Master's Thesis– master Water Science and Management

A Rainwater Harvesting System based Blueprint for Excess Runoff Management on Caribbean Small Island Developing States

Investigating the Feasibility of the Rigofill System Combined with New Dam Structures in the Coral Estate Resort – Curacao

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Executive Summary

Freshwater is essential to public health, food security, livelihoods, and healthy and resilient ecosystems. However, water scarcity is amongst the major problems faced by societies today. Drinkwater supply on islands is an even more complex matter as all naturally occurring freshwater on SIDS originates from precipitation. Many SIDS are located in semi-arid areas north and south of the equator, these experience high losses of surface water through evaporation. These high evaporation losses make groundwater the prime freshwater source in many SIDS. Insufficient recharge of groundwater will result in a shrinking freshwater buffer and cause water stress. Due to its position relative to the sea, groundwater storage is difficult. Anthropogenic forces, such as an increase in potable water demand, triggered by prosperity growth and tourism, will put an even greater pressure on its freshwater supplies. Therefore, RWH can be used to collect rainwater from artificial surfaces and sometimes natural surfaces as a resource to be used for potable supply of non-drinking purposes.

The Caribbean island of Curaçao is a typical example of a small island where a combination of natural and anthropogenic factors leads to insufficient groundwater recharge. Within Curacao's NDP 2015-2030 a long-term vision for the change of Curaçao has been established. The objective is to create a liveable and sustainable Curaçao. In the context of "water", this translates to the use of water for the development of the island, while ensuring the protection of water as a natural resource.
During this research it was investigated how MRWH can serve to buffer storm water runoff to minimize flooding and erosion. The stored water can additionally be reused for domestic non-potable purposes. The research was in fact a pilot to see whether MRWH offers a solution against both the flood-related problems during the wet season and the water shortage-related problems during the dry season.

The CN Method has been used to determine how much water is available as excess runoff from intense rainfall events. The outcome was compared with CER's annual water demand, after which it was determined what percentage of their water consumption can be covered. Based on the comparison, it has been determined that the total capacity of the MRWH system to be implemented must be 5000 cubic meters. Wherein, four reservoirs, of different sizes (300, 700, 1000 and 3000 cubic meters), will be implemented alongside the access road. An average of 45% of CER's water consumption can be covered annually, where it serves non-potable purposes. This results in annual cost savings of approximately EUR 32,000.

In addition, it has been calculated how much excess runoff can be buffered, so that flood-related problems are reduced. A reduction of at least 50% of runoff by road is ensured, which can increase to a 100% runoff reduction in case of smaller rainfall events. Considering CER's total catchment area, at least 8% of runoff can be buffered, which can increase to 20% when smaller events occur. Despite these percentages, it can be stated that the implementation of this MRWH system is not economically feasible and profitable due to its long payback period. However, this does not include feasibility regarding flood reduction. By including the costs of damage suffered and the costs incurred as a result of the excess runoff in the consideration, a different conclusion may be stated. This could be determined by further in-depth research.

Opportunities exist for MRWH in other parts of the Caribbean because these systems are less costly than concrete and metal storage systems; have an enormous storage capacity; and by means of its multifunctionality, a larger market can be reached through large-scale application. However, these large scale systems are not yet feasible due to their current price structure. It is possible that if used on a smaller scale, feasibility will increase.

Preface

Acknowledgements

During a period of six months I researched the possibility of applying a modular rainwater harvesting system on Curacao and wrote my thesis about this. It was a period in which I learned not only to set up a valid and reliable research, but also to do this independently in a time and place where there was a lot of uncertainty. I didn't do this alone. Therefore, I would like to express my gratitude to the persons who have advised, helped and supported me during my research.

To start, I would like to dedicate this thesis to my internship supervisor Peter Oostwouder, who passed away during my time in Curacao. I am grateful to him for the opportunities he has given me and the trust he has placed in me. I would also like to thank Peter´s wife Lya Oostwouder and Hans Verkruijsse for taking care in difficult times.

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Glossary

Catchment area	The area that drains its water via a river.
Cistern	An artificial underground reservoir for the storage of drinking or household water.
Interception	The amount of water that does not reach the drainage system (soil), but is instead intercepted by vegetation and the land surface from where it directly evaporates (i.e. evapotranspiration).
Retention area	Is a flood prevention area where the water can be temporarily stored during intense rainfall events, with the aim of protecting downstream areas from flooding.
Ridgeline	The boundary between two river basins and usually consists of a height difference in the landscape.
Tiered Structure	Refers to a series of rows or layers or a level or grade in the hierarchy of an organization or system. A tiered structure describes a system with distinct levels or layers.

Nomenclature

AMC	Antecedent Moisture Conditions
CARMABI	Caribbean Marine Biological Institute
CER	Coral Estate Resort
CN Method	Curve Number Method
GWL	Groundwater Level
MAR	Managed Aquifer Recharge
MDC	Meteorological Department Curacao
MRWH	Modular Rainwater Harvesting
NDP	National Development Plan
RWH	Rainwater Harvesting
SWI	Seawater Intrusion
SLR	Sea Level Rise
SIDS	Small Island Developing State

1. Introduction

Freshwater is essential to public health, food security, livelihoods, and healthy and resilient ecosystems. However, water scarcity is amongst the major problems faced by societies today. Currently, approximately 1.2 billion people live in water-scarce regions (United Nations, 2014), and it is expected that, by 2025, as many as 3.5 billion could experience water scarcity (Water Resource Institute, n.d.). These consequences are no different for Small Island Developing States (SIDS). SIDS were first identified as a separate group of developing countries in 1991 at the Earth Summit in Rio de Janeiro, Brazil (Gheuens et al., 2019). The UNUESCO definition of a 'small island', classifies an island with an area not greater than 2,000 km^2 or whit a width smaller than 10 km to be small (UNESCO, 1991). As however, a set of characteristics was never defined, the following general set of features defines this geographical grouping: small size, remoteness, vulnerability to external (demand and supply-side) shocks, narrow resource base, and exposure to global environmental challenges (ibid).

Drinkwater supply on islands is a complex matter. Not only have islands, a relatively small surface surrounded by masses of salt water, but also a considerable part of the precipitation evaporates almost immediately (United Nations, 2014b). All naturally occurring freshwater on SIDS originates from precipitation (Falkland, 1991; Falkland, 1993). The types of natural freshwater occurrences can be described as: precipitation water, surface water and groundwater (Carrard et al., 2019). Precipitation can occur as dew, fog, hail, rain, and snow, in which rainfall is the most prevalent form. Because there is little space available to collect and store water, Rainwater Harvesting (RWH) is often used to collect rainwater from artificial surfaces and sometimes natural surfaces as a resource to be used for potable supply of non-drinking purposes (Table 1).

Table 1, Possible options for rainwater utilisation.

Cooling	Toilet flushing
Firefighting	Landscape irrigation
Laundry	Industrial re-use
Street flushing	Fountains/water squares
Swimming pool recharge	Blue energy
Allotment gardens	Infiltration/groundwater recharge
Car washing	Cleaning purposes

Surface water occurs on SIDS in the form of ephemeral and perennial streams and rivers, springs, freshwater lagoons, lakes and swamps. The assessment of surface water resources however is difficult as surface water occurs, in many cases, in the form of many small river catchments (ibid). Groundwater occurs on SIDS in two main forms: perched and basal aquifers. A perched aquifer is an aquifer that occurs above the regional water table (Groundwater Dictionary, n.d.). Basal aquifers occur however, below the water table, in the form of coastal aquifers of freshwater lenses overlying sea water (Falkland, 1991; Falkland, 1993). Due to the fresh-water/sea-water interaction these lenses are vulnerable to saline intrusion (Falkland, 1993). Due to its position relative to the sea, groundwater storage is difficult. Anthropogenic forces, such as an increase in potable water demand, triggered by prosperity growth and tourism, will put an even greater pressure on its freshwater supplies.

1.2 SIDS´s Water Systems

The importance of groundwater resources as prime source of freshwater in SIDS worldwide can hardly be over-emphasized (Carrard et al., 2019; UNESCO, 2000; UNESCO, 2019; White et al., 2007). Many SIDS are located in semi-arid areas north and south of the equator, these experience high losses of surface water through evaporation. One of these SIDS, Curacao, will be the focus of this research. These high evaporation losses make groundwater the prime freshwater source in many SIDS. Insufficient recharge of groundwater will result in a shrinking freshwater buffer and cause water stress. Groundwater stored in coastal aquifers is susceptible to salinization due to seawater intrusion (SWI). SWI has been described as the landward movement of water from the sea into the coastal aquifer (Idowu & Lasisi, 2020). SWI is the main driver of groundwater salinization, resulting in the degradation of groundwater quality worldwide (Barlow and Reichard 2010; Bocanegra et al., 2010, Custodio 2010; Steyl & Dennis, 2009; Werner, 2009). In SIDS, some form of water management is needed with an emphasis on management that is "climate resilient".

The Caribbean island of Curaçao is a typical example of a small island where a combination of natural and anthropogenic factors leads to insufficient groundwater recharge. Within Curacao's National Development Plan (NDP) 2015-2030 a long-term vision for the change of Curaçao has been established. The objective is to create a liveable and sustainable Curaçao. In the context of "water", this translates to the use of water for the development of the island, while ensuring the protection of water as a natural resource. A lot is needed to achieve this objective, in particular a lot of fresh water. The main problem in this situation however, is that water, partly due to the islands skewed precipitation distribution, is not available throughout the year. Causing considerable problems for both nature and society as the risk of water shortages increases. In addition, this problem is exacerbated by a welfare-driven increased water demand, tourism, and climate change. Consequently, a large structural buffer is missing to meet potable water demand, causing Curacao to be heavily dependent on their desalinisation (reverse osmosis) plant (Antilliaans Dagblad, 2019). The disadvantage of such a plant is the high level of energy consumption, and its additional energy costs.

1.3. Curacao's Water Future

The aforementioned long-term vision for the change of Curaçao, described in the NDP 2015-2030, expresses its objective, to create a liveable and sustainable Curaçao, among other this, into the following goals (Government of Curaçao, 2020; UNDP, 2016):

- "Achieving 100 % circular water management, which revolves around the renewable use of all freshwater flows."
- "Sustainably managed flood risks, whereby we also strive for a more effective management of our surface waters and groundwater."

As a result, the government will commit itself to: "Adjusting the legislation in the context of construction and housing, whereby water collection becomes mandatory for sites with a size of >1000 m^2" (Government of Curaçao, 2020).

1.3.1 Pilot Project - Coral Estate Resort

One of the construction sites that fall under this policy is the Coral Estate Resort (CER). CER, is located on the former estate of Rif St. Marie and has been developed into a complex since the late 1980's. Since its start, CER has made sustainability a top priority. This is expressed, among other things, by means of a sustainable design of the area (i.e. relatively low building densities), the preservation of important landscape elements and vegetation, the presence of a waste water treatment installation and the design of so-called corridors between built-up areas for bird migration.
CER is located in a landscape where excessive rainfall leads to flash floods and erosion, causing damage to surrounding land and objects and thus strongly influencing the landscape. CER has asked GSO Caribbean to develop a system to manage the excess runoff. A seasonal river bed, alongside the access road (Fig. 1), runs through the CER area, causing similar problems as described before (i.e. erosion, flooding). The seasonal river bed drains lots of water during the wet season but is dry during the dry season. In some sections the access road is situated lower than the seasonal river bed, which means that during intense rainfall events, in addition to the water that is supplied via other paved surfaces, a lot of water flows onto the road.

A Modular Rainwater Harvesting (MRWH) approach using the Rigofill system (see Chapter 2.4) is proposed by GSO as a potential solution for these challenges that affect CER, and which is in line with the objectives set by the government. The idea is to make the combination with a new, yet to be constructed, series of low dams. The purpose of the combined systems, is to capture and store water during excessive rainfall events, which has the added advantage of reducing excess runoff and preventing flash floods. The stored water can be reused to compensate for the water shortages that arise later during the year. The remaining stored water can be used for infiltration into the soil.
The purpose of the dams is to slow down the water upstream and thus reducing the fraction of rainfall that reaches the access road in a short time. In addition, this measure can, based on the underlying idea of the old traditional earthen dam structures (see Chapter 2.2), increase the infiltration of rainwater and contribute to the desalination of the soil.
Rainwater that falls on the paved surfaces runs off faster than rainwater that falls on unpaved terrain. The purpose of the Rigofill system is to collect, from the access road, store and reuse (relatively) clean rainwater in order to comply with CER's assignment to manage the excess rainfall. The clean rainwater is extremely suitable for non-potable purposes such as primary landscape irrigation and groundwater replenishment.

In this situation, it is possible that, when intense rainfall events occur, a retention basin (i.e. new dam) to store rainwater is created above the underground buffer basin (i.e. Rigofill). Important to note is that; the term “dam” in Curaçao refers to both the dyke and its reservoir (van Buurt, 2015). In general, a much considered measure is the use of retention areas upstream of the area where discharges must be reduced. Rainwater retention can be useful to reduce the frequency of extreme discharges in small catchment areas and may also have a lowering effect on water levels. (Kwadijk, 2007).
The idea is to construct the new dams in stages in the elevated catchment area to create retention areas (Fig. 2). The underlying concept of these dams is that of Managed Aquifer Recharge (MAR). MAR has the purpose of recharge of water to aquifers for subsequent recovery or environmental benefit (IAH - Commission on Managing Aquifer Recharge, 2021). The water is stored at the surface and can infiltrate by means of natural and "forced infiltration” to the subsoil where it benefits the groundwater level (GWL). Natural recharge, by infiltration, of deep aquifers is a slow process because groundwater moves slowly through the unsaturated zone and the aquifer (U.S. Geological Survey, n.d.). Due to CER’s geological characteristics (see Chapter 1.4), additional forced infiltration is

needed. Through forced infiltration, water is inserted into the ground, making natural infiltration a little easier. The excess rainwater is transported by gravity, via a pipe construction filled with porous material (gravel, volcanic stones), to the groundwater. The surplus of water that the retention area (i.e. new dam) cannot store, will flow via an emergency overflow, to a downstream retention area of the next dam.

Figure 1. Envisioned design, from above, of the combination Rigofill and new dam structures.

The Rigofill system will be used underground, beneath the dams, and will also be applied in stages. Hence the underground will first be excavated to make room for the installation of the system. After installation, the system is covered with an infiltration cloth and provided with an inlet (connected to the drainage system of grids), integrated inspection pits, a filtration device and an overflow. The infiltration cloth is a geotextile that ensures infiltration from the crate system into the soil is possible, without backfill material entering the system. This is an independent system that is separate from the dam structures, therefore there is no interaction between the water from both systems. The water entering the Rigofill system, from intense rainfall events, that flows, as runoff, down the access road will be collected in the drainage system of grids. After that, it passes through a pre-separator in which sediments are filtered out (Fig. 2). The filtered water is then collected in the crate system. Subsequently there are two options, either the crate in which the water ends up has a storage function or an infiltration function. When it ends up in a storage crate, the water will be stored for longer. The water ending up in an infiltration crate can infiltrate into the surrounding soil via the side walls and bottom. An underground pipe connection will be made between the different reservoirs, which allows the excess water to drain to a lower basin (i.e. Rigofill). From the lowest reservoir, water can be pumped up, via a pump installation, for reuse. After implementation, the original material will be returned after which an overlying retention area is formed by the construction of a dam.

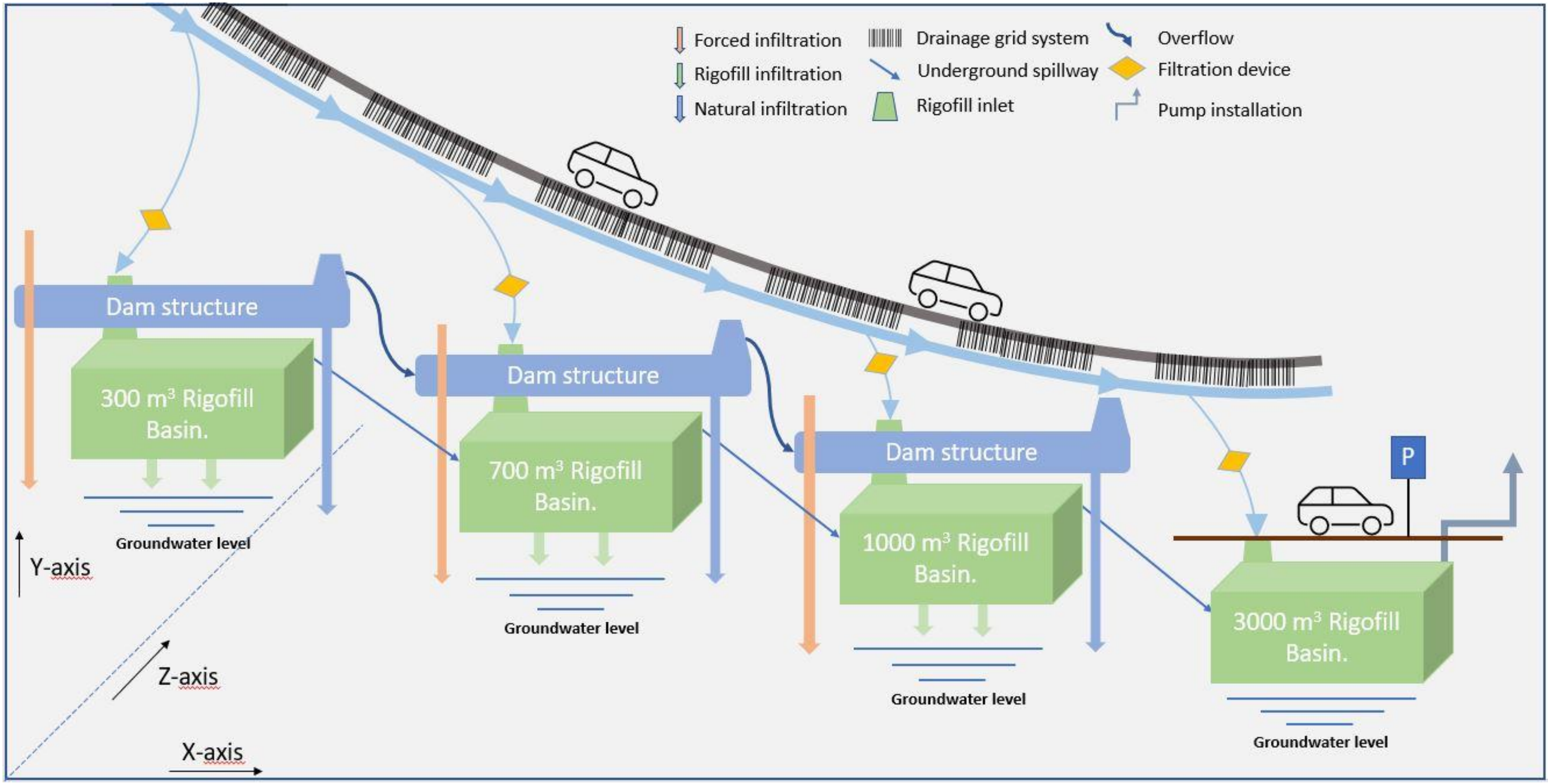

Figure 2. Schematic representation of the envisioned design of the Rigofill-dam structure combination. The water that flows over the road is collected via a drainage system of grids, which are installed parallel to the road. The coarsest material (e.g. twigs and leaves) will remain behind due to the filter action of these grids. The collected water will pass through a rainwater filtration device, where the majority of smaller particles are retained. The water then flows through a pipe construction ending up in a Rigofill basin. From the bottom basin, constructed beneath the parking lot, the water be pumped up for reuse purposes.

1.4. Research Objective

The new policy drawn up by the government and the existing water problems cause CER to come up with a solution. The Rigofill system offers a solution for the current water problems and is at the same time in line with the stated objectives for Curacao's water policy. However to date, the applicability of the Rigofill system has been investigated in urban areas, as it was originally developed for. The current envisioned application at CER with semi-arid climate, has never been researched. In addition, the intention is to apply the Rigofill system cascading in an elevated area, whereas current applicability has always been done in a flat area.

As it is not clear yet how to implement the different systems, the first aim of this research is to investigate the feasibility of the Rigofill system in combination with new dam structures to collect, manage and reuse the excess runoff, in order to combat the associated problems, in Coral Estate resort - Curacao. The second aim of this research is to analyse the potential of the Rigofill system to be used as component of a blueprint for excess runoff management on other Caribbean SIDS. Based on the aims of the study, the following research question has been formulated:

RQ: To what extent can the implementation of Rigofill provide a solution for the excess runoff at the Coral Estate Resort, plus account for its own freshwater supply; and what is the potential for implementation of this type of RWH system on other SIDS?

Answering the research question consists of a number of phases. To determine whether it´s feasible to implement the Rigofill system on CER, first a comparison will be made between CER's demand and the natural supply. Showing how much of the demand can possibly be covered and whether this is sufficient. This is the second phase. Consideration, in this phase, is also given to when the collection of rainwater takes place (in which months), what quantities are collected, and for how long. The Curve Number method is used to determine how much water approximately runs off, as surface runoff, during an intense rainfall event and can be collected.

In the third phase, it will be assessed whether it is feasible to create the relevant storage on CER by means of Rigofill. Herein, the water yield, payback time, flood risk reduction and CER's image are considered.

By subsequently looking at the prerequisites for the system on Curacao, and comparing these with environmental factors on other SIDS, Rigofill's applicability on other SIDS will be discussed in the last phase. The research is provided with the following sub-questions

1. What is the average annual amount of rainwater available to the Coral Estate Resort?
2. How much of CER's annual water demand can be replaced by runoff water from excessive rainfall events?
3. How large is the potential runoff and how large should the capacity of CER´s Rigofill system be?
4. Is the implementation of the Rigofill system feasible for the Coral Estate Resort?
5. What are the prerequisites for the Rigofill system to be applied on other SIDS in the Caribbean?

1.4 Geological Site Description

Curaçao is situated at the boundary of the Caribbean and South-American plates. The geology of the island of Curacao is characterized by four different rock types (see Appendix A): (i) the Curacao Lava formation (also referred to as Diabase), which covers more than half of the island (NW and SE part of the island); (ii) the Knip formation, which mainly occurs on Banda'bou (Western part of the island); (iii) the Midden Curaçao formation and; (iv) the Seroe Domi formation or limestone terraces (Baake, 2016; Beets, 1972; Beets & MacGillavry, 1977; Louws 1997). The current coastal zone, including CER, consists of these recently formed coral limestone deposits (Fig. 3). Soil infiltration capacity in limestone areas is usually considered high (Calvo-Cases et al., 2003 & Li et al., 2011).

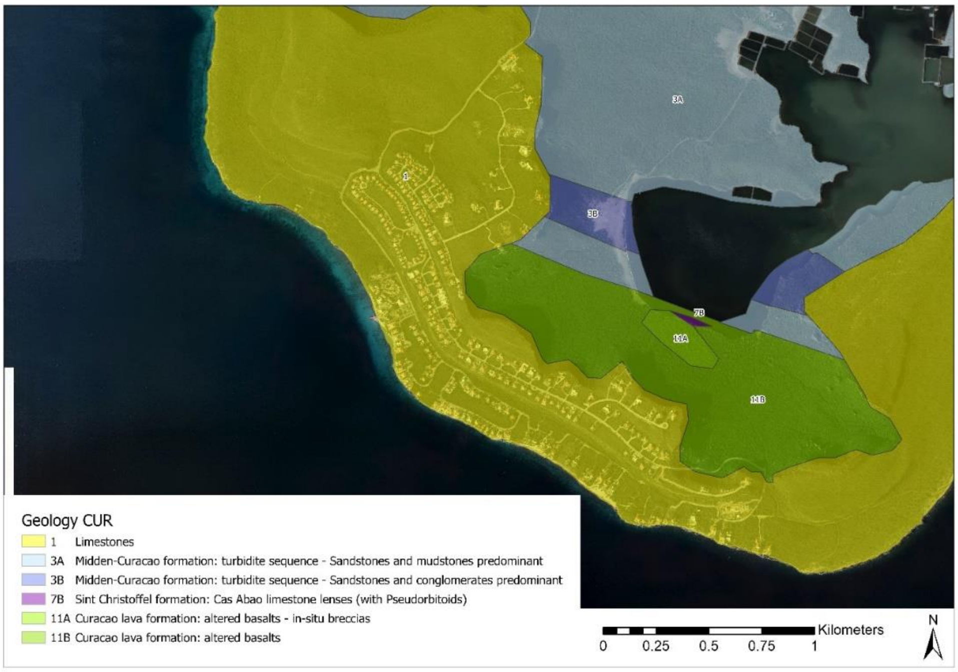

Figure 3, Overview different formations on Coral Estate Resort (CARMABI, 2020).

Various soils arise on these different geological formations. Grontmij & Sogreah (1968) distinguished three main groups: (i) soils on limestone formation; (ii) soils on Diabase and; (iii) alluvial and colluvial soils. Only the former is of interest for this study as CER is located on limestone terraces. About 28% of Curacao's surface area consists of these types of soils. The soils on limestone formations classify as highly porous, shallow, and mainly saline (de Vries, 2000). Most of these soils are located near the coast on erosional terraces and have a shallow profile varying in thickness between about 0.1 and 0.4 metres (de Vries, 2000). As in most soils, $CaCO_3$ and other soluble salts are present, calcification (reversed weathering) often takes place. This process occurs under semi-arid conditions, where evapotranspiration exceeds precipitation (Gunal & Ransom, 2006). Wherein evaporation causes the soluble salts present in the groundwater to accumulate in the topsoil, resulting in an increase of the salt concentration. This ongoing process will eventually lead to an deposition of mineral salts (Steila & Pond, 1989). The process of calcification in the upper soil horizons can lead to the formation of thick accumulative calcareous crusts (Kovda et al., 2011). The latter being a given on CER, making it difficult for water to infiltrate naturally, whereby forced infiltration has been proposed as a way to assist natural infiltration.

2. Background of the Curacao Water System

Curacao is characterized by a semi-arid climate, with an annual precipitation of around 550 mm (Martis et al., 2002). The dry season runs from February through June, whereas the rainy season starts in October and ends in January (Meteorological Department Curaçao, n.d.). On average, once every 5 to 6 years, a wet period occurs with more than 1000 mm of precipitation, while precipitation in dry years can be limited to 200 mm/year. (Louws et al., 1997). Moreover, the islands average maximum temperature is 31.5° C, and the average minimum temperature is 25.9° C, resulting in high evapotranspiration rates that vary between five and eight mm/day (Meteorological Department Curaçao, n.d.). The annual potential evapotranspiration can be 2500 mm and thus greatly exceeds the average annual precipitation (Meteorological Department Curaçao, 2011).

Curacao has 47 catchment areas with an average surface area of 5 km^2, without the presence of rivers and lakes (Louws et al., 1997). Groundwater reservoirs, of which 15 have been recorded, are only recharged during intense rainfall events, as the water flows into the underlying rock through fractures and diaphragms. It has been established that 1,300,000 m^3/year can be safely extracted from these reservoirs (i.e. without deterioration of quantity and quality) (Rowbottom & Winkel, 1979). In addition, Grontmij & Sogreah (1968) mention the presence of eight aquifers with a collectively safe water abstraction of approximately 700,000 m^3/year.

Until the twentieth century, the freshwater demand was met using rain- and groundwater. In 1915 Shell built an oil refinery and bought up plantations for the (ground)water supply. Louws et al (1997) stated at the time: "that most groundwater is suitable for irrigation. Much less groundwater is suitable for drinking water given the high chloride and nitrate concentrations." However, the Government of Curaçao (2020) concluded that "the quality of the groundwater can be called poor, due to saltwater intrusion, sea spray, a relatively high evaporation and insufficient replenishment of the groundwater by rainwater." The government ended groundwater extraction in 1962. Shell stopped groundwater extraction in 1973.

Since then, the drink water requirement has been met by a seawater distillation plant (Louws et al., 1997). The plant production capacity was 18,000 m^3/day in 2005, supplying about 45% of the average drink water consumption of the Island. In 2012 however, the plant went through an expansion to fulfil the increasing demand of potable water, increasing the water production to 25,100 m^3/day (Aladyr, 2019; Kim-Hak et al., 2014).

Poor groundwater recharge and groundwater salinization are problems that possibly cause desertification in the long term. Semi-arid regions usually cannot support large vegetation types because of the limited amount of precipitation. Small plants, usually grasses, shrubs and small trees dominate the landscape of semi-arid regions (Verweij, 2016). Vegetation cover in the dry period differs from that in the wet period. Shrubs occur in wetter conditions, whereas in drier conditions, the vegetation is more sparse like a semi-desert (Lane & Nichols, 1999). The higher the vegetation, the deeper the roots and the better the root penetration of the soil. Loosening the soil and, therefore increasing the absorption capacity of the soil (Bellot et al., 1999; Pingping et al., 2013). Whereas Curacao’s natural vegetation, shallow-rooted plants like bushes and shrubs, have the opposite effect, namely, decreasing the absorption capacity of the soil.

The island’s high evaporation rates cause the bare clayey topsoil to dry out, solidify, and lose their ability to absorb water, affecting infiltration rates even further (Nciizah & Wakindiki, 2015). Dry, compacted soil means that rainfall is less easily absorbed and infiltrated into the ground, making it harder to recharge the groundwater. Louws et al. (1997) stated that the fraction of Curacao’s precipitation that recharges groundwater is estimated to be up to 3.5%. While globally normally, 10 to 20% enters water-bearing aquifers (Petruzzello, n.d.). In addition, the number of wells has tripled in the last 30 years, indicating an increased consumption of groundwater (Government of Curaçao, 2020). Another problem is that the quality of the groundwater that remains, is also deteriorating. Due to sea spray, relatively high evaporation rates, and sea level rise (SLR) induced saltwater intrusion the groundwater's salinity is increasing. Curacao's groundwater is rather brackish, as chloride levels vary between 115 mg/l (fresh water) and 17.000 mg/l (almost seawater) (van Sambeek et al., 2000).

2.1 Curacao's Water System during the Wet Season.

In the rainy season however, a whole other set of problems, related to the increased surface runoff, arise. Namely: flooding, erosion and, sedimentation. The dry compacted soil, which originates from the dry period, cannot absorb the intense seasonal rainfall. What starts as increased runoff can quickly turn into excess surface runoff with the potential risk of flooding (Alaoui et al., 2018). Loss of property value and an increased risk of damage to it as a result, being additional problems (Government of Curaçao, 2020). The 2010 flooding for example, accounted for more than ANG 110 million (USD 63mln) (Central Bureau of Statistics, 2017).

An associated problem with the increased amount of surface runoff is that of increased soil erosion. Flushing away soil particles, organic matter and nutrients from agricultural areas. Making the soil less fertile and less suitable for agricultural purposes. Sedimentation being an additional off-site problem to erosion. Posing no thread when the fertile soil is deposited elsewhere on land. However, when sedimentation takes place in sea, it kills coral reefs. The suspended sediments interfere with the filter feeding of seabed organisms (e.g. clams) and block the light needed for photosynthesis and growth of corals and seagrasses (Risk & Edinger, 2011). Impacting both the agricultural and tourism sector, on which the island is heavily depended (Government of Curaçao, 2020).

Furthermore, as intense rainfall events are not uncommon on Curacao, there has been a focus for years on water drainage systems that enable a quick and direct discharge of rainwater, via the sewer system, to the sea (ibid.). Due to the changing climate these events are lasting longer and become more intense, causing drainage systems to be no longer sufficient enough. In addition, due to the quick and direct discharge, the rainwater cannot infiltrate, reinforcing the aforementioned point of not recharging the GWL.

2.2 Old Solutions to Store Water: Low Dam Structures.

In the past, a solution was devised for both the problem of erosion and sedimentation as for the poor recharge of the GWL. Since the early colonial times, a whole system of low earthen dams for water conservation was developed. The intention was to hold the run-off water in many places during good rainy years for the benefit of agricultural production As the runoff rainwater is spread over a large area, large numbers of "wet spots" (i.e. shallow pools) are created in which agricultural activities could take place. These low dams enabled part of the rainwater to infiltrate into the soil, recharging and maintaining GWLs and, contributing to the desalination of the soil.

In the 1940s and early 1950s, Shell built new dams in collaboration with the government. These, however, had a completely different character from the old ones. Instead of the hundreds of low dams that had to spread the run-off water to as many agricultural usable areas as possible, a few dozen very high, located near unusable agricultural areas, were constructed. Their objective was a to improve the GWL by infiltration. The consequences for the old smaller dams located close to the sea were however counterproductive (Fig. 4). Since the large dams upstream held back all water, the old dams no longer received their portion of 'desalinating water' during the good rainy years, which only accelerated their decline. Making restoration a poor option. Additional housing developments and a lack of maintenance have led to the destruction of many dams today (Fig. 5).

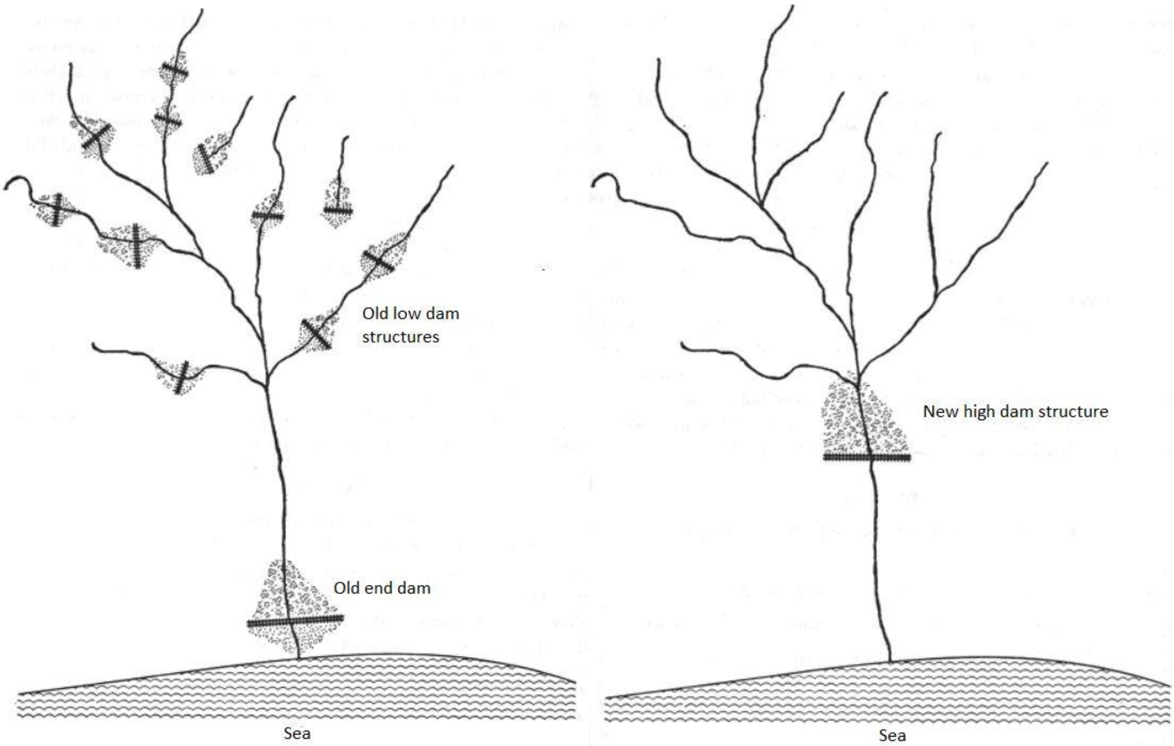

Figure 4. Comparison of "old" and "new" dams structures (Römer, 1977).

Figure 5. Old earthen dam structure. The dam head has been undercut by overflowing water. In its present state the dam is not functional anymore (van Buurt, 2015).

In the context of water stress on SIDS, the installation of RWH systems represents a valuable and effective solution to reduce the use of drinkable water consumption for domestic uses. The use of these systems has additional benefits, such as the retaining of flood from rainfall events and the consequent control of stormwater flood volume (Freni & Liuzzo, 2019). In addition, the GWL and desalinisation of groundwater can also be improved.

2.3 Rainwater Harvesting as an Option to Reduce Stormwater Runoff.

The Caribbean Environmental Health Institute (2006) defined RWH as follows: "Rainwater Harvesting is the method of capture of rainwater from man-made surfaces (typically rooftops and other constructed surfaces) and its storage for various applications which can include household, agricultural (irrigation and livestock watering) and commercial."
A typical RWH system has four main components (The Caribbean Environmental Health Institute, 2009): (i) a catchment area, commonly a roof surface or pavement; (ii) a conveyance system, a network of guttering and pipes to transport the water from the catchment area to the storage device; (iii) the storage device, often a tank above or below the ground; and (iv) the distribution system, which transports the water from the storage device to the facility the water is used for. A pump may be used to transmit the water through the system. A complement filtering device can be used to maintain and improve water quality.

However, this relatively abundant and available water source has initially been neglected because of the expected massive demand in storing capacity (Gleick, 2000). Fortunately, RWH is gaining interest again worldwide, the major driving forces for implementation are water scarcity, drinking water reduction or sustainability (Hofman & Paalman, 2014). Traditionally RWH has been used on small scale, wherein individual systems are designed for a single house, apartment blocks or office buildings. However, as a result of increasing problems worldwide with intensified rainstorm events and droughts, commercial firms (e.g. Atlantis, FRÄNKISCHE Rohrwerke, Geogreen Solutions, GRAF U.K., GS Tanks, Rainsmart Solutions, Shenzhen Doctor Rain Company and Wavin) have come up with solutions to collect, discharge, reuse and store rainwater on a far greater scale, as a measure to cope with extreme rainfall (Hofman & Paalman, 2014). The current trend is to improve rainwater harvesting strategies, so that the harvested water is stored for later use, and also infiltrates to minimize flooding and erosion while promoting groundwater recharge (Kinkade-Levario, 2007). Currently, underground cistern-like Modular Rainwater Harvesting (MRWH) (Fig. 6), predominates the field. In this research the possibility for this type of application to reduce stormwater runoff is investigated.

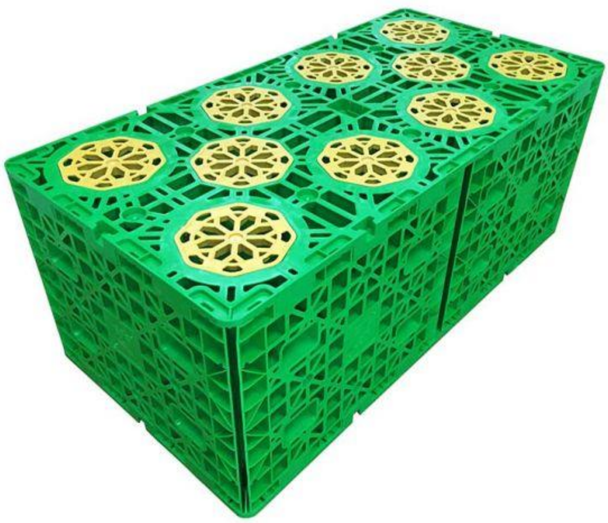

Figure 6. A Modular Rainwater Harvesting module (Shenzhen Doctor Rain Company, n.d.).

FRÄNKISCHE Rohrwerke has developed such a MRWH system, in which the natural cycle of the rainwater is simulated, the Rigofill Drainage and Infiltration System. These are highly water-permeable boxes that are used, underground, for the collection and storage (Fig. 7), infiltration (Fig. 8), and reuse (Fig. 9) of rainwater. This system is intended to infiltrate rainwater from hardened surface into the soil. This could be from a roof, terrace, driveway or in this case from the Coral Estate access road. Infiltration facilities ensure that water does not flow away and causes problems at lower locations. The collected water can be reused for flushing toilets, landscape irrigation, pool recharge etc. Curacao could make use of the Rigofill system to collect, reuse, store and discharge the excess runoff regulated. The surplus of precipitation from the rainy period can thus be used for the shortage that arises in the dry period. The collected rainwater can help to improve the quality and quantity of the groundwater and reduce the degree of flooding and erosion. An overview of additional advantages can be seen in Appendix E.

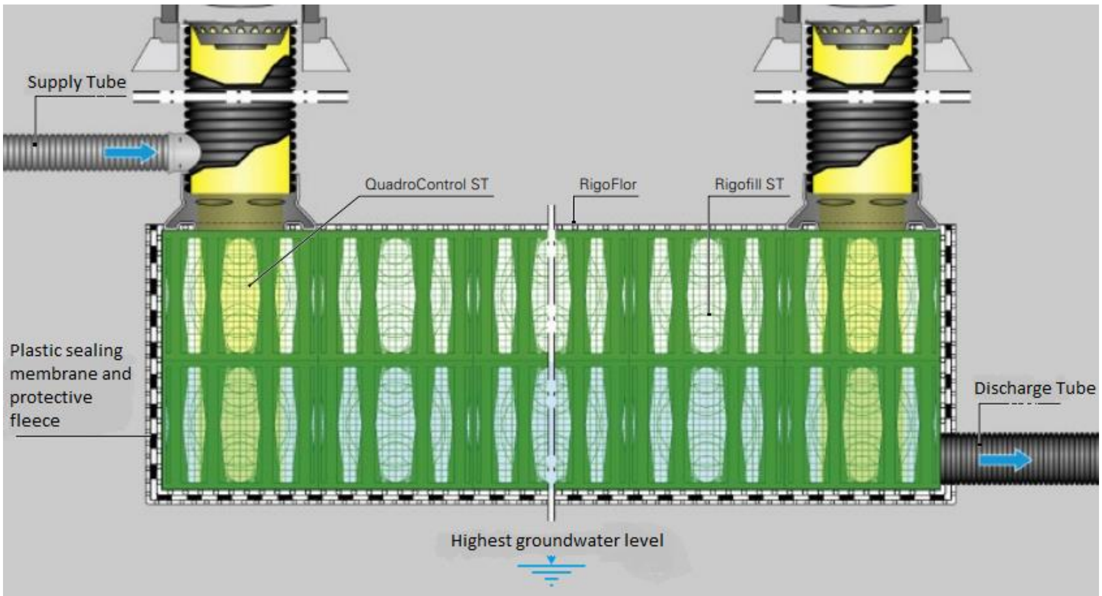

Figure 7. Collection & storage installation (FRÄNKISCHE, 2016).

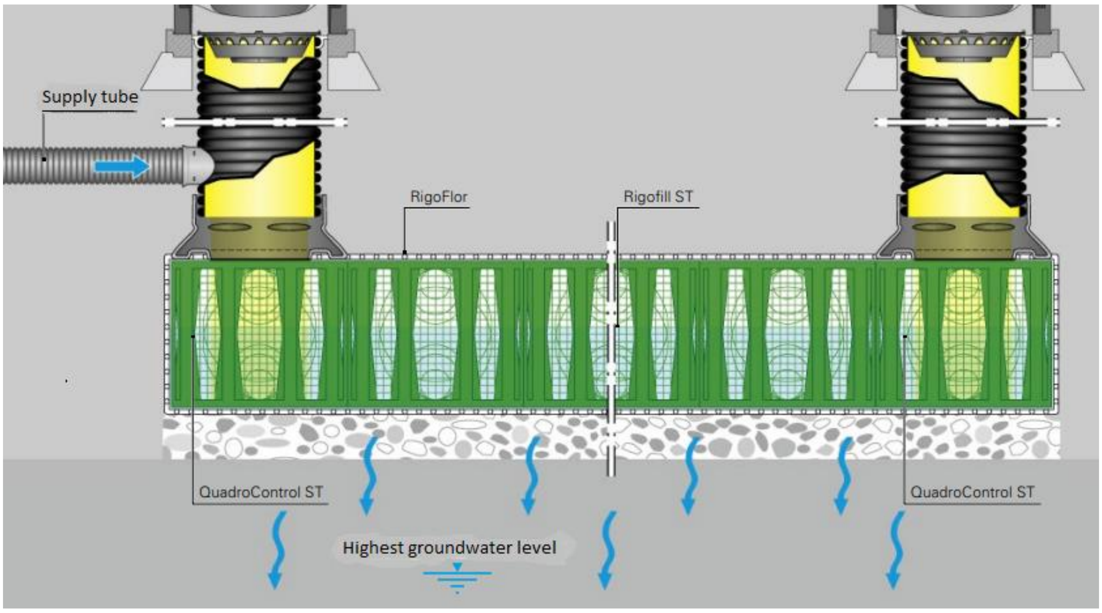

Figure 8. Infiltration installation (FRÄNKISCHE, 2016).

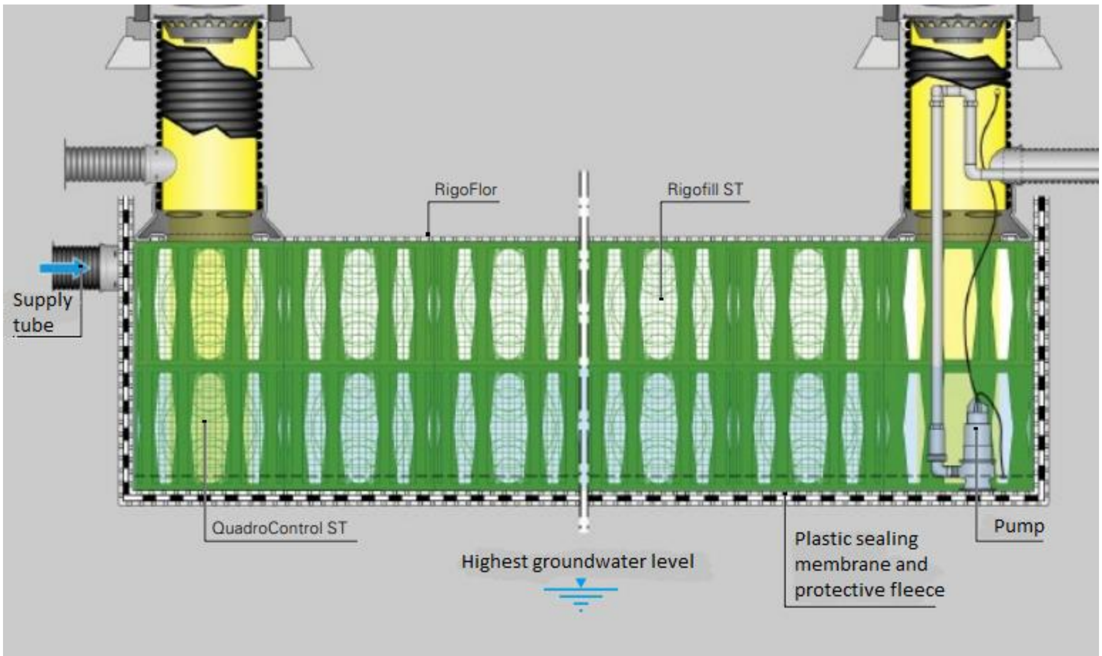

Figure 9. Reuse installation (FRÄNKISCHE, 2016).

3. Methods

The research consisted of several phases, namely: data collection, data processing and a literature study. These research methods will be reflected in the sub-questions below.

3.1 What is the average annual amount of rainwater available on the Coral Estate Resort?

It is assumed that he annual water availability in the CER catchment area is determined by a number of factors: (i) the precipitation, (ii) the surface area of the catchment area, and (iii) the level of interception in which evapotranspiration contributes the most.
Annual, monthly and daily rainfall data was obtained from the Meteorological Department Curacao (MDC), which is part of the Department of Traffic, Transport and Urban Planning. Additional scientific papers were used (i.e. De Vries, 2000; Louws et al., 1997; Martis et al., 2002; van Sambeek, 2000). The surface area of CER's catchment area was established via an elevations map (see Appendix B), which weas obtained via The Department of Public Works. This map was used to define heights and height differences that define the ridgeline. By nature, water always flows from high to low. As the ridgeline is known, the CER catchment area (m^2) was be established.
For the determination of CER's average annual rainwater availability, three approaches were taken to establish the amount of losses (i.e. evapotranspiration and interception). First, these losses were addressed by means of the available knowledge and information of the internship supervisor Mr. Oostwouder; the second approach was based on, in literature found percentages and values; thirdly, values were calculated from the MDC dataset by means of the Hargreaves equation.

3.1.1 Rainwater Availability Approach - Mr. Oostwouder.

Mr. Oostwouder assumed that annually on average about 75% of the precipitation falls on, and/or evapotranspirates from, surfaces that do not directly flow into the catchment area (= interception loss) (Ajami, 2021), and that the remaining 25% directly enters the catchment area for collection. Based on the 25:75 percent assumption, the annual precipitation data and the size of the catchment area, it has been calculated how much water is on average annually available on the CER.

3.1.2 Rainwater Availability Approach - Literature based.

Part of the precipitation (P) that ends up on the ground evaporates from plants, waterbodies and the soil (ET), another part infiltrates into the soil (I), and a part flows aboveground as runoff to surface water (Q) (Eq. 1). Curacao's mean annual precipitation is strongly influenced by a high evapotranspiration (about 85-95% of the precipitation) and about 10% of the precipitation is runoff (De Vries, 2000). Groundwater recharge is an estimated 10% of the precipitation and is approximately 28.7 mm/year (Alam, 1977). Louws et al. (1997) however, states that the fraction of the precipitation that replenishes the groundwater is estimated to be a maximum of 3.5%, corresponding to 20 mm/year.

$$P = ET + I + Q \tag{1}$$

Where,

ET = Evapotranspiration,
I = Infiltration,
P = Precipitation,
Q = Runoff.

Runoff (Q) indicates roughly how much water is available per m^2. By multiplying Q with the surface area of the CER catchment area, it was deduced how much water is available on an annual basis.

3.1.3 Rainwater Availability Approach – Hargreaves method (C)

Because Curacao's evapotranspiration, about 85-95% of the precipitation, is only mentioned in De Vries (2000), the potential evapotranspiration (ETo) was also determined using the 1985 Hargreaves' method (Eq. 2). The Hargreaves method provides evapotranspiration estimates when only air temperature data are available, although it requires previous local calibration for an acceptable performance (Jung et al., 2016). Gao et al. (2017) evaluated reference evapotranspiration methods in arid, semi-arid and humid regions, and showed that the 1985 Hargreaves methods worked best in the arid and semiarid regions. Additional, the Hargreaves method is recommended by the FAO (Allen et al, 1998) as an alternative method for estimating ETo if insufficient meteorological data are available for the Penman-Monteith method. Therefore, due to a limited availability of data, this method was used to function as a check on De Vries (2000). The 1985 Hargreaves method (Hargreaves and Samani, 1985), can be expressed as follows:

$$ET_o = 0.0023(T_{mean} + 17.8)(T_{max} - T_{min})^{0.5}\, R_a \tag{2}$$

Where,

R_a = Extra-terrestrial radiation	[MJ/m^2/day]
T_{mean} = Daily mean temperature	[°C]
T_{max} = Daily mean maximum temperatures	[°C]
T_{min} = Daily mean minimum temperatures	[°C]

All three calculation methods assume the same average annual amount of precipitation. But the calculation of the average annual amount of evapotranspiration, which determines water availability in this climate so much, differs per method. Oostwouder's method is based on a 25:75 ratio influx and losses respectively. The literature-based method takes into account a minimum of 85% evapotranspiration. The final calculations are based upon the Hargreaves method.

3.2 How much of CER's annual water demand can be replaced by runoff water from excessive rainfall events?

Secondly, the amount of water that can be replaced by runoff rainwater was determined (in cubic meters and as percentages). Meter readings of the various complexes on CER have provided insight. Based on these, the total annual consumption from different facilities was established. After determining CER's total annual water consumption for different usage, it was deduced how much of this drinking water can be replaced by rainwater. This was done by a literature study and using common sense. For example, filling pools, which are supposed to be attractive bright blue for tourists, with slightly brownish runoff rainwater, is not something a high end resort would do. However, replenishing them with it is a possibility.

3.3 How large is the potential runoff and how large should the capacity of CER´s Rigofill system be?

Since precipitation is distributed unevenly over the year, water will have to be stored during the wet period in order for it to be used in the dry period. Therefore, it was examined whether CER's water demand can be covered by runoff rainwater from intense rainfall events occurring during the wet period. The daily precipitation data, obtained from MDC, was therefore used. Before the size of the Rigofill system could be established, the collection capacity of the system was calculated. As Rigofill's storage capacity is intended to store runoff rainwater to reduce the effects of flash floods, the Curve Number Method (CN Method) was used to calculate the potential runoff rainwater that runs off during the most intense rainfall events (24 hour time period) (Eq. 3). The CN Method was used because of its simplicity, the start requirements for this method are very low. Only rainfall amount and curve number are needed to produce output. And even though little input variables are needed, this method incorporates the area's: hydrologic soil group, hydrologic condition, land use and land treatment (United States Department of Agriculture, 1986). In addition, this method was developed as a tool for runoff modelling in small basins (Grimaldi et al., 2012), just like the CER catchment area. Two approaches were taken:

- By means of the first approach, the potential amount of runoff within the entire CER catchment area has been determined. The same catchment area used to answer sub-question one (see Appendix B) was used to see if the CER's water demand could be met. Because it is difficult to say whether the runoff water from the entire basin actually flows into the system, a second approach has been implemented.
- In the second approach, the catchment area is limited to the paved pavement surfaces within the catchment area only (i.e. roads, sidewalks and indirectly from roofs) (see Appendix B). Paved pavement surfaces are relatively impermeable, allowing precipitation to run off much faster than it does from vegetated or undeveloped surfaces (i.e. the rest of the CER catchment). Playing a far greater role in the occurrence of floods. Therefore, it is important to first calculate how much water will run off over paved surfaces as excess runoff. After which can be calculated what percentage can be collected and stored and thus benefits flood reduction.

The CN Method was originally developed by the Soil Conservation Service (Soil Conservation Service 1964; 1972), and is a simple, widely used and efficient method for determining the approximant amount of runoff from a rainfall event in a particular area.

$$Q = \frac{(P - Ia)^2}{(P - Ia) + S}$$

Where, (3)

Q = Runoff volume,
P = Precipitation,
I_a = Initial abstraction,
S = Potential maximum soil retention.

An empirical relationship was developed between I_a and S based on rainfall and runoff data. S is representative of the capacity of the soil for infiltration, which is a function of both the physical characteristics of the soil, and of the available storage within the soil matrix. The available storage is dependent on the existing moisture content of the soil. The relationship is:

$$Ia = 0.2S$$

Gives the rainfall-runoff relationship of: (3.1)

$$Q = \frac{(P - 0.2S)^2}{(P - 0.8S) + S}$$

The CN is related to the potential maximum soil retention by the following equation: (3.2)

$$CN = \frac{1000}{S + 10}$$

(3.3)

The CN for a particular area was selected from a table (see Appendix C), based on the hydrologic soil group of the soils in the area. These tables are based on an average AMC II, AMC I or AMC III, which are representative of normal, dry and wet Antecedent Moisture Conditions (AMC) respectively. Runoff is affected by the soil moisture before a precipitation event, this research is based on AMC III conditions because the precipitation falls during the rainy period. During this period, the soil moisture does not have time to evaporate from the soil.

Based on the calculated maximum amount of runoff, the gross volume (422 litres) and the collection capacity (406 litres) of one crate, it was calculated how many crates are required to reach the total needed storage volume of the system. In addition, it has been calculated what percentage of the potential runoff water that was calculated and flows into the Rigofill system can be collected. Based on this information, the schematic design and in combination with the characteristics of the research area, a design has been made of what the system should look like in the future (Fig. 10).

3.4 Is the implementation of the Rigofill system feasible for the Coral Estate Resort?

A feasibility study is an analysis that takes all relevant factors of a project into account—including economic, technical, legal, and scheduling considerations—to ascertain the likelihood of completing the project successfully (Kenton, 2020). In this study the feasibility of the implementation of the Rigofill system is assessed from three dimensions. These dimensions have been chosen due to time constraints and because these are considered to be the most important aspects for CER. The following dimensions are considered:

- Economic feasibility. The full impact of the project from an economic standpoint was considered. That entails the determination of the estimated costs of implementation and the projected return on investment, to give a general assessment of the economic viability of the project.
- Flood reduction, the research was partly started to investigate the applicability of Rigofill to the Coral Estate Resort in order to reduce the excess runoff and additional flooding. Therefore, it is calculated what percentage of runoff can be captured, and thus will not contribute to flooding.
- Image, from the start CER has taken the direction of making sustainability a top priority. While CER may be described as an eco-resort, the construction of such a system as Rigofill may enhance the appeal of CER to eco-tourists and is an addition to the label they would like to put on themselves.

3.5 What are the prerequisites for the Rigofill system to be applied on other SIDS?

The last sub-question was answered based on a consultation with an employee of the Dutch-based Drain Design Construct BV, which is a partner of FRÄNKISCHE. In addition, a literature review has highlighted other RWH measures that can serve to absorb storm water runoff. The advantages and disadvantages are explained and in addition, these have been compared with MRWH.

4. Results

This chapter presents the results of the calculation of the annual average amount of precipitation; the Curve Number Method and; Coral Estate's water demand. In addition, the feasibility of the implementation of the Rigofill system is discussed.

4.1 - What is the average annual amount of rainwater available on the Coral Estate Resort?

The annual average precipitation is found through a literature study and other internet source, and is said to be 550 millimetres. This value is used to calculate whether the water availability in the catchment area is large enough to cover CER's annual water demand. Several scientific papers (De Vries, 2000; Louws et al., 1997; Martis et al., 2002; van Sambeek, 2000) indicate similar values shows below in Table 2.

The surface area, 0.32 km^2, of CER's catchment area was established through the use of an elevation map in combination Google Earth. The additional "paved catchment area" that was established has a surface area of 0.051 km^2 (see Appendix B).

Table 2, Different annual precipitation rates accordingly to their source.

Source:	Annual precipitation (mm/year)
van Sambeek, 2000	580
De Vries, 2000	574
Martis et al., 2002	550
Louws et al., 1997	525

Based upon the findings described above (i.e. the annual average precipitation and the catchment area), the average annual rainwater availability was established. For all approaches, the results (Table 3) of all methods are discussed below.

Table 3, Annual water availability of CER's catchment area.

Source:	Oostwouder (m^3/year)	Literature (m^3/year)	Hargreaves (m^3/year)
van Sambeek, 2000	46,246	27,748	-834,648
De Vries, 2000	45,768	27,461	-836,562
Martis et al., 2002	43,854	26,313	-844,216
Louws et al., 1997	41,861	25,117	-852,190

Based on Mr. Oostwouder´s 25:75 percent assumption, it has been calculated, by comparing different annual rainfall data from both MDC and literature, that between 41,000 and 47,000 cubic meters will effectively flow into CER´s catchment area. The literature based calculation resulted in a varying flow of water between 25,000 and 28,000 cubic meters.

The differences between Mr Oostwouder's results and the literature based method differ quite considerably. This can be explained by the fact that the Oostwouder method assumes 25% influx into the catchment area, while the literature assumes approximately 10%. The Oostwouder method is based on an assumption, which in turn is based on personal experience. However, this assumption is not scientifically substantiated. The literature-based results are scientifically substantiated and are therefore more reliable. Nevertheless, the results of both calculation methods cover CER's average annual water demand. Literature (TU Delft, 2015) even mentions extremes where 96% of the precipitation in semi-arid climates evaporates and only 4% flows into the catchment area.

The Hargreaves method was used to determine the evaporation. However, calculated with this method is the potential evapotranspiration (ET_p). The ET_p that was calculated was 3196 mm a year [1994-2020], exceeding the rate measured by MDC of 2531 mm a year [1981-2010]. Though, The ET_p can be greater than the annual precipitation. The ET_p is the evapotranspiration that would occur if there were no limits to water availability. In a semi-arid climate however, there are limits to the water availability, this method only shows the climate's potential to evapotranspirate and can therefore differ from the actual measured evapotranspiration. The ET_p is related to the energy from solar radiation absorbed by the earth. In semi-arid areas, there is no shortage of solar energy, but rather small amounts of precipitation. The ET_p can then easily exceed the precipitation. Therefore, the actual average annual evapotranspiration will approach the average annual precipitation. Thus, the annual average runoff will remain small. Explaining why the annual water availability calculated by means of the Hargreaves method showed contradicting values. The results of this method are reliable, however, turn out to be useless.
Because the literature-based results appear to be the most reliable, it can be stated that the average annual amount of rainwater available from the CER catchment area is between 25,000 and 28,000 cubic meters.

4.2 How much of CER's annual water demand can be replaced by runoff water from excessive rainfall events?

Table 4 below shows CER's annual water demand. Both in cubic metres and in euros for the years 2019 and 2020, taking 2019 as the reference year. This is because CER was hit more severely by the Covid-19 epidemic in 2020 than in 2019. As a result, the 2019 results are more closely related to reality, suggesting that CER's annual water demand is approximately between 10,000 and 15,000 cubic meters (potable and non-potable).

Table 4, Water consumption of the different facilities of the Coral Estate Resort and its accompanying prices.

Facility:	Water consumption 2019 [m³]:	Water consumption 2020 [m³]:	Pricing 2019 [Euro]:	Pricing 2020 [Euro]:
Centre	5,568	3,242	32,869.91	19,138.69
Apartments (76 pcs)	4,488	3,054	26,494.28	18,028.86
Entrance building Centre	378	263	2,231.47	1,552.58
Spa 8.	2,617	1,678	15,449.09	9,905.84
La Puerta Business Centre	393	331	2,320.02	1,954.01
Total	**11,751**	**7,507**	**69,370.38**	**44,316.52**

On an annual basis, this means that the water demand can be covered by the average annual amount of precipitation. However, slightly contaminated rainwater cannot replace all drinking water. During this study it is assumed that rainwater can only be used to replace non-potable purposes (i.e. toilet flushing, landscaping, dishwashing), because the replacement of potable water requires specific purification, which is not possible in case of the Rigofill system.
A report of the Water Research Foundation (2016), indicates that residential household use such as: toilet flushing, clothes washing, gardening, household cleaning etc. represents 61% on average. In addition, research shows that "domestic/restroom" end use (i.e. drinking, cooking, washing hands and body) of water in resort type hotels is estimated to be 30% of total water consumption (United States Environmental Protection Agency, 2016 and Colorado WaterWise, 2007). Therefore at least 70% (i.e. landscaping, cooling/heating, pools, dishwashing) of water in hotels can be replaced by somewhat purified non-potable rainwater for which drinking water would otherwise be used. "At

least" is stated because the 30% also includes restroom use.
This 70% is passed on in the water consumption of various facilities within the CER. Table 5 below shows the results of this calculation. What becomes clear from this table, is that no more than 5,500 cubic meters is needed as stored rainwater. Replacing 5,500 cubic meters of CER's drinking water with rainwater saves approximately 45% on annual water costs.

Table 5, The proceeds of scenarios A and B. Expressed in cubic meters, guilders, euros and percentages.

Savings:	**2019**	**2020**
Water (m^3):	5,439.60	3,332.80
Monetary (NAF):	69,626.88	42,659.84
Monetary (EURO):	32,111.92	19,674.72
Percentage (%)	46.3%	44.4%

4.3 How large is the potential runoff and how large should the capacity of CER´s Rigofill system be?

The results of sub-question one and two show that there is sufficient annual rainfall to meet CER's annual water demand. However, the precipitation is not evenly distributed throughout the year. Therefore, the coverage of CER's water demand is dependent on intense precipitation events. By means of climatic data, covering the years 1994-2021, the highest and second highest daily precipitation value in 24 hours is determined. Based on this, the corresponding amounts of runoff were calculated by means of the CN Method. The results of both catchments are shown below. These results were used to define the size and shape of Rigofill.

4.3.1 Total catchment area, Coral Estate Resort

The results of the CER's total catchment are shown in Table 6. In addition, Table 6 lists the corresponding number of crates required to store the runoff and the associated purchase price.

Table 6, Recorded daily (24 hrs) precipitation values and calculated daily (24 hrs) runoff amounts (m^3) in CER's total catchment. AMC III is representative for wet Antecedent Moisture Condition. Associated storage quantities in crates and their costs.

Total catchment area CER	**Precipitation [mm/m^2]**	**Runoff [m^3/catchment area]**	**Crates needed [pcs]**	**Price [Euro]**
Highest total precipitation:	189.00	60,280	-	-
Highest total runoff, AMC III condition:	179.27	57,176	140,827	21,124,050
2nd Highest total precipitation:	106.80	34,063	-	-
2nd Highest total runoff, AMC III condition:	97.33	31,043	76,459	11,468,850

Assuming the highest measured amount of runoff in the past 30 years, taking into account AMC III (wet) conditions (see Appendix C), the Rigofill system will have to have a storage capacity of around 57,000 cubic meters to buffer all runoff from the most intense rainfall event. This is equivalent to around 140,000 crates, with price of around 21 million euros. In this scenario it is assumed that the runoff, from the entire catchment area, determined by means of the CN Method, will all flock to the access road. However, Rigofill systems are simply not designed to capture and store such huge quantities of water. Therefore the paved catchment area approach was set up.

4.3.2 Paved catchment area, Coral Estate Resort

In this approach it was assumed that, since the idea is to apply the water collection system (drainage system of grids) alongside the road, only the water running off via paved surfaces was considered to be relevant for flooding. Thus, buffering this water directly reduces flood risk. The results for this approach are shown in Table 7.

Table 7, Highest recorded daily (24 hrs) precipitation value and calculated associated daily (24 hrs) runoff (m^3) in the CER paved catchment area. AMC III is representative for wet Antecedent Moisture Condition. Associated storage quantities in crates and their costs.

Paved catchment area CER	Precipitation [mm/m^2]	Runoff [m^3/catchment area]	Crates needed [pcs]	Price [Euro]
Highest total precipitation:	189.00	9639	-	-
Highest total runoff, AMC III condition:	179.99	9,179	22,608	3,391,295
2nd Highest total precipitation:	106.80	5447	-	-
2nd Highest total runoff, AMC III condition:	98.01	4998	12,311	1,846,720

Assuming the highest measured amount of runoff in the past 30 years, taking into account AMC III, the Rigofill system will have to have a storage capacity of around 9,000 cubic meters to buffer all runoff from the most intense rainfall event. This is equivalent to around 22,600 crates, with price of around 3.3 million euros.

4.4 Is the implementation of the Rigofill system feasible for the Coral Estate Resort?

Based on the above results (i.e. amount runoff, demand coverage, costs and CER's water consumption), it has been determined, in consultation with Rigofill expert Leo Koster, that the total capacity of the system should be 5,000 cubic meters. The previously developed schematic representation of the envisioned Rigofill design (Fig. 2) has been further elaborated on the basis of the above results. The choice was made to implement four basins (from top to bottom) with a storage volume of 300, 700, 1000 and 3000 cubic meters respectively (Fig. 10). Table 8 summarizes what the purchase of a 5,000 cubic meters Rigofill system means for CER.

Table 8, Overview of implications of acquiring a 5000 m^3 Rigofill reservoir.

5000 m^3 Capacity Rigofill System	Highest total runoff, AMC III condition:	2nd Highest total runoff, AMC III condition:
Runoff storage [%], Total catchment area CER	8.6	15.6
Runoff storage [%], Paved catchment area CER	54.5	100.0
Yearly water savings [%]	42.5	
Yearly saving [euro]	32,112	
Costs [euro]	1,847,291	
Payback period [years]	57.5	

For this research, feasibility is looked at from three perspectives: economic, flood prevention and image. From each aspect a number of considerations can be made based on the above results.

4.4.1 Economic feasibility

Two main aspects, that emerge from Table 8, that should be considered form an economic point of view are:

- A 5000 cubic meter reservoir ensures an annual water saving of ~42%, which is reflected in the water cost reduction of around 32,000 euro´s annually.
- The investment costs of a 5000 cubic meter Rigofill system are so high that the payback period is almost 58 years.

Even though Rigofill saves more than 40% in potable water and associated costs annually, it can be stated that, from an economic point of view, the implementation of a 5000 cubic meter Rigofill system is, due to its long payback period, not feasible for CER.

4.4.2 Flood prevention feasibility

With a capacity of 5000 cubic meters, the Rigofill system provides for the following degree of flood protection:

- Assuming runoff from the total CER catchment area, a 5000 cubic meter Rigofill system can buffer approximately 9% of the resulting runoff in the case of the highest recorded precipitation value in the past 30 years.
  In the case of the second highest recorded rainfall in the past 30 years, approximately 16% of the resulting runoff can be buffer.
- Assuming runoff from the paved catchment area only, a 5000 cubic meter Rigofill system can buffer approximately 55% of the resulting runoff in the case of the highest recorded precipitation value in the past 30 years. And in case of the second highest recorded rainfall in the past 30 years, all runoff can be buffered

If the total CER catchment area is considered, Rigofill's buffer capacity could be considered weak (<10%) at the highest recorded rainfall. However, this quickly rises to at least 20% from the fifth highest measured amount of precipitation (see Appendix D), and can therefore be called moderate. With the implementation of a 5000 cubic meter Rigofill system, a substantial portion, 50 up to a 100% and more, of runoff water flowing over paved surfaces can be buffered. As this significant amount of fast-flowing runoff water is reduced, so is the risk of flooding the access road. From a flood prevention perspective it could therefore be stated that, the implementation of a 5000 cubic meter Rigofill system is, due to its substantial buffer capacity, feasible for CER.

4.4.3 Image feasibility

From the start CER has taken the direction of making sustainability a top priority. While CER may be described as an eco-resort, the construction of such a system such as Rigofill, may enhance the appeal of CER to eco-tourists. As ecotourism appeals to ecologically and socially conscious individuals wherein environmental responsibility is a focal point. What can be stated is that the construction of Rigofill will certainly be a positive addition to CER's image and would therefore be feasible. However, to what extent is hard to tell, because quantifying an image is difficult, because image is difficult to measure. This could be done after implementation of Rigofill has taken place, by taking a survey among guests.

Figure 10. Representation of the envisioned design of the Rigofill-dam structure combination. 1. Drainage system of grids from which water flows to the interception baskets and into the system; 2. Dam structures with overflow; 3. Rigofill storage reservoirs (300, 700, 1000 and 3000 cubic meters (only three shown)); 4. Inspection well; 5. Rainwater filtrating device and; 6. Interception basket for leaves and other course materials.

4.5 What are the prerequisites for the Rigofill system to be applied on other SIDS?

After consultation with Mr. Koster, it appears that there are no specific prerequisites for applying Rigofill anywhere in the world. I quote: "In fact, the Rigofill system can be used everywhere. However, the installation instructions must be followed properly." The most important installation regulations that must be complied with for correct implementation are shown in Table 9.

Table 9, Rigofill's installation regulations for it to be complied correctly.

1.	Before placing the Rigofill crates, a horizontal, flat support layer with a good load-bearing capacity must be installed. An approximately 10 cm thick levelling layer, preferably consisting of split or gravel (without fine grains), must be applied to the bottom of the construction pit.
2	Non-heavy, non-frozen ground material with a maximum grain size of 32 mm should be used for backfilling.
3.	The backfill material should be applied evenly on all sides and compacted in layers of maximum 30 cm using a light or medium compaction device.
4.	The infiltration crate must be covered in accordance with the draft directive. For the covering, non-heavy soil materials suitable for compaction should be used with a maximum grain size of 32 mm.
5.	Infiltration crates are underground structures and must therefore be sufficiently stable to withstand the loads acting on them from soil and traffic. With common installation parameters, cover heights of 2.5 m and installation depths of 4 m are possible for infiltration systems.

5. Discussion

In this chapter the reliability of CN Method results; implications and recommendations for follow-up research; Modular Rainwater Harvesting's applicability on other Caribbean SIDS and; the scientific relevance are discussed.

5.1 Reliability Curve Number Method

The CN Method has been developed to determine the runoff of one single rainfall event. Caution should however be given when recreating an actual storm, as modelling accuracy decreases. The method does not contain an expression for time and, therefore, does not account for rainfall duration or intensity. This should be taken into account when interpreting the results. As the data used, is that of 24 hours, several rainfall events may occur in 24 hours with intensities unknown, making the results of the CN Method not entirely reliable.

Another disadvantage of the method is the lack of clear guidance on how to vary Antecedent Moisture Conditions. During this research, the CN is treated as a constant, while actually varies from storm to storm as they are based on the amount of 5-day antecedent rainfall (Jain et al., 2006; Mishra & Singh, 2006). Hence, it cannot be determined which AMC is the right one for which past storm event. Given that most precipitation events occur during the rainy season, where the Antecedent Moisture Condition is high, AMC III was used.

Overall, it can therefore be stated that the results of the CN Method are acceptable in terms of order of magnitude, however, not very precise.

At last, there is a remarkably large difference (82.2 mm/m^2) between the highest measured amount of precipitation and the second highest amount. This could indicate an incorrect measurement. In any case, it is an exceptionally high amount of precipitation, even for Curacao. Other high precipitation amounts record between 75 and 100 mm/m^2. This may indicate that on average, in percentage terms, the system can store more water than is currently apparent (8.6%) (Table 8).

5.2 Implications & Recommendations

As this study gives a good basis for the implementation of the Rigofill system in the CER catchment, recommendations for improvement and further research can be given.

The initial intention of this research was that it would be a very practical one. Probing would be done to determine the bearing capacity of the soil. In addition, groundwater surveys would be performed to determine the height of the GWL. This level determines how deep Rigofill will be implemented, as it must be implemented at least 80 cm above the GWL. Unfortunately, due to circumstances, the research has taken a different direction. Currently, a model sketch has been designed which shows how the system could best be implemented. However, before actual implementation can be started, the above steps will have to be taken.

In addition, the current simply calculated payback period is extremely long. The project's economic viability rests on this. A suggestion for further research would be, to determine the payback period on the basis of an elaborative cost model. Hofman & Paalman (2014) suggest a model (RainCycle® 2.0, SudSolutions, 2005) that has been developed by Roebuck (2007). This software is capable of making a detailed analysis of the water balance and economics of the system and uses a Whole Life Costing method to assess the economics. WLC is believed to give robust results because it includes all costs for investment, operation and maintenance (Hofman & Paalman, 2014).

5.3 MRWH's Applicability

MRWH is being used more frequently and successfully in a variety of large scale engineering projects around the world (e.g. Australia, China, Germany, India, Kuwait, Netherlands, U.S.A.). Particularly China based companies (i.e. Shenzhen Doctor Rain Company and Greening Solution Company) build MRWH fields with enormous water storage capacity (i.e. 3,000 up to 200,000 cubic meters). Clients use MRWH systems to deal with rainwater and as flood control measure in urban areas. In case of RWH for hot, dry climates, the focus is on efficient collection from large, occasional events. Thus, MRWH systems can be an improvement on the current traditional way of RWH often applied to SIDS, due to its multiple functions (i.e. retention, recharge, infiltration, detention) and many advantages (see Appendix E) over traditional Domestic Rainwater Harvesting (DRWH). In the Bahamas, Bermuda, and other Caribbean islands, rainwater cisterns must be included in all new constructions under governmental economical support (Campisano et al., 2017). Whereby opportunities arise for MRWH because these systems are less costly than concrete and metal storage systems; have an enormous storage capacity; and by means of its multifunctionality, a larger market can be reached through large-scale application. For example, local governments and NGOs can be involved as reservoirs can function as fire-fighting water supplies or benefit GWL and thus help to conserve nature areas. When successful implementation and operation can be demonstrated, the concept may be applicable regionally (Caribbean region) as a product, perhaps even worldwide on SIDSs in semi-arid areas.

5.4 Scientific Contribution

The contribution that this research can make to the scientific society does not consist in introducing a new concept. In particular the manner of where and how the concept of MRWH is applied and what its function is differs. MRWH is a form of storm water management that is often applied during the development of new large-scale urban projects, because, due to the high degree of construction, rainwater cannot infiltrate and causes problems. The function is to temporarily buffer the water and then discharge it in a controlled manner.

During this research however, the intention was to apply an MRWH system in a relief-rich rural environment. As a result, the system´s design is not single-layered, but tiered, with the various reservoirs linked together. Like so, water is already captured in the upper reaches preventing problems in the lower reaches. As for its function, where current urban systems mainly serve as storm water management practice, the focus during this study is on efficient collection from large, occasional events, in order to meet the increasingly pressurized water demand while at the same time reducing flood risk. Additionally, water is being used to replenish groundwater levels, benefitting nature.

6. Conclusion

During this research it was investigated how MRWH can serve to buffer storm water runoff, to minimize flooding and erosion. The stored water can additionally be reused for domestic non-potable purposes. The research was in fact a pilot to see whether MRWH offers a solution against both the flood-related problems during the wet season and the water shortage-related problems during the dry season. The study was conducted at the Caribbean SIDS, Curacao. The pilot in this study is the Coral Estate Resort on Curacao. The tested MRWH system is the Rigofill system from the German manufacturer Fränkische. The possible implementation option of this system has been examined, and to what extent this system is considered feasible.

The capacity of the Coral Estate Resort's Rigofill system is determined based upon: CER's annual water demand and the amount of water available that flows in from intense rainfall events. A tiered structure of the system with a total capacity of 5000 cubic meters is considered to be the best option. Wherein, four reservoirs, of different sizes (300, 700, 1000 and 3000 cubic meters), will be implemented alongside the access road. This size reservoir can cover approximately 42% of CER's annual water demand, where it serves non-potable purposes. In addition, a reduction of at least 50% of runoff by road is ensured, which can increase to a 100% runoff reduction in case of smaller rainfall events (see Appendix D). Considering CER's total catchment area, at least 8% of runoff can be buffered, which can increase to 20% when smaller events occur (see Appendix D).

Overall feasibility is considered complicated. First of all, it can be stated that under the current price structure the payback period is too long, making the system economically unprofitable, resulting in no economic feasibility. On the other hand, the tiered structure allows the system to buffer the runoff in the entire course of the catchment with a total capacity of 5000 cubic meters. This is a significant part of the runoff that can be captured, reducing flood risk significantly and its costs from subsequent damage. Additional positive image boosting among eco-tourists should not to be neglected, as it may generate extra income too. A follow-up research, using the RainCycle® 2.0 model, may give a more detailed and substantiated answer to the question whether the implementation of Rigofill is feasible for CER or not.
However, under the current price structure, the purchase of similar large scale systems is not feasible, due to their lack of large financial buffers, for other SIDSs worldwide. It is possible that if used on a smaller scale, feasibility will increase.

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Appendix A

Geological Map Curacao

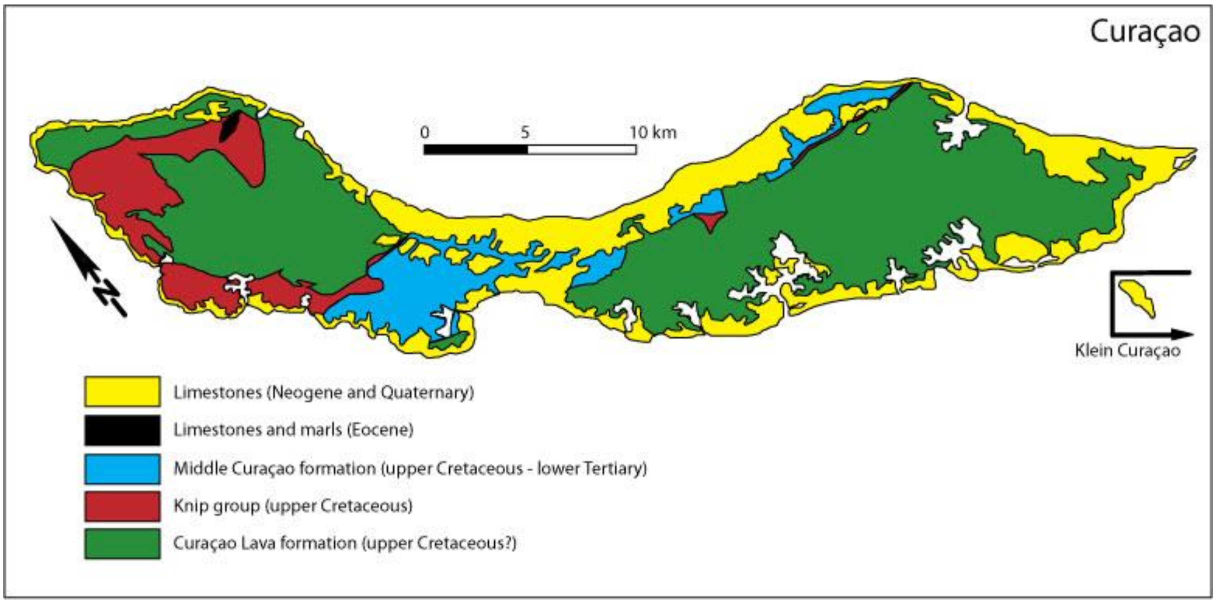

Figure A1. Geological map Curacao (CARMABI, n.d.).

Appendix B

Elevation Map and Catchment Area Coral Estate Resort

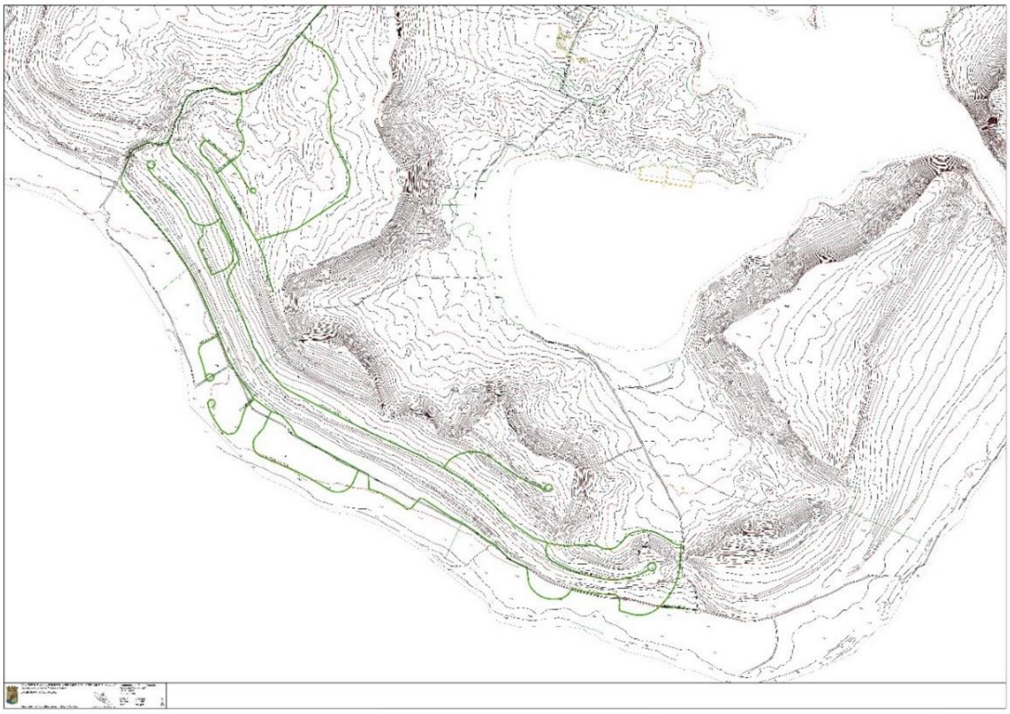

Figure B1. High Resolution Elevation Map of the Coral Estate Resort (Ministerie van Verkeer, Vervoer & Ruimtelijke Planning - Openbare Werken, 2021).

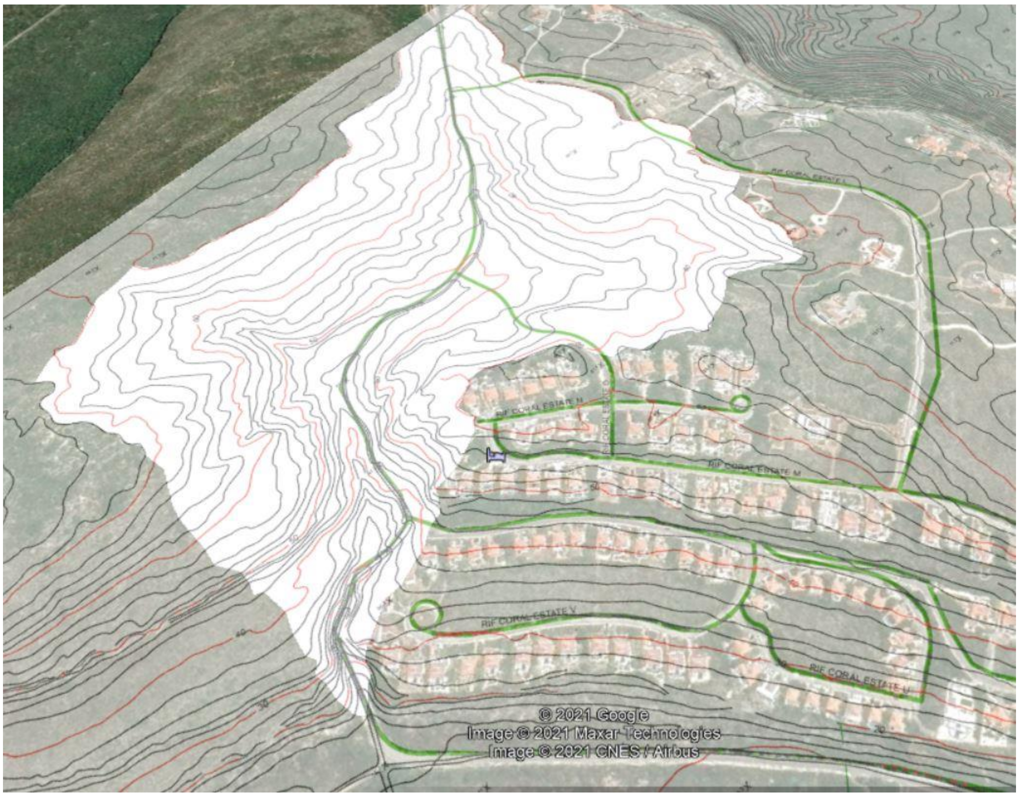

Figure B2. The surface area of the Coral Estate Resort's total catchment area.

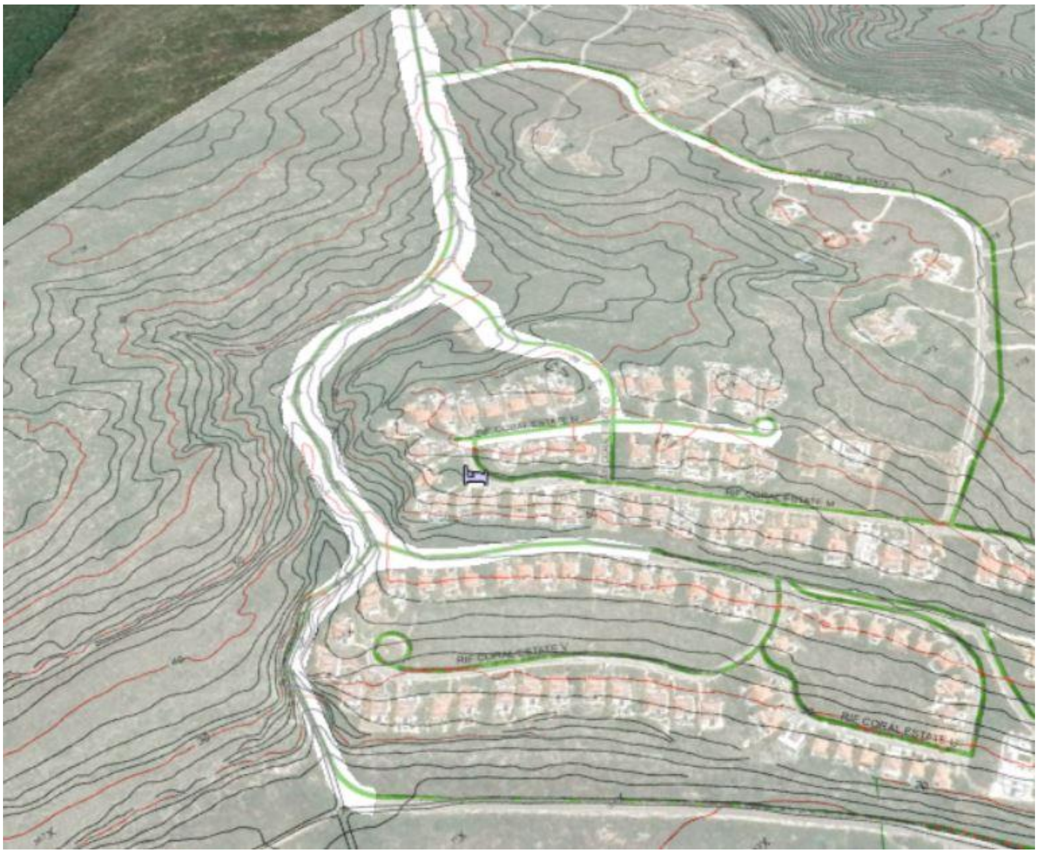

Figure B3. The surface area of the Coral Estate Resort's paved catchment area.

Appendix C

Curve Number Table

Arid and semiarid rangelands

Cover description		Curve numbers for hydrologic soil group			
Cover type	**Hydrologic condition[A]**	**A[B]**	**B**	**C**	**D**
Herbaceuous—mixture of grass, weeds, and low-growing brush, with brush the minor element	Poor	—	80	87	93
	Fair	—	71	81	89
	Good	—	62	74	85
Oak-aspen—mountain brush mixture of oak brush, aspen, mountain mahogany, bitter brush, maple, and other brush	Poor	—	66	74	79
	Fair	—	48	57	63
	Good	—	30	41	48
Pinyon-juniper—pinyon, juniper, or both; grass understory	Poor	—	75	85	89
	Fair	—	58	73	80
	Good	—	41	61	71
Sagebrush with grass understory	Poor	—	67	80	85
	Fair	—	51	63	70
	Good	—	35	47	55
Desert shrub—major plants include saltbush, geasewood, creosotebush, blackbrush, bursage, palo verde, mesquite, and cactus.	Poor	63	77	85	88
	Fair	55	72	81	86
	Good	49	68	79	84

[A] Poor: <30% ground cover (litter, grass, and brush overstory); Fair: 30 to 70% ground cover; Good: >70% ground cover.
[B] Curve numbers for group A have been developed only for desert shrub.

Figure C1. Curve Number Table for Arid and Semi-arid Rangelands (USACE Hydrologic Engineering Center, n.d.).

Appendix D

Runoff Table and Additional Prices

Table D1. Recorded daily (24 hrs) precipitation values and calculated daily (24 hrs) runoff amounts (m^3) in the CER catchment. AMC III is representative for wet Antecedent Moisture Condition.

Total catchment area CER	mm/m^2	Runoff [m^3/catchment area]	5000 m^3 Runoff storage [%]
4th Highest total precipitation:	95.40	-	-
4th Highest total runoff, AMC III condition:	86.00	27,429	18.2
5th Highest total precipitation:	88.10	-	-
5th Highest total runoff, AMC III condition:	78.75	25,118	19.9
6th Highest total precipitation:	82.90	-	-
6th Highest total runoff, AMC III condition:	73.60	23,473	21.3

Table D2. Recorded daily (24 hrs) precipitation values and calculated daily (24 hrs) runoff amounts (m^3) in the Paved CER catchment. AMC III is representative for wet Antecedent Moisture Condition.

Paved catchment area CER	mm/m^2	Runoff [m^3/catchment area]	5000 m^3 Runoff storage [%]
4th Highest total precipitation:	95.40	-	-
4th Highest total runoff, AMC III condition:	86.67	4,420	113.1
5th Highest total precipitation:	88.10	-	-
5th Highest total runoff, AMC III condition:	79.42	4,050	123.5
6th Highest total precipitation:	82.90	-	-
6th Highest total runoff, AMC III condition:	74.25	3,787	132.0

Appendix E

Pros and Cons of Subsurface Modification RWH Measures

Table F1. Advantages and disadvantages of Modular Rainwater Harvesting systems.

	Advantages	Disadvantages
1.	Durable, up to 55 years design life.	Requires specified excavation and burial preparation to ensure longevity of product.
2.	High storage rate, void ratio from up to 96%. Possible for long durations due to pump circulation devices.	Internal cleaning is not possible so the inlet filtration component of the rainwater collection system is extremely vital. Internal inspection however is possible.
3.	Appropriate for heavy traffic volumes and weights, loading capacity above 75 tons/sqm.	
4.	Environmental friendly, the plastic modules are made of high grade PP materials, non-toxic and harmless which is a 100% circular product.	
5.	Easy to clean, equipped with inspection pits.	
6.	Convenient for construction. Completely flexible in shape, layout, and depth. Assembly is easy and can be done quickly onsite (one or two days).	
7.	Easy and relatively inexpensive shipping. Using split design, the modules can be disassembled at will, saving valuable transportation space.	

Table F2. Advantages and disadvantages of traditional Domestic Rainwater Harvesting systems.

	Advantages	Disadvantages
1.	Domestic rainwater harvesting systems provide an independent water source in areas where other water sources are costly or unavailable.	Storage limits. Small storage capacity.
2.	Reduces (monthly/yearly) water bills.	Rainwater harvesting systems require regular maintenance They can become breeding grounds for many animals or algae growth if not properly maintained.
3.	Reduces floods and soil erosion (relatively little).	Initial high costs. Traditional systems have long pay-back times.
4.	Easy to maintain, maintenance requires little time and energy.	Does not benefit groundwater recharge.