0 described drinking water systems, only slightly bigger than the existing infrastructure, due to the solar panel infrastructure. The conclusion is that there is an increase in impact due to import and a slight increase in ecological impact. Compared to Alternative 1 the scoring is similar. The criterion Planet for infrastructure in normal circumstances is Inadequate (-).

B.1.2. Mitigation & Preparedness

Mitigation refers to the structural and non-structural changes that limit the impact of disasters. Preparedness is a state of readiness, a continuous cycle of planning, organizing, training, equipping, exercising, evaluating, and taking corrective action [FEMA Federal Emergency Management Agency, 2022]. Mitigation & Preparedness for Alternative 2 is the upkeep and placement of locations and facilities that prevent damage by a storm and the spreading of knowledge needed for this.

The Alternative will have more building costs and needs more planning than a non-disaster-proof RO-plant would have.

The changes only serve to limit the impact of disasters. The long-term structural changes can be built together with the average components of the building and facilities of the whole structure which need to be completed between two hurricane seasons. If this is not possible, overlap between phases will occur. This means that the Infrastructure needs to be constructed within 10 months. All infrastructure components are needed for the alternative to function. The structural and non-structural changes to limit the impact of disasters for Alternative 2 are the placement and location of the facilities that prevent both flooding from pluvial and storm surges in the case of a tropical storm. There is also the infrastructure for possibly providing a waterbag during the next stages. wateradd info waterbagThese infrastructure components are a financial obligation and a planned agreement with a supplier. For example, the water bag can be stored on another island or be situated in Florida, after the hurricane the cost of the water bag will be paid to the supplier.

The overall score of Alternative 2 Mitigation & Preparedness infrastructure is Inadequate -1+0+0=-1 This is based on the following partial scores.

People In order to achieve a state of preparedness with effective mitigation measures, it is essential to secure the necessary financial commitment and establish a planned agreement with a supplier. If resources or equipment are not in daily use, people tend to move or use them without replacing them. With Grand Bahama citizens there is a tendency to individualism. Citizens have a low uncertainty avoidance index and can think there is a "better" usage of the resources. It is uncertain that the money will be available in the next stage, Preparation. There are steps being taken to avoid misplacement of resources [PDC, Pacific Disaster Center, 2022]. The availability is uncertain, similar to Alternative 1. Compared to Alternative 0, which does not have any mitigation measures which can disappear Alternative 2 is more vulnerable. The criterion People for infrastructure in Mitigation & Preparedness is Inadequate(-).

Profit For profit in this phase, the extra costs due to hurricane-proofing are highlighted. Extra costs will be made, du e to hurricane precaution measures. The results of these precautions are helping to reduce damage and impact in the next phases. The significant impact during the construction is due to normal construction, the additional costs due to hurricane prevention are minimal. Compared to Alternative 0 there are no significant extra costs. The criterion Profit for infrastructure in Mitigation & Preparedness is Neutral(0).

Planet For the planet, the most impact during this phase in the construction is the materials of the normal construction and import of these materials. The added impact due to hurricane prevention is minimal. With the minimal size increase the same ship transport could be used. Compared to Alternative 0 there is no significant increase or decrease in impact. The criterion Planet for infrastructure in Mitigation & Preparedness is Neutral(0).

B.1.3. Preparation

As stated before, the preparation phase only has at most 48 hours to complete its goals. For this Alternative, similar to Alternative 1, in these hours a water buffer can be made using the freshwater storage tank. This fresh drinking water can be used during the Recovery phase if the storage tank is not contaminated during the disaster event or Recovery phase. For this alternative, it is recommended to always have a water buffer available in normal circumstances. This means that the filling up of the freshwater aquifer is an ongoing precaution during the previous phases. However, filling it completely during this phase prevents damage during a storm. Increased water weight lessens the impact of wind damage, due to components not blowing away. Furthermore, an increase in water pressure reduces the possibility of contamination. In order to prevent hurricane damage, it is necessary to secure the RO facility and solar energy production facilities. An example of securing can be by setting up hurricane-proof windows. Also, dissembling and storage of the solar panels need to be completed before the disaster strikes. To complete the precautions for the disaster skilled manpower is needed. The availability of manpower is crucial.

The overall score of Alternative 2 Preparation infrastructure is Inadequate -1+0+0=-1 This is based on the following partial scores.

People For the criterion of preparation of people in infrastructure, the focus will be on the general population. According to the Alternative, the population should focus on personal preparation in this phase, similar to Alternative 1. As stated in Subsection 2.3.2, FEMA and NEMA recommend is storage of drinking water for at least three weeks. This means two liters or more per person in the household to store in clean containers. The infrastructure stays active to provide drinking water for these people till the moment of the shutdown of the system. The Uncertainty Avoidance and Power Distance index of Grand Bahama makes it uncertain that all inhabitants take this precaution. This assumption is similar to Alternative 0 , but Hurricane Dorian and other disasters have shown it is not a reliable assumption. The situation has changed compared to Alternative 0 . Meaning that the importance of this need for self-reliability regarding water during a disaster has increased. The criterion People for Infrastructure in Preparation is Inadequate (-1).

Profit In this phase, the wells of Alternative 0 are being locked up and the distribution of freshwater is halted. RO is a more central system meaning lockdown can occur more immediately than a system where the wells are distributed all over the island. There is no increase in cost due to the lockdown compared to Alternative 0. Alternative 1 used grid power instead of solar power, which needs to be packed up the prevent damage in this phase. Meaning that longer distribution could be possible, but can not be due to the unavailability of energy. This makes this Alternative similar to Alternative 0. For the profit, there is no increase in cost compared to Alternative 0, similar to Alternative 1. There is only personal risk, which is explained in the people in the paragraph above. The criterion Profit for Infrastructure in Preparation is Neutral (0).

Planet For the planet, there is no increase in resource utilization compared to Alternative 0. This implies that neither natural resources nor material resources are being consumed, similar to Alternative 0 and Alternative 1. The criterion Planet for Infrastructure in Preparation is Neutral (0).

B.1.4. Response

The Response phase is a reaction to a disaster or emergency. It is assumed that the water treatment plant will not be operating during the disaster. During the previous phase, the Preparation phase, the facilitates are prepared for the disaster. It is assumed there will be no human or other external changes made to the facilities except directly by the storm. Search and rescue activities are not within the scope of the alternative

In this phase, the possible damage to the Solar panels is the difference between Alternative 2 and Alternative 1, which used grid power. Solar panels can withstand some wind. Solar panels are used in other places in the Caribbean that cope with hurricanes. In Puerto Rico, an island southwest of Grand Bahama, hurricane Maria significantly damaged five utility-scale photovoltaic(PV) plants. The damage ranged from undamaged to considerable damage. The damage depended on the location compared to the landfall point of the hurricane. The failure mode in all of these PV plants was PV modules blown away by the wind except for a smaller number of panels that were damaged due to flying debris. Damage severity may be dependent on the orientation of the PV modules with respect to wind direction and whether there was some geographic feature that enhanced or mitigated the effect of these winds. For example, hills can protect or enhance the damage of the wind. Seemingly, it is always possible to make improvements to harden their design by, for example, using thicker metal beams for the frames, but such solutions have a higher cost [Kwasinski, 2018a]. To the west of Grand Bahama is Florida. Most places in Florida require solar installations to withstand winds of 258 km/h minimum, and in a place like Houston, Texas, where Hurricane Harvey caused massive destruction, that number is 177 km/h [Zientara, 2021].

The overall score of Alternative 2 Response Infrastructure Scenario 1 is neutral 0+0+0=0. The overall score of Alternative 2 Response Infrastructure Scenario 2 is neutral 0+0+0=0. First, the expected effects of the two Scenarios are given, and then the overall derived scores above are given in the paragraph People, Profit, and Planet.

Scenario 1 Tropical storm The tropical storm is the second point of the three-point approach(3PA) with a 2-year return period. The second point is initiated by designing a facility that protects against a storm event in predictive conditions. Meaning that the facility should be able to handle a scenario described by the second point of 3PA and will break when the condition becomes worse.

The expected damage to the system after a tornado or a brush with a hurricane is similar and has maximum sustained winds of 63 to 117 km/h. Everything left outside the hurricane-proof structures should be assumed to have been unfazed, moved, lost, or slightly damaged. There will be damage to the connecting infrastructure, external piping, and electricity. With this design, no flooding is assumed at the location. A system is more vulnerable to pathogens when flooded. Still, pathogens might have infiltrated the system. Pipes need to be cleaned before usage in the next phase, but no future restoration might be needed [Schembri, 2018]. If solar panels are safely stored, they can again be installed in the next phase with no issues. Even in the case that they are not stored properly, with the wind suspected in this Scenario most solar panels should be operational after a cleaning. The system bent and did not break [Kwasinski, 2018b].

Scenario 2 Hurricane The Hurricane Dorian scenario is the third point of the three-point approach (3PA) with a 15-year return period. Point three of the 3PA represents a situation where the protection level is exceeded by applying a lower occurrence rate event: The system fails. The importance of minimizing damage to a failing system and maximizing its ability to cope and recover is emphasized by point three of 3PA.

A hurricane does a lot of damage, more than a tropical storm does. Hurricanes are known to topple water towers, ravage homes and let toilets spew raw sewerage. A compromised water supply is to be expected in the case of such a strong storm and created a lingering crisis for drinking water supplies. The biggest difference between tropical storms and hurricanes is the possibility of industrial contamination of the drinking-water supply chain [Incorporated, 2018]. During the scenarios of Hurricane Dorian, category 5 with winds exceeding 321 km/h, the solar panels will likely be blown away. Everything left outside the hurricane-proof building can be assumed moved, lost, or damaged. It can be assumed there will be damage to the building due to wind damage despite the hurricane-proofing. Also, there will be significant damage to the external infrastructure, which will need weeks to replace. Industrial contamination of the drinking water source and its effect on drinking water production is the biggest difference in damage. Potentially more power is needed due to the groundwater being more brackish/salty than before the hurricane hit the island. Restoration or replacement of the pipes that are lost might be needed.

People For people, there is no direct interaction between the population and the water treatment plan in this phase. During the preparation phase, the population is asked to fill clean water containers with drinking water. Also to prevent the impact in case of losing the water supply to the residence it is recommended to fill up the sinks and bathtubs with water for washing [CDC, Centers for Disease Control and Prevention, 2019], usable for the household. The population is asked to stay inside for the duration of the storm, which can be a few hours to a few days. There is limited interaction with the water treatment during this phase and similar action compared to Alternative 0. The criterion People for Infrastructure in Response is Neutral(0).

Profit The water system decreases in value due to damage to the system. After a tropical storm, as described in Subsection 5.1.3, the condition of the infrastructure is presumed to be as follows; Pre-filtration (no impact), Reverse osmosis (no impact), Energy recovery (no impact), Post-treatment(no impact), Freshwater storage (possible contaminated), Saltwater storage (possible contaminated), Piping (possible contaminated), (Remote) monitoring and control (no impact), Building (no impact), Solar panels,(disconnected), Solar frame (no impact), and Storage space for solar panels(No impact). Most of the system did not “break” but did “bend” by only being possibly contaminated. The biggest impact of the tropical storm is the disconnection of the solar panels, which was done to prevent further damage. This is similar to the damage suspected in Alternative 0. The criteria Profit for Infrastructure in Response in Scenario 1 is Neutral(0).

After a hurricane, as described in Subsection 5.1.3, the condition of the infrastructure is presumed to be as follows; Pre-filtration (contaminated), Reverse osmosis (contaminated), Energy Recovery (contaminated), Post-treatment (contaminated), Freshwater storage (collapsed), Saltwater storage (collapsed), Piping (contaminated), (Remote) monitoring and control(disrupted), Building (mild damage), Solar panels (disconnected), Solar frame (damaged) and Storage space for solar panels (mild damage). All filters need to be replaced or cleaned, with the resources on the island being likelier to replace them. Most parts can be reused, but are contaminated. The parts that are likely to be contaminated are; fresh and saltwater tanks, pipes, and filters. It is assumed that the elevated water storage is built on a higher ground level and not like a water tower making it not have an increase in risk. The water reservoirs still are the most likely damaged by the disaster as they are outside the concrete building. Solar frames are also outside of the hurricane-proof building and will be mildly damaged. This added damage doesn’t increase the impact comparably with Alternative 0. The criterion Profit for Infrastructure in Response in Scenario 2 is Neutral(0).

Planet For the planet, within the scope of the case study, there are no resources used. Meaning there are no natural resources or material resources used, by Alternative 0 or Alternative 1 & 2. This is similar to Alternative 0. This is the same for both Scenarios 1 and 2. The criterion Planet for Infrastructure in Response is Neutral(0).

B.1.5. Recovery

For the Recovery of this alternative, the biggest component is the re-installation of solar panels and the start of electricity production. The difference in impact depends on the intensity of the disaster. The specifics of the intensity of the disaster are elaborated on in the paragraphs below. After the disaster, the operation of the RO needs to be started as quickly as possible. Recovery has three stages of temporary water production. The functionality of these stages depends on the available infrastructure. To determine which stage is applicable assessment and cleaning of the system is crucial.

In Stage 1 the goal is to start producing water as quickly as possible. In stage 1, the water can not yet be distributed or produced by the water system and the waterbag will be used. Disaster control measures are added to the design to provide a fallback option if the main drinking water supply systems fail. A large volume of water will be shipped to the Grand Bahamas. Which will sustain the island till the rest of the alternatives will be restarted. The bags, tanks, or bottles will be produced in Florida or another location unaffected by the hurricane. In this stage, the solar panels will be reinstalled and the rest of the system will be checked, repaired, and cleaned. Compared to Alternative 1 this takes more time but has more buffer due to the temporary water supply by waterbags.

In Stage 2 production of drinking water with RO starts with on-site electricity production, with solar panels. This water will go no further than the reservoir and will not yet be distributed over the island. Water will be produced with RO with on-site electricity production. In the second stage connecting the water treatment plant to the water distribution is vital to get it back to normalcy.

In Stage 3 producing of drinking water with RO into the reservoir and distributed over the island with power from the solar panels. Stage three is the full normal stage and has no difference compared to the normal situation.

During all these stages it might be possible to have the water treatment plant operate at half capacity. The reason to do this might be contamination, damaged material, lack of electricity, lack of pressure, etc. The RO has parallel watertracks and it could be possible to produce on a lower capacity. Crucial infrastructural components need to be still operational. Components also still would need to be cleaned before use.

The overall score of Alternative 2 Recovery Infrastructure Scenario 1 is Inadequate 0-1+0=-1. The overall score of Alternative 2 Recovery Infrastructure Scenario 2 is Inadequate 0-1+0=-1. First, the expected effects of the two Scenarios are given, and then the overall derived scores above are given in the paragraph People, Profit, and Planet.

Scenario 1 Tropical storm A contaminated water supply is to be expected in the case of a tropical storm [Incorporated, 2018]. Contamination of the water distribution network and disconnection from the grid power is to be expected. However, contamination in the drinking water treatment plant will be minimal, due to the low impact a tropical storm has on a hurricane-proof building. Meaning that stage 2 is in effect immediately. To the user, in Scenario 1 the fact there is no direct distribution of water is the most inconvenient. The whole infrastructure between the user and the water treatment plant needs to be checked for contamination.

Scenario 2 Hurricane A hurricane does a lot of damage, more than a tropical storm does. Hurricanes are known to topple water towers, ravage homes and let toilets spew raw sewerage. A compromised water supply is to be expected in the case of such a strong storm and created a lingering crisis for drinking water supplies. The biggest difference between tropical storms and hurricanes is the possibility of industrial contamination of the drinking-water supply chain [Incorporated, 2018].

More tests need to be done safely to asses the water resource to begin stage 1. For this thesis, stage 2 the fixing of the contamination and connection of the drinking water supply chain is out of the scope, but the drinking water source is not. Industrial contamination and salt contamination of the drinking water source and its aftereffect on drinking water production are the biggest differences in damage, compared to Alterative 1, but similar to Alternative 0. The RO still can be safely operational with boil water advisories in place. But the water can not be distributed by pipes, due to possible industrial contamination down the distribution line. Possibly more power is needed due to the groundwater being more brackish/salty than before the hurricane hit the island. Compared to Scenario 1, more tests need to be done safely asses the water resource to begin stage 1. Additional tests are needed to start stage 2 to ensure safe distribution by the pipe system. Solar panels left outside in this Scenario, in the previous phase, will be lost. These need to be replaced to start up the complete water system. For this thesis, stage 2 the fixing of the contamination and connection of the drinking water supply chain is out of the scope, but the drinking water source isn't.

People For people, compared to Alternative 1, there is less reliance on each individual to handle themselves in stage 1 of the recovery. This means that there is more reliability in the recovery stage. A possible loss of an individual water buffer is solved by the quick availability of a waterbag. This means there is less difference in the scenarios, compared to Alternative 1. Filling up and shipping the waterbag takes some time which makes this similar to recovery Alternative 1 Scenario 1. The criterion People for Infrastructure in Recovery in Scenarios 1 & 2 are Neutral (0).

Profit The cost incurred during this phase is by reinstalling the solar panels and possibly repairing the solar frames. The damage that needs to be dealt with depends on the angle and placement compared to a storm and seems less to do with the intensity of a Scenario. The fortune of how a storm hits the solar frames and the success of storing the solar panels seem to be more relevant. This is why the scenarios are combined. The components that need replacement, are only maintenance components, the membranes. Membranes will be assessed in maintenance. Compared to Alternative 1 and Alternative 0 there is a slight decrease in profit. The criterion Profit for Infrastructure in Recovery is Inadequate (-1).

Planet For the planet, there are no resources used. Meaning there are no natural resources or material resources used. Compared to Alternative 0 there is no increase or decrease in planet. The criterion Planet for Infrastructure in Recovery is neutral(0).

B.2. Maintenance & Operation

As stated in the previous Section 5.1, the term maintenance includes replacement and care for operations purposes in normal circumstances as part of the alternatives. "Maintenance" groups impacts related to replacement parts and periodic repairs and also includes emissions of greenhouse gas and discharge of polluting material.

Maintenance for Alternative 2 is less frequently required, due to brackish-water usage as compared to a saltwater source, of Alternative 1. The maintenance during this period of operation highlighted the following items as needing intervention and in most cases complete replacement. The maintenance components are the following;

Brackish water pump The pumps, in this case study, have an expected pump life of up to 20 years and a replacement period for wearing parts of 5-l0 years.

Batteries The lifetime battery is typically 5-8 years, depending on how the battery is treated.

Multi-media filters For the MMF the operation between maintenance of 3 years per filter is assumed.

Cartridge filters The core of the cartridge filter has been changed regularly every 3 months.

Membrane Brackish RO membranes lifetime was considered 10 years.

B.2.1. Normal circumstances

In normal circumstances, the water treatment plant functions as any other reverse osmosis-based water treatment running on solar energy. The difference is that all the equipment is placed at a height that is assumed to be flood-proof, and the building is designed to withstand hurricane conditions. During normal operation, there are no emissions of greenhouse gases.

In normal circumstances, there is a discharge of concentrated brackish water. When a RO is operated not all water goes through the system to become clean freshwater. Some water remains, which contains everything that was in the original water. This means everything that was "bad" is now concentrated in the water that is discharged.

The overall score of Alternative 2 normal circumstances maintenance is Inadequate -1-1+1=-1 This is based on the following partial scores.

People For people in the maintenance technicians and operators are the stakeholders that are highlighted here. RO is a more technology-heavy Water treatment than the Alternative 0 described system. It might be difficult to have always staff available on the island with the right skills to operate the water treatment plant at the right times. Grand Bahamas does better economically than most of the other islands in the Bahamas, but still, has difficulty retaining skilled labor. Compared to Alternative 0 and Alternative 1, which both are less technology-heavy than Alternative 2, it might be more difficult to find the people to properly operate and maintain the water system. The criterion for People for Maintenance & Operation in normal circumstances is Bad (–).

Profit The maintenance components of Alternative 2 are a Brackish water pump, Batteries, Multi-media filters, Cartridge filters, and a Membrane. This is an increase in maintenance components compared to Alternative 0 and Alternative 1, due to the added batteries. For profit, the RO is costly compared to other drinking water treatment methods. The source of Alternative 2 is brackish water, which needs less energy than seawater. RO needs pressure to function, which consumes energy. Electricity consumption is part of the operation. Compared to Alternative 0 the cost per freshwater litre will increase due to the need for energy in the high-pressure process of RO. Compared to Alternative 1 costs are less, due to the switch to brackish water. The criterion Profit for Maintenance & Operation in normal circumstances is Inadequate (-).

Planet For the planet, the water source that is used is brackish water in Alternative 2. Seawater can be assumed to be an endless resource, which is not the case for brackish water. This means that depletion of the water resource poses a risk to the environment. For Alternative 2 the production of energy is inside the scope of the thesis, compared to the grid power which is produced outside the scope. The inclusion of Solar energy makes Alternative 2 more positive compared to Alternative 0 and Alternative 1. The Energy is produced with an endless resource, Sun Power. The discharge of concentrated brackish water is impacting the environment through high local salt concentrations and higher concentrations of other possible pollution. These higher concentrations were in the brackish water before in lower concentrations, but due to the extraction of water are now concentrated. The brackish groundwater has lower pollution levels than surface water or seawater, meaning that even though concentrated the environmental impact is minimal.

The discharge of concentrated brackish groundwater makes Alternative 2 friendlier than Alternative 1 and similar to Alternative 0 in the environmental impact. Due to the usage of Sun power and the lower impact of the concentrated discharge, Alternative 2 scored slightly better than Alternative 0 and much better than Alternative 1.

The criterion Planet for Maintenance & Operation in normal circumstances is Adequate(+).

B.2.2. Mitigation & Preparedness

Mitigation refers to the structural and non-structural changes that limit the impact of disasters. Preparedness is a state of readiness, a continuous cycle of planning, organizing, training, equipping, exercising, evaluating, and taking corrective action [FEMA Federal Emergency Management Agency, 2022]. Mitigation & Preparedness for Alternative 2 is the upkeep and placement of locations and facilities that prevent damage by a storm and the spreading of knowledge needed for this.

The upkeep of the Mitigation & Preparedness is part of the Maintenance & Operation. Most of the mitigation aspects are scored in the WM aspect Infrastructure. Maintenance & Operation focuses on keeping the infrastructure in a state which is needed for the next phases. Mitigation & Preparedness also focus on that people have the knowledge, the required material, and resources to prepare for a disaster.

The overall score of Alternative 2 mitigation maintenance is Adequate 2-1+0=1 This is based on the following partial scores.

People For people in the maintenance technicians and operators are the stakeholders that are highlighted here. RO is a more technology-heavy Water treatment than the Alternative 0 described system, especially when solar panels are added. The state of readiness is informing the stakeholders to be able to plan, organize, and train. The compatibility of the planning, organizing, and training with the stakeholders is more difficult in Alternative 2 than in Alternative 0 and Alternative 1. Alternative 2 is a more technology-heavy system compared to Alternative 1 and Alternative 0, due to the solar panels. Just like in normal circumstances it might be difficult to find skilled labor to implement the measures needed to make Alternative 2 successful. Short-term gratification also reduces the willingness to focus on maintenance. As stated in Alternative 1, the writer of this thesis sees possibilities to improve the compatibility of operators with Mitigation & Preparedness measures. But It needs to be packaged in a way with is compatible with the political climate, as explained in Alternative 1 Maintenance & Operation. Maintaining solar panels could also be more interesting for the operators by naming sections of solar panels. By naming clusters of solar panels, sponsorship, and brand awareness can be combined with this eco-friendly-looking product. Cleaning of solar panels can be an event due to the cleaning being visually satisfying.

If maintenance of the Mitigation & Preparedness can be made a national news event Alternative 2 is slightly better than Alternative 0 and Alternative 1 in handling Mitigation & Preparedness.

The criterion People for Maintenance & Operation in Mitigation & Preparedness is Good(++).

Profit The maintenance components are Batteries (5-8 years), Multi-media filters (3 years), Cartridge filters (3 months), Membrane (10 years), and Brackish water pump (pump life 20 years and a replacement period of 5-l0 years). Hurricanes with comparable rain intensity like Dorian are expected to occur once every 15 years and Grand Bahama interacts with a tropical storm every two years. A tropical storm frequency of 2 years is incompatible with the lifespan of most maintenance components, but the intensity and impact of a tropical storm ensure minimal damage to those maintenance components. Compared to Alternative 1 the pump works longer, which also makes it less compatible with the re-occurrence of a Dorian-like hurricane, with a pump life of 20 years being longer than 15 years. A similar pump to Alternative 1 which works better under the condition of brackish water, becomes less compatible due to the frequency of replacement exceeding the frequency of a Hurricane.

The probable duration of 15 years between the extreme hurricane can be nicely divided by the Multi-media filters(3 years) and, Cartridge filters(3 months). The better-expected performance duration of 10-year membranes makes them less compatible with the frequency of the hurricane scenario, similar to these alternative pumps.

Alternative 1 maintenance components fit the intervals of the frequency of the disaster events better than Alternative 2. The criterion Profit for Maintenance & Operation in Mitigation & Preparedness is Inadequate (-)

Planet For the planet, there are no resources used specifically for the use of mitigation or Preparedness for Maintenance & Operation. Meaning there are no natural resources used or material resources used, by Alternative 0 or Alternative 2. Compared to Alternative 0 there is no increase or decrease in planet. The criterion Planet for Maintenance & Operation in Mitigation & Preparedness is Neutral(0).

B.2.3. Preparation

As stated before, the Preparation phase only has a maximum of 48 hours to meet its goals. The goal of Maintenance & Operation in the Preparation phase is to ensure that planned precautions and actions are taken in this small window of time. The water system should be shut down and disconnected from external water and pollution sources. Before this shutdown, the water buffer should be created using the freshwater storage tank and according to the normal operating procedure. This fresh drinking water can be used during the next phase of recovery if the storage tank is not contaminated during the disaster event/recovery phase.

To complete the precautions for the disaster skilled manpower is needed. In order to prevent hurricane damage, it is necessary to secure the RO facility. An example of securing can be by setting up hurricane-proof windows. The waterbag infrastructure and availability need to be checked and assessed for functionality. The waterbag secures the water buffer during the Recovery phase till normal or partial operation has resumed. Depended on the direction and intensity of the hurricane the Solar panels need to be stored in a hurricane-proof location, these activities need manpower. Similar to Alternative 1 the availability of manpower is crucial. The maintenance components of Alternative 2 are Batteries, Multi-media filters, Cartridge filters, Membrane, and Brackish water pump.

The overall score of Alternative 2 Preparation maintenance is Inadequate -1+0+0=-1 This is based on the following partial scores.

People For people, there is the factor of manpower. This means that multiple people need to put the needs of the collective, securing the water treatment plant above their individual needs of looking up their private residence or moving to another island. Even though it will be their job, there is a personal sacrifice. With the stated Individualism vs. Collectivism of Grand Bahama, it might be possible that it would not be done.

This is comparable to Alternative 0, where the willingness to put job responsibilities above individual and private affairs in a crisis situation. For Alternative 2 it is more crucial that goals of the securing the water treatment plant are met, due to the central location, compared to the scattered location of the wells in Alternative 0. There is no fallback on an external second parallel system. Due to the increase in risk, Alternative 2 is slightly worse compared to Alternative 0. The criterion People for Maintenance & Operation in Preparation is Inadequate (-).

Profit There is no increase in cost due to the lockdown compared to Alternative 0. Next to some additional manpower, there are no costs made or gained compared to Alternative 0. The criterion Profit for Maintenance & Operation in Preparation is Neutral (0).

Planet For the planet, there is no increase in resource utilization compared to Alternative 0. This implies that neither natural resources nor material resources are being consumed in either Alternative 0 or Alternative 2. The criterion Planet for Maintenance & Operation in Preparation is Neutral(0).

B.2.4. Response

The Response phase is a reaction to a disaster or emergency. It is assumed that the water treatment plant will not be operating during the disaster. During the previous phase, the preparation phase, the facilitates are prepared for the disaster. It is assumed there will be no human or other external change made to the facilities except directly by the hurricane. Search and rescue activities are not within the scope of the alternative.

The maintenance components of Alternative 2 are Batteries, Multi-media filters, Cartridge filters, Membrane, and Brackish water pump.

The overall score of Alternative 2 Response Maintenance & Operation Scenario 1 is Neutral 0+0+0=0. The overall score of Alternative 2 Response Maintenance & Operation Scenario 2 is Inadequate 0-1+0=-1. This is based on the following partial scores.

People In this phase, the search and rescue is assumed to be out of scope. There have been stories heard during the workshop of operators trying to prevent further damage when the 3-day hurricane Dorian hit the island, but again this is out of the scope of this thesis. For people, there is no direct planned interaction between the operators and the water treatment plan in this phase, similar to Alternative 0. The criterion People for Maintenance & Operation in Response is Neutral (0).

Profit The water system decreases in value due to damage to the system components. In this criterion, only maintenance components will be scored. The infrastructure components are scored under infrastructure.

The maintenance components of Alternative 2 are Batteries (contaminated), Multi-media filters(contaminated), Cartridge filters(contaminated), Membrane(contaminated), and Brackish water pump(contaminated), as seen in Subsection 5.1.3

The possibility of contamination is there, but due to the placement of the filter and membrane in the case of a tropical storm, it is minimal. Compared to Alternative 0 this is a similar loss as in the case of Scenario 1. The criterion Profit for Maintenance & Operation in Response in Scenario 1 is Neutral(0).

After a hurricane, as described in Subsection 5.1.3, the condition of the maintenance components is presumed to be as follows; Batteries (contaminated), Multi-media filters (contaminated), Cartridge filters (contaminated), Membrane (contaminated), and Brackish water pump (contaminated). All filters need to be replaced or cleaned. It is more likely to replace the filters given the limited resources available on the island. Most parts can be reused, but are contaminated, this doesn't include the membrane. Which are costly aspects of maintenance. Compared to Alternative 0 this is a bigger loss in the case of Scenario 2. The criterion Profit for Maintenance & Operation in Response in Scenario 2 is Inadequate(-).

Planet For the planet, within the scope of the case study, there are no resources used. Meaning there are no natural resources and material resources used, by Alternative 0 or Alternative 1. This is the same for both Scenarios 1&2. The criterion Planet for Maintenance & Operation in Response is Neutral(0).

B.2.5. Recovery

For the Recovery phase of this alternative, the biggest issue is the need for grid power. The difference in impact depends on the intensity of the disaster. The specifics of the intensity of the disaster are elaborated on in the paragraphs below. After the disaster, the operation of the RO needs to be started as quickly as possible. It has 3 stages of temporary water production. The functionality of these stages is depending on the available infrastructure. To determine which stage is applicable assessment and cleaning of the system is crucial.

In Stage 1 the goal is to start producing water as quickly as possible. To be able to produce water with RO the facilities themselves need to be operational. These RO facilities are the infrastructure components mentioned earlier. To be able to produce on-site electricity again the solar panels need to be operational, which needs manpower. In stage 1, the water can not yet be distributed or produced. Locals are dependent on their personal storage of drinking water. The first stage is the repairing stage. To provide water to the residents a waterbag and other water containers will be made available.

In Stage 2 production of drinking water with RO starts with on-site electricity production, the solar panels. This water will go no further than the reservoir and will not yet be distributed over the island. In the second stage connecting the water treatment plant to the water distribution is vital to get it back to normalcy.

During all these stages it might be possible to have the water treatment plant operate at half capacity. The reason to do this might be contamination, damaged material, lack of electricity, lack of pressure, etc. The RO has parallel watertracks and it could be possible to produce on a lower capacity. Crucial infrastructural components need to be still operational. Components also still would need to be cleaned.

The overall score of Alternative 2 Recovery Maintenance & Operation Scenario 1 is Neutral 0+1-1=0. The overall score of Alternative 2 Recovery Maintenance & Operation Scenario 2 is Inadequate 0+0-1=-1. First, the expected effects of the two Scenarios are given, and then the overall derived scores above are given in the paragraph People, Profit, and Planet.

People For the operators, this phase is a very busy time. The impact of the storms and hurricane needs to be fixed, replaced, or cleaned. The precise difference in work cannot be estimated by this thesis, but on the scale on which the phases are viewed, it is comparable and the difference is negligible. Therefore for the operators, the scoring Alternative 0 the current situation in both Scenarios. The criterion People for Maintenance & Operation in Recovery is Neutral (0).

Profit During this phase, operators need to work hard to detect and fix problems in the system, similar to Alternative 0. This is easier, due to the central placement of Alternative 2 compared to Alternative 0. This positive aspect is hindered if replacement components need to be shipped, which takes more time. Due to the quicker possible start-up because of the centralization the criterion Profit for Maintenance & Operation in Recovery in Scenario 1 is Adequate (+). In the case of Scenario 2 replacement of the membrane is assumed, which adds time and cost, compared to Alternative 0, but is still a centralized system. The criterion Profit for Maintenance & Operation in Recovery in Scenario 2 is Neutral(0)

Planet For the planet, in the case of Scenario 1, there is a chance that the tropical storm hit the solar panels and frames unfortunately, which causes damage. Meaning there is a change that material resources, in the form of solar replacement, are used in Scenario 1. For Scenario 2 there are material resources used, and membranes need to be shipped from the mainland. The criterion Planet for Maintenance & Operation in Recovery in Scenario 1 is Inadequate (-1). The criterion Planet for Maintenance & Operation in Recovery in Scenario 2 is Inadequate (-1).

B.3. End-of-Life

The term End-of-life (EoL) is used here to refer to the end of the lifespan of a system or one of its components.

The WM criteria grouped under "End-of-Life" include reuse, redistribution, recycling, and the environmental effects of demolition. For long-lived products, like a water system, the impact of EoL processes such as demolition and disposal will occur in the distant future. For construction materials, EoL processes are often estimated to occur within 50 to 100 years[Frijia et al., 2012],[Sandin et al., 2014]. A non-disaster-stricken Water treatment system has a lifespan of 50-year. These longer time frames cause technological uncertainty, meaning new technology could be developed for disposal and the type of substituted technology can change. Straight-line depreciation times of 100 years do exist in financial accounting for long-lived assets. The use of straight-line depreciation is difficult to justify if a disaster can rapidly decrease the value of the system to zero. A hurricane disrupts the process of depreciation, meaning that straight-line depreciation is impractical. The nature of EoL processes is highly uncertain, even without disasters. This time-dependent uncertainty has previously been acknowledged as a challenge for life cycle assessments (LCA) in the construction industry [Singh et al., 2011] [Verbeeck and Hens, 2007] [Sandin et al., 2014]. EoL particularly focuses on uncertainties regarding the means of disposal, the expected technology development of disposal processes, and the type of substituted technology. Despite its significance, the element of uncertainty is frequently overlooked in the LCA of constructions and construction materials. This oversight persists even when the objective is to inform decisions regarding long-lasting constructions[Bribián et al., 2011],[Habert et al., 2012],[Lundie et al., 2004],[Persson et al., 2006], [Sandin et al., 2014]. Until now, there has been insufficient consideration of EoL uncertainties of long-lived products, which may hamper sound decision-making for sustainable development [Sandin et al., 2014].

A scenario can be used to cope with this uncertainty surrounding EoL. Setting up scenarios to account for different possible futures of EoL has been done before [Bouhaya et al., 2009]. When modeling future disposal processes several fundamentally different scenarios are needed according to [Mathiesen et al., 2009]. The construction of a complete model of EoL is out of the scope of this thesis. [Sandin et al., 2014] recommend cornerstone scenarios to capture the range of possible outcomes of temporally more dynamic impact assessments. These Cornerstone scenarios are similar to the scenarios suggested by the Three-Point Approach used in the thesis. Combining the need for EoL scenarios with the scenarios in this thesis will boil down to Normal circumstances, tropical storms, and hurricanes. The Normal circumstances will assume that the whole 50 years of the water system lifespan will be utilized. Making a comparison of the alternative with Alternative 0 in the case no disaster will strike in that time frame. In the disaster phases the degradation in the system value by the disaster will be compared and scored, this will be scenario-dependent.

In the case-study regular transportation is equivalent to international shipping. Transportation has a higher impact on an island. Normally transportation and supply-chain processes would be of lower importance when contrasted to demolition [Sandin et al., 2014].

Promoting transportation to have an environmental effect will be a significant element in the EoL. Another element of EoL is the emissions and waste which occur during EoL processes. Waste is an unavoidable by-product of most human activity. The term “waste” refers to any product or substance which is no longer suited for its intended use [Balwan et al., 2022].

For Alternative 2, the End-of-Life (EoL) impact of Reverse Osmosis (RO) is similar to that of maintenance of RO just as in Alternative 1. At the end of the life cycle of a RO system, nearly all components will have been replaced. The only components which in normal circumstances would not be replaced are infrastructure components such as; freshwater storage, saltwater storage, piping, building, and (Remote) monitoring and control. RO generates continuous waste during operation, like concentrated water and replacement infrastructure. RO does not face specific waste management problems at the end of its life cycle.

B.3.1. Normal circumstances

In Normal circumstances, it is expected that the entire 50-year lifespan of the water system will be utilized. Making a comparison of the alternative with Alternative 0 in the case no disaster will strike in that time frame.

For Alternative 2, at the end of the whole life cycle of a RO system, nearly all components will have been replaced. The pump, membranes, and filters will already have been replaced 4 times after 50 years of RO operation. The only components that would not be replaced in normal circumstances are infrastructure components such as; freshwater storage, saltwater storage, piping, building, and (Remote) monitoring and control. RO generates continuous waste during operation, like concentrated salt water and replacement infrastructure, membrane, and filters. RO does not face specific hazardous waste management problems at the end of its life cycle

The overall score of Alternative 2 normal circumstances end of life is Neutral x+0+0=0 This is based on the following partial scores.

People For the criterion people there is no score given because it does not apply, see Subsection 3.2.1 for more details.

Profit Compared to Alternative 1, some infrastructure components are underground, to be able to extract brackish groundwater. This makes the demolition costs similar to that of Alternative 0. The depreciation period is similar to that of Alternative 0, and better than Alternative 1 due to the usage of brackish water. The criterion Profit for End-of-Life in Normal circumstances is Neutral (0).

Planet The infrastructure could be reused and recycled to be used in other infrastructure projects on the island. The environmental effects of demolition are similar to those of Alternative 0. The criterion Planet for End-of-Life in Normal circumstances is Neutral(0).

B.3.2. Mitigation & Preparedness

The length of the Mitigation & Preparedness phase is too short for the EoL depreciation time frame in the case of Scenario 1, 2 years. The length of the Mitigation & Preparedness phase in Scenario 2 is just long enough to have some EoL depreciation, it is equivalent to more than a third of the time frame, 15 years. The goal of the Mitigation & Preparedness phase is to anticipate the next phases of the disaster cycle, which consumes material but does not produce waste. The overall score of Alternative 2 mitigation end of life is Neutral x+0+0=0 This is based on the following partial scores.

People For the criterion people there is no score given because it does not apply, see Subsection 3.2.1 for more details.

Profit In the time frame of this disaster phase depreciation occurs, especially in Scenario 2. However, this is similar to the depreciation of Alternative 0. The criterion Profit for End-of-Life in Mitigation & Preparedness is in both Scenario 1 and Scenario 2 Neutral (0).

Planet No waste is produced during this phase and no future environmental effects of demolition occur. This is comparable to Alternative 0 in this phase. The criterion Planet for End-of-Life in Mitigation & Preparedness is Neutral (0).

B.3.3. Preparation

As stated before, the Preparation phase only has a maximum of 48 hours to complete its goals. The length of the Preparation phase is too short for the EoL depreciation time frame. The goal of the Preparation phase is to prepare for the disaster, which consumes material and manpower but doesn't produce waste. The overall score of Alternative 2 Preparation End-of-Life is Neutral x+0+0=0 This is based on the following partial scores.

People For the criterion people there is no score given because it does not apply, see Subsection 3.2.1 for more details. .

Profit In this time frame of this disaster phase, no depreciation occurs. This is similar to the depreciation of Alternative 0 and Alternative 1. The criterion Profit for End-of-Life in Preparation is Neutral (0).

Planet No waste is produced during this phase and no future environmental effects of demolition occur. This is comparable to Alternative 0 and Alternative 1 in this phase. The criterion Planet for End-of-Life in Preparation is Neutral (0).

B.3.4. Response

The length of the Response phase is too short for the EoL depreciation time frame, but it is shortened by the disaster. During the Response phase waste is produced, with components that can no longer operate in their original function. Also, rapid degradation takes place due to the disaster event.

The overall score of Alternative 2 Response End-of-Life is Neutral x+0+0=0 This is based on the following partial scores.

People For the criterion people there is no score given because it does not apply, see Subsection 3.2.1 for more details.

Profit In this time frame of this disaster phase, depreciation occurs, due to the disaster and not due to time passing. This is similar to the depreciation of Alternative 0. The criterion Profit for End-of-Life in Response is Neutral (0).

Planet Waste is produced during this phase and environmental effects of demolition occur. These are however linked to the disaster event and not to the water system. This is comparable to Alternative 0 in this phase. The criterion Planet for End-of-Life in Response is Neutral(0). .

B.3.5. Recovery

The goal of the Recovery phase is to bring the affected area back to some degree of normalcy. Recovery involves decisions and actions relative to rebuilding homes, replacing property, resuming employment, restoring businesses, and permanently repairing and rebuilding infrastructure. Recovery activity produces waste to be able to get back to normal.

The overall score of Alternative 2 Recovery End-of-Life Scenario 1 is Neutral x+0+0=0. The overall score of Alternative 2 Recovery End-of-Life Scenario 2 is Neutral x+0+0=0. First, the expected effects of the two Scenarios are given, and then the overall derived scores above are given in the paragraph People, Profit, and Planet.

People For the criterion people there is no score given because it does not apply, see Subsection 3.2.1 for more details.

Profit In this time frame of this disaster phase, no depreciation occurs. This is similar to the depreciation of Alternative 0 . The criterion Profit for End-of-Life in Recovery is Neutral (0).

Planet Waste is produced during this phase and environmental effects of demolition occur. These are however linked to the disaster event and not to the water system. This is comparable to Alternative 0 in this phase. The criterion Planet for End-of-Life in Recovery is Neutral (0).

Water management criteria	Infrastructure		Maintenance		End of life	
Scenario	Tropical storm	Dorian hurricane	Tropical storm	Dorian hurricane	Tropical storm	Dorian hurricane
Disaster criteria						
Normal circumstances	0		-		0	
M & P phase	-	-	+	+	0	0
Preparation phase	-	-	-	-	0	0
Response phase	0	0	0	-	0	0
Recovery phase	-	-	0	-	0	0

Table B.1: MCA scores for Alternative 2

B.4. Overview infrastructure

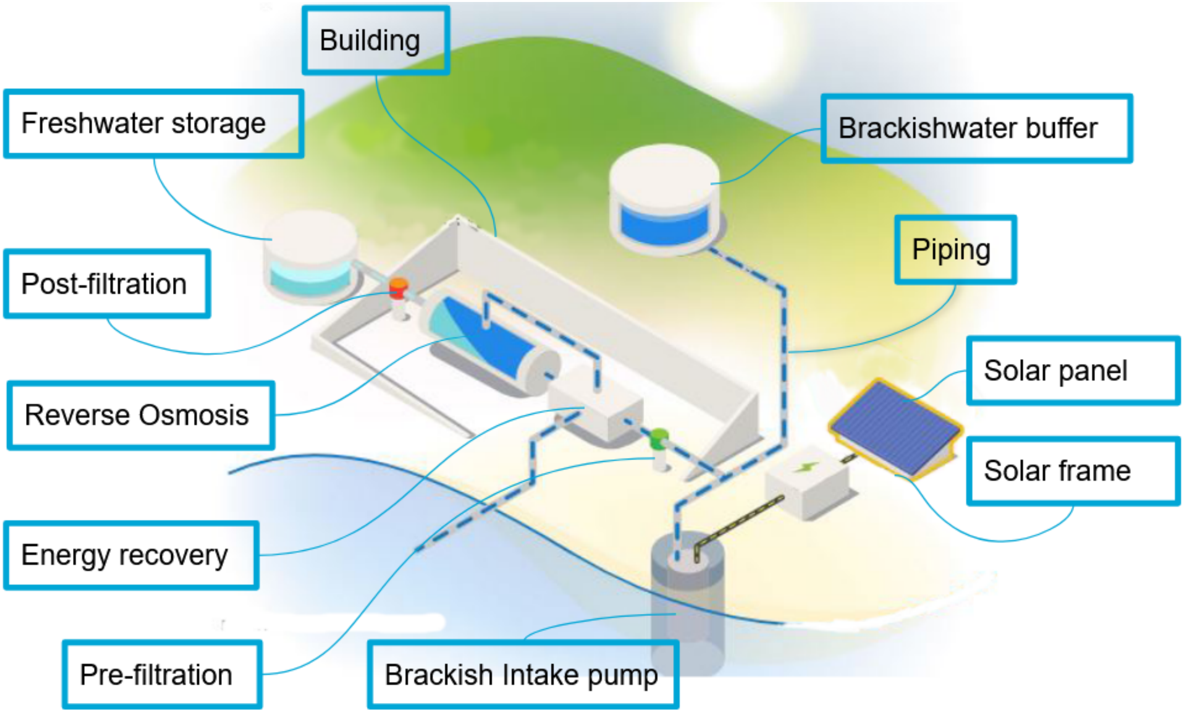


Figure B.1: An overview of design Alternative 2. Infrastructure and flows of solar-powered reverse osmosis drinking water facility with brackishwater as the source. The freshwater storage at the plant serves as central drinking water storage for the island. This is the normal condition of Alternative 2

Figure B.2: **[Disaster measure]**; Water bag. The Water bag will provide water in the first part of the Recovery phase[Rivero, 2020]

(a) **[Solar panels]**

(b) **[Solar frames]**

Figure B.3: All components for the solar panel reverse osmosis alternative

(a) [**Intake pump**] is where the water enters the pump intake system. The pressure provided by the pump distributes the water in the system. Most pumps have to be replaced yearly when used for salt water.

(b) [**Pre-filtration**] will prevent larger polluting particles to enter the RO, which is an easily clogged membrane. To avoid frequent membrane replacement, the pre-treatment will be designed for your site-specific situation. This can involve sand filtration, cartridge filtration, and more

(c) [**Reverse osmosis**] is a membrane that rejects solutes and other particles while at the same time having a throughput (flux) of water. The high pressure used for this process is made by pumps which run on electricity.

(d) [**Energy recovery**] enables re-using of the brine pressure. The already high pressure present in the runoff water makes it possible to reuse that same energy again. Energy recovery helps recover some of the energy typically lost from the pumps and membrane system. The primary objective is to recover much of the energy held in the pressurized RO concentrate stream. Before continuing to disposal or treatment, the concentrate is sent through an energy recovery device, and the recovered energy is used to partially power the pumps.[Greenlee et al., 2009]

(e) [**Post-treatment**] is possible specific applications that can add fresh water treatment steps to the system, for example, remineralization, UV treatment before end use, or preservation dosing to make it suitable for longer-term storage.

(f) [**Salt water-buffer tank**] & [**Fresh water-buffer tank**] are buffer tanks of concrete, build as a basin to ensure stable pressure in the system. The saltwater tank is elevated to ensure constant pressure. The freshwater tank is a location in which the produced fresh water is stored. This ensures pressure in the system and helps the availability of freshwater for the users.

(g) [**Piping**] is used for long-distance transportation of liquid. Pipe sections should withstand high pressures, and salt water, offer flexibility to be placed in bends, and withstands forces from outside.

(h) [**(Remote) monitoring control**] This included all electronics equipment to maintain the system. The units are equipped with internet-based monitoring for remote control and alarm messaging. This is to check in on the water supply from anywhere

Figure B.4: All components for Alternative 2 the solar panel reverse osmosis

C

Performance Alternative 3

In this chapter, the performance of Alternative 3 will be worked out. This is the third of 3 Alternatives dealing with three Scenarios; Normal conditions, a Tropical Storm, and a Hurricane. There are three water management aspects assessed; Infrastructure, Maintenance & Operation, and End-of-Life. These assessments are crossed with five disaster sub scenarios; Normal Circumstances, Mitigation & Preparedness, Preparation, Response, and Recovery. The categories are scored on sustainability, which will be based on PPP pillars (People, Profit, Planet).

Alternative 3 is based on a design made during an earlier workshop [van der Hucht et al., 2021]. The goal of the workshop was to Build Back Better. The main solution was based on collective protection by building a levee using the natural landscape. This levee would protect the densely populated area from storm surge flooding, which would make it easier to bounce back with the economic center of the island intact. Another benefit of the levee is that it also protects the fresh groundwater bubble under the area from the effects of saltwater surface flooding. During such flooding, salt water would infiltrate into the soil and mix with the lighter freshwater making the water brackish or even salty.

The levees help to maintain the situation of Alternative 0. Levees prevent salt infiltration into the freshwater resource of Alternative 0. Levees are very expensive and if this alternative only served to keep the drinking water system feasible, then it would not be a reasonable option. This alternative would not be considered if this levee did not have as its primary reason the protection of economic and social interests from storm surges. As can be seen in Figure 5.2, the placement of the levee would protect part of the freshwater lens. It is assumed that the levee will protect the part of the groundwater lens under Freeport is from seawater infiltration, preventing it from becoming brackish. The levee helps protect the status quo of the drinking water system.

Rivers, levees, and highways are notorious for cutting off communities from one another. Bahamians do not often walk long distances and primarily use the car for transport, due to the climate (air-condition) and habit. For the Grand Bahama community to remain unobstructed, the levee should be easily traversed by car. Freeport is built on the highest elevation of Grand Bahama and is the biggest city and economic center. If the levee is finished, then there would be a large wall around the busiest part of Grand Bahama. The protection of the groundwater lens in this location is also assisted by increased rainwater filtration in that area, as seen in Figure 5.3.

C.1. infrastructure

The infrastructure is the hardware of the system of the alternative. For Alternative 3, the main infrastructure components are five levees/dikes, some Wells, a rain infiltration system, the original water treatment plant (chlorination), freshwater storage, piping, building, and grid power, as stated in Subsection 5.1.4

C.1.1. Normal circumstances

Under normal circumstances, Alternative 0 supplies the residents of Grand Bahama with pumped-up fresh groundwater which is chlorinated before distribution. The difference is that a high levee surrounds the area of Freeport. Another difference is that in a multitude of locations on the ground of Grand Bahama, the permeability is increased to help infiltration and reduce flooding. Compared to Alternative 0 the circumstances do not change except for the added rain infiltration systems. The main change is a mitigation measure, the levee/dike, which is scored under another criterion. The fresh water will still be pumped out of the existing well which will be protected by the levee.

The overall score of Alternative 3 Normal Circumstances Infrastructure is Neutral 0-2+2=0. This is based on the following partial scores.

People As observed by this researcher, the citizens of Grand Bahama are very knowledgeable about the need for change in the drinking water system, but they are not really willing to change. Primarily it is the price tag that is making them nervous. Cost is a big part of the acceptance of technology. The assessment of the cost is included in the profit criterion. For the short term, keeping the status quo is in line with the short-term gratification, but the mitigation measure is not. Building a levee can take multiple years, especially with the limited resources available on the island, but this falls under the mitigation part of the scoring. Compared to Alternative 0 this alternative will produce drinking water in a similar manner. Because the changes are only scored under other criteria, the criterion People for Infrastructure in Normal circumstances is Neutral(0)

Profit For the criterion Profit for infrastructure in normal circumstances, the cost is compared to Alternative 0 of Grand Bahama in 2019. In case the levee is integrated into the scope of this alternative there is an extreme deviation in the cost of the main infrastructure components when compared to the current drinking water treatment systems. The criterion for Profit for Infrastructure in Normal Circumstances is Bad(–).

Planet Alternative 3 is maintaining the status quo. Except for the added rain infiltration systems and the levees, no other infrastructures will be added, compared to Alternative 0. These two infrastructures also assist the environment by keeping the groundwater fresh. Only four Bahamian islands have the ecology possible for the special freshwater forest, and Grand Bahama is one of them [Lloyd et al., 2011],[Antalffy et al., 2021], as stated in Subsection 2.1.2. The criterion Planet for infrastructure in Normal circumstances is Good (++).

C.1.2. Mitigation & Preparedness

The structural and non-structural changes to limit the impact of disasters for Alternative 3 are levees that surround the main area of Freeport. The levees prevent flooding as a result of a storm surge. Levees can be used effectively to protect flood-prone areas. These structures can be controversial as they provide protection in one place, but not all, and may cause unintentional side-effects [FEMA Federal Emergency Management Agency, 2022].

The overall score of Alternative 3 Mitigation & Preparedness Infrastructure is Inadequate -1-2+2=-1. This is based on the following partial scores.

People For the people, a levee has an impact on the surrounding area, as it blocks lines of sight and may hinder movement. A levee can be a quiet reminder of possible flooding and an advertisement for hurricane preparedness. This advertisement might not be as necessary due to the frequency of hurricanes in the area, but awareness can be seen as a plus. The construction clashes with the need for Short-Term Orientation of the political climate. A levee needs to be maintained and will not be finished building within the time of a political cycle of 5 years, as stated in Subsection 2.1.9. Compared to Alternative 0 there is more impact on the inhabitants. The levee gives a positive direction for preparedness but is mediocre due to its incompatibility with the political culture and its impact on the residents. The criterion People for Infrastructure in Mitigation & Preparedness is Inadequate (-).

Profit For profit, a levee is a costly and long-lasting endeavor, compared to the construction of the other Alternatives. In the long term, there might be a beneficial cost due to the prevention of damage and loss of economic and social value, but this is out of the scope of this thesis. Compared to Alternative 0 the cost significantly increases. The criterion Profit for Infrastructure in Mitigation & Preparedness is Bad (–).

Planet For the planet, a levee has a massive ecological impact, good and bad. Native flora and fauna rely on fresh groundwater, which will be protected. A levee will shape the underground flow of water and block possible land migration if that is the case in the area. During a previous study [van der Hucht et al., 2021], there was no clear negative effect observed on the planet by building a levee. Compared to the situation of

Alternative 0 the environmental impact is positive due to it protecting the needed fresh groundwater used by native flora and fauna. The criterion Planet for Infrastructure in Mitigation & Preparedness is Good (++).

C.1.3. Preparation

> "If you stay ready. You have not got to get ready" Suga Free 20th May 1997.

As stated before, the preparation phase only has a maximum of 48 hours to complete its goals. Due to the disaster measure of a levee needs no preparation actions, only mitigation, the time constraint is of less relevance compared to other alternatives. This alternative is protecting the existing fresh reservoir from storm surges and saltwater flooding. If properly maintained during the mitigation phase this alternative is always ready and doesn't need any special preparation. The buffer is the existing fresh groundwater. Due to nothing needing to be prepared it is ready for the next phase.

The overall score of Alternative 3 Preparation Infrastructure is Neutral 0+0+0=0. This is based on the following partial scores.

People For the criterion of preparation of people in infrastructure, the focus will be on the general population. Compared to Alternative 0, 1, and 2 there is still a need for inhabitants to store drinking water for at least three weeks as recommended by NEMA and FEMA. This means two liters or more per person per day in the household to store in clean containers.

The criterion People for infrastructure in Preparation is Neutral(0) relative to Alternative 0.

Profit In this phase, the wells described in Alternative 0 are being locked up and the distribution of freshwater is halted. There is no change in the distribution process compared to Alternative 0 for Alternative 3. There are also no extra operational costs or personal costs. The criterion Profit for Infrastructure in Preparation is Neutral (0).

Planet For the planet, there is no increase in resources used compared to Alternative 0. Meaning there are no natural resources or material resources used, in Alternative 0 or Alternative 3. The criterion Planet for infrastructure in Preparation is Neutral (0).

C.1.4. Response

The Response phase is a reaction to a disaster or emergency. It is assumed that fresh drinking water production will not be operating during the disaster. During the previous phase, the preparation phase, the facilitates are prepared for the disaster. In this alternative, the facilities are the current extraction wells and corresponding groundwater treatment facilities. It is assumed there will be no human or other external change made to the facilities except directly by the storm.

The levee will protect the densely populated area from storm surge flooding. Compared to the other phases no flooding would occur during the disaster, but the other dangers of the hurricane still transpire. The levee assists with search and rescue, but search and rescue activities are not within the scope of the alternative. If the levee is not completed the benefits are no longer applicable.

The overall score of Alternative 3 Response Infrastructure Scenario 1 is Neutral 0+0+0=0. The overall score of Alternative 3 Response Infrastructure Scenario 2 is Good 1+2+0=3. First, the expected effects of the two Scenarios are given, and then the overall derived scores above are given in the paragraph People, Profit, and Planet.

Situation 1 Tropical storm The tropical storm is the second point of the three-point approach(3PA) with a 2-year return period. The second point is initiated by designing a facility that can handle a storm event in predictive conditions. This means that the facility should be able to handle a scenario described by the second point of 3PA and will only fail when the conditions of the storm become more severe.

In the case of a Tropical storm, the completion or in-completion of the levee is irrelevant, due to the absence of a storm surge. There will be still wind damage. The expected wind damage to the system after a tropical storm or a brush with a hurricane is caused by the maximum sustained winds of 63 to 117 km/h. Properties might be moved, lost, or damaged. The damage will be mainly to the connecting infrastructure, external piping, and electricity. Still, pathogens might have infiltrated the system. Pipes need to be cleaned before usage, but no additional repairs are expected. The typical process for clearing water systems of contaminants is a chlorination process similar to what you would do with a swimming pool. Chlorine sits in the system for about 24 hours. This seems to work well with current contaminants, but bacteria or chemicals from industrial facilities might cause a threat not covered in the scope of this thesis.

Situation 2 Hurricane The Hurricane Dorian scenario is the third point of the three-point approach (3PA) with a 15-year return period. Point three of the 3PA represents a situation where the protection level is exceeded by a threat with a high return period: The protection system fails. The importance of minimizing damage to a failing system and maximizing its ability to cope and recover is emphasized by point three of 3PA.

In the case of a hurricane, the completion or in-completion of the levee is relevant, due to the threat of a storm surge. The expected damage to the system during a hurricane is significant. Extreme wind, storm surge, and pluvial flooding threaten the island. The alternative protects against storm surges. Models that have been run during the workshop have shown that flooding can still occur inside the protected area due to pluvial flooding [van der Hucht et al., 2021]. The flooding is local, due to the specific water pockets caused by the landscape shape. The models showed that the biggest water pockets due to rain were not enhanced or created by the levee. It shows that parts that are wet due to the hurricane rain will stay wet longer, increasing infiltration.

Everything outside the protected zone will be flooded in this Scenario. Infrastructure parts might be moved, lost, or damaged. The damage outside the protected area will be significant, but not more than in Alternative 0 or after implementation of Alternative 1 or 2. The connecting infrastructure, external piping, and electricity, but also the freshwater pockets outside the barrier will be made brackish. Pathogens will infiltrate the unprotected system. Most outside infrastructure will be lost. The remaining pipes need to be cleaned before usage. The typical process for clearing water systems of contaminants is a chlorination process similar to what you would do with a swimming pool. Chlorine sits in the system for about 24 hours. This seems to work well with current contaminants, but bacteria or chemicals from industrial facilities might cause an unknown threat. Restoration or replacement of the pipes that are lost might be needed.

People For people, there is no direct interaction between the population and the water production. During the preparation phase, the population is asked to fill clean water containers with drinking water. Also to prevent the impact in case losing the water supply to the residence it is recommended to fill up the sinks and bathtubs with water for washingCDC, Centers for Disease Control and Prevention [2019], usable for the household.

The population is asked to stay inside for the duration of the storm, which can be a few hours to a few days. This alternative has however a primary objective which is protecting the area surrounded by the levee. In the case of a tropical storm, the criterion People for Infrastructure in Response is Neutral (0). In the case of a hurricane, the criterion People for Infrastructure in Response is Adequate (+), due to the added security in the protected area compared to Alternative 0.

Profit The water system decreases in value due to damage to the system. After a tropical storm, as described in Subsection 5.1.4, the condition of the infrastructure is presumed to be as follows; levees/dikes (in need of inspection), Wells (no impact), Rain infiltration system (in need of cleaning), Original chlorination water treatment plant (no impact), Freshwater storage (contaminated), Piping (contaminated), Building(no impact) and Grid power (disconnected).

Most of the system did not “break” but did “bend” by only being possibly contaminated. The biggest impact of the tropical storm is the disconnection of the grid power. This is similar to the damage suspected in Alternative 0. The criteria Profit for Infrastructure in Response in Scenario 1 is Neutral(0).

After a hurricane, as described in Subsection 5.1.4, the condition of the infrastructure is presumed to be as follows; 5 levees/dikes (in need of repair), Wells (in need of repair), Rain infiltration system (in need of cleaning and repair), Original chlorination water treatment plant(contaminated), Freshwater storage (collapsed), Piping (contaminated), Building (mild damage), and Grid power (disconnected).

Repairing a levee is costly and necessary after a Hurricane event like Dorian. The overflow and wave damage will have damaged the levees in a way that they can no longer function at the protection level needed. Most parts of the drinking water treatment system can assumed contaminated. The damage is considerably reduced when compared to Alternative 0. The criterion Profit for Infrastructure in Response in Scenario 2 is Good(++).

Planet For the planet, within the scope of the case study, there are no resources used. Meaning there are no natural resources or material resources used, by Alternative 0 or Alternative 1 & 2. This is similar to Alternative 0. This is the same for both Scenarios 1 and 2. The criterion Planet for Infrastructure in Response is Neutral(0).

C.1.5. Recovery

For the Recovery phase of this alternative, the biggest issue is the need for grid power, similar to Alternative 1. The difference in impact depends on the intensity of the disaster and the completion of the levee. Recovery of this alternative has 2 stages of temporary water production. The functionality of these stages depends on the available infrastructure. To determine which stage is applicable assessment and cleaning of the system is crucial.

In Stage 1 the goal is to start producing water as quickly as possible. To be able to produce water the facilities themselves need to be operational. To be operational the facilities need to be repaired and cleaned from the damage done by the event. In Alternative 3 there are no fallback options and the dependence on the stored water by the inhabitants is high. In Stage 1, the water can not yet be distributed or produced.

In Stage 2 production of drinking water starts with the current infrastructure and distribution over the island with power from the electricity network. Stage 2 is the full normal stage and has no difference compared to the normal situation.

In the case of an incomplete levee system, when a Dorian-like storm hits the island, stage 1 will not only involve repairing and cleaning the drinking water system infrastructure but also dealing with contamination of the drinking water source. In 2019 the drinking water became so brackish and the wells were so salty that even two years after the hurricane it still was not suited for drinking. This would be a devastating scenario if repeated.

Between the stages, it might be possible to have the water treatment plant operate at half capacity. The reason that the plant only at half capacity can work is caused by contamination, damaged material, lack of electricity, lack of pressure, etc. The wells can operate independently, they have their own water treatment system and can operate parallel. It could be possible to produce at a lower capacity. Crucial infrastructural components need to be still operational. Components also still would need to be cleaned before use.

The overall score of Alternative 3 Recovery Infrastructure Scenario 1 is Neutral 0+0+0=0. The overall score of Alternative 3 Recovery Infrastructure Scenario 2 is Neutral 0+0+0=0. First, the expected effects of the two Scenarios are given, and then the overall derived scores above are given in the paragraph People, Profit, and Planet.

People In Alternative 3, Stage 1 of the Recovery is similar to Alternative 1 and Alternative 0. Both alternatives assume that residents have their own water available. This water is collected by the residents in earlier phases. The difference between the Alternative 1 and Alternative 3 is that people now can rely on their personal wells, due to the protection given by the levees. In Alternative 0 the wells will contain undrinkable water due to salt intrusion, which makes them unusable without technology-heavy treatment. This results in similar scores for Scenarios 1 and 2, because of the similarity with Alternative 0. The criterion People for Infrastructure in Recovery Scenarios 1 & 2 is Neutral (0).

Profit The significant costs, which are made by the recovery of the grid and water distribution network, are out of the scope of this MCA. No infrastructure components are assumed to be in need of replacement, only maintenance components, like the pumping system. Compared to Alternative 0there is no increase or decrease in profit. The criterion Profit for infrastructure in Recovery is Neutral(0).

Planet For the planet, there are no resources used. Meaning there are no natural resources or material resources used, by Alternative 0 or Alternative 3. Compared to the current system there is no increase or decrease in planet. The criterion Planet for infrastructure in Recovery is Neutral(0)

C.2. Maintenance & Operation

As stated in the previous Section 5.1, the term maintenance includes replacement and care for operations purposes in normal circumstances as part of the alternatives. "Maintenance" groups impacts related to replacement parts and periodic repairs and also includes emissions of greenhouse gas and discharge of polluting material.

Maintenance for the water treatment system of Alternative 3 is less frequently required compared to Alternative 1 & 2, due to fresh-water usage as compared to a salt or brackish water source, of Alternative 1 & 2. The maintenance during this period of operation highlighted the following items as needing intervention and in most cases complete replacement. The maintenance components are the following;

Levees/dikes Levees are maintained based on 5-yearly inspections, the levee will be repaired on that specific location, within a month.

Rain infiltration system Regular garden maintenance will be done once a month.

Fresh water pump The pumps, in this alternative, are assumed to have an expected pump life of up to 25 years and a replacement period for wearing parts of 10 years.

C.2.1. Normal circumstances

In normal circumstances, the current water treatment plant operates as usual. The difference is that there is a levee in the distance. The building is designed to withstand hurricane conditions. With the current grid power plant, gasses like carbon dioxide are produced during electricity production. The production of grid power is out of scope in the Normal circumstance. Compared to Alternative 1 & 2 there is no concentrated water discharged.

The overall score of Alternative 3 Normal Circumstances Maintenance is Neutral 0+0+0=0. This is based on the following partial scores.

People For people in the maintenance technicians and operators are the stakeholders that are highlighted here. Compared to Alternative 1 and 2 there is no technology change likened to Alternative 0. The criterion People for Maintenance & Operation in Normal Circumstances is Neutral (0).

Profit The maintenance components of Alternative 3 are Levees, a Rain infiltration system, and Freshwater pump. In Alternative 3, energy is used to pump up water from the ground aquifer, this energy consumption of transporting water from the source is similar to Alternative 0. Compared to Alternative 0 the cost per freshwater liter will stay the same, as the cost of the levee is not directly connected to the production of water. The levees are a one-time big cost expense that will protect a multitude of systems and infrastructures. The criterion Profit for Maintenance & Operation in Normal circumstances is Neutral(0).

Planet For the planet, the water source that is used is fresh groundwater in Alternative 3. This source needs to be protected by the levee and is vulnerable to depletion. Maintaining a fresh groundwater aquifer also protects flora and fauna that need these conditions to thrive, these benefits are scored in Infrastructure Normal circumstances planet. In Alternative 3, similar to Alternative 0 and Alternative 1, diesel-fueled grid power is used. As stated before, the production of this electricity is out of the scope of this thesis. Alternative 0 uses grid power to operate the pumps of the wells. With the levee and rain infiltration combination maintaining the status quo and the added protection to flora and fauna being scored somewhere else the score comes out to be similar to Alternative 0.The criterion Planet for Maintenance & Operation in Normal circumstances is Neutral (0).

C.2.2. Mitigation & Preparedness

Mitigation refers to the structural and non-structural changes that limit the impact of disasters. Preparedness is a state of readiness, a continuous cycle of planning, organizing, training, equipping, exercising, evaluating, and taking corrective action [FEMA Federal Emergency Management Agency, 2022].

The overall score of Alternative 3 mitigation & Preparedness Maintenance is Inadequate -1+1-1=-1. This is based on the following partial scores.

People For the people aspect of maintenance technicians and operators are the stakeholders that are highlighted here. The compatibility of the planning, organizing, and training with the stakeholders is slightly more difficult for Alternative 3 than in Alternative 0. Alternative 0 has been in use for years and it is also a less technology-heavy water treatment system. To this, the levee and rain infiltration systems are added. Just like in normal circumstances it might be difficult to find skilled labor to implement the measures needed to make

Alternative 3 successful. In particular, the levee inspection and the follow-up reconstruction would be difficult aspects to ensure will be completed. The compatibility of the maintenance technicians and operators to Alternative 3 is less than in Alternative 0. They know the system better due to it being implemented for years, but incompatibility with the added maintenance for the Mitigation measures makes the operators have less affinity with Alternative 3 than Alternative 0.

The criterion People for Maintenance & Operation in Mitigation & Preparedness is Inadequate (-).

Profit The maintenance components are Levees (5-yearly inspections, repaired within a month), Rain infiltration system (once a month), and Fresh water pump (pump life of up to 25 years, replacement period 10 years). Hurricanes with comparable rain intensity like Dorian are expected to occur once every 15 years and Grand Bahama interacts with a tropical storm every two years. In Alternatives 1 & 2 some maintenance components show a clear reduction in value due to the reduction of usage, due to storm impact. The lifetime of the maintenance component would have been more in the case where the system would be situated in a location that would deal with storms. For the Rain infiltration system, the time between maintenance is very short. Though there is an additional clean-up after an incident, these do not really affect the cost of such a system when compared to a Rain infiltration system that is located in a safer area. The freshwater pump lifetime is longer than the 15-year return period of a Dorian-like hurricane, but the replacement period of 10 years is shorter. This means there is some reduction in value compared to a non-disaster area. This is however similar to Alternative 0. Levee maintenance and loss in value is difficult to assess, due to the size and scale of the structure. Standard maintenance will be done regularly in small sections and major maintenance should be done after events. The levee is an ongoing maintenance project. The criterion Profit for Maintenance & Operation in Mitigation & Preparedness is Adequate (+).

Planet In Alternative 1 & 2 there are no resources used specifically for the use of mitigation or Preparedness for Maintenance & Operation. This is not the case for Alternative 3. To maintain a levee a lot of material is needed. Levees tend to compress and sink, decreasing their height, which needs to be mitigated. Next to the normal settling, there is the repairing of impact by the human hand. For instance, a car could have hit the levee and now it should be filled in again. Compared to Alternative 0 there is an increase in the environmental impact. The criterion Planet for Maintenance & Operation in Mitigation & Preparedness is Inadequate (-).

C.2.3. Preparation

> "If you stay ready. You have not got to get ready" Suga Free 20th May 1997.

As stated before, the preparation phase only has a maximum of 48 hours to complete its goals. The goal of Maintenance & Operation in the Preparation phase is to ensure that planned precautions and actions are taken in this small window of time. The quote of Suga free shown above is topical for Alternative 3. Due to the levee, if properly maintained, the system will be ready for flooding without preparation. The system should still be prepared for wind damage. To prepare for wind damage the water system should be shut down and disconnected from external water and pollution sources. Before this shutdown, the water buffer should be created using the freshwater storage tank and according to the normal operating procedure. This fresh drinking water can be used during the next phase of recovery if the storage tank is not contaminated during the disaster event/recovery phase. To complete the precautions for the disaster skilled manpower is needed.

The overall score of Alternative 3 Preparation Maintenance is Adequate 1+0+0=1. This is based on the following partial scores.

People For people in the maintenance technicians and operators are the stakeholders that are highlighted here. In the Preparation phase, there is the factor of manpower. This means that multiple people need to put the needs of the collective, securing the water treatment plant above their individual needs of looking up their private residence or moving to another island.

Despite the fact that it falls within their job responsibilities, there is a personal sacrifice involved. With the stated Individualism vs. Collectivism of Grand Bahama, it is plausible that such a task might not be carried out. This is comparable to Alternative 0, where the willingness to put job responsibilities above individual and private affairs in a crisis situation.

For the technicians and operators, it is very positive that no manpower or other human factors needed for flooding protection of the infrastructure in this phase, compared to Alternative 0. The criterion People for Maintenance & Operation in Preparation is Adequate (+).

Profit There is no increase in cost due to the lockdown compared to Alternative 0. Next to some additional manpower, there are no costs made or gained compared to Alternative 0. The criterion Profit for Maintenance & Operation in Preparation is Neutral (0).

Planet For the planet, there is no increase in resource utilization compared to Alternative 0. This implies that neither natural resources nor material resources are being consumed in either Alternative 0 or Alternative 1. The criterion Planet for Maintenance & Operation in Preparation is Neutral(0).

C.2.4. Response

The Response phase is a reaction to a disaster or emergency. It is assumed that the water treatment plant will not be operating during the disaster. During the previous phase, the Preparation phase, the facilitates are prepared for the disaster. It is assumed there will be no human or other external change made to the facilities except directly by the hurricane. Search and rescue activities are not within the scope of the alternative, even though the levee will have an impact on those aspects.

The overall score of alternative 3 Response Maintenance & Operation scenario 1 is Neutral 0+0+0=0. The overall score of alternative 3 Response Maintenance & Operation scenario 2 is Inadequate 0-1+0=-1.

People In this phase, the search and rescue is assumed to be out of scope. There have been stories heard during the workshop van der Hucht et al. [2021] of operators trying to prevent further damage when the 3-day hurricane Dorian hit the island, but again this is out of the scope of this thesis. For people, there is no direct planned interaction between the operators and the water treatment plan in this phase, similar to Alternative 0. This is the same for both Scenarios 1&2. The criterion People for Maintenance & Operation in Response is Neutral (0).

Profit After a tropical storm, as described in Subsection 5.1.4, the condition of the maintenance components is presumed to be as follows; Levees (in need of inspection), Rain infiltration system (in need of cleaning), and freshwater pump (contaminated). Compared to the current situation this is a similar loss as in the case of Scenario 1. The criterion Profit for Maintenance & Operation in Response in Scenario 1 is Neutral(0).

After a hurricane, as described in Subsection 5.1.4, the condition of the maintenance components is presumed to be as follows; Levees (in need of repair), Rain infiltration system (in need of cleaning and repair), and freshwater pump (contaminated) Compared to Alternative 0 this is a bigger loss in the case of Scenario 2, due to the impact or repair of the levee. The criterion Profit for Maintenance & Operation in Response in Scenario 2 is Inadequate(-).

Planet For the planet, within the scope of the case study, there are no resources used. Meaning there are no natural resources and material resources used, by Alternative 0 or Alternative 1. This is the same for both Scenarios 1&2. The criterion Planet for Maintenance & Operation in Response is Neutral(0).

C.2.5. Recovery

For the recovery phase of this alternative, the biggest issue is the need for grid power, similar to Alternative 1. The difference in impact depends on the intensity of the disaster. The specifics of the intensity of the disaster are elaborated on in the paragraphs below. It has 2 stages of temporary water production. The functionality of these stages depends on the available infrastructure. To determine which stage is applicable assessment and cleaning of the system is crucial.

In Stage 1 the goal is to start producing water as quickly as possible. To be able to produce water the facilities themselves need to be operational. To be operational the facilities need to be repaired and cleaned from the damage done by the event. In Alternative 3 there are no fallback options and the dependence on the stored water by the inhabitants is high. In Stage 1, the water can not yet be distributed or produced.

In Stage 2 production of drinking water starts with the current infrastructure and distribution over the island with power from the electricity network. Stage 2 is the full normal stage and has no difference compared to the normal situation.

After the disaster, the operation of the RO needs to be started as quickly as possible. It has 3 stages of temporary water production.

In Stage 1 the goal is to start producing water as quickly as possible. To be able to produce water with RO the facilities themselves need to be operational. These RO facilities are the infrastructure components mentioned earlier. To be able to produce on-site electricity diesel generators and fuel need to be available after the disaster. In Stage 1, the water can not yet be distributed or produced. Locals are dependent on their personal storage of drinking water. The first stage is the repairing stage.

In Stage 2 production of drinking water with RO starts with on-site electricity production, the generators. This water will go no further than the reservoir and will not yet be distributed over the island. In the second stage connecting the water treatment plant to the water distribution is vital to get it back to normalcy.

In Stage 3 production of drinking water starts with RO into the reservoir and distribution over the island with power from the electricity network. Stage 3 is the full normal stage and has no difference compared to the normal situation.

In the case of an incomplete levee system, when a Dorian-like storm hits the island, stage 1 will not only involve repairing and cleaning of the drinking water system infrastructure but also dealing with contamination of the drinking water source. In 2019 the drinking water became so brackish and the wells were so salty that 2 years after the hurricane it still was not suited for drinking. This will be a devastating scenario if repeated. Between the stages, it might be possible to have the water treatment plant operate at half capacity. The reason that the plant is operating at half capacity is caused by contamination, damaged material, lack of electricity, lack of pressure, etc. The wells can operate independently because they have their own water treatment system and can operate parallel. It could be possible to produce at a lower capacity. Crucial infrastructural components need to be still operational. The components also need to be cleaned before use.

The overall score of Alternative 3 Recovery Maintenance & Operation Scenario 1 is Neutral 0+0+0=0. The overall score of Alternative 3 Recovery Maintenance & Operation Scenario 2 is Neutral 0+0+0=0. First, the expected effects of the two Scenarios are given, and then the overall derived scores above are given in the paragraph People, Profit, and Planet.

People For the operators, this phase is a very busy time. The impact of storms and hurricanes needs to be fixed, replaced, or cleaned. The precise difference in work cannot be estimated by this thesis, but on the scale on which the phases are viewed, it is comparable and the difference is negligible. Therefore for the operators, the scoring is similar to Alternative 0 in both Scenarios. The criterion People for Maintenance & Operation in Recovery is Neutral (0).

Profit During this phase, operators need to work hard to detect and fix problems in the system, similar to Alternative 0. Repairing the levee falls under mitigation. This is because the prepares for the next event but is not needed for the operation of the water treatment system. The criterion Profit for Maintenance & Operation in Recovery in Scenario 1 & 2 is Neutral(0).

Planet For the planet, there are no increased resources used compared to Alternative 0. Meaning there are no natural resources or material resources used. For Scenario 2 there are material resources used, and membranes need to be shipped from the mainland. The criterion Planet for Maintenance & Operation in Recovery is Neutral (0).

C.3. End-of-Life

The term End-of-Life (EoL) is used here to refer to the end of the lifespan of a system or one of its components.

The WM criteria grouped under "End-of-Life" include reuse, redistribution, recycling, and the environmental effects of demolition. For long-lived products, like a water system, the impact of EoL processes such as demolition and disposal will occur in the distant future. For construction materials, EoL processes are often estimated to occur within 50 to 100 yearsFrijia et al. [2012],Sandin et al. [2014]. A non-disaster-stricken Water treatment system has a lifespan of 50 years. These longer time frames cause technological uncertainty, meaning new technology could be developed for disposal and the type of substituted technology can change. Straight-line depreciation times of 100 years do exist in financial accounting for long-lived assets. The use of straight-line depreciation is difficult to justify if a disaster can rapidly decrease the value of the system to zero. A hurricane disrupts the process of depreciation, meaning that implementation of a straight-declining line is impractical. The nature of EoL processes is highly uncertain, even without disasters. This time-dependent uncertainty has previously been acknowledged as a challenge for life cycle assessments (LCA) in the construction industry [Singh et al., 2011] [Verbeeck and Hens, 2007] [Sandin et al., 2014]. EoL particularly focuses on uncertainties regarding the means of disposal, the expected technology development of disposal processes, and the type of substituted technology. Despite its significance, the element of uncertainty is frequently overlooked in the LCA of constructions and construction materials. Decision makers suffer from this blind spot even when the objective is to inform decisions regarding long-lasting constructions[Bribián et al., 2011],[Habert et al., 2012],[Lundie et al., 2004],[Persson et al., 2006], [Sandin et al., 2014]. Until now, there has been insufficient consideration of EoL uncertainties of long-lived products, which may hamper sound decision-making for sustainable development [Sandin et al., 2014].

A scenario can be used to cope with this uncertainty surrounding EoL. Setting up scenarios to account for different possible futures of EoL has been done before [Bouhaya et al., 2009]. When modeling future disposal processes several fundamentally different scenarios are needed according to Mathiesen et al. [2009]. The construction of a complete model of EoL is out of the scope of this thesis. Sandin et al. [2014] recommend cornerstone scenarios to capture the range of possible outcomes of temporally more dynamic impact assessments. These Cornerstone scenarios are similar to the scenarios suggested by the Three-Point Approach used in the thesis. Combining the need for EoL scenarios with the scenarios in this thesis will boil down to Normal circumstances, tropical storms, and hurricanes. The Normal circumstances will assume that the whole 50 years of the water system lifespan will be utilized. Making a comparison of the alternative with Alternative 0 in the case no disaster will strike in that time frame. In the disaster phases, (Mitigation & Preparedness, Preparation, Recovery, and Response) the degradation in the system value by the disaster will be compared and scored, this will be scenario-dependent.

In the case study regular transportation is equivalent to international shipping. Transportation has a higher impact on an island. Normally transportation and supply-chain processes would be of lower importance when contrasted to demolition [Sandin et al., 2014].

To have transportation have an environmental effect will be a significant element in the EoL. Another element of EoL is the emissions and waste which occur during EoL processes. Waste is an unavoidable by-product of most human activity. The term “waste” refers to any product or substance that is no longer suited for its intended use [Balwan et al., 2022].

At the end of the life cycle of a chlorinated system, nearly all components will have been replaced. The only components which in normal circumstances would not be replaced are infrastructure components. Of the components only the levee has a longer lifespan than the water system.

C.3.1. Normal Circumstances

In Normal circumstances, it is expected that the entire 50-year lifespan of the water system will be utilized. Making a comparison of the alternative with Alternative 0 in the case no disaster will strike in that time frame.

In Alternative 3, similar to Alternative 0, the water gets pumped up from the freshwater aquifer, which then is chlorinated and distributed. This freshwater aquifer is now protected by a levee from flooding by salt water, preventing salinization. This levee is the only infrastructure component remaining after the end-of-life period of the water system.

The overall score of Alternative 3 Normal Circumstances End-of-Life is Neutral x+0+0=0. This is based on the following partial scores.

People For the criterion people there is no score given because it does not apply, see Subsection 3.2.1 for more details.

Profit Similar to Alternative 2, some infrastructure components are underground, to be able to extract fresh groundwater. This makes the demolition costs similar to that of Alternative 0. The depreciation period is similar to that of Alternative 0, and better than Alternative 1 due to the usage of freshwater. The criterion Profit for End-of-Life in Normal circumstances is Neutral (0).

Planet The infrastructure could be reused and recycled to be used in other infrastructure projects on the island. The environmental effects of demolition are similar to those of Alternative 0. The criterion Planet for End-of-Life in Normal circumstances is Neutral(0).

C.3.2. Mitigation & Preparedness

Similar to Alternative 1 & 2 the length of the Mitigation & Preparedness phase is too short for the EoL depreciation time frame in the case of Scenario 1, 2 years, especially for the levee. The length of the Mitigation & Preparedness phase in Scenario 2 is just long enough to have some EoL depreciation, it is equivalent to more than a third of the time frame, 15 years. The goal of the Mitigation & Preparedness phase is to anticipate the next phases of the disaster cycle, which consumes material but does not produce waste. The overall score of Alternative 1 Mitigation & Preparedness End-of-Life is for both Scenario 1 and Scenario 2 Neutral x+0+0=0 This is based on the following partial scores.

People For the criterion people there is no score given because it does not apply, see Subsection 3.2.1 for more details.

Profit In the time frame of this disaster phase depreciation occurs, especially in Scenario 2. However, this is similar to the depreciation of Alternative 0. The criterion Profit for End-of-Life in Mitigation & Preparedness is in both Scenario 1 and Scenario 2 Neutral (0).

Planet No waste is produced during this phase and no future environmental effects of demolition occur. This is comparable to Alternative 0 in this phase. The criterion Planet for End-of-Life in Mitigation & Preparedness is in both Scenario 1 and Scenario 2 Neutral (0).

C.3.3. Preparation

As stated before, the Preparation phase only has a maximum of 48 hours to complete its goals. The length of the Preparation phase is too short for the EoL depreciation time frame. The goal of the Preparation phase is to prepare for the disaster, which consumes material and manpower but doesn't produce waste. The overall score of Alternative 3 preparation End-of-Life is Neutral x+0+0=0. This is based on the following partial scores.

People For the criterion people there is no score given because it does not apply, see Subsection 3.2.1 for more details.

Profit In this time frame of this disaster phase, no depreciation occurs. This is similar to the depreciation of Alternative 0. The criterion Profit for End-of-Life in Preparation is Neutral (0).

Planet No waste is produced during this phase and no future environmental effects of demolition occur. This is comparable to Alternative 0 in this phase. The criterion Planet for End-of-Life in Preparation is Neutral (0).

C.3.4. Response

The length of the Response phase is too short for the EoL depreciation time frame, but it is shortened by the disaster. During the Response phase waste is produced, with components that can no longer operate in their original function. Also, rapid degradation takes place due to the disaster event.

The overall score of Alternative 3 Response End-of-Life Scenario 1 is Neutral x+0+0=0. The overall score of Alternative 3 Response End-of-Life Scenario 2 is Neutral x+0+0=0. First, the expected effects of the two scenarios are given, and then the overall derived scores above are given in the paragraph People, Profit, and Planet.

People For the criterion people there is no score given because it does not apply, see Subsection 3.2.1 for more details.

Profit In this time frame of this disaster phase, depreciation occurs, due to the disaster and not due to time passing. This is similar to the depreciation of Alternative 0. The criterion Profit for End-of-Life in Response is Neutral (0).

Planet Waste is produced during this phase and environmental effects of demolition occur. These are however linked to the disaster event and not to the water system. This is comparable to Alternative 0 in this phase. The criterion Planet for End-of-Life in Response is Neutral(0).

C.3.5. Recovery

The goal of the Recovery phase is to bring the affected area back to some degree of normalcy. Recovery involves decisions and actions relative to rebuilding homes, replacing property, resuming employment, restoring businesses, and permanently repairing and rebuilding infrastructure. Recovery activity produces waste to be able to get back to normal.

The overall score of Alternative 3 Recovery End-of-Life Scenario 1 is Neutral x+0+0=0. The overall score of Alternative 3 Recovery End-of-Life Scenario 2 is Neutral x+0+0=0.

First, the expected effects of the two scenarios are given, and then the overall derived scores above are given in the paragraph People, Profit, and Planet.

People For the criterion people there is no score given because it does not apply, see Subsection 3.2.1 for more details.

Profit In this time frame of this disaster phase, no depreciation occurs. This is similar to the depreciation of Alternative 0. The criterion Profit for End-of-Life in Recovery is Neutral (0).

Planet Waste is produced during this phase and environmental effects of demolition occur. These are however linked to the disaster event and not to the water system. This is comparable to Alternative 0 in this phase. The criterion Planet for End-of-Life in Recovery is Neutral (0).

Water management criteria	Infrastructure		Maintenance		End of life	
Scenario	Tropical storm	Dorian hurricane	Tropical storm	Dorian hurricane	Tropical storm	Dorian hurricane
Disaster criteria						
Normal circumstances	0		0		0	
M & P phase	-	-	-	-	0	0
Preparation phase	0	0	+	+	0	0
Response phase	0	+ +	0	-	0	0
Recovery phase	0	0	0	0	0	0

Table C.1: MCA scores for Alternative 3

C.4. Overview infrastructure

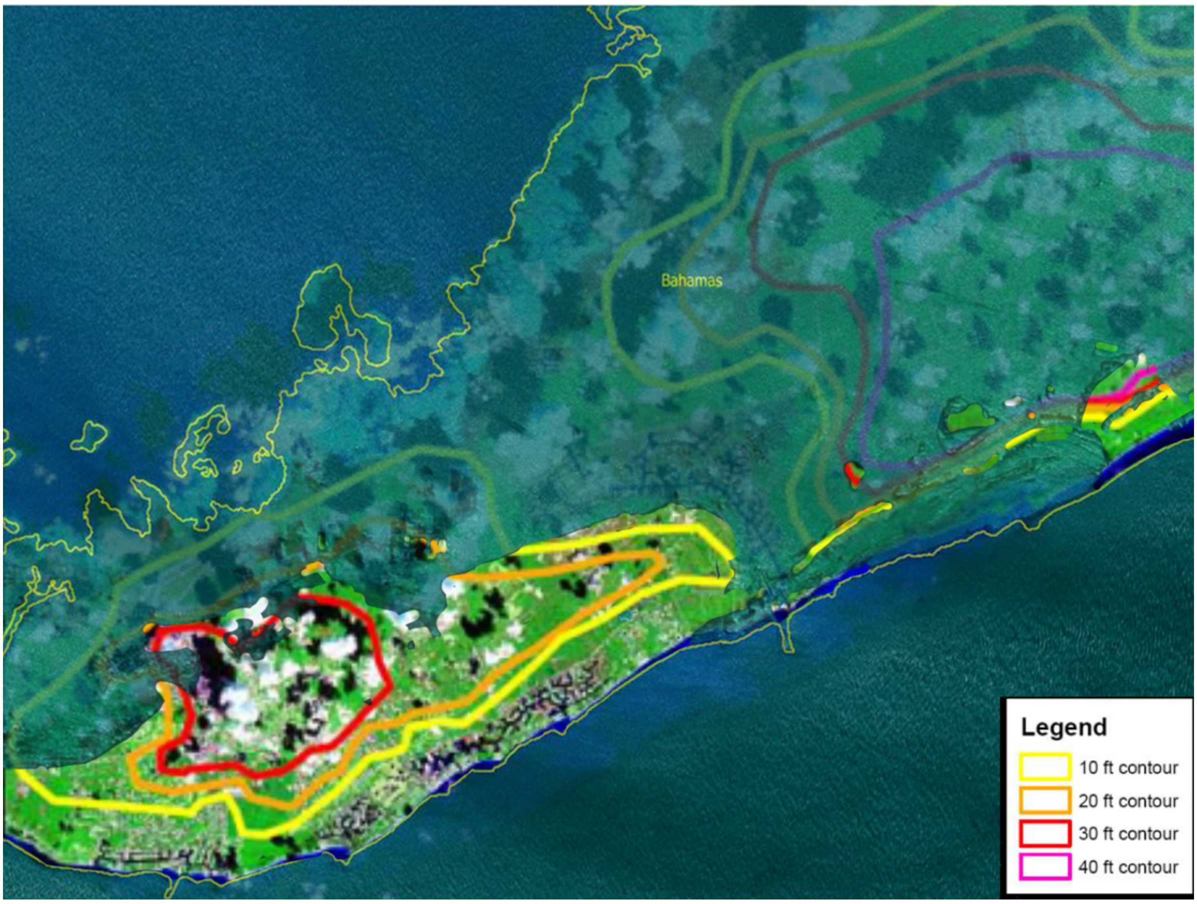


Figure C.1: **Waterlensen with a depth combined with the flooding of a Dorian like storm.**

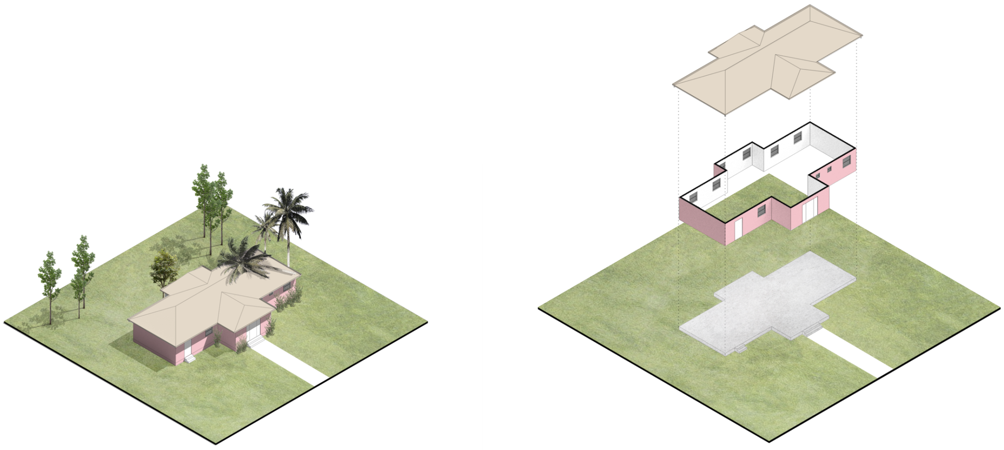
The current situation in Grand Bahama is as follows. The Grand Bahama Utility Company (GBUC) is responsible for the collection and distribution of quality potable water throughout Grand Bahama Island (with the exception of an area developed by Tamarind Development Limited in Lucaya).

There are four water treatment plants that are strategically located within the city limits of Freeport, that draw water from the Grand Bahama aquifer. This water is supplied by the four (4) different pumping stations throughout Grand Bahama Island. These pumping stations supply water to a constructed, interconnecting network of transmission and distribution lines, interfacing with fire hydrants, water meters, and other equipment.

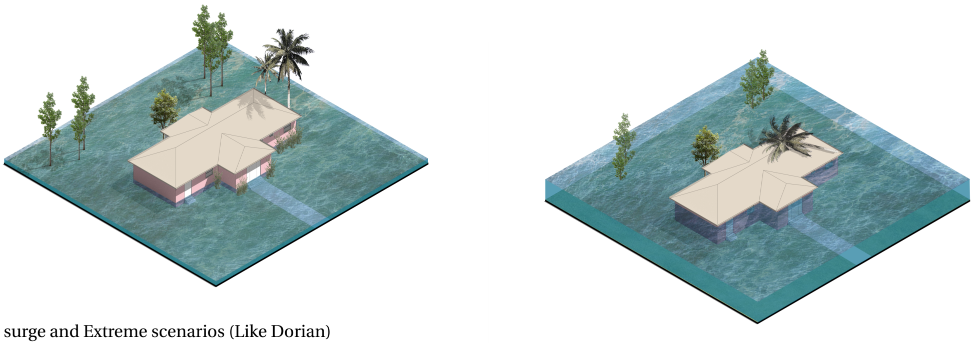
Water is taken from shallow wells, with open-hole construction. At the four (4) water treatment plants water is disinfected via chlorination (Gas), pumped into storage tanks, and ultimately into the distribution system, and tested for quality daily. GBUC, Grand Bahama Utility Company [2020],van der Hucht et al. [2021]

D

Pictures



(a) Analysis of the typical Bahamian architecture



(b) Sea surge and Extreme scenarios (Like Dorian)

Figure D.1: Bahamian architecture credit; F. Ortiz

(a) The social functions

(b) The critical functions

(c) The economic function's.

(d) The industrial facilities

Figure D.2: Location of functions and activities. Note, data from Grand Bahama Port Authority and Office of Coast Survey made by P. Grgic

Figure D.2a	The social functions	Functions including all the activities that make the social and cultural of the inhabitants richer, such as the art centres, churches, libraries, parks, public buildings, sports facilities, and other social facilities.
Figure D.2b	The critical functions.	These are all the activities and functions that are fundamentally important during an extreme hurricane scenario and for the recovery of the urban environment after an extreme event. These are the health facilities, governmental offices, clinics, courthouses, fire stations, hospitals, airports, education facilities, police stations, post offices.
Figure D.2c	The economic function's.	The functions and activities crucial for the island's economy, both in the daily scenario and after a storm. These are places of worship and in general tourism facilities, offices, companies, commercial activities, fast foods, hotels, marketplaces, nightclubs, retails, restaurants, and other shops.
Figure D.2d	The industrial facilities	Industrial facilities are the most difficult to integrate with the residential function, because of managerial and technical reasons. These are farms, hangars, car rentals, construction sites, crematoriums, industrial facilities, parking plots, storage, rentals, and warehouses.

Table D.1: functions and activities. data from Grand Bahama Port Authority and Office of Coast Survey

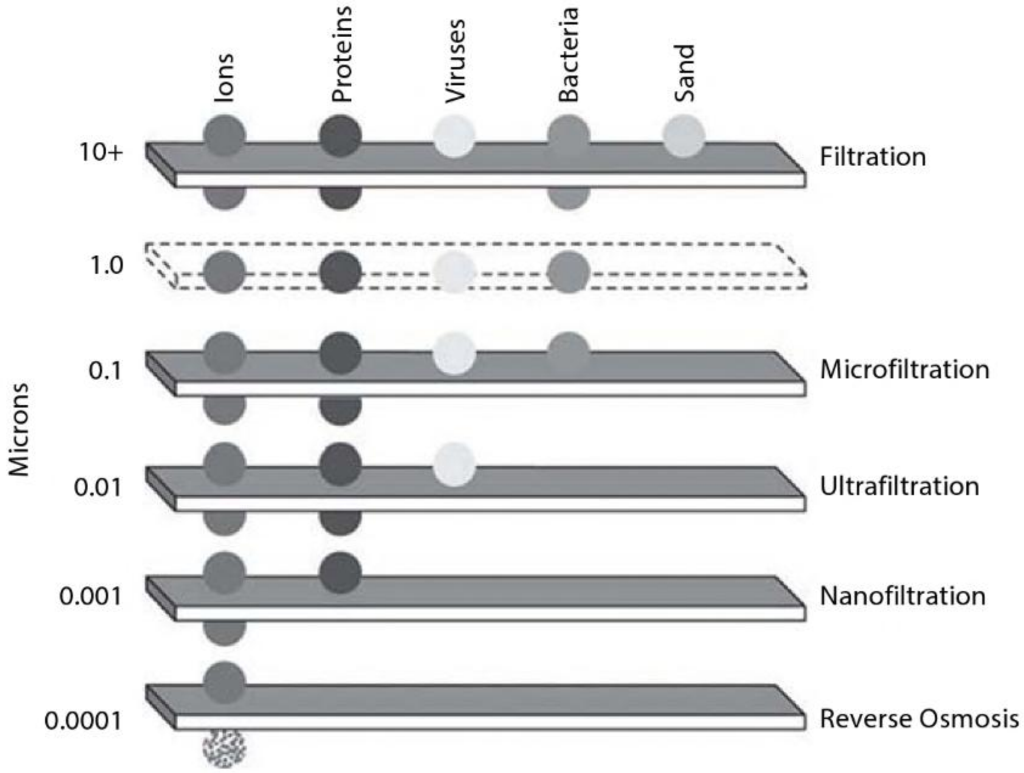


Figure D.3: "Filtration Spectrum" comparing the rejection capabilities of reverse osmosis with other membrane technologies and with the separation afforded by conventional, multimedia filtrationKucera [2015]

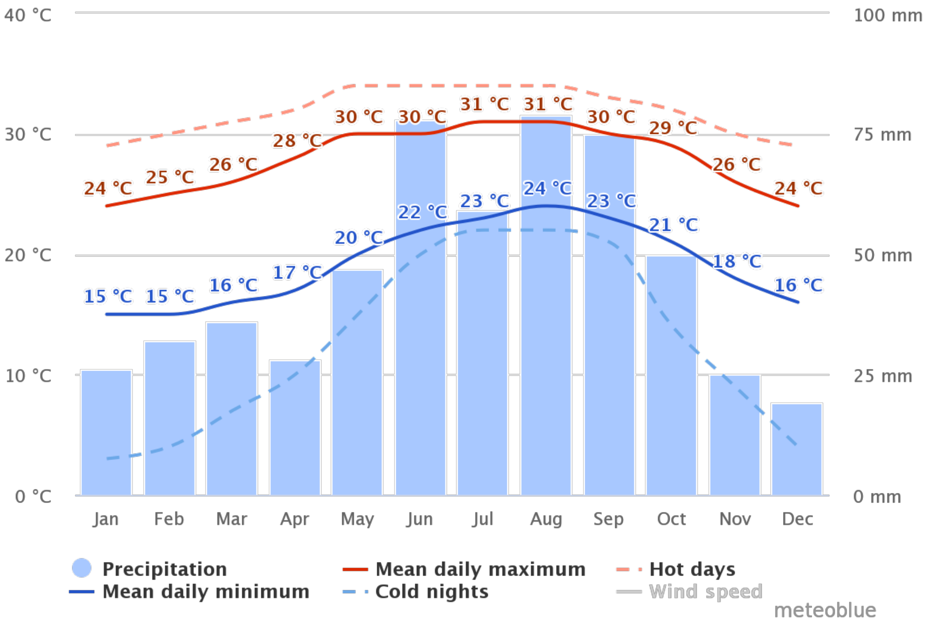


Figure D.4: Freeport modelled climate graph Meteo Blue [2022]

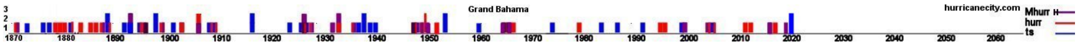


Figure D.5: Mhurr= Mayor hurricane hurr=hurricane ts=tropical storm. Includes brushes form both hurricane and tropical storms.

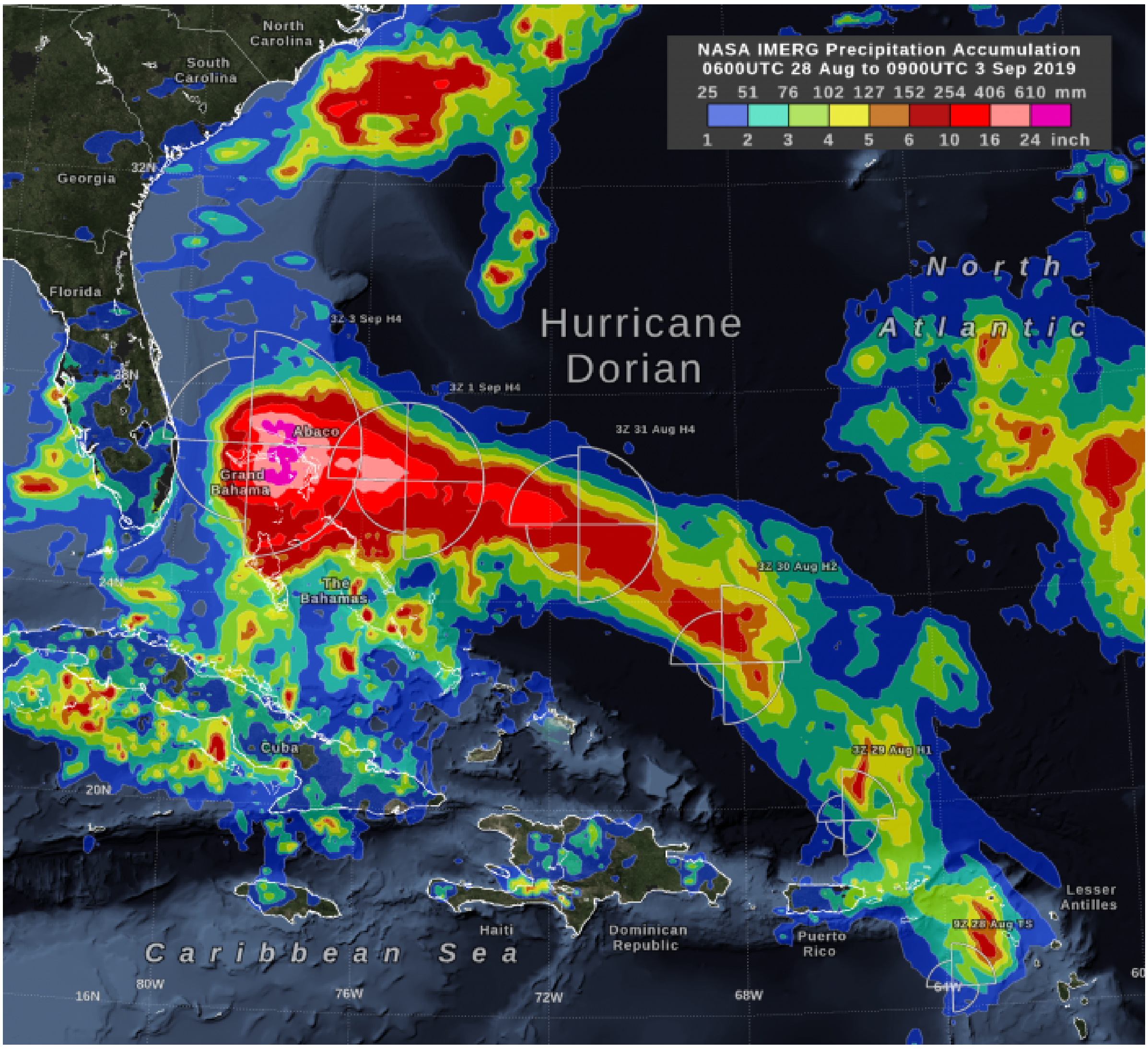


Figure D.6: Rainfall accumulation for Hurricane Dorian from August 28th to September 3rd, 2019. Credit: Owen Kelley (NASA GSFC) Reed [2019, August 29]

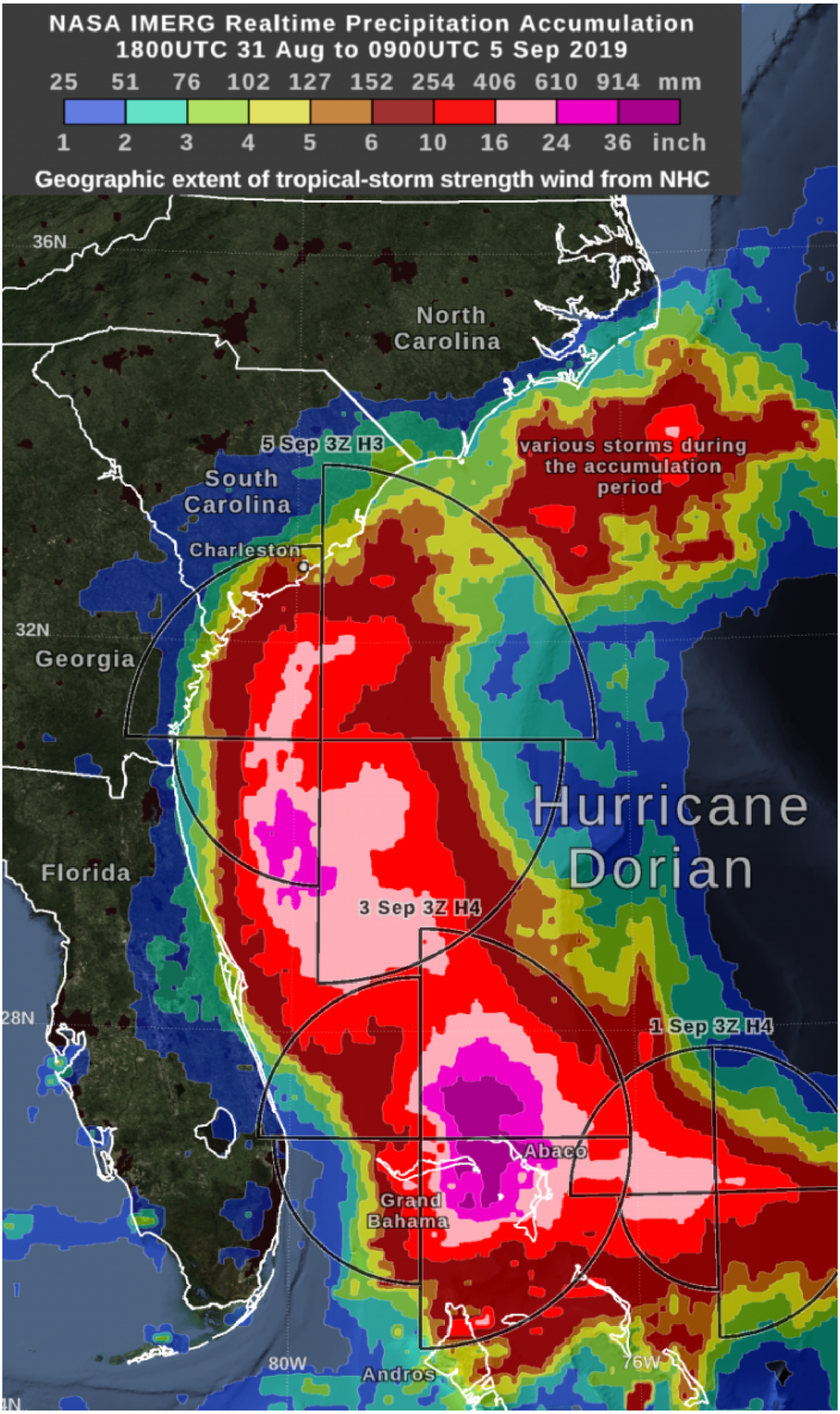


Figure D.7: Estimated rainfall totals for Hurricane Dorian from August 31st - September 5th, 2019. Credit: Owen Kelley (NASA GSFC) Reed [2019, August 29]

(a) Destroyed school building on the university campus that had been flooded by a storm surge credit; T. Özdemir

(b) Destroyed dorm on the university campus that had been flooded by a storm surge credit; F. Ortiz

(c) Landscape of residential area flooded by a storm surge credit; F. Ortiz

(d) Outside a destroyed residential house flooded by storm surge of Dorian credit; F. Ortiz

(e) Inside destroyed residential house flooded by storm surge of Dorian credit; F. Ortiz

Bibliography

AAA Japan Co. Ltd. Bahamas import regulation for japan used cars, Dec 2021. URL `https://aaajapan.com/information/car-import-rules-from-japan/bahamas`.

M. Abou Rayan and I. Khaled. Seawater desalination by reverse osmosis (case study). Desalination, 153(1): 245–251, 2003. ISSN 0011-9164. doi: https://doi.org/10.1016/S0011-9164(02)01143-8.

M. D. Afonso, J. O. Jaber, and M. S. Mohsen. Brackish groundwater treatment by reverse osmosis in jordan. Desalination, 164(2):157–171, 2004.

Z. Al Suleimani and V. R. Nair. Desalination by solar-powered reverse osmosis in a remote area of the sultanate of oman. Applied Energy, 65(1-4):367–380, 2000.

M. L. Anderson and M. Auffhammer. Pounds that kill: The external costs of vehicle weight. Review of Economic Studies, 81(2):535–571, 2014.

K. Andersson, S. Dickin, and A. Rosemarin. Towards “sustainable” sanitation: challenges and opportunities in urban areas. Sustainability, 8(12):1289, 2016.

M. M. Andreasen, C. T. Hansen, P. Cash, M. M. Andreasen, C. T. Hansen, and P. Cash. Change, development, and conceptualization: Setting the scene. Conceptual Design: Interpretations, Mindset and Models, pages 13–34, 2015.

J. M. Antalffy, M. G. Rowley, S. B. Johnson, S. Cant-Woodside, E. H. Freid, K. E. Omland, and M. E. Fagan. Comparing global and local maps of the caribbean pine forests of andros, home of the critically endangered bahama oriole. Environmental Monitoring and Assessment, 193:1–16, 2021.

APnews. A look at previous hurricanes that have affected the bahamas. The Associated Press, 08 2019. URL `https://apnews.com/0e4771697208445db7a05ebfeda1b1b5`.

A. H. Aubert, R. Bauer, and J. Lienert. A review of water-related serious games to specify use in environmental multi-criteria decision analysis. Environmental modelling & software, 105:64–78, 2018.

P. Bak. How nature works: the science of self-organized criticality. Springer Science & Business Media, 1996.

W. K. Balwan, A. Singh, and S. Kour. 5r’s of zero waste management to save our green planet: A narrative review. European Journal of Biotechnology and Bioscience, 10(1):7–11, 2022.

G. Barjoveanu, I. M. Comandaru, G. Rodriguez-Garcia, A. Hospido, and C. Teodosiu. Evaluation of water services system through lca. a case study for iasi city, romania. The International Journal of Life Cycle Assessment, 19:449–462, 2014.

BCED, The Bahamas Customs & Excise Department. General customs procedures, 2020a. URL `https://www.bahamascustoms.gov.bs/imports-and-exports/about-ecas/`.

BCED, The Bahamas Customs & Excise Department. General customs procedures, 2020b. URL `https://www.bahamascustoms.gov.bs/imports-and-exports/common-rates-of-duty/`.

BCED, The Bahamas Customs & Excise Department. General customs procedures, 2020c. URL `https://www.bahamascustoms.gov.bs/serz-extension/`.

I. Ben Ali, M. Turki, J. Belhadj, and X. Roboam. Systemic design and energy management of a standalone battery-less pv/wind driven brackish water reverse osmosis desalination system. Sustainable Energy Technologies and Assessments, 42:100884, 2020.

N. Bethel. Junkanoo, territory and identity: The locality of competition, page 16. Media Enterprises, 01 2003. ISBN 9789768170569.

H. Blanco, M. Alberti, R. Olshansky, S. Chang, S. M. Wheeler, J. Randolph, J. B. London, J. B. Hollander, K. M. Pallagst, T. Schwarz, F. J. Popper, S. Parnell, E. Pieterse, and V. Watson. Shaken, shrinking, hot, impoverished and informal: Emerging research agendas in planning. Progress in Planning, 72(4):195–250, Nov. 2009. doi: 10.1016/j.progress.2009.09.001. URL `https://doi.org/10.1016/j.progress.2009.09.001`.

BMoT, The Bahamas Ministry of Tourism. Characterization of visitor arrivals, 2019. URL `https://www.tourismtoday.com/services/statistics/visitor-arrivals`.

T. M. Boers and J. Ben-Asher. A review of rainwater harvesting. Agricultural water management, 5(2):145–158, 1982.

J. Borell and K. Eriksson. Learning effectiveness of discussion-based crisis management exercises. International Journal of Disaster Risk Reduction, 5:28–37, Sept. 2013. doi: 10.1016/j.ijdrr.2013.05.001. URL `https://doi.org/10.1016/j.ijdrr.2013.05.001`.

J. Bosboom and M. Stive. Coastal Dynamics 1. TU Delft Open, 2015. doi: 10.5074/T.2021.001. URL `https://textbooks.open.tudelft.nl/textbooks/catalog/book/37`.

J. Bosboom and M. Stive. Coastal dynamics 2 lecture slides, 2020. URL `https://brightspace.tudelft.nl/`.

L. Bouhaya, R. Le Roy, and A. Feraille-Fresnet. Simplified environmental study on innovative bridge structure. Environmental science & technology, 43(6):2066–2071, 2009.

I. Z. Bribián, A. V. Capilla, and A. A. Usón. Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. Building and environment, 46(5):1133–1140, 2011.

G. Brumfiel and A. Hurt. Satellite imagery shows extent of devastating flooding on grand bahama island. NPR, Sep 2019. URL `https://www.npr.org/2019/09/03/757139724/satellite-imagery-shows-extent-of-devastating-flooding-on-grand-bahama-island`.

B. Buckingham. King Tide causing record flooding in coastal South Florida. Accuweather, September 2019. URL `https://www.accuweather.com/en/weather-news/king-tide-to-cause-flooding-in-portions-of-coastal-south-florida/592178`.

R. J. Bull, L. BIRNBAUM, K. P. Cantor, J. B. Rose, B. E. Butterworth, R. Pegram, and J. Tuomisto. Water chlorination: essential process or cancer hazard? Toxicological Sciences, 28(2):155–166, 1995.

R. J. Burby et al. Cooperating with nature: confronting natural hazards with land-use planning for sustainable communities. Joseph Henry Press, 1998.

W. C. Burns. Pacific island developing country water resources and climate change. The world's water, 2003: 113–131, 2002.

R. V. Cant and P. S. Weech. A review of the factors affecting the development of ghyben-hertzberg lenses in the bahamas. Journal of Hydrology, 84(3):333–343, 1986. ISSN 0022-1694. doi: https://doi.org/10.1016/0022-1694(86)90131-9. URL `https://www.sciencedirect.com/science/article/pii/0022169486901319`.

N. Caravaggio, S. Caravella, A. Ishizaka, and G. Resce. Beyond CO2: A multi-criteria analysis of air pollution in europe. Journal of Cleaner Production, 219:576–586, May 2019. doi: 10.1016/j.jclepro.2019.02.115. URL `https://doi.org/10.1016/j.jclepro.2019.02.115`.

L. Catel, E. Couliou, L. Guerin-schneider, J. L. Lablee, E. Risch, P. Roux, and G. Russo. Notice et aide du logiciel - acv4e.inrae.fr, Apr 2018. URL `https://acv4e.inrae.fr/wp-content/uploads/2018/06/Notice-et-Aide-ACV4E_v7.pdf`.

CDC, Centers for Disease Control and Prevention, Oct 2019. URL `https://www.cdc.gov/disasters/hurricanes/before.html`.

F. Chen, N. Duic, L. Manuel Alves, and M. da Graça Carvalho. Renewislands—renewable energy solutions for islands. Renewable and Sustainable Energy Reviews, 11(8):1888–1902, 2007. ISSN 1364-0321. doi: https://doi.org/10.1016/j.rser.2005.12.009. URL `https://www.sciencedirect.com/science/article/pii/S1364032106000232`.

Chief Census Office. 2010 Census of Population and Housing. the Department of Statistics, 2012. URL `http://www.bahamas.gov.bs/statistics`.

Chief Census Office. 2010 Census of Population and Housing, 3rd release Migration report, Volume II Internal migration. the Department of Statistics, 2014. URL `http://www.bahamas.gov.bs/statistics`.

W. J. Clinton. Key propositions for building back better: lessons learned from tsunami recovery. Office of the United Nations Secretary-General's Special Envoy for Tsunami Recovery, 2006. doi: 10.1016/j.pdisas.2019.100003. URL `http://dx.doi.org/10.1016/j.pdisas.2019.100003`.

L. M. G. Coelho, H. M. G. Coelho, and L. C. Lange. 12 life cycle assessment applied to support sustainable wastewate r treatment in developing countries. In Life Cycle Assessment of Wastewater Treatment, pages 243–268. CRC Press, 2018.

G. Cuofano. What is a multi-criteria analysis? multi-criteria analysis in a nutshell, Jan 2023. URL `https://fourweekmba.com/multi-criteria-analysis/`.

Deltares. Ecosystem-based adaptation measures for a climate resilient city, Aug 2019. URL `https://publicwiki.deltares.nl/download/attachments/136413790/KBS_handoutEN_selection.pdf?version=1&modificationDate=1620205254292&api=v2`.

Department for Communities and Local Government: London. Multi-criteria analysis: a manual: DETR appraisal guidance. opsi.gov.uk, Jan 2009. URL `https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/7612/1132618.pdf`.

DHS, U.S. Department of Homeland Security. Hurricanes, Nov 2022. URL `https://www.ready.gov/hurricanes`.

C. Dierkes, L. Kuhlmann, J. Kandasamy, and G. Angelis. Pollution retention capability and maintenance of permeable pavements. In Global Solutions for Urban Drainage, pages 1–13. Global Solutions for Urban Drainage, 2002.

J. S. Dodgson, M. Spackman, A. Pearman, and L. D. Phillips. Multi-criteria analysis: a manual. Department for Communities and Local Government: London, 2009.

N. Duić, G. Krajačić, and M. da Graça Carvalho. RenewIslands methodology for sustainable energy and resource planning for islands. Renewable and Sustainable Energy Reviews, 12(4):1032–1062, 2008. ISSN 1364-0321. doi: https://doi.org/10.1016/j.rser.2006.10.015. URL `https://www.sciencedirect.com/science/article/pii/S1364032106001560`.

S. Ehrenberg, G. Eberli, M. Keramati, and S. Moallemi. Porosity-permeability relationships in interlayered limestone-dolostone reservoirs. AAPG bulletin, 90(1):91–114, 2006.

J. Elkington. Cannibals with forks: The triple bottom line of 21st century business, capstone, 1997.

U. A. H. Ezzeghni. Performance improvement of tajoura reverse osmosis seawater desalination (swro) plant. College of Engineering Technology–Janzour, 2016.

T. Fang. A critique of hofstede's fifth national culture dimension. International journal of cross cultural management, 3(3):347–368, 2003.

FEMA Federal Emergency Management Agency. Academic emergency management and related courses (aemrc) for the higher education program, 2022. URL `https://training.fema.gov/hiedu/aemrc/booksdownload/emoutline/`. accessed: 02-08-2022.

J. Feo-García, A. Ruiz-García, E. Ruiz-Saavedra, and N. Melián-Martel. Energy consumption assessment of 4,000 m3/d swro desalination plants. Desalination and Water Treatment, 57(48-49):23019–23023, 2016.

G. Fernandez and I. Ahmed. "build back better" approach to disaster recovery: Research trends since 2006. Progress in Disaster Science, 1:100003, 2019.

C. G. G. Fratini, J. Kluck, and P. Mikkelsen. Three points approach (3pa) for urban flood risk management: A tool to support climate change adaptation through transdisciplinarity and multifunctionality. Urban Water Journal, 9(5):317–331, 2012. doi: 10.1080/1573062X.2012.668913. URL `https://doi.org/10.1080/1573062X.2012.668913`.

I. Freuze, S. Brosillon, A. Laplanche, D. Tozza, and J. Cavard. Effect of chlorination on the formation of odorous disinfection by-products. Water Research, 39(12):2636–2642, 2005.

H. P. Friesema. Aftermath: Communities after natural disasters. Sage Publications, 1979.

S. Frijia, S. Guhathakurta, and E. Williams. Functional unit, technological dynamics, and scaling properties for the life cycle energy of residences. Environmental Science & Technology, 46(3):1782–1788, 2012.

GBPA, Grand Bahama Port Authority. gis-datafiles, Jun 2017. URL `https://github.com/GBPA/gis-datafiles`.

GBPA, Grand Bahama Port Authority. Keep grand bahama clean, Jan 2020. URL `https://gbpa.com/keep-grand-bahama-clean/`.

GBUC, Grand Bahama Utility Company. Company profile, Aug 2020. URL `https://grandbahamautility.com/our-company/company-profile/`.

GBUC, Grand Bahama Utility Company Ltd. Groundwater supply and sustainability yield and storm surge vulnerability study. The Grand Bahama Utility Company Limited, Freeport, Grand Bahama Island, September 2008.

GEE, Google Earth Engine, 2021. URL `https://earthengine.google.com/timelapse/`.

G. D. Geldof and J. Kluck. The three points approach. In Proceedings of 11th ICUD-international conference on urban drainage, volume 31, 2008.

G. D. Giovanni and L. Chelleri. Why and how to build back better in shrinking territories? Emerald Discover, 28(4):460–473, jan 2019a. doi: 10.1108/dpm-12-2017-0322. URL `https://doi.org/10.1108/dpm-12-2017-0322`.

G. D. Giovanni and L. Chelleri. Why and how to build back better in shrinking territories? Disaster Prevention and Management: An International Journal, 28(4):460–473, Jan. 2019b. doi: 10.1108/dpm-12-2017-0322. URL `https://doi.org/10.1108/dpm-12-2017-0322`.

U. Global Change Research Program. Global climate change impacts in the united states 2009 report legacy site, 2009. URL `https://nca2009.globalchange.gov/freshwater-lens/index.html`.

D. R. Godschalk. Urban hazard mitigation: Creating resilient cities. Natural Hazards Review, 4(3):136–143, Aug. 2003. doi: 10.1061/(asce)1527-6988(2003)4:3(136). URL `https://doi.org/10.1061/(asce)1527-6988(2003)4:3(136)`.

D. J. Gooden, R. C. Preziosi, et al. Cultural values and leadership behavior in the united states, jamaica, and the bahamas. International Business & Economics Research Journal (IBER), 3(3), 2004.

Google, 2020. URL `https://www.google.nl/maps/@27.1519799,-78.4285531,251913m/data=!3m1!1e3?`

P. Gordon, H. W. Richardson, B. Davis, C. Stein, A. Vasishth, et al. The business interruption effects of the northridge earthquake. (No Title), 1995.

S. Goudzari. Hurricane alley heats up. livescience, 05 2006. URL `https://www.livescience.com/723-hurricane-alley-heats.htm`. Retrieved 9 September 2008.

L. F. Greenlee, D. F. Lawler, B. D. Freeman, B. Marrot, and P. Moulin. Reverse osmosis desalination: Water sources, technology, and today's challenges. Water Research, 43(9):2317–2348, 2009. ISSN 0043-1354. doi: https://doi.org/10.1016/j.watres.2009.03.010.

P. Grundy. Scenarios: An explorer's guide, 2003. URL `https://s05.static-shell.com/content/dam/shell/static/public/downloads/brochures/corporate-pkg/scenarios/explorers-guide.pdf`.

L. Guerin-Schneider, M. Tsanga-Tabi, P. Roux, L. Catel, and Y. Biard. How to better include environmental assessment in public decision-making: Lessons from the use of an lca-calculator for wastewater systems. Journal of Cleaner Production, 187:1057–1068, 2018.

J. P. Gutiérrez, L. G. Delgado, D. Van Halem, P. Wessels, and L. C. Rietveld. Multi-criteria analysis applied to the selection of drinking water sources in developing countries: A case study of cali, colombia. Journal of Water, Sanitation and Hygiene for Development, 6(3):401–413, 2016.

L. Guérin-Schneider, L. Catel, E. Couliou, M. Tsanga Tabi, and P. Roux. Public decision support and lca: feedback from testing a simplified lca tool for wastewater systems, 2011. URL `https://acv4e.inrae.fr/wp-content/uploads/2016/05/ACV4E_Poster-SETAC-2016-avec-compl%C3%A9ment.pdf`.

J. E. Haas, R. W. Kates, and M. J. Bowden. Reconstruction following disaster. In Reconstruction following disaster. US The Massachusetts Institute of Technology, 1977.

M. Haasnoot, H. Middelkoop, E. van Beek, and W. P. A. van Deursen. A method to develop sustainable water management strategies for an uncertain future. Sustainable Development, 19(6):369–381, Nov. 2009. doi: 10.1002/sd.438. URL `https://doi.org/10.1002/sd.438`.

G. Habert, D. Arribe, T. Dehove, L. Espinasse, and R. Le Roy. Reducing environmental impact by increasing the strength of concrete: quantification of the improvement to concrete bridges. Journal of Cleaner Production, 35:250–262, 2012.

R. Hansmann, H. A. Mieg, and P. Frischknecht. Principal sustainability components: empirical analysis of synergies between the three pillars of sustainability. International Journal of Sustainable Development & World Ecology, 19(5):451–459, 2012.

N. B. Harmancioglu, F. Barbaros, and C. P. Cetinkaya. Sustainability issues in water management. Water Resources Management, 27(6):1867–1891, Oct. 2012. doi: 10.1007/s11269-012-0172-4. URL `https://doi.org/10.1007/s11269-012-0172-4`.

E. Harshfield, D. Lantagne, A. Turbes, and C. Null. Evaluating the sustained health impact of household chlorination of drinking water in rural haiti. The American journal of tropical medicine and hygiene, 87(5): 786, 2012.

R. Heijungs, G. Huppes, and J. B. Guinée. Life cycle assessment and sustainability analysis of products, materials and technologies. toward a scientific framework for sustainability life cycle analysis. Polymer Degradation and Stability, 95(3):422–428, 2010. ISSN 0141-3910. doi: https://doi.org/10.1016/j.polymdegradstab.2009.11.010. URL `https://www.sciencedirect.com/science/article/pii/S0141391009003607`. Special Issue: MoDeSt 2008.

F. Hernández-Padilla, M. Margni, A. Noyola, L. Guereca-Hernandez, and C. Bulle. Assessing wastewater treatment in latin america and the caribbean: Enhancing life cycle assessment interpretation by regionalization and impact assessment sensibility. Journal of Cleaner Production, 142:2140–2153, 2017.

D. C. Hicks, W. A. Fearn, C. M. Pleass, and D. Staples. Development, testing and the economics of a composite/plastic seawater reverse osmosis pump. Desalination, 73:95–109, 1989.

B. Hillier, R. Burdett, J. Peponis, and A. Penn. Creating life: or, does architecture determine anything? Architecture & Comportement/Architecture & Behaviour, 3(3):233–250, 1986.

G. Hofstede. Allemaal andersdenkenden, omgaan met cultuurverschillen (vijfde druk). amsterdam: Contact. vertaling (1991) van: Cultures and organizations, software of the mind, 1995.

G. Hofstede. Business goals for a new world order: beyond growth, greed and quarterly results. Asia Pacific Business Review, 15(4):481–488, 2009. doi: 10.1080/13602380903102029.

G. Hofstede and G. J. Hofstede. Geert hofstede site cv work life theory 6 dimensions of culture gert jan, Feb 2021. URL http://geerthofstede.com/landing-page/.

E. Holden, K. Linnerud, and D. Banister. The imperatives of sustainable development. Sustainable development, 25(3):213–226, 2017.

L. H. Holthuijsen. Waves in oceanic and coastal waters. Cambridge university press, 2007.

F. Hooimeijer, J. Bricker, and K. Iuchi. An interdisciplinary approach to urban reconstruction after the 2011 tsunami. TU Delft DeltaLinks, 2018.

F. Hooimeijer, J. Bricker, A. Pel, A. Brand, F. Van de Ven, and A. Askarinejad. Multi-and interdisciplinary design of urban infrastructure development. Proceedings of the Institution of Civil Engineers-Urban Design and Planning, 175(4):153–168, 2022.

Hurricanecity. Grand bahama island's history with tropical systems, may 2021. URL http://www.hurricanecity.com/city/grandbahama.htm.

IITC, INTERNATIONAL INDIAN TREATY COUNCIL. "water is life" the human right to water and indigenous peoples, Apr 2007. URL https://www2.ohchr.org/english/issues/water/contributions/civilsociety/InternationalIndianTreatyCouncil.pdf.

M. Incorporated. The impact of hurricane season on local water supplies, Nov 2018. URL https://www.meco.com/hurricane-season-impact/.

I. J. Jacoby and D. Greenfader. Government and private-sector coordination and the potential role of solar-power in disaster response: Hurricanes irma and maria in puerto rico. Natural Hazards Review, 22(3): 02521004, 2021.

O. Jolliet, M. Saadé, P. Crettaz, and S. Shaked. Analyse du cycle de vie, comprendre et réaliser un écobilan. 2e édition, lausanne, presse polytechniques et universitaires romandes, 107 p. Science et ingénierie de l'environnement, 2010.

Y. Kajikawa. Research core and framework of sustainability science. sustain sci 3: 215–239, 2008.

Z. R. Kassis, W. Guo, R. G. Maliva, W. S. Manahan, R. Rotz, and T. M. Missimer. Pumping-induced feed water quality variation and its impacts on the sustainable operation of a brackish water reverse osmosis desalination plant, city of hialeah, florida, usa. Sustainability, 15(6):4713, 2023.

T. Keinonen and R. Takala. Product concept design: A review of the conceptual design of products in industry, 2006.

J. Kennedy, J. Ashmore, E. Babister, and I. Kelman. The meaning of 'build back better': evidence from post-tsunami aceh and sri lanka. Journal of contingencies and crisis management, 16(1):24–36, 2008a.

J. Kennedy, J. Ashmore, E. Babister, I. Kelman, and J. Zarins. Disaster mitigation lessons from "build back better" following the 26 december 2004 tsunamis. In Water and urban development paradigms, pages 315–320. CRC Press, 2008b.

H. Khan, L. G. Vasilescu, A. Khan, et al. Disaster management cycle-a theoretical approach. Journal of Management and Marketing, 6(1):43–50, 2008.

S. Khasalamwa. Is 'build back better 'a response to vulnerability? analysis of the post-tsunami humanitarian interventions in sri lanka. Norsk Geografisk Tidsskrift-Norwegian Journal of Geography, 63(1):73–88, 2009.

T. M. Klessens, D. Daniel, Y. Jiang, B. M. Van Breukelen, L. Scholten, and S. Pande. Combining water resources, socioenvironmental, and psychological factors in assessing willingness to conserve groundwater in the vietnamese mekong delta. Journal of Water Resources Planning and Management, 148(3):05021034, 2022.

D. S. Knowles. The investigation of site conditions on the island of grand bahama the bahamas post hurricane dorian commissioned by dr. nader azab, university of bahama in collaboration with bahamas information services, department of archives and local government., 11 2019.

N. Kralik and J. Chrzan. Sustainable Procurement for Infrastructure. American Society of Civil Engineers, 2020. doi: 10.1061/9780784483107. URL `https://ascelibrary.org/doi/abs/10.1061/9780784483107`.

D. Krantz. Solving problems like maria: a case study and review of collaborative hurricane-resilient solar energy and autogestión in puerto rico. Journal of Sustainability Research, 3(1), 2020.

J. Kucera. Reverse osmosis: industrial processes and applications. John Wiley & Sons, 2015.

A. Kwasinski. Effects of hurricane maria on renewable energy systems in puerto rico. In 2018 7th International Conference on Renewable Energy Research and Applications (ICRERA), pages 383–390, 2018a. doi: 10.1109/ICRERA.2018.8566922.

A. Kwasinski. Effects of hurricane maria on renewable energy systems in puerto rico. In 2018 7th International Conference on Renewable Energy Research and Applications (ICRERA), pages 383–390. IEEE, 2018b.

E. Lai, S. Lundie, and N. Ashbolt. Review of multi-criteria decision aid for integrated sustainability assessment of urban water systems. Urban water journal, 5(4):315–327, 2008.

Z. Laing. Hofstede's six dimensions of national culture: Bahamas local news, Jun 2017. URL `https://www.bahamaslocal.com/newsitem/177258/Hofstedes_six_dimensions_of_national_culture.html`.

M. Latva, J. Inkinen, J. Rämö, T. Kaunisto, R. Mäkinen, M. Ahonen, J. Matilainen, and S. Pehkonen. Studies on the magnetic water treatment in new pilot scale drinking water system and in old existing real-life water system. Journal of Water Process Engineering, 9:215–224, 2016.

B. Lennertz, A. Lutzenhiser, and A. Duany. The charrette handbook: The essential guide to design-based public involvement. Chicago, IL: APA Planner Press, 2014.

N. Limphitakphong, C. Pharino, and P. Kanchanapiya. Environmental impact assessment of centralized municipal wastewater management in thailand. The International Journal of Life Cycle Assessment, 21:1789–1798, 2016.

M. Lisica. How do cruise ships get fresh water?, Jul 2021. URL `https://www.pontooners.com/how-do-cruise-ships-get-fresh-water`.

B. Little, D. Buckley, P. Henry, J. Mather, et al. Land resources of the bahamas: A summary. Pascal and Francis, 1977.

Z. Liu. Storm surge predictions for hurricane dorian, Sept 2019. URL `https://medium.com/@oneconcerninc/storm-surge-predictions-for-hurricane-dorian-2019-75457c0acce9`.

J. D. Lloyd, G. Slater, et al. Abundance and distribution of breeding birds in the pine forests of grand bahama, bahamas. Journal of Caribbean Ornithology, 24(1):1–9, 2011.

P. Loubet, P. Roux, E. Loiseau, and V. Bellon-Maurel. Life cycle assessments of urban water systems: A comparative analysis of selected peer-reviewed literature. Water Research, 67:187–202, 2014. ISSN 0043-1354. doi: https://doi.org/10.1016/j.watres.2014.08.048.

A. Lowrey. American cars are getting heavier and heavier. is that dangerous?, Jun 2011. URL `https://slate.com/business/2011/06/american-cars-are-getting-heavier-and-heavier-is-that-dangerous.html`.

S. Lundie, G. M. Peters, and P. C. Beavis. Life cycle assessment for sustainable metropolitan water systems planning, 2004.

M. Lytle. Geology of the bahamas. tropical marine ecology pre-course presentation topic papers. jrscience, 05 2006. URL `http://jrscience.wcp.muohio.edu/fieldcourses06/PapersMarineEcologyArticles/GeologyoftheBahamasFinalP.htm`.

Machinex , Industries Inc. Renew bahamas opens country's first recycling plant, Oct 2016. URL `https://www.machinexrecycling.com/news/renew-bahamas-opens-countrys-first-recycling-plant/`.

S. Mannakkara and S. Wilkinson. Post-disaster legislation for building back better. Construction Law Journal, 29:495–506, 01 2013.

S. Mannakkara and S. Wilkinson. Re-conceptualising “building back better” to improve post-disaster recovery. International Journal of Managing Projects in Business, 2014.

M. A. Massoud, A. Tarhini, and J. A. Nasr. Decentralized approaches to wastewater treatment and management: applicability in developing countries. Journal of environmental management, 90(1):652–659, 2009.

P. Matanle. Post-disaster recovery in ageing and declining communities: the great east japan disaster of 11 march 2011. Geography, 98(2):68–76, July 2013. doi: 10.1080/00167487.2013.12094370. URL `https://doi.org/10.1080/00167487.2013.12094370`.

B. V. Mathiesen, M. Münster, and T. Fruergaard. Uncertainties related to the identification of the marginal energy technology in consequential life cycle assessments. Journal of Cleaner Production, 17(15):1331–1338, 2009.

A. Matin, Z. Khan, S. Zaidi, and M. Boyce. Biofouling in reverse osmosis membranes for seawater desalination: phenomena and prevention. Desalination, 281:1–16, 2011.

A. C. Mehner. Multimedia and ultrafiltration for reverse osmosis pretreatment aboard naval vessels. Inquiry: The University of Arkansas Undergraduate Research Journal, 11(1):14, 2010.

I. Mergel. Social media practices in local emergency management: Results from central new york. University of Konstanz Information, 2014.

M. Meteo Blue. Weather maps: Live satellite & weather radar, 2022. URL `https://www.meteoblue.com/en/weather/maps/index`.

J. W. Miles. On the generation of surface waves by shear flows. part 4. Journal of Fluid Mechanics, 13(3): 433–448, 1962.

J. K. Mitchell. The Long Road to Recovery: Community Responses to Industrial Disaster. UN University Press,, Tokyo ;. 1996, 1996.

M. K. Mooij. Wereldmerken: hoe reclame omgaat met cultuurverschillen. Kluwer, 1998.

G. R. Moss. Rates of duty frequently imported items processing, environmental levy; and vat fees, Jul 2019. URL `https://drive.google.com/file/d/1NalVAGGjEJhJDQ8up443vq5QGBLfotoF/view`.

I. Muñoz and A. R. Fernández-Alba. Reducing the environmental impacts of reverse osmosis desalination by using brackish groundwater resources. Water Research, 42(3):801–811, 2008.

F. Naz and M.-C. Buisson. Multiple actors, conflicting roles and perverse incentives: The case of poor operation and maintenance of coastal polders in bangladesh. In Revitalizing the Ganges Coastal Zone: Turning Science into Policy and Practices Conference Proceedings. Colombo, Sri Lanka: CGIAR Challenge Program on Water and Food (CPWF). 600pp, page 147, 2015.

Nederland Monumentenland, openmonumentendag. Over open monumentendag, Sep 2023. URL `https://www.openmonumentendag.nl/over-ons/`.

NEMA, National Emergency Management Agency, May 2006. URL `www.bahamas.gov.bs/nema`.

B. News. Hurricane dorian: Storm inches north west, leaving devastation in bahamas, (2019, September 3. URL `https://www.bbc.com/news/world-latin-america-49561450`.

NHC, National Hurricane Center, Aug 2019. URL `https://www.nhc.noaa.gov/aboutsshws.php`.

NOAA, National Oceanic and Atmospheric Administration. Hurricane dorian, September 2019. URL `https://www.nhc.noaa.gov/archive/2019/al05/al052019.public.041.shtml`.

NOAA, National Oceanic and Atmospheric Administration. Tropical cyclone climatology, 2020. URL `https://www.nhc.noaa.gov/climo/`.

NSPE, National Society of Professional Engineers. Code of ethics, Jul 2019. URL `https://www.nspe.org/resources/ethics/code-ethics`.

R. Olshansky and S. Chang. Planning for disaster recovery: Emerging research needs and challenges. Progress in planning, 72(4):200–209, 2009.

B. J. O'Callaghan and E. Murdock. Are we building back better? evidence from 2020 and pathways for inclusive green recovery spending. UN environment programme, 2021.

J. Packard. Grand bahama struggles to recover after hurricane dorian, 2019, September 12. URL `https://www.newsy.com/stories/grand-bahama-struggles-to-recover-after-hurricane-dorian`.

E. Parson, V. Burkett, K. Fisher-Vanden, D. Keith, L. Mearns, H. Pitcher, C. Rosenzweig, and M. Webster. Global-change scenarios: Their development and use. U.S. Climate Change Science Program and the Subcommittee on Global Change Research, 07 2007.

B. Parsons and D. Denney. Sustainability, Apr 2023. URL `https://www.asce.org/communities/institutes-and-technical-groups/sustainability`.

PDC, Pacific Disaster Center. Pdc assessment and exercise aid bahamas hurricane season preparedness and drr - bahamas, Jul 2022. URL `https://reliefweb.int/report/bahamas/pdc-assessment-and-exercise-aid-bahamas-hurricane-season-preparedness-and-drr`.

M. Pelling. The vulnerability of cities; natural disasters and social resilience, Earthscan, London. Earthscan, 01 2003. ISBN 1-853838292.

B. Peñate and L. García-Rodríguez. Current trends and future prospects in the design of seawater reverse osmosis desalination technology. Desalination, 284:1–8, 2012.

C. Persson, M. Fröling, and M. Svanström. Life cycle assessment of the district heat distribution system. part 3: Use phase and overall discussion (10 pp). The International Journal of Life Cycle Assessment, 11:437–446, 2006.

Purdue OWL; College of Liberal Arts, Purdue Online Writing Lab. Stage 1: Conceptual design, Aug 2023. URL `https://owl.purdue.edu/owl/subject_specific_writing/writing_in_engineering/engineering_project_documentation/stage_one_conceptual_design.html`.

B. Purvis, Y. Mao, and D. Robinson. Three pillars of sustainability: in search of conceptual origins. Sustainability science, 14:681–695, 2019.

R. G. Raluy, L. Serra, J. Uche, and A. Valero. Life cycle assessment of water production technologies-part 2: reverse osmosis desalination versus the ebro river water transfer (9 pp). The International Journal of Life Cycle Assessment, 10:346–354, 2005.

J. Reed. Gpm imerg measures rainfall accumulation from hurricane dorian in the caribbean, 2019, August 29. URL `https://appliedsciences.nasa.gov/our-impact/news/gpm-imerg-measures-rainfall-accumulation-hurricane-dorian-caribbean`.

P. Rei, J. P. Fonseca, N. Duic, and M. Carvalho. Integration of renewable energy sources and hydrogen storage in the azores archipelago. In Proceedings of the International Conference on New and Renewable Technologies for Sustainable Development, 2002.

J. Ren. Methods in Sustainability Science: Assessment, Prioritization, Improvement, Design and Optimization. Elsevier, 2021.

Research, F. R. S. R. Statistics Department, and S. D. B. M. of Tourism. Frequently requested tourism statistics report, 2019. URL `https://www.tourismtoday.com/sites/default/files/frequently_requested_statistics_brochure_2019_latest_1.pdf`.

REVERSE OSMOSIS, International Division. Fresh water: Reverse osmosis desalination systems. Islands Magazine, 11(6), 1991. ISSN 0745-7847.

B. S. Richards and A. I. Schäfer. Design considerations for a solar-powered desalination system for remote communities in australia. Desalination, 144(1-3):193–199, 2002.

E. Risch, P. Loubet, M. Núñez, and P. Roux. How environmentally significant is water consumption during wastewater treatment?: Application of recent developments in lca to wwt technologies used at 3 contrasted geographical locations. Water Research, 57:20–30, 2014a.

E. Risch, P. Loubet, M. Núñez, and P. Roux. How environmentally significant is water consumption during wastewater treatment?: Application of recent developments in lca to wwt technologies used at 3 contrasted geographical locations. Water Research, 57:20–30, 2014b. ISSN 0043-1354. doi: https://doi.org/10.1016/j.watres.2014.03.023.

E. Risch, O. Gutierrez, P. Roux, C. Boutin, and L. Corominas. Life cycle assessment of urban wastewater systems: Quantifying the relative contribution of sewer systems. Water Research, 77:35–48, 2015a. ISSN 0043-1354. doi: https://doi.org/10.1016/j.watres.2015.03.006.

E. Risch, O. Gutierrez, P. Roux, C. Boutin, and L. Corominas. Life cycle assessment of urban wastewater systems: Quantifying the relative contribution of sewer systems. Water research, 77:35–48, 2015b.

D. Rivero. Six months after dorian, grand bahama scrambles for clean drinking water, Mar 2020. URL `https://wusfnews.wusf.usf.edu/2020-03-09/six-months-after-dorian-grand-bahama-scrambles-for-clean-drinking-water`.

L. P. J. Roebuck and T. Ortiz. Water resources assessment of the bahamas. Technical report, US Army Corps of Engineers, Dec 2004. URL `https://www.sam.usace.army.mil/Portals/46/docs/military/engineering/docs/WRA/Bahamas/BAHAMAS1WRA.pdf`.

A. Ruiz-García and E. Ruiz-Saavedra. 80,000 h operational experience and performance analysis of a brackish water reverse osmosis desalination plant. assessment of membrane replacement cost. Desalination, 375: 81–88, 2015.

S. Ryan and E. Nimick. Multi-criteria decision analysis and gis, Aug 2019. URL `https://storymaps.arcgis.com/stories/b60b7399f6944bca86d1be6616c178cf`.

P. Samanta, I. Kim, S. Uryasev, J. Penoyar, and W. Vesely. Emergency diesel generator: Maintenance and failure unavailability, and their risk impacts. Technical report, Nuclear Regulatory Commission, 1994.

G. Sandin, G. M. Peters, and M. Svanström. Life cycle assessment of construction materials: the influence of assumptions in end-of-life modelling. The International Journal of Life Cycle Assessment, 19:723–731, 2014.

M. A. Sanza, V. Bonnélyea, and G. Cremerb. Fujairah reverse osmosis plant: 2 years of operation. Desalination, 203(1-3):91–99, 2007.

D. Scarinci. The geology of the bahama islands. donald scarinci., 07 2016. URL `https://donaldscarinci.com/geology-bahama-islands/`.

A. Schelwald-van der Kley and L. Reijerkerk. Water: A way of life. CRC Press, Mar. 2009. doi: 10.1201/9780203872369. URL `https://doi.org/10.1201/9780203872369`.

F. Schembri. Testing and cleaning north carolina's water supply post-florence could prove tricky. a microbiologist explains why, Sep 2018. URL `https://www.science.org/content/article/testing-and-cleaning-north-carolina-s-water-supply-post-florence-could-prove-tricky`.

G. J. Schiereck and H. J. Verhagen. Introduction to bed, bank and shore protection (4th ed.). CRC Press, 2019.

M. Scholz, V. C. Uzomah, S. A. Almuktar, and J. Radet-Taligot. Selecting sustainable drainage structures based on ecosystem service variables estimated by different stakeholder groups. Water, 5(4):1741–1759, 2013.

E. D. Schoolman, J. S. Guest, K. F. Bush, and A. R. Bell. How interdisciplinary is sustainability research? analyzing the structure of an emerging scientific field. Sustainability Science, 7:67–80, 2012.

D. W. Seckler. The new era of water resources management: from" dry" to" wet" water savings, volume 1. Iwmi, 1996.

J. Senán-Salinas, R. García-Pacheco, J. Landaburu-Aguirre, and E. García-Calvo. Recycling of end-of-life reverse osmosis membranes: Comparative lca and cost-effectiveness analysis at pilot scale. Resources, Conservation and Recycling, 150:104423, 2019. ISSN 0921-3449. doi: https://doi.org/10.1016/j.resconrec.2019.104423.

P. Signorini, R. Wiesemes, and R. Murphy. Developing alternative frameworks for exploring intercultural learning: a critique of hofstede's cultural difference model. Teaching in Higher Education, 14(3):253–264, 2009.

A. Singh, G. Berghorn, S. Joshi, and M. Syal. Review of life-cycle assessment applications in building construction. Journal of architectural engineering, 17(1):15–23, 2011.

L. K. Singh, M. K. Jha, and V. Chowdary. Multi-criteria analysis and gis modeling for identifying prospective water harvesting and artificial recharge sites for sustainable water supply. Journal of cleaner production, 142:1436–1456, 2017.

L. J. Speijker, J. M. Van Noortwijk, M. Kok, and R. M. Cooke. Optimal maintenance decisions for dikes. Probability in the Engineering and Informational Sciences, 14(1):101–121, 2000.

P. Sphere. Humanitarian charter and minimum standards in disaster response. The Sphere Project, Geneva, Switzerland, 2004.

The Bahamas investor. Florida biodiesel delivers plant to grand bahama power co, Sep 2015. URL `https://advancedbiofuelsusa.info/florida-biodiesel-delivers-plant-to-grand-bahama-power-co/`.

the Commonwealth of the Bahamas. The constitution of the commonwealth of the commonwealth of the bahamas, Aug 2023. URL `https://www.bahamas.gov.bs/wps/wcm/connect/0e8ecb04-ec4f-4aa7-afaf-f330efef994b/Chap+5+Parliament.pdf?MOD=AJPERES`.

The goverment of the bahamas. The national emergency management agency, july 2021. URL `http://bahamas.gov.bs`. Cabinet and Disaster Management (NEMA)> Government > About NEMA > The National Emergency Management Agency 09 july 2021.

The government of the bahamas. Nema conducts table-top simulation exercise in preparation for 2021 hurricane season, 2021. URL `http://bahamas.gov.bs`. Cabinet and Disaster Management (NEMA) > Government > About Cabinet Office > Overview of Cabinet, retrieved: 09 july 2021.

W. Uijttewaal. Lecture notes turbulence cie5312. Technical report, TU Delft, 2020. URL `https://brightspace.tudelft.nl/`.

UN General Assembly. Un general assembly resolution 42/187 of december 11, 1987 "report of the international commission on environment and development", 1987.

UNDRR. Sendai Framework for Disaster Risk Reduction 2015-2030. United Nations - Headquarters, United Nations Office for Disaster Risk Reduction, 2015.

Vacher H. L., Quinn T. M. Geology and Hydrogeology of Carbonate Islands. J. Geophys. Res., 54, 2004.

F. H. van de Ven, F. Hooimeijer, and P. Storm. Recovery capacity: To build back better. In Climate Resilient Urban Areas, pages 85–108. Springer, 2021.

J. Van der Hoek, J. Hofman, and A. Graveland. The use of biological activated carbon filtration for the removal of natural organic matter and organic micropollutants from water. Water Science and Technology, 40(9): 257–264, 1999.

L. van der Hucht, C. Hoogervorst, P. Storm, P. Grgic, F. Ortiz Velasquez, and T. Özdemir. Grand bahama after hurricane dorian: Interdisciplinary approach to build back better, Jan 2021. URL `http://resolver.tudelft.nl/uuid:88c3ed7e-bead-401a-b5d4-dcfc23ac757d`.

G. A. Vecchi, C. Landsea, W. Zhang, G. Villarini, and T. Knutson. Changes in atlantic major hurricane frequency since the late-19th century. Nature communications, 12(1):4054, 2021.

G. Verbeeck and H. Hens. Life cycle optimization of extremely low energy dwellings. Journal of Building Physics, 31(2):143–177, 2007.

A. Volker. Source of brackish ground water in pleistocene formations beneath the dutch polderland. Economic geology, 56(6):1045–1057, 1961.

G. Water dept. $5 million reverse osmosis system for grand bahama completed by gbuc, Oct 2021. URL `https://grandbahamautility.com/news/utility/5-million-reverse-osmosis-system-for-grand-bahama-completed-by-gbuc/`.

C. J. Weschler, H. C. Shields, and D. V. Naik. Ozone-removal efficiencies of activated carbon filters after more than three years of continuous service. Ashrae Transactions, 100(2):1121–1129, 1994.

D. Whittington, J. Briscoe, X. Mu, and W. Barron. Estimating the willingness to pay for water services in developing countries: A case study of the use of contingent valuation surveys in southern haiti. Economic development and cultural change, 38(2):293–311, 1990.

L. Wilson. Tourism Satellite Accounts 2012. Department of Statistics, Ministry of Tourism, The Central Bank of The Bahamas, 2012. URL `http://www.bahamas.gov.bs/statistics`.

L. Wilson. National accounts report 2020. Department of statistics Ministry of Finance, June 2020. URL `http://www.bahamas.gov.bs/statistics`.

W. Worldwide Power Products. A turnkey installation on a new diesel generator to a water treatment facility in texas., Jul 2023. URL `https://www.wpowerproducts.com/project-examples/`.

C.-S. Wu, A. A. Taylor, J. Chen, and W. A. Shaffer. 3.5 tropical cyclone forcing of ocean surface waves. Fifth Conference on Coastal Atmospheric and Oceanic Prediction and Processes, pp. 62-64, 2003. URL `https://www.weather.gov/media/mdl/WuHWav_AMS082003.pdf`.

B. Yilmaz and N. B. Harmancioglu. An indicator based assessment for water resources management in gediz river basin, turkey. Water Resources Management, 24:4359–4379, 2010.

Y. Zang, Y. Li, C. Wang, W. Zhang, and W. Xiong. Towards more accurate life cycle assessment of biological wastewater treatment plants: a review. Journal of Cleaner Production, 107:676–692, 2015.

M. Zarghami and F. Szidarovszky. Multicriteria analysis: applications to water and environment management. Springer Science & Business Media, 2011.

B. Zientara. What happens to solar panels in a hurricane?, Sep 2021. URL `https://www.solarreviews.com/blog/what-happens-to-solar-panels-in-a-hurricane`.