Suitability analysis of three artificial reef types in the Dutch Caribbean

A comprehensive comparison of three artificial reef types on the islands of Saba and St. Eustatius

Daniel Heesink
&
Callum Reid

ARCOSSTA
Artificial Reefs on Saba and St. Eustatius

van hall larenstein
university of applied sciences

Supervisors:

Alwin Hylkema University of Applied Science, Van Hall Larenstein

Alwin.hylkema@hvhl.nl

Patrick Bron University of Applied Science, Van Hall Larenstein

Patrick.bron@hvhl.nl

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Final thesis

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Daniel Heesink 1980
&
Callum Reid 2105

University of Applied Science, Van Hall Larenstein

Supervisors
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Patrick Bron

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Acknowledgement

This report is the final product of our 5-month thesis in Coastal and Marine Management. During this time, we worked in collaboration with the Saba Conservation Foundation on Saba, and with St. Eustatius National Parks and Caribbean Netherlands Science Institute on St. Eustatius, in the Dutch Caribbean. We would like to extend our gratitude towards everyone at SCF and STENAPA for their support, their assistance, and for making this an experience worth remembering.

We've learned a lot about working in the field, the limitations of working on an island, and organizing a thesis within five months.

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Abstract

Coral reefs have been in decline over the past decades. This has greatly increased the need for restorative measures. The islands of Saba and St. Eustatius, two special Dutch municipalities in the Dutch Caribbean, are not exempt to this decline. The Saba Conservation Foundation and St. Eustatius National Parks requested University of Applied Sciences Van Hall Larenstein and Wageningen Marine Research for a suitable option to be placed in their surrounding waters. In spring 2018 data was gathered on fish and coral abundance, and fish and coral species richness. Furthermore, data on the costs of construction and deployment, and data on hurricane resilience was gathered. A total of 149 fish surveys were conducted over a two-month period. Through visual census 2576 fish observations were recorded, which averaged at 9,6 (Reef Balls), 36,6 (Layered Cakes), 16,2 (Rock Reefs) fish counts per artificial reef, compared to 25,7 (Patch Reef) fish counts on natural reefs. A total of 46 different species were observed, averaging at a species richness of 4,7 (Reef Balls), 10,2 (Layered Cakes), 5,2 (Rock Reefs) per artificial reef, compared to 4,2 (Patch Reef) on natural reefs. Differences may be explained by different levels of complexity. Furthermore, eight coral surveys were conducted, resulting in the recording of 149 coral recruits, consisting of at least three species. In order of abundance; *Porites sp., Favia fragum,* and *Agaricia agaricites* were found. These species are brooding species, corals that are able to spawn year-round. No broadcast spawning species were found. Broadcast spawning took place around the same time as Hurricanes Irma and Maria, possibly explaining their absence on the artificial reefs. Reef Balls (n=3) held 57 corals in total (19 average), Layered Cakes (n=3) held 62 corals (20,67 average), and Rock Reefs (n=2) held 30 corals (15 average). Despite Rock Reefs being the cheapest option, they are also most vulnerable to hurricanes. Reef Balls and Layered Cakes are costlier, yet substantially more resilient to hurricanes. A multi criteria analysis was conducted to find the most suitable reef. Six variables (Fish abundance, Fish species richness, Hard coral abundance, Costs, Man-hours, and Hurricane resilience), helped define the artificial reefs. Weight, resulting from a questionnaire carried out among staff of STENAPA, SCF, and AROSSTA researchers, scored the artificial reefs on scale of 1-10. Moreover, a SWOT analysis provided additional insight into aspects of the artificial reefs disregarded in the MCA and questionnaire. Due to the local nature of hurricanes, two scenarios were described; one which included hurricane resilience, and the other that disregarded it. Final scoring resulted in Layered Cakes ranking highest, being the most suitable, in scenario 1 (including hurricane resilience). Rock Reefs rank highest in scenario 2 (excluding hurricane resilience).

Content

1.0 Introduction

Coral reefs are considered the most diverse and valued ecosystems in the world. Often found within a 30^{o} band north or south of the equator, coral reefs cover less than 0.1% of the ocean floor. They are home to over 25% of known marine species and date back almost 500 million years (Global Reef Project, 2018; Kaiser et al., 2011). A 2008 study into the value of coral reefs estimates an annual net-benefit of $29.8 billion USD. Of which, $9.6 billion goes towards tourism and recreation, coastal protection accounts for $9 billion, fisheries for $5.7 billion, and biodiversity for $5.5 billion (Conservation International, 2008). Throughout recent decades, coral reefs have come under increased stress due to local anthropogenic effects and climate change. Local anthropogenic influences such as coastal development, agriculture, and fisheries have pushed corals into a decline (Hughes et al., 2003). Climate change is a direct threat to all the coral reefs in the world, increasing sea water temperature, which results in bleaching events. Bleaching causes corals to expel the symbiotic algae living in their tissue. Prolonged bleaching events can severely damage coral reefs (Hoegh-Guldberg et al., 2007; Hoegh-Guldberg & Bruno, 2010). Climate change is not only a direct threat to coral reefs, it also accelerates the degradation of coral reefs by warming waters, fuelling hurricanes. This does not necessarily increase the frequency of the hurricanes, yet it does cause them to intensify (Cheal et al., 2017).

The Caribbean coral reefs are no exception to the global decline (NOAA, 2017). As many people in the Caribbean are directly dependent on coral reefs for their income and food, this greatly impacts them and their future. This also holds true for the reefs of Saba and St. Eustatius, two islands in the Dutch Caribbean, in the Eastern Caribbean Sea (Figure 1).

Figure 1. Location of Saba and St. Eustatius, Dutch Caribbean in the Eastern Caribbean Sea (WorldAtlas, 2017).

On Saba, 66% of tourism driven income is dive related (UNEP, 2014). Local fishermen fish on a large coral bank called the Saba Bank, where they fish primarily on Spiny lobster (*Panulirus argus*) and snapper (*Lutjanidae*). Losing the coral reef, and with that the Saba Bank, would greatly impact the fishermen, local dive operators, and respectively the local economy (de Graaf et al., 2015).

Coral reefs near the island of St. Eustatius declined from a >20% coral cover before 2007 to a coral cover of 5% in 2015. Recovery is unlikely without adaptive management, due to lack of three-dimensional structure, high macro algae cover, continued fishing pressure, and low *Diadema* densities (de Graaf et al., 2015).

This noticeable decline caused local nature conservation organisations St. Eustatius National Parks (STENAPA) and Saba Conservation Foundation (SCF) to join heads with Wageningen Marine Research and University of Applied Sciences Van Hall Larenstein with the aim to conserve the coral reefs. Artificial reefs were mentioned by STENAPA as an instrument to help conserve local coral reefs (Hylkema & Debrot, 2016). This collaboration led to the Artificial Reefs on Saba and St. Eustatius (AROSSTA) project, in which three different types of artificial reef are compared on both islands. The three-dimensional structure of artificial reefs mimics the natural coral structure, providing habitat and shelter for fish.

The three different types of artificial reefs used are: Rock Reefs, Layered Cakes, and Reef Balls. The Rock Reefs consist of locally sourced basaltic rock. These are stacked in a pyramid form. A basket made of concrete mesh supports the base and the structure. The Layered Cakes and Reef Balls are two artificial reefs developed by the Reef Ball Foundation (Reefball.org, 2018). Both artificial reefs are built with marine grade concrete. The reefs are constructed in a circular form and have a diameter of 90 cm and a height of 60 cm. The difference of the reefs is the shape of the reefs. Reef Balls are a dome-like structure, with large round holes in its walls. Layered Cakes have a cake-like structure, four layers of concrete with spaces between each layer (Figure 2).

Figure 2. A Rock Reef, a Layered Cake, and a Reef Ball.

The Rock Reefs, Layered Cakes, and Reef Balls are different with regards to their three-dimensional structure and materials. Structural complexity is important for fish recruitment and aggregation, and increases total species richness and fish biomass (Sherman et al., 2002; Charbonnel et al., 2002). The Rock Reefs and Layered Cakes have more complexity than the Reef Balls, therefore there might be a difference in fish community development between artificial reef types. Building materials also influence fish community development; however, these materials are more important for coral recruitment and benthic community development. When compared to dead coral (the building block for coral reef growth) concrete is recommended for artificial reef construction as the observed community development is most similar to the natural situation, and concrete is durable in seawater and can be shaped to specification (Fitzhardinge & Bailey-Brock, 1989). A different consideration in building artificial reefs, however, is the costs of the materials and man-hours involved. Basaltic rock is cheap and widely available in the area, and therefore a favourable material to use.

1.1 Problem description

More research is needed to fulfil the objectives of artificial reefs in management plans, only 50% of the artificial reef projects worldwide meet their objectives. For artificial reefs to fulfil their objective, quality of planning and management is needed (Baine, 2001). Multiple studies show that the used materials in artificial reefs influence the benthic and fish community development (Fitzhardinge & Bailey-Brock, 1989; Lukens & Selberg, 2004; Burt et al., 2009; Campbell et al., 2011). However, little data about the effects of locally available resources in the Caribbean on the development of artificial reefs is available. Due to the limited amount of data, it is unknown which type of artificial reef would be best suitable for the islands Saba and St. Eustatius. Suitable is defined by the various variables; fish abundance, fish species richness, hard coral settlement, costs and, hurricane resilience.

1.2 Research aim

The aim of this research is to provide local nature organisations, STENAPA and SCF, with an instrument to conserve local coral reefs. This is done by comparing the three artificial reef types: Rock Reefs, Layered Cakes, and Reef Balls. Conclusively, this will result in a multi criteria analyses of the artificial reef types, providing a comprehensive tool for decision making.

1.3 Research questions

To achieve this aim, the following main research question was formulated:

Which of three artificial reef types; Rock reefs, Reef Balls, or Layered Cakes, placed around St. Eustatius and Saba, is most suitable for the conservation of coral reefs in the Dutch Caribbean?

To answer this question effectively, numerous sub questions were formulated:

1) What is the effect of each artificial reef type on fish abundance and fish species richness?
2) What is the effect of each artificial reef type on the hard-coral settlement on the artificial reefs?
3) What are the costs of the different types of artificial reefs?
4) How were the artificial reefs affected by hurricanes Irma and Maria?

1.4 Hypothesis

Fish abundance and fish species richness are largely dependent on three-dimensional structure (Hylkema & Debrot, 2016). Artificial reefs with more relatively small holes, like Rock Reefs and Layered Cakes, will result in higher fish abundance and fish species richness compared to an artificial reef with relatively few big holes, like Reef Balls (Hixon & Beets, 1989; Charbonnel et al., 2002; Sherman et al., 2002). Therefore, it is expected that Rock Reefs and Layered Cakes will have a higher fish abundance and fish species richness than Reef Balls. Preliminary monitoring of the artificial reefs from December 2017 till February 2018 showed high amounts of sediment and turf algae on the artificial reefs (Griend & Heesink, 2018). Turf algae and sediment combined can prevent hard coral larvae from settling on substrate (Birrel et al., 2005). It can be expected that few hard-coral recruits will be found on the artificial reefs. Rock Reefs only require basaltic rocks and a concrete mesh basket, both sourced locally. Reef Balls and Layered Cakes require labour intensive and time-consuming mixing, pouring, and curing of concrete. The materials and man-hours required increase the price of Reef Balls and Layered Cakes. Therefore, Rock Reefs might be a less costly option. However, a hurricane damage assessment conducted during the first monitoring period in November 2017 showed that Rock Reefs were more likely to be affected by the effects of hurricanes than Reef Balls and Layered Cakes.

2.0 Materials and methods

2.1 Research design

This final thesis research was part of ARROSTA. The ARROSTA project started in February 2017 and will lasts for about 2,5 years (Hylkema & Debrot, 2016). The first artificial reefs were deployed in April 2017. The first monitoring phase started mid-November 2017. However, two hurricanes (Irma and Maria) hit the area in September 2017 and damaged the artificial reefs. Therefore, actual monitoring started in December 2017.

This thesis research project was conducted over a period of 5 months and focused on the second monitoring phase, from March 2018 until the end of May 2018. The first weeks, starting on the 5th of February 2018, were used to writing a research proposal (Appendix VIII). After completion of the research proposal, data was gathered on Saba. Another team of students gathered data on the artificial reefs on St. Eustatius. Two months were spent monitoring the artificial reefs on Saba. The last weeks were used to analyze the gathered data and write the thesis. The gathered data from both islands was exchanged and pooled.

2.2 Locations and set up of the artificial reefs

The artificial reefs are located near the islands Saba and St. Eustatius in the eastern Caribbean Sea. Both islands are part of the Leeward Islands and the distance between the islands is approximately 30 KMs. Two bays were chosen on both islands. Ladder Bay and Big Rock Market are locations on Saba, Twin Sisters and Crooks castle were chosen on St. Eustatius (Figure 3). However, due to major swell in March 2018 the location Ladder Bay was lost. The reefs were covered in such quantities of sediment, that in some cases only the top of the reef breached the surface. The Layered Cakes were not found. The remaining locations host one experimental block. Each block consists all types of artificial reef, set out in experimental plots. These plots measure approximately 1,25 m wide, 1,60 m long, and 0,60 m high. Each plot consists of one type of artificial reef, a control plot, and where possible a natural patch reef. There are, however, exceptions to these blocks, Big Rock Market hosts two Rock Reefs and Twin Sisters lacks a natural reef patch since there are no patch reefs in the area. Two types of control plot exist. One type consists of bare substrate, whereas the other consists of a natural reef patch. These are marked by a 1-meter long iron bars in their corners. In total this results in 13 experimental plots: five Rock Reefs, four Layered Cakes, and four Reef Balls plus an additional seven control reefs: three natural patch reefs and four control plots.

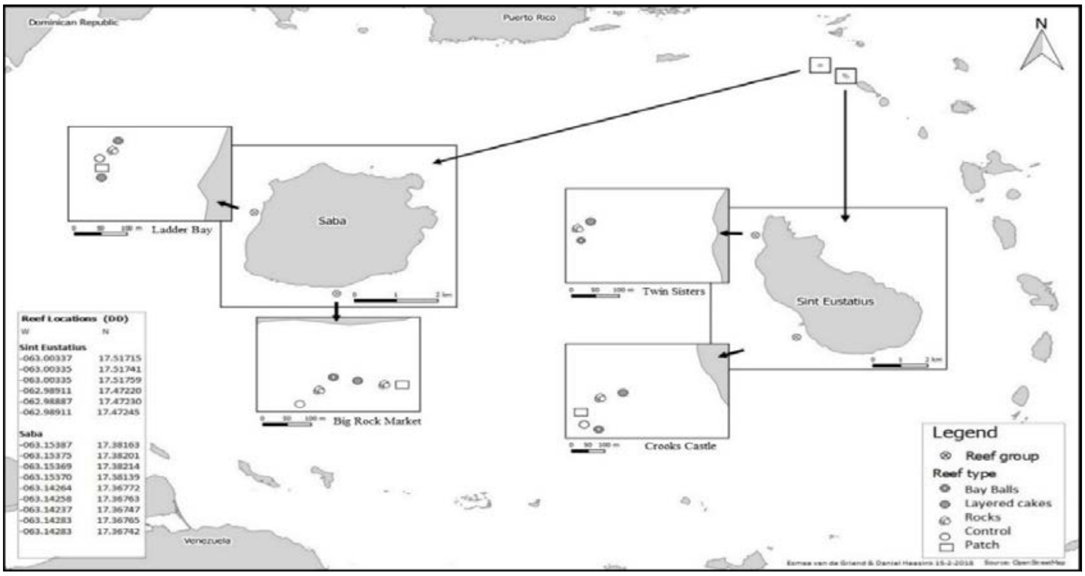

Figure 3. Map of the Caribbean, Lesser Antilles. Insets of Saba and St. Eustatius with locations of the artificial reefs.

2.3 Data collection and sample size

2.3.1 Fish data and survey

Fish data was collected by visual census. Fish data was gathered 10 times per artificial reef, with the exception of the patch reef on St. Eustatius. This was monitored 9 times. The total number of species of fish, the abundance, and the size of each fish were classified in size categories 0-5, 5-10, 10-15, 15-20, 20-25, 25-30, 30-40, 40-50, 50-60, etc, cm total length (TL) (Figure 4). All fish were identified up to species level. Only fish within a virtual cylinder (measuring 1 meter sideways and 2 meters upwards from the bottom) were counted (Figure 5). To measuring a ray, the TL of the tips of the pectoral fins were estimated. Gobies and blennies were pooled in the category "Gobies and Blennies". These were removed for the purpose of analysis as their observations were inconclusive and proved difficult due to their habitual nature. All surveys were filmed with a GoPro, with an underwater light, for future references and to aid in the identification of unknown species.

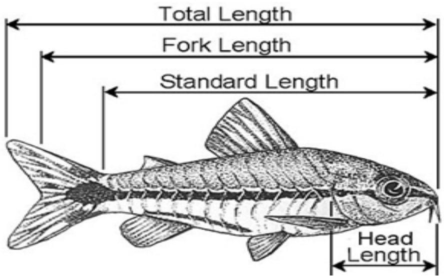

Figure 4. Total length of a fish (Fishe, 2016).

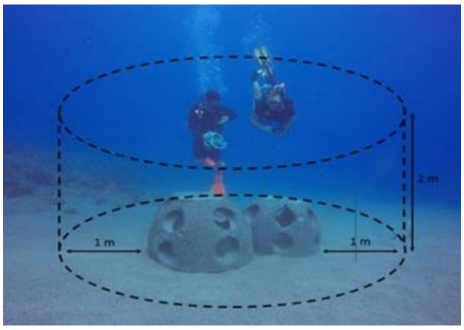

Figure 5. The virtual cylinder, fish inside the cylinder were counted.

Two divers conducted the fish survey. Diver 1 recorded all fish species, size, and abundance on a slate. Diver 2 filmed the survey with a GoPro. Each fish survey dive started at the outer experimental plot of an experimental block (*e.g.* North), every next fish survey on the same experimental block started at the other outer plot of the block (*e.g.* South). Before entering the water, the names of the observers were filled in on the slate, along with; location, time, and date. Divers descended at least 10 meters away from the first plot. Diver 1 slowly swam towards the experimental plot while diver 2 situated himself slightly behind diver 1 and started recording. Diver 1 started noting all fleeing fish at 5 meters distance of the reef. At 2 meters distance a stationary count was conducted for 3 minutes. Where present, schools of fish were counted first, followed by the remaining fish. After the stationary count diver 1 searched the reefs thoroughly for hiding fish or lobsters. A torch was used to illuminate dark crevices and holes. It was important not to count any new fish swimming into the virtual cylinder. Significant events happening on the reef (*e.g.* Sergeant majors laying eggs on Layered Cakes) were noted, along with the depth (lowest point of the reef), and temperature. After finishing an experimental plot, the same procedure was conducted at the next experimental plot, until the entire experimental block was surveyed. Due to the disturbing nature of fish surveys, fish are often spooked for a prolonged period of time. As such, surveys are recommended to be conducted a minimum of 17 hours apart (Emslie, et al., 2018). A step by step protocol is laid out in Appendix I.

2.3.2 Hard coral settlement surveys

Hard coral settlement data was collected during survey dives. During a night dive and with the aid of an underwater UV light, and clip-on UV masks, each reef was visually surveyed for hard corals. The UV light causes corals to light up, making them easier to observe. The locations of the corals were marked on a map of the artificial reef. The following day, divers searched for previously marked corals to photograph them. The photo's served as identification aids and input for ImageJ. An image processing program that allows for accurate measurement of a surface area. This data provides a reference point, so that future monitoring can determine survival and growth rate. A step by step protocol is laid out in Appendix II.

2.3.3. Costs

A 2017 article by Jeremy Hance states how nature conservation is chronically underfunded (Hance, 2017). As such, the costs of projects play an increasingly bigger part in the decision-making process. To gain insight into the costs of artificial reefs, costs were determined by two variables; material costs and man-hours. The values were based on the construction and placement phase of AROSSTA (Spring 2017). Variable costs and fixed costs are distinguished. The fixed costs consist of purchasing a mould (and accessories) from the Reef Ball Foundation.

2.3.4 Hurricane resilience

Two hurricanes Irma, August 30, 2017 – September 13, 2017, and Maria, September 16, 2017 – October 2, 2017 passed Saba and St. Eustatius. The hurricanes created swells and massive quantities of sediment displacement, causing a radical change of the scape of the natural coral reefs (personal observation, Reid, C., 2018). Since the artificial reefs were located closely to the coral reefs, they were moved around and/or affected by this event. Two students from Van Hall Larenstein conducted a hurricane assessment during the first monitoring period, right after the hurricanes in November 2017. The data gathered by these students, which can be found in Appendix IV, was used to assess each type of artificial reef (Griend & Heesink, 2018). This data determined how hurricanes Irma and Maria affected each reef type. Observed damage, sediment accumulation, and average meters of displacement of each reef indicate the resilience of artificial reefs towards hurricanes.

2.4 Control variables

Throughout the study, data of several control variables were recorded. Variables that were measured are:

1. Temperature
2. Depth
3. Water turbidity

These variables were recorded as they may influence the data. Temperature was recorded from the dive computers, along with depth. Both were recorded at the lowest point of the artificial reef. Visibility was recorded by estimating visibilty between artificial reefs. Distance between artificial reefs measures 25m and the distance from which fish surveys were started was 5m. If one artificial reef was visibile from another, visibility was recorded as > 25m. Was the next artificial reef not visibile, but were reefs visibile from at least 5m, visibility was recorded as >5m.

2.5 Multi-Criteria analysis

Finding the most suitable artificial reef type for Saba and St. Eustatius was achieved by conducting a Multi-criteria analysis (MCA). Its customizability made an MCA highly suitable for the appraisal of options for policy and decision making (Dept. of Communities and Local Government, 2009). This study’s intent was to rank options and identify a single most suitable option for the relevant stakeholder, based on several variables:

1. Fish abundance
2. Fish species richness
3. Hard coral settlement
4. Material Cost
5. Man-hours
6. Hurricane resilience

The scoring of each variable was based on data intervals (Dept. of Communities and Local Government, 2009). In this study, the score is divided into three intervals. Different scores were awarded for reefs matching certain categories of criteria (Table 1). Criteria were divided in three categories, these were mostly result based or based on preliminary research. The scores of fish abundance and fish species richness were based on preliminary research conducted by VHL students in November 2017 – February 2018 (Griend & Heesink, 2018). The score of coral recruits was based on a study where concrete and several natural substrates where compared regarding coral settlement in the United Arab Emirates (AUE). Although, basalt rocks, like the ones used in this project, where not used. Gabbro, a rock that has the similar composition to basalt (CompareNature, 2018), was studied. The number of coral recruits found on concrete was 2,2 per m^2 and for gabbro 6,0 per m^2 in the AUE. The surface area of Bay Balls (the type of Reef Ball Used) is approximately 2,8 m^2 (Reefball.org, 2018). These results suggest any value found above 15 coral recruits per artificial reef to be high. The score for costs are based on the actual numbers found during the research, since there is a huge gap between the Rock Reefs and the concrete structures this interval was chosen. The feature man-hours was categorized even though the actual numbers are fairly close. This because man-hours should be multiplied by the amount of people needed to carry out the work. This would increase the differences found. Hurricane resilience was categorized in: collapsed, moved and/or damaged, and unscathed.

Table 1. The intervals allocated to the features of an artificial reef.

Variable	Score: 1	Score: 2	Score: 3
Fish abundance	0-15	15-30	30+
Fish species richness	0-5	5-10	10+
Hard coral settlement	0-5	5-10	10+
Material costs ($)	1000+	500-1000	0-500
Man-hours	Highest value	Median value	Lowest value
Hurricane resilience	Collapsed	Damaged and/or Moved	Unscathed

2.5.1 Questionnaire

A questionnaire was sent out to STENAPA, SCF and AROSSTA researchers (Appendix III). The questionnaire allows for the appraisal of features. It is important to weigh these variables as one variable may be more important than another. An artificial reef that holds many different fish species yet bears high costs may not be a suitable option. In contrary, a cheap option that is easily impacted by a hurricane may not be ideal either. These variables were weighed based on questionnaire filled in by staff members of SCF, STENAPA and ARROSTA. The questionnaires provided insight into what organizations find important and how heavily a variable should be weighed. Participants had to allocate 100 points. Final scores were obtained by averaging all questionnaire results.

2.5.2 Two scenarios

Since some islands in the Dutch Caribbean are not located in the hurricane belt (NOAA, 2018), two scenarios are calculated, one including the feature hurricane resilience and one without. This widens this studies applicability.

2.6 SWOT analysis

Despite a wholistic approach, (conducting an MCA and weighing the MCA with the results of a questionnaire) results may needs additional description and consideration. A SWOT analysis allows for the analysis of a features' strengths, weaknesses, opportunities, and threats. The analysis is result based and disregards weight.

2.7 Statistical analyses

Data gathered during this study was subject to statistical analyses. Answering the sub questions of this study, and thereby answering the main question, was done by conducting statistical tests on the data with the use of statistical software. In this study, an independent sample Kruskal-Wallis was deemed suitable for sub-question 1, as this required comparison of averages between multiple groups. A 95% confidence ($p = <0,05$) interval was used. Independent variables (fish abundancy and fish species count) were tested against reef type, location, and island.

The data failed the assumption of a normal distribution; therefore, a Kruskal-Wallis was used. A Kruskal-Wallis is a rank-based nonparametric test capable of testing differences between more than two groups.

3.0 Results

3.1 The effect of each artificial reef type on fish abundance and fish species richness

Throughout a period of two months, a total of 149 fish counts were conducted. Of which, 60 were conducted on Saba and 89 on St. Eustatius. A total of 2576 fish observations were recorded, excluding Blennies and Gobies. These were excluded due to inconclusive and inconsistent monitoring.

3.1.1 Fish abundance

An independent sample Kruskal-Wallis tested the average fish count across the different reef types. Significant differences were found ($p<0,001$) (Figure 6).

Similar results were found. An independent sample Kruskal-Wallis test found significant differences between reef types ($p<0,001$), across all groups and locations (Figure 7). However, when tested further, there seems to be no difference per location ($p=0,325$) nor per island ($p=0,797$) (Figure 8).

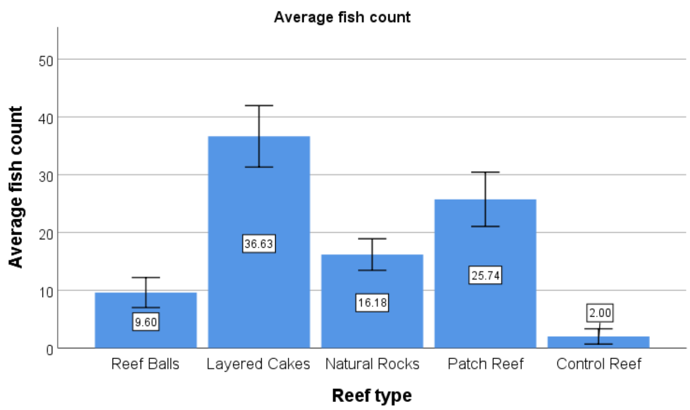

Figure 6. Average fish counts per reef type.

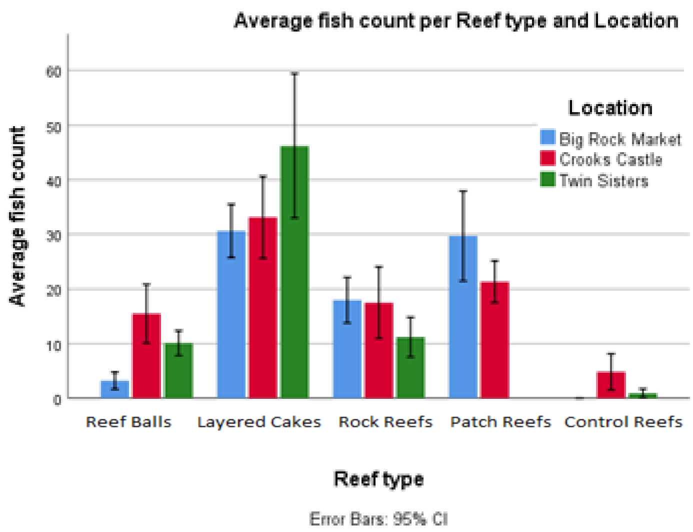

Figure 7. Average fish counts per reef type and location.

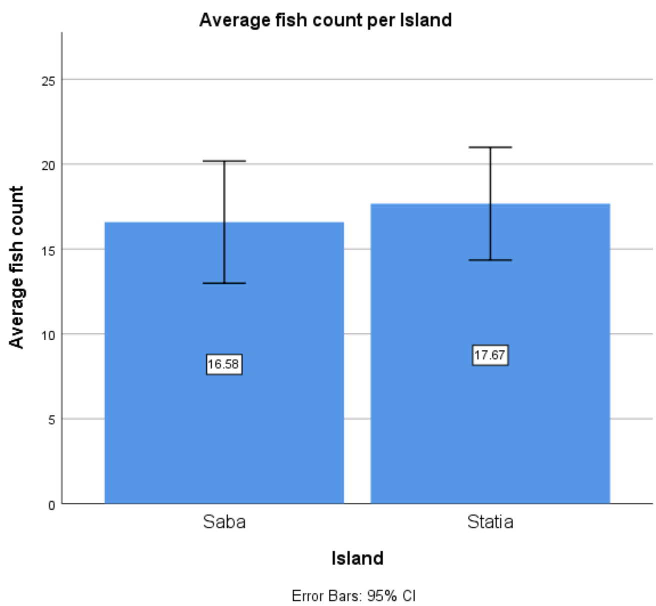

Figure 8. Average fish count per island.

3.1.2. Fish species richness

An independent sample Kruskal-Wallis tested fish species richness per reef type, resulting in significant differences ($p<0{,}001$). Further testing included location and island. These too proved different; per location ($p<0{,}0018$) and per island ($p<0{,}0014$) (Figures 9, 10, and 11).

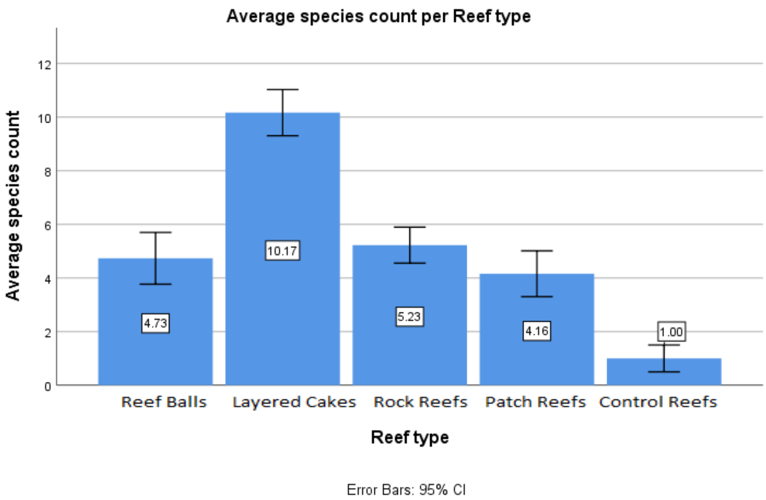

Figure 9. Average fish species count per reef type.

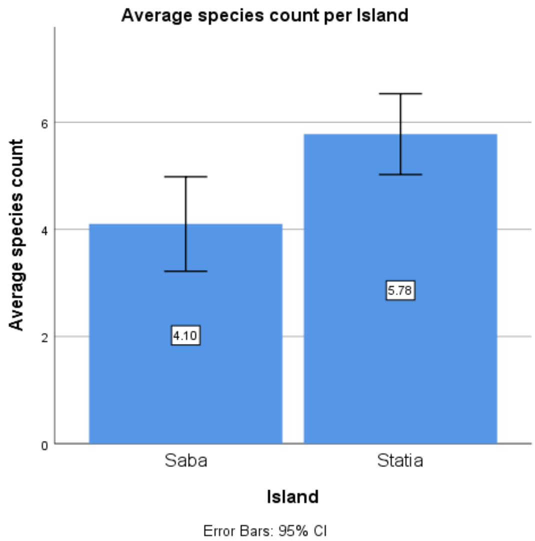

Figure 10. Average fish species count per island.

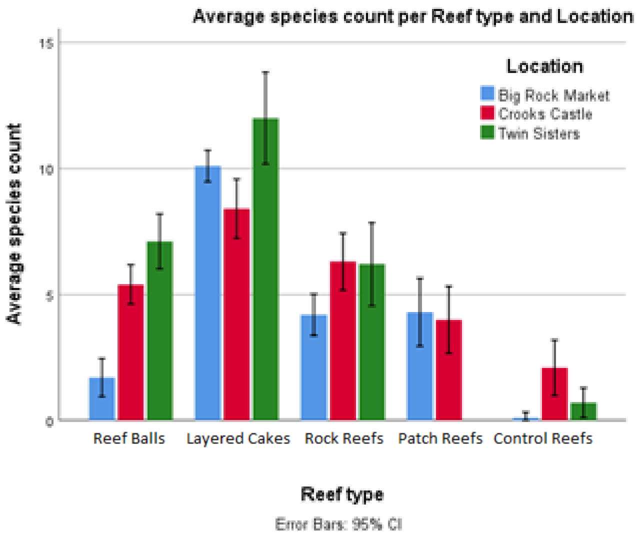

Figure 11. Average fish species count per reef type and location.

3.2 Coral species and coral abundance found on the artificial reefs

During the second and third week of April 2018 three night-dives were conducted, one on Saba and two on St. Eustatius, followed by four hard coral settlement surveys.

3.2.1 Coral species

At least three species of coral were found on the reefs: *Porites* sp., *Agaricia agaricites*, and *Favia fragum* (Figure 12).

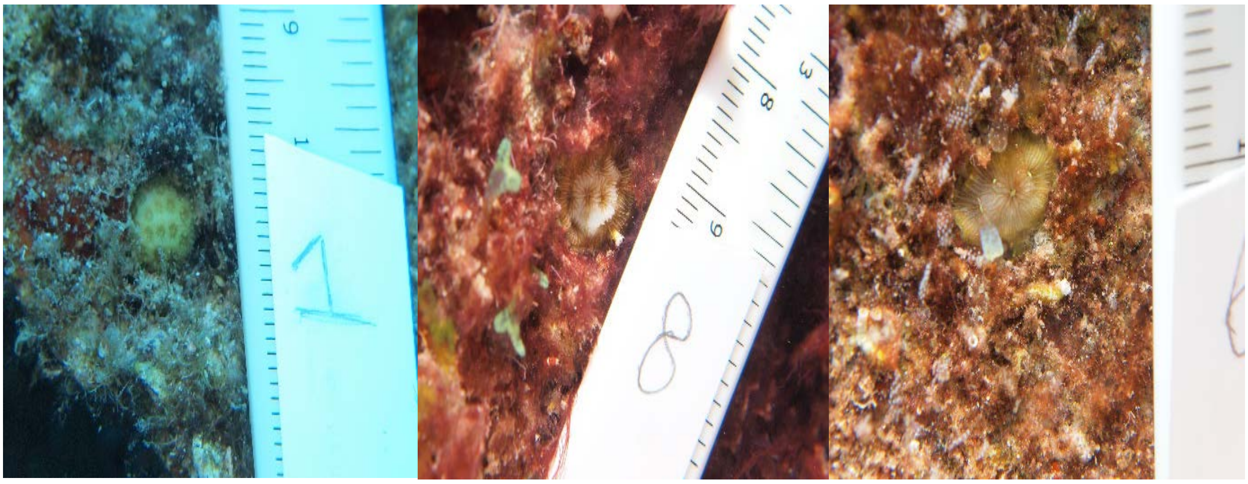

Figure 12. Porites sp., Favia fragum, and Agaricia agaricites recruits found on the artificial reefs on Saba, Big Rock Market.

3.2.2 Coral counts

The total number of corals found was 149, of which 81 were found on Saba. The remaining 68 were found on St. Eustatius (Table 2). A total of 62 coral recruits were found on the Layered Cakes (n=3), 57 corals recruits on the Reef Balls (n=3) and 30 coral recruits on the Rock Reefs (n=2) (Figure 13). Overlap of the error bars suggests there is no significant difference between the different types of reefs (Figure 14).

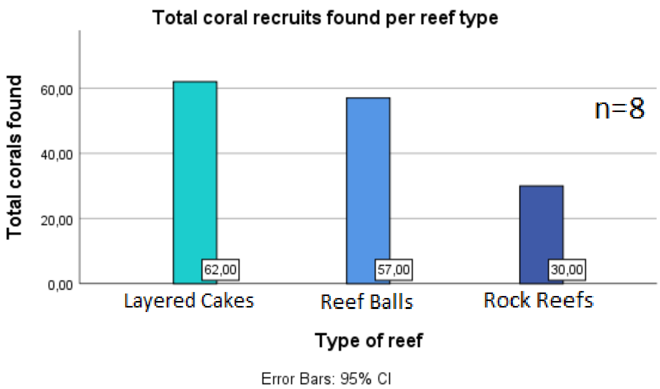

Figure 13. Total coral recruits found on the artificial reefs.

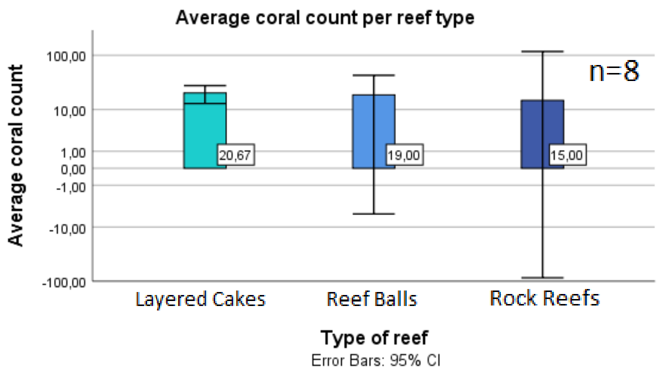

Figure 14. Average coral count per reef type.

Rock Reefs on St. Eustatius were not recorded, since these reefs were built post hurricane Irma and therefore had a shorter experimental runtime than the other artificial reefs. Most coral recruits found were *Porites sp.*, with a total number of 108. 19 *Agaricia agaricites* recruits and 6 *Favia fragum* were found (Figure 17). 16 recruits were unable to be identified, due to the quality of the photo, size of the polyp or because the coral polyp was not found on the photo.

Table 2. Total numbers of corals found on Saba and St. Eustatius, sorted on species.

Coral species	Saba	St. Eustatius	Total
Agaricia agaricites	10	9	19
Favia fragum	5	1	6
Porites sp.	57	51	108
Undetermined	9	7	16
Total	**81**	**68**	**149**

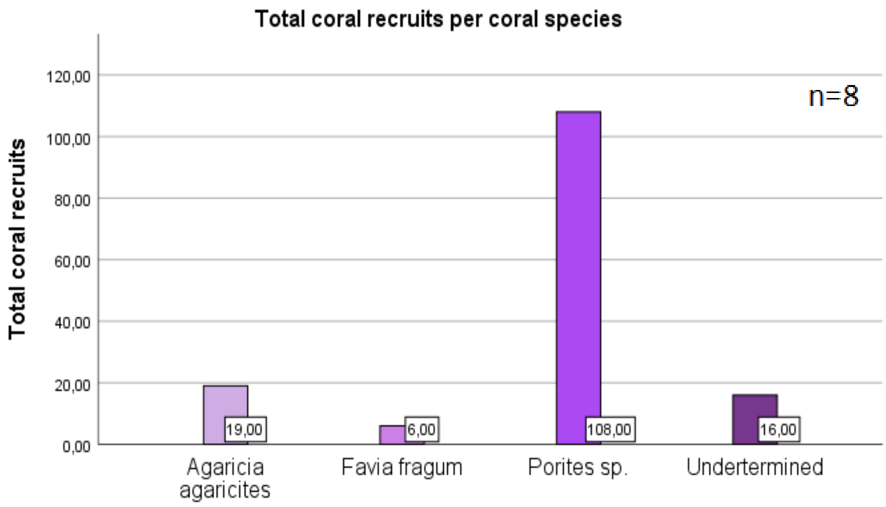

Figure 17. Total coral recruits per coral species.

3.3 The costs of the different types of artificial reefs

An overview of construction and deployment costs provides insight in the total costs involved with artificial reef projects (Table 3 & 4). The overview was split in two, one table depicting the total costs of all three reef types, and the other depicting the man-hours and costs of all reef types. An overview of all material costs can be found in Appendix V.

Table 3 shows high initial fixed costs to build Reef Balls and/or Layered Cakes ($3533,-) and relatively low costs per additional reef ($52,63), whereas the construction costs of Rock Reefs are relatively low overall ($51,-). Furthermore, the cost of labour varies per island. A ranger on Saba costs $12,50 an hour. A ranger on St. Eustatius costs $8,00 an hour, averaging between the islands at $10,25. This sets deployment costs at $61,50 per Reef Ball, $66,63 per Layered Cake, and $30,75 per Rock Reef.

Table 3. Total costs per reef type and costs per additional reef.

Reeftype	Fixed costs	Material costs	Total $	Costs per additional reef
Reef Ball	$ 3533,-	$ 52,63	**$ 3.588,63**	$ 52,63
Layered Cake	$ 3533,-	$ 52,63	**$ 3.588,63**	$ 52,63
Rock Reef	$ 0,-	$ 51,-	**$ 51,-**	$ 51,-

Table 4. Construction and deployment hours and costs per reef.

Reeftype	Construction (in hours)	Deployment (in hours)	Total hours	Total $
Reef Ball	2	4	6	**$ 61,50**
Layered Cake	2,5	4	6,5	**$ 66,63**
Rock Reef	0,5	2,5	3	**$ 30,75**

3.4 The effects of the hurricanes Irma and Maria on the artificial reefs

All artificial reefs were affected in some way by the hurricanes. All Rock Reefs were collapsed after the hurricanes and most of the rocks were buried in the sand (Figure 18). Rock Reefs are made of smaller natural rocks stacked on top of each other. This makes them vulnerable to big swells. One of the Rock Reefs at Ladder Bay, Saba totally disappeared under a layer of sand and could not be located after the hurricanes.

Figure 18. A collapsed Rock Reef at Big Rock Market, Saba in November 2017.

The Layered Cakes and Reef Balls were moved around by the swell and some were deeply buried in sand. On average Layered Cakes moved 0,6 meters from their original location, with a maximum of 3,6 meters in Big Rock Market. Reef Balls moved an average of 2,1 meters from their original location, with a maximum of 10,6 meters in Big Rock Market (Figure 19). Despite this, only two concrete reefs were damaged because of the movements. One Reef Ball and one Layered Cake at Big Rock Market were destroyed by the hurricanes. Overlap in error bars indicate there is no significant difference between the reefs. Most artificial reefs were partially buried in the sand, having almost 50% of their surface covered. Each layered cake and Reef Ball measures 60,0 cm tall. The average highest point of the Layered Cakes was 47,8 centimeters and the average highest point of the Reef Balls was 51,1 cm (Figure 20). However, overlap of error bars indicate there is no significant difference between the reef types.

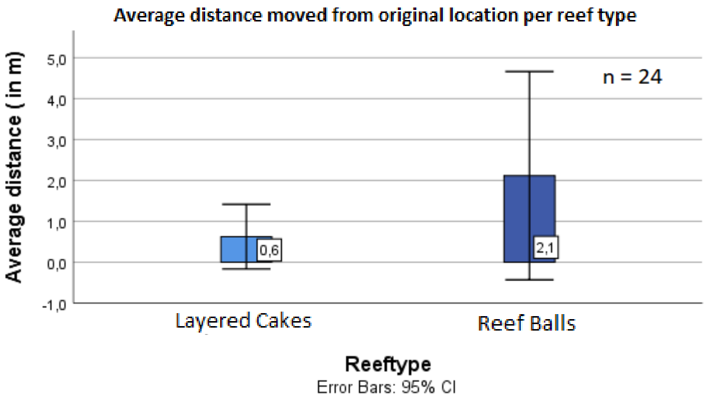

Figure 19. The average distance the artificial reefs moved after the hurricanes in November 2017.

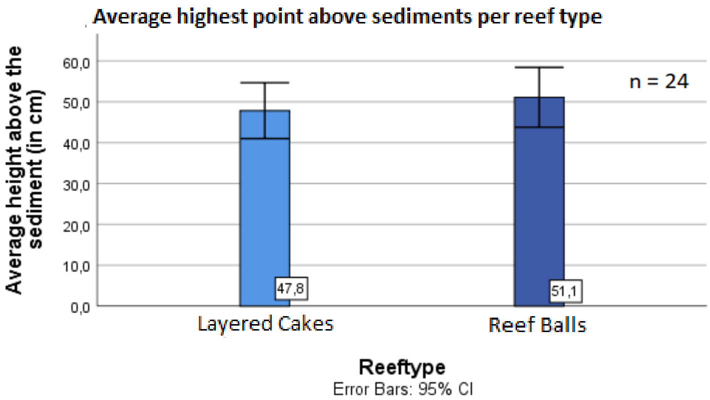

Figure 20. The average highest point above the sediment of the artificial reefs after the hurricanes in November 2017.

3.4.1 Reconstruction time

Reconstruction time for each reef differs greatly. Rock Reefs were easiest and fastest to reconstruct. Two experienced divers could repair a Rock Reef within 30 minutes. Layered Cakes and Reef Balls require a minimum of three people to dig out and move. Reef Balls trap a lot of sand within their structure, which makes repairing a Reef Ball a time-consuming process. Layered Cakes are easier to dig out, but are heavier than Reef Balls, which makes them harder to move.

Figure 21. Measuring the distance and the highest point of the Reef Balls after the hurricanes in Ladder Bay, Saba in November 2017.

3.5 Multi criteria analysis

A total of 9 participants filled in the questionnaire. The results of the questionnaire can be found in Appendix VI. The questionnaire revealed what features of artificial reefs are most important according to participants. Specific features of artificial reefs were given a score to determine which feature is more important than others.

Table 5 shows the total score of each feature combined. Hard coral settlement is the most important feature according to participants, followed by hurricane resilience. Fish abundance and fish species richness are found in the middle, and material costs and man-hours are considered least important.

Table 6 shows the score per feature per type of artificial reef. The acquired data scores features per artificial reef based on Table 1. The higher the score, the more favourable the artificial reef. Table 6 shows that the Rock Reefs are the most suitable with a score of 14, followed by the Layered Cakes with a score of 13. Reef Balls are least favourable with a score of 10. Since some features are more important than others these scores are multiplied by the results acquired from the questionnaires (Appendix VII).

Table 5. Total score of each feature combined.

Feature	***Total score combined all interviewees***
Fish abundance	151
Fish species richness	164
Hard coral settlement	232
Material Costs	94
Man hours	67
Hurricane resilience	193

Table 6. The score per feature per type of artificial reef, based on acquired data.

Variable / Reef type	Fish abundance	Fish Species Richness	Hard coral settlement	Material costs	Man-hours	Hurricane resilience	Total:
Reef Balls	1	1	3	1	2	2	**10**
Layered Cakes	3	3	3	1	1	2	**13**
Rock Reefs	2	2	3	3	3	1	**14**

This results in a final score per reef (Table 7). The final score is transformed into a score of 1-10, with 1 being the least suitable and 10 being the most suitable reef type. Reef Balls are the least suitable artificial reefs with a score of 5,41 with hurricane resilience and 4,13 without hurricane resilience to be used in the (Dutch) Caribbean. If hurricane resilience is taken into consideration Layered Cakes are the most suitable artificial reef with a score of 7,29. Rock Reefs score a 6,67 with hurricane resilience taken into consideration. If hurricane resilience is not taken into consideration Rock Reefs are the most suitable reefs with a score of 6,02, followed up by Layered Cakes with a minimum difference of 6,00.

Table 7. Final total score and score on a scale 1-10 per artificial reef, with and without hurricane resilience scenarios.

Final scores	***With*** hurricane resilience (Scale 1-10)	***Without*** hurricane resilience (scale 1-10)
Reef Balls	**5,41**	**4,13**
Layered Cakes	**7,29**	**6,00**
Rock Reefs	**6,67**	**6,02**

3.6 SWOT Analysis

A SWOT analysis may provide more insight in the pros and cons of each reef type and how each reef type came to its score.

Reef Balls:

- Strengths: This study has shown Reef Balls to be equally attractive for (hard) coral settlement as other tested artificial reefs. Furthermore, along with Layered Cakes, Reef Balls were least affected by two category 5 hurricanes that hit the area in September 2017.
- Weaknesses: This study has shown Reef Balls to be least attractive in terms of fish aggregation, fish species richness, and costs.
- Opportunities: Reef Balls are used the world over and are considered successful in their use. One a large scale, these structures are relatively costly, yet simple to construct. Deployment on a large scale is fast, with the use of a barge and crane. Furthermore, Reef Balls offer a variety of uses, including breakwater construction, sea wall fortification, coral transplantation, mangrove restoration and/or creation and oyster reef restoration.
- Threats: No threats are recognized with the use of Reef Balls.

Layered Cakes:

- Strengths: This study has shown Layered Cakes to be equally attractive for (hard) coral settlement as other tested artificial reefs. Furthermore, along with Reef Balls, Layered Cakes were least affected by two category 5 hurricanes that hit the area in September 2017. This study also showed Layered Cakes to be most suitable with regards to fish aggregation and fish species richness, far exceeding other tested artificial reefs, and natural Patch Reefs.
- Weaknesses: Besides being costly to construct, Layered Cakes also proved more time consuming to build and deploy. Furthermore, Layered Cakes are somewhat limited in their use. Its shape requires more care to be taken in deployment and does not provide the same options as a Reef Ball (a Hollow dome shaped structure), making it unsuitable for sea wall fortification, breakwater construction, mangrove restoration and oyster reef restoration.
- Opportunities: Layered Cakes have large flat surface areas, of which the top and outer surfaces are suitable for coral transplantation.
- Threats: Few threats are recognized with the use of Layered Cakes, besides deployment. Due to their method of construction, weaknesses can easily be created if not poured correctly, or if pillars between layers are insufficient in strength. Furthermore, deployment requires more manual work and precision, large scale deployment, as is possible with Reef Balls, is not recommended when deploying Layered Cakes.

Rock Reefs:

- Strengths: This study has shown Rock Reefs to be equally attractive for (hard) coral settlement as other tested artificial reefs. Furthermore, Rock Reefs appear most attractive with regards to costs and man-hourss required to construct and deploy.
- Weaknesses: On a small scale (as used in this project), rocks were selected and gathered by hand. Next, they were deployed by dropping each individual rock on the desired location, donning SCUBA gear, and building a pyramid shaped reef. Furthermore, Rock Reefs were deemed unsuitable with regards to hurricane resilience. Rock Reefs on both locations on Saba had collapsed after two category 5 hurricanes hit the area in September 2017.
- Opportunities: The nature of Rock Reefs, being sourced from local rock, makes them highly suitable to be deployed on a larger scale.
- Threats: As mentioned in its weaknesses, the threat of an artificial Rock Reef is its vulnerability to weather events. The use of larger rocks could mitigate this effect, however even large rocks used as a breakwater in Saba harbour, were moved by the hurricane(s).

4.0 Discussion

The main aim of this study was to find the most suitable artificial reef type for the islands Saba and St. Eustatius, in the Dutch Caribbean. Three artificial reef types (Reef Balls, Layered Cakes, and Rock Reefs) were surveyed on fish abundance, species richness, hard coral settlement, and studied on costs, and hurricane resilience. Two research teams (consistent of two students from VHL University of applied sciences each) conducted surveys over a period of two months (April – May).

Determining suitability would be achieved by comparing the three reef types. The sheer lack of literature suggests that no such comparison had been conducted in the Caribbean before. This stressed the need for such a study.

Several proposed aspects of this study were not concluded, due to complexity of proposed aspects (i.e. volume calculations of artificial reefs), limited accessibility to the site (i.e. boat and staff availability), and limited time on the island. Besides volume calculations, one aspect that was deemed inconclusive was the shelter count and size calculations. Although still considered a determining factor and certainly considered worthy of further research, this study was unable to conclude the subject.

4.1 Survey Results

Nature is known to be inherently dynamic, this too was evident on the natural reefs surrounding the experimental plots. Personal observations gave the impression that natural patch reefs differ greatly around the artificial reefs. Some reefs are positioned closer to natural reefs, and the health status of these reefs appeared to be different. Both factors are suspected to affect fish aggregation and species richness. Recommendations are made to conduct surveys on these natural reefs, which could provide a means of comparing artificial reefs with natural (patch) reefs.

Furthermore, surveys were conducted over a period of two months, in spring 2018. This provides an accurate view on the state of the artificial reefs and natural reefs in spring, however it is widely known that fish peak spawning activity takes place in spring (February, March, April) (Burke, 2018; Domeier, 1997; Robinson, 2004). This seasonal bias most likely influenced results. Personal observations support this theory as fish surveys on 16-4-2018, 18-4-2018, and 02-05-2018 showed large increases in Chromises (*Chromis cyanea* and *Chromis multilineata*) and Bluehead Wrasses (*Thalassoma bifasciatum*) on Big Rock Market. Large schools of fish larvae (unidentified) were observed on St. Eustatius from 04-04-2018 till 10-04-2018.

Lastly, with regards to survey results; the location Ladder Bay was lost after major swell in March 2018. This reduced the number of experimental plots from four to three. The decision was made not to dig up the reefs and restore them to their prior state, as this would provide no results for this study. As it was a natural event that caused the location to be covered by sand, perhaps a natural event will uncover the location in the (near) future. This location may become available in future, allowing it to be surveyed once more. It may allow for a more comprehensive comparison between reef types and between locations.

4.2 Fish survey results

Across both islands, a total of 149 individual surveys were conducted, across three different locations; Big Rock Market (Saba), Crooks Castle (St. Eustatius), and Twin Sisters (St. Eustatius). The surveys resulted in a total of 2576 fish observations excluding Blennies and Gobies. These were excluded due to inconclusive and inconsistent monitoring. However, personal observations gave the impression that one species of goby had an influence on the presence of other species on the artificial reefs. *Elacatinus evelynea*, the Sharknose goby, acts as a cleaner fish, turning the artificial reefs into a cleaning station (IUCN, 2018). On many reefs in Big Rock Market the Sharknose goby was observed, cleaning bigger fish like pufferfish, coneys, and parrotfish. This species is easily observed and might be of importance of the development of fish communities on artificial reefs.

Statistical analysis resulted in significant differences of fish abundance across artificial reefs ($p<0,001$). No significant differences were found between abundances per location nor per island. This confirms that certain artificial reef types are more favorable for fish aggregation than others. Layered Cakes appear to be most favorable for fish aggregation, averaging at 36,63 fish per reef. This is remarkably higher than the natural Patch Reef, which averages at 25,74. Natural Rocks and Reef Balls seem least suitable averaging at 16,18 and 9,60 fish respectively. However, it is important to recognize that although an increase in fish abundance can be considered favorable, these results disregard size, biomass, or species. A standardized measurement, like the Reef Health Index (RHI), could provide insight in the performance of individual artificial reef types. To calculate this; coral coverage, fleshy algal coverage, commercial species (i.e. snappers and groupers), and herbivore species (i.e. parrotfishes) need to be analyzed. Furthermore, RHI allows for widespread comparison across the Caribbean, and other parts of the world (CaribNode, 2018).

Differences in fish abundance may be explained by reef complexity, or rugosity. Literature suggests this is a leading factor for high levels of fish aggregation (Gratwicke, 2005; González-Rivero, et al., 2017). However, a recent study (Paxton et al., 2017) suggests this not to be the case after all. Paxton et al. found that intermediate levels of reef complexity maximize fish abundancy. This could explain why the less complex Layered Cakes attract higher levels of fish abundancy, than the more intricate, complex Rock Reefs. Perhaps shelter sizes on Rock Reefs are too small for larger fish, making them unfavorable. The paper suggests that fish size has a unimodal relationship with reef complexity. Suggestions could be made to analyze fish size and reef complexity in future.

4.3 Coral survey results

The coral surveys surprised the researchers as they hypothesized few corals to inhabit the artificial reefs. Large numbers of coral recruits were found on the artificial reefs. The UV-light method made it significantly easier to find coral recruits. During the UV-night dive the corals were easy to spot, while during a day-dive the coral recruits are almost impossible to find without knowing where to look. In total, 149 coral recruits were found, mapped, and documented. Further research could provide insight into survival and growth rate.

An average coral recruit count of 20,0 and 19,7, suggest Layered Cakes and Reef Balls are slightly more attractive than Rock Reefs, which averaged at 15,0 coral recruits. However, due to low n-values, no statistical tests were conducted. It is thought that coral recruits favour natural stone materials over concrete to settle (Burt et al., 2009). Burt et al. found that gabbro, a rock similar to basalt rocks, had the highest density of coral recruits, however, the gabbro used in Burt et al.'s research was coarse grained and the concrete had a smooth surface. In this research the basaltic rocks were smooth and the concrete coarse grained, indicating that such physical features influence coral larvae settlement (Whalan et al., 2015).

At least three species of coral recruits were found: *Porites* sp., *Agaricia agaricites* and *Favia fragum. Porites sp.* could not be determined in species level due to their current size. *Porites* sp., *Agaricia agaricites* and *Favia fragum* are all brooding species. It is thought that brooding coral species can spawn all-year round in a circatrigintan cycle (ca. 30-day cycle) (Linden, Huisman, & Rinkevich, 2018), and usually settle close to their parent colony. This indicates that the found corals are most-likely from locally found colonies (Vermeij, et al., 2007). Most broadcast coral species spawn in early to mid-September or early to mid-October (CARMABI, 2017). However, no broadcast spawning species were found on the artificial reefs. This implies something happened to the coral larvae after the spawning event. It is suspected that the hurricanes caused this disturbance, however based on currently available data, no conclusive statements can be drawn.

4.4 Costs

The final product of this study is an aid tool for management decisions, designed to help local nature organisations (STENAPA and SCF) in deciding which artificial reef type is most suitable for their conditions. Naturally, the cost of such a project is something that needs to be taken into consideration.

The cost of producing artificial reefs varies greatly. Reef Balls and Layered Cakes have high initial costs, which originate from buying materials, moulds etc. The cost per additional Reef Ball or Layered Cake is relatively low, yet still higher than that of Rock Reefs of the same format. It is important to keep in mind that costs of Rock Reefs will increase exponentially with size, whereas costs of Reef Balls and Layered Cakes grow linearly. With regards to deployment, it is important to remember that costs are highly dependent on how far from point of origin the reefs are to be deployed. Naturally, a 5-minute trip from port is less costly than a 30-minute journey.

Furthermore, the cost of man-hours varies greatly per island. The current costs are assumed that of a marine park ranger, whom receives hourly wages differing per island. On Saba, a marine park ranger receives $12,50 an hour (personal communication, Van der Velde, J., 2018), whereas on St. Eustatius a ranger receives $8,- an hour (personal communication, Houtepen, E., 2018). This averages out on $10,25 per hour, the Figure used to calculate construction and deployment costs. Important Figures that have been left out in this calculation are: the time spent scouting for suitable locations, waiting for the Reef Balls and/or Layered Cakes to cure, and the cost of running a boat capable of deploying the preferred reef type.

With regards to the curing of Reef Balls and/or Layered Cakes, other activities can be conducted whilst doing so, which qualify as operational costs thus not necessarily construction costs. Furthermore, the cost of running a boat are considered operational costs and are therefore not included in the analysis.

Another aspect that was left out of consideration was that these organisations often have volunteers available, which could reduce construction and deployment costs substantially. Furthermore, man-hours are based on a single person working, after having received instruction from representatives from the Reef Ball Foundation. A ‘recipe’ and list of instructions was drafted up afterwards, however it may prove valuable to plan additional time for construction and deployment. Also, a minimum of two people is recommended when constructing artificial reefs. For deployment, a minimum of three people is recommended.

4.5 Hurricane resilience assessment

The hurricane resilience assessment conducted in November 2017 showed that artificial reefs are somewhat vulnerable to hurricanes. All artificial reefs were, in some way, affected by hurricanes Irma and Maria. Huge sediment displacements caused profound damage to the coral reefs and the artificial reefs. The assessment showed that all Rock Reefs were collapsed during the hurricanes, suggesting that the use of natural rocks of this size as a reef is not suitable for this area. It is likely that the Rock Reefs collapsed due to sediment movements, since there was no stable base. The rocks were stacked directly on sand. The Rock Reefs have since been modified. A metal cage keeps the rocks together, this should improve stability and resilience of the Rock Reefs during strong currents and swells. However, this modification remains untested and was therefore excluded from the analysis. The Layered Cakes and Reef Balls were more resilient to the hurricanes. With only one Reef Ball and one Layered Cake being destroyed. Most artificial reefs were displaced by swell caused by the hurricanes. Layered Cakes moved an average of 0,6m from their original location, whereas Reef Balls moved an average of 2,1m.

This can be explained by the fact that Reef Balls are lighter than Layered Cakes (estimated 250kg per Reef Ball opposed to 300-350kg per Layered Cake) (Reefball.org, 2018). A problem that occurred was that artificial reefs got (partially) covered with sand. On few occasions artificial reefs were covered by almost 50 percent. Benthic growth on parts of these reefs was covered, causing it to die. Furthermore, the reefs 'sank' into the sediment. On average Layered Cakes sank 12,2 cm, the Reef Balls sank an average of 8,9 cm. This caused the bottom layer of both Layered Cakes and Reef Balls to be covered in sediment, resulting in the death of any growth on those areas. Only in December 2017 on Saba and January 2018 on St. Eustatius when all artificial reefs were dug out and repaired, was life able to fully settle on the reefs again.

This hurricane resilience assessment shows the aftermath of two extremely strong hurricanes hitting the area. However, it is impossible to tell which hurricane caused what damage to the reefs. Also, it is unlikely that a hurricane of similar magnitude will hit the area again anytime soon. The last hurricane with the same power as Irma and Maria in the Caribbean was in 2005 (AccuWeather, 2013). Although, researchers believe that ocean warming caused by climate change threatens coral reefs indirectly by fuelling the energy of hurricanes. It is possible this will cause more intense hurricanes to hit the Caribbean (Cheal et al., 2017).

4.6 Multi criteria analysis

To aid in the creation of a decision-making tool, a multi criteria analysis (MCA) was conducted. For this analysis, the following criteria were used: fish abundance, fish species richness, hard coral settlement, materials costs, man-hours, and hurricane resilience. Based on the features alone, the following results came forth: with a final score of 10; Reef Balls prove least suitable. Followed by Layered Cakes, which scored 13 in the analysis. Both are trumped by Rock Reefs, which score 14. However, with weighed results from the questionnaire the Layered Cake seems to be the most suitable. Hard coral settlement is considered the most important feature of an artificial reef, most likely because corals have a high economic value (Conservation International, 2008). Corals also improve local fisheries and tourism (UNEP, 2014; de Graaf et al., 2015). Hurricane resilience ranked second, probably due to recent hurricane activity

4.7 SWOT analysis

In order to gain more insight in the MCA results, a SWOT analysis analysed the strengths, weaknesses, opportunities, and threats of each artificial reef. Based on results, personal experience, and observations, the SWOT analysis provides insight into artificial reefs beyond the studied variables.

5.0 Conclusion

From April 2018 till the end of May 2018, a comparison between three artificial reef types, in particular their aggregated fish abundance, fish species richness, hard coral settlement, costs, and hurricane resilience was conducted. In total 149 fish surveys and eight hard coral settlement surveys were conducted, resulting in the observation of 2576 fish of 47 individual species, and 149 corals of at least three species; *Porites sp., Agaricia agaricites*, and *Favia fragum.* Data from previous internships was gathered to gain insight into the costs and hurricane resilience of the artificial reefs. These data helped answer the main question of this study:

''Which of three artificial reef types Reef Balls, Layered Cakes, or Rock Reefs, placed around St. Eustatius and Saba, is most suitable for the conservation of coral reefs in the Dutch Caribbean?''

Information on fish abundance and species richness indicates Layered Cakes to be most favorable in both aspects. Rock Reefs rank second in abundance, followed by Reef Balls. The same ranking applies to species richness. When comparing the artificial reefs to natural patch reefs, Layered Cakes are the only type of reef that outperforms natural reef on abundance. With regard to species richness, all artificial reefs outperform natural patch reefs. This gives the impression that increasing species richness can be achieved by placing any of the artificial reefs. If the intent is to increase fish abundance, Layered Cakes would be deemed most suitable. This can be explained by reef complexity, which is supported by the observations of many fish hiding between layers, using the reef as shelter. Another explanation could be the distance from artificial reef to natural reef, allowing for traffic between reefs. Conclusively, more research is required to make hard statements of what causes this difference in fish abundance and species richness.

The biggest (and most pleasant) surprise of this study was the abundance of corals found on the artificial reefs. This study hypothesized that very few, or possibly even no corals, would be found on the artificial reefs. Reef Balls proved most favorable for (at least) three brooding species, observed during a total of eight hard coral settlement surveys. Layered Cakes rank second on coral abundance, followed by Rock Reefs. Based on our data, any explanations for these differences would be speculation. However, Whalan et al. suggests that physical features of materials influence the development of reefs (Whalan et al., 2015).

Data from Phase 1 of AROSSTA (scouting locations, constructing, and deploying artificial reefs) provided insight into the costs and man-hours required to construct and deploy these artificial reefs. Due to similarities in material and construction method, Reef Balls and Layered Cakes both result highest in costs and man-hours. These structures require more effort to build, yet allow for high levels of customizability, resulting in a wide range of uses. Rock Reefs however allow for fast and cheap artificial deployment, which is attractive in today's conservation climate where funding is often scarce.

Finally, data from what was supposed to be Phase 2, the first monitoring of the reefs, provided insight into hurricane resilience. Both Layered Cakes and Reef Balls were displaced to a certain degree. However, the Rock Reefs had collapsed completely, resulting in any fish and benthic community development to be lost. Alterations were made, adding a steel cage under the Rock Reefs, which is designed to increase stability.

A multi criteria analysis summarized all results and classed them in value intervals. Without weight (which was derived from questionnaires), the MCA scored Reef Balls the lowest score, Layered Cakes came second, and Rock Reefs received the highest score. Adding the weight, Layered Cakes scored highest, which coincides with personal observations and opinion. Making them the most suitable artificial reef type for the islands of Saba and St. Eustatius. However, a second scenario was calculated, where hurricane resilience was not considered. In which case, Rock Reefs are deemed most suitable.

6.0 Recommendations

In order to gain a better understanding of different artificial reef types and how these influence fish aggregation and coral settlement, more extensive research needs to be done. Also, it is recommended to repeat similar surveys as the one in this study, to continue monitoring the artificial reefs. Several recommendations follow below:

1. Blennies and Gobies are not counted for on a consistent basis. However, the Sharknose goby, *Elacatinus evelynea*, seems to be of big importance in the development of an artificial reef by turning the reef into a cleaner station. It is recommended that this fish will be added on the fish survey list.
2. In the current setup, each fish is valued the same. Per example: an artificial reef full of Bluehead Wrasses is deemed just as valuable as an artificial reef full of parrotfish, despite this being a key coral reef species. Recommendations are made to identify key species and value these differently than others.
3. A new method should be developed to accurately measure the volume of the shelter spaces of the artificial reefs and to determine how many shelter spaces are present in the artificial reefs. This could describe the differences found in fish abundance and species richness between the artificial reefs.
4. Continued surveying of coral recruits could prove valuable to gain insight in different survival and growth rates.
5. Natural reef surveys are recommended to see if there is a difference in fish abundance and fish species richness on the natural reefs. The artificial reefs might also cause fish to aggregate close to the experimental plots, this can cause a shift of distribution of fish communities across the natural reefs.
6. A standardized method, like the Reef Health Index (RHI), could provide a better tool to see which experimental plots are more favourable. However, more data, like biomass of herbivore and commercial species and fleshy macro algae coverage is needed.

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Appendix I

Fish survey protocol v1.2 February 2018

Divers require extensive training in fish identification, and abundance and size estimation prior to conducting the survey.

Materials

- Dive computer
- Secchi disk
- Go pro + under water light
- Slates, pencils, and sheets printed on underwater survey paper

Method

Divers will start with the outer experimental plot of an experimental block. This plot will be surveyed using the described method. After finishing the first survey, divers continue to the adjacent experimental plot, survey this plot, and continue to the next experimental plot, etc. For measuring a ray, the TL of the tips of the pectoral fins are estimated. Gobies and blennies are lump summed in the category "small cryptic".

1. Check if all the equipment is present and working and go to the right location
2. Fill in the names of the observers and the date, time, and location
3. Measure horizontal Secchi disk depth (HSDD) with 10 cm precision. The Secchi disk should face the sun. HSDD should be at least 5 meters to proceed with the survey.
4. Start survey dives on alternating outer experimental plots (*e.g.* start first survey at north side, second at south side, third at north, etc)
5. Descend at least 10 m away from the experimental plot
6. While slowly swimming towards the survey area horizontally, diver 1 will record the fish, while diver 2 is filming the survey for future reference and for identification of unknown species. As diver 2 is not to disturb the fish before the counting, he will swim slightly behind/next to diver 1.

All the fish within a virtual cylinder (1 meter sideways of the plot and 2 meters upward from the bottom) around the experimental plot are included in the survey. Fish in the cylinder are identified up to species level, counted, and classified in size categories 0-5, 5-10, 10-15, 15-20, 20-25, 25-30, 30-40, 40-50, 50-60, etc., cm TL (from the tip of the snout to the tip of the longer lobe of the caudal fin).

7. Start with filming the survey sheet, so date, time, location, HSDD are visible on film.
8. Start recording **fleeing fish** at 5 meters distance of the artificial reef.
9. At 2 meters stop swimming and start stationary count for **3 minutes (use the go pro to monitor the time)**.
10. During the stationary count, **all** fish in the cylinder, also fish entering during the survey, are included in the survey. You count a fish only once, even if it repeatedly swims in and out the cylinder.
11. First record all schools, then record the other fish.
12. After 3 minutes, the artificial reefs will be thoroughly searched to record all the hiding fish. New fish entering the cylinder will not be included in the survey. Use a torch if necessary.
13. Unknown fish will be described as detailed as possible (e.g. Large blackish striped grouper) and can be identified later using video footage.
14. Count all lobster and estimate their carapace length
15. **Note anything striking on the artificial reefs** (e.g. Under water visibility only 4 meters, or: Sergeant majors laying eggs on Layered Cakes)
16. Determine temperature and bottom depth of the experimental plot.
17. When all fish are counted move towards the next experimental plot and repeat step 6 to 16.

18. If 50 Bar is reached, ascend slowly to 5 meters to make a safety stop for 3 minutes.
19. After safety stop ascend slowly to the surface and signal the boat.
20. **Fill in your data as soon as possible, always on the same day! Always take a picture of the original survey sheets.**

Appendix II

Benthic survey protocol

Divers require extensive training in benthos identification, and abundance and size estimation prior to conducting the survey.

Materials

- Dive computer + compass
- Photo camera
- Callipers
- Slates, pencils, and sheets printed on underwater survey paper

Method

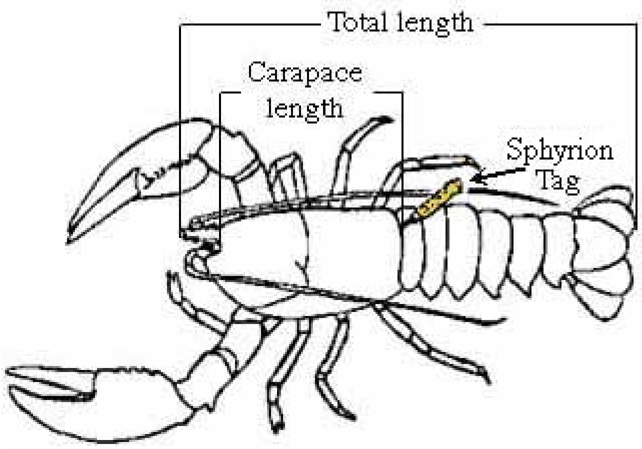
Divers will start with the outer experimental plot of an experimental block. This plot will be surveyed using the described method. After finishing the first survey, divers continue to the adjacent experimental plot, survey this plot, and continue to the next experimental plot, etc.

All plots will be systematically searched for hard corals and mobile benthos. Other benthic organisms will be surveyed using point intercept transect (PIT) method. The three bay balls or Layered Cakes of an artificial reef are sampled separately using the same method. The transect tape will be placed around the top the artificial reef unit and a diver will hold the tape in place. Sessile benthic organisms will be recorded every 10 cm of the transect tape and classified in categories: hard coral, octocoral, encrusting sponge, massive sponge, crustose coralline algae (CCA), articulated coralline algae, turf algae (filamentous algae <1 cm in height), fleshy macroalgae, cyanobacteria, tunicate, bryozoan, hydrocorals (milleporids) bare substratum (including dead coral) or other benthos.

After the transect is recorded, the transect tape will be replaced 10 cm downwards or, if this is on a notch of a layered cake, whenever possible. This will be repeated a third time. For the rock pile reef and the control plot on sand, the transect tape will be placed systematically around and over the plot, always keeping 10 cm distance between different parts of the tape. The aim is to record 200 points per plot.

1. Check if all the equipment is present and working, go to the right location and descend
2. Fill in the name of the observers and the date, time, and location
3. Search the artificial reef for mobile benthos (sea cucumber, lobster, crab, sea urchin, etc).
4. Measure all sea-urchins with callipers (body without spines) and estimate the carapace length of the lobster (see Figure below)
5. Search the artificial reef for stony corals. Look carefully, brush away algae, etc.
6. Photograph each individual with callipers attached and map the location of the stony corals (so you can find them back).
7. Record species and size of stony corals
8. Survey the plot with the PIT method. When a group is overgrowing another, only the overgrowing group is scored. If points are on mobile benthic organisms as sea cucumbers or sea urchins, the biota underneath it will be recorded. If points are on a hole or notch of a reef, they will not be recorded.
9. If the transect tap is be replaced (on Reef Ball or layered cake or to the next Reef Ball or layered cake) use a division sign, so it is clear where on the reef the data is recorded.
10. Determine the depth of the experimental plot (bottom) and temperature.
11. Move towards the next experimental plot and repeat step 3 to 9.

12. When all the artificial reefs are surveyed, finish your dive with monitoring the control plot on sand
13. If 50 Bar is reached, ascend slowly to 5 meters to make a safety stop for 3 minutes.
14. After safety stop ascend slowly to the surface and signal the boat.



Appendix III

Questionnaire AROSSTA – Artificial reefs on Saba and St. Eustatius

Name:

Function:

Organization:

Please score each feature of an artificial reef. Give more points to the feature you find more important than the other feature, and less points to features you find less important. Please note: a total maximum of 100 points can be given.

Feature	*Score*
Fish abundance	
Fish species richness	
Hard coral settlement	
Material Costs	
Man-hours	
Hurricane resilience	

Appendix IV

Damage assessment after hurricanes									
	Saba, Ladder Bay								
	LB1	LB2	LB3.1	LB3.2	LB3.3	LB4	LB5.1	LB5.2	LB5.3
	Control	Rocks	Layered cakes	Layered cak	Layered cak	Rocks	Reef Balls	Reef Balls	Reef Balls
Datum:	21-11-2017	21-11-2017	21-11-201721-11-201721-11-2017			21-11-2017	21-11-2017	21-11-2017	11/21/2017
Observer:	Daniel, Esmee & Ay	Daniel, Esm	Daniel, Esmee & Ayumi		Daniel, Esme	Daniel, Esmee &	Daniel, Esm	Daniel, Esm	Daniel, Esmee
grootste hoogte boven sediment (cm):			39	34	48	45	51	36	45
gem hoogte boven sediment (cm)			24	30	24	27	27	24	27
afstand van originele plek (m):			1.2	-	-	n.v.t.	3.25	n.v.t.	n.v.t.
beschadigingen:			Geen beschadigingen, één layered cake 1,2 meter verwijderd van de rest.			De pyramide is ingestort. Stenen liggen er	Geen schade aan de reefballs, één reefball meer dan 3 meter verwijderd van de rest.		
Bijzonderheden:	Niet gevonden	Niet gevonden	VIS! Vissen schuilen in de ruimte tussen de lagen.				Weinig activiteit of leven te bekennen.		
Hersteld (ja/nee) en op wat voor manier:		Nee, wordt niet hersteld	ja, terug op plek gezet met liftbags, spanbanden en mankracht	Ja, uitgegraven en met een liftbag en spandband en	Ja, uitgegraven en met een liftbag en spandband en	ja, mand gemaakt van een betonnet. deze te water gelaten en op de plek naast het oude	ja, terug op plek gezet met liftbags, spanbanden en mankracht	Ja, uitgegraven en met een liftbag en spandband en	Ja, uitgegraven en met een liftbag en spandbanden verplaats naast LB5.1
Datum hersteld:			22-Nov-17	4-Dec-17	4-Dec-17	30-Nov-17	22-Nov-17	4-Dec-17	4-Dec-17

Damage assessment after hurricanes									
	Saba, Big Rock Market/Giles Quarter (between the dive moorings)								
	BR1.1	BR1.2	BR1.3	BR2.1	BR2.2	BR2.3	BR3	BR4	BR6
	Reef balls	Reef balls	Reef balls	Layered cak	Layered cak	Layered cakes	Rocks	Rocks	Control
Datum:	11/22/2017	11/22/2017	11/22/2017	11/22/2017	11/22/2017	11/22/2017	11/22/2017	11/22/2017	11/22/2017
Observer:	Daniel, Esmee & Ay	Daniel, Esm	Daniel, Esmee &	Daniel, Esm	Daniel, Esm	Daniel, Esmee &	Daniel, Esm	Daniel, Esm	Daniel, Esmee
grootste hoogte boven sediment (cm):	36	58	X	43	60	60	30		n.v.t.
gem hoogte boven sediment (cm)	27	34	X	34	33	36	36		n.v.t.
afstand van originele plek (m):	5,80m	10.6	n.v.t.	2.77	3.60	n.v.t.	n.v.t.	n.v.t.	n.v.t.
beschadigingen:	Goed kapot, onderste deel niet gevonden.			kapot, door midden.			uit elkaar gevallen	uit elkaar gevallen	
Bijzonderheden:	ver uitelkaar		in 3 stukken 3de stuk is weg			in tweeen gebroking			
Hersteld (ja/nee) en op wat voor manier:	ja, terug op plek gezet met liftbags, spanbanden en mankracht	ja, terug op plek gezet met liftbags, spanbanden en mankracht	ja, terug op plek gezet met liftbags, spanbanden en mankracht	ja, terug op plek gezet met liftbags, spanbanden en mankracht	ja, terug op plek gezet met liftbags, spanbanden en mankracht	ja, terug op plek gezet met liftbags, spanbanden en mankracht, helfde pasten goed op elkaar.	Ja, mand van betonnet (1,5x1m)	Ja, mand van betonnet (1,5x1m) en hoogste punt 90 cm	nieuwe reebars er in geslagen
Datum hersteld:	6-Dec-17	6-Dec-17	6-Dec-17	6-Dec-17	6-Dec-17	6-Dec-17	6-Dec-17	5-Dec	6-Dec-17

Damage assessment after hurricanes

	Statia, Twin Sisters						
	TS1.1	TS1.2	TS1.3	TS2	TS3.1	TS3.2	TS3.3
	Reef balls	Reef balls	Reef balls	Control	Layered cak	Layered cakes	Layered cak
Datum:	28-Nov	28-Nov	28-Nov	24-Nov	24-Nov	24-Nov	24-Nov
Observer:	Alwin	Alwin	Alwin	Alwin	Alwin	Alwin	Alwin
grootste hoogte boven sediment (cm):	50	60	55		45	45	35
gem hoogte boven sediment (cm)	40	60	55		45	45	35
afstand van originele plek (m):	0	0	1.5		0	0	0
beschadigingen:	0	0	0		0	0	0
Bijzonderheden:	Geen beschadigingen, maar diep in het sediment. Niet veel vis. Één stonefish, een black			niet meer te vinden	Geen beschadigingen, maar diep in het sediment. Veel vis, maar andere soorten		
Hersteld (ja/nee) en op wat voor manier:	ja, uitgegraven en 2 meter verplaaatst	ja, uitgegraven en 2 meter verplaaatst			ja, uitgegraven en 2 a 3 meter verzet	ja, uitgegraven en 2 a 3 meter verzet	ja, uitgegraven en 2 a 3 meter verzet
Datum hersteld:	29-Nov	11/29/2017			5-Jan-18	5-Jan-18	5-Jan-18

Damage assessment after hurricanes

	Statia Crooks Castle						
	CC1.1	CC1.2	CC1.3	CC2.1	CC2.2	CC2.3	CC3
	Reef balls	Reef balls	Reef balls	Layered cak	Layered cake	Layered cakes	Control
Datum:	22-Nov	22-Nov	22-Nov	22-Nov	22-Nov	22-Nov	
Observer:	Alwin	Alwin	Alwin	Alwin	Alwin	Alwin	
grootste hoogte boven sediment (cm):	65	65		70	50	45	
gem hoogte boven sediment (cm)	65	65		70	50	40	
afstand van originele plek (m):	0	0		1.5	1.5	1.5	
beschadigingen:	0	0	kapot (niet door de orkanen, was al kapot bij	0	0	0	
Bijzonderheden:	Redelijk wat vis, grote red hind, begroeid met vooral		incompleet	Geen beschadigingen, wel één diep onder het zand. Veel vis en veel			niet meer te vinden
Hersteld (ja/nee) en op wat voor manier:	ja, uit het zand gehaald	ja, uit het zand gehaald	ja, uit het zand gehaald, tegen andere aan gezet	ja, uitgegraven en 2 a 3 meter verplaatst	ja, uitgegraven en 2 a 3 meter verplaatst	ja, uitgegraven en 2 a 3 meter verplaatst	
Datum hersteld:	9-Jan-18	9-Jan-18	9-Jan-18	10-Jan-18	10-Jan-18	10-Jan-18	

Appendix V

Material:	Cost per unit:	# Required	Fixed needs	Fixed costs	Variable needs:	Variable costs
Cement (Portland Type II)	$ 5,25	48	0	$ -	2	$ 10,50
Sand per kg	$ 0,02	5000	0	$ -	28,35	$ 0,64
Gravel per kg	$ 0,02	5000	0	$ -	28,35	$ 0,64
Micro silica 25kg	$ 12,00	12	0	$ -	0,5	$ 6,00
Micro fibre	$ 5,00	8	0	$ -	0,330	$ 1,65
Adva 140 (L)	$ 4,76	8	0	$ -	0,05	$ 0,24
Sugar (kg)	$ 2,00	1	0	$ -	0,01	$ 0,02
Plywood	$ 40,00	2	1	$ 40,00		$ -
Shovel	$ 50,00	1	1	$ 50,00		$ -
Wheelbarrow	$ 100,00	1	1	$ 100,00		$ -
Gasoline (L)	$ 1,07	10	0	$ -	0,42	$ 0,45
Fibreglass Rebar 4''	$ 2,00	100	4	$ 8,00		$ -
2200 lb Lift bag	$ 675,00	1	1	$ 675,00		$ -
120 lb lift bag	$ 95,00	2	1	$ 95,00		$ -
3000 lb cargo net	$ 750,00	2	1	$ 750,00		$ -
Air tank yoke for lift bags	$ 65,00	1	1	$ 65,00		$ -
Bay Ball Mould	$ 1.250,00	1	1	$ 1.250,00		$ -
ReefBall Standard Tool Kit	$ 500,00	1	1	$ 500,00		$ -
Cement mill	$ 65,00	12	0	$ -	0,5	$ 32,50
Total cost:				**$ 3.533,00**		**$ 52,63**

Total Fixed Costs	**$ 3.533,00**
Total Variable Costs per Reef Ball	**$ 52,63**
Total cost to build 1 Reef Ball:	**$ 3.585,63**

Material	Cost per unit	Fixed needs	Fixed costs	Variable needs	Varable costs
Rebar cage	45	0	0	1	45
Rocks (price of gravel) per kg	0,02	0	0	300	6
Total costs:			**0**		**51**

Appendix VI

MCA questionnaire response

Name Alwin Hylkema	
Feature	*Score*
Fish abundance	20
Fish species richness	15
Hard coral settlement	25
Material Costs	10
Man-hours	5
Hurricane resilience	25

Name Daniel heesink	
Feature	*Score*
Fish abundance	15
Fish species richness	20
Hard coral settlement	25
Material Costs	5
Man-hours	10
Hurricane resilience	25

Name Callum Reid	
Feature	*Score*
Fish abundance	20
Fish species richness	20
Hard coral settlement	25
Material Costs	10
Man-hours	5
Hurricane resilience	20

Name Kai Wulf	
Feature	*Score*
Fish abundance	15
Fish species richness	15
Hard coral settlement	25
Material Costs	10
Man-hours	10
Hurricane resilience	25

Name Ayumi	
Feature	*Score*
Fish abundance	15
Fish species richness	20
Hard coral settlement	20
Material Costs	5
Man-hours	10
Hurricane resilience	30

Name Marijn van der Laan	
Feature	*Score*
Fish abundance	25
Fish species richness	10
Hard coral settlement	25
Material Costs	25
Man-hours	0
Hurricane resilience	15

Name Marit Pistor	
Feature	*Score*
Fish abundance	20
Fish species richness	20
Hard coral settlement	30
Material Costs	10
Man-hours	5
Hurricane resilience	15

Name Erik Houtepen	
Feature	*Score*
Fish abundance	10
Fish species richness	15
Hard coral settlement	25
Material Costs	15
Man-hours	15
Hurricane resilience	20

Name Jelle van der Velde	
Feature	*Score*
Fish abundance	11
Fish species richness	29
Hard coral settlement	32
Material Costs	4
Man-hours	7
Hurricane resilience	18

Appendix VII

	Total score	MCA score Reef ball	Questionnaire x MCA		
Fish abundance	151	1	151		
Fish species richness	164	1	164		
Hard coral settlement	232	3	696		
Material Costs	94	1	94		
Man-hours	67	2	134	**Final score with hurricanes**	**Final score w/o hurricanes**
Hurricane resilience	193	2	386	**1624**	**1239**

	Total score	MCA score Layered cakes	Questionnaire x MCA		
Fish abundance	151	3	452		
Fish species richness	164	3	491		
Hard coral settlement	232	3	696		
Material Costs	94	1	94		
Man-hours	67	1	67	**Final score with hurricanes**	**Final score w/o hurricanes**
Hurricane resilience	193	2	386	**2186**	**1800**

	Total score	MCA score Rock reefs	Questionnaire x MCA		
Fish abundance	151	2	301		
Fish species richness	164	2	327		
Hard coral settlement	232	3	696		
Material Costs	94	3	281		
Man-hours	67	3	201	**Final score with hurricanes**	**Final score w/o hurricanes**
Hurricane resilience	193	1	193	**2000**	**1807**

Appendix VIII