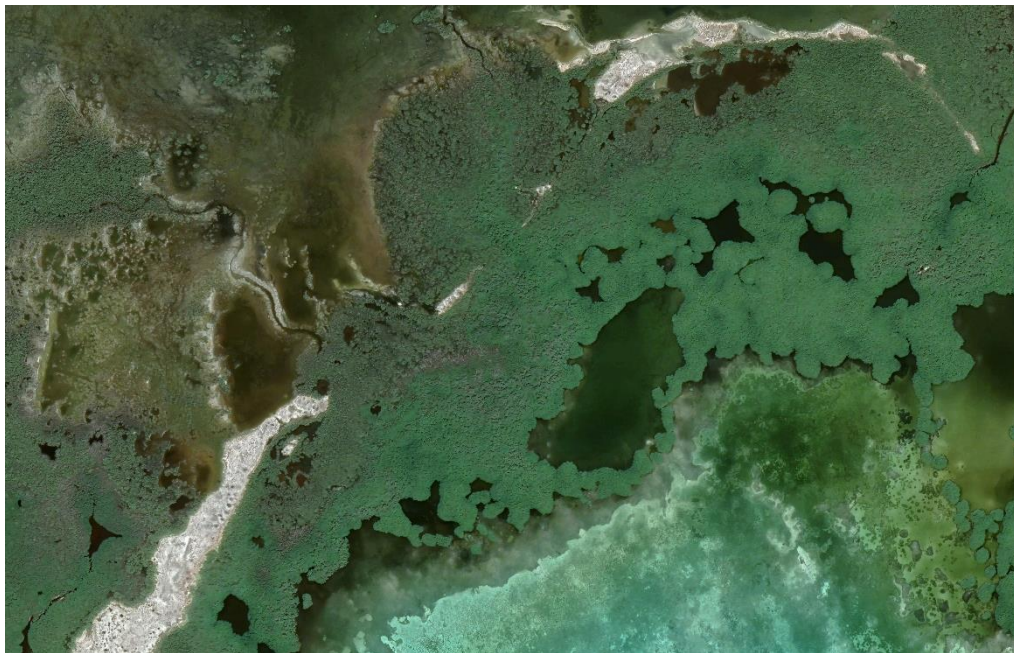


Mapping of the Potential Erosion in the Catchment of Lac Bay

A case study of water erosion on Bonaire



BSC thesis by Lan Remeta

September 2022

**Soil Physics and
Land Management**



WAGENINGEN UNIVERSITY
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Mapping of the Potential Erosion in the Catchment of Lac Bay

A case study of water erosion on Bonaire

Bachelor thesis Soil Physics and Land Management Group
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Abstract:

Over the past decades coastal ecosystems have been increasingly threatened and have been reducing at alarming rates. Similar is happening on Bonaire, where increased sediment transport and decrease in the freshwater inflow is responsible for high mortality of the mangrove forest in Lac Bay. Factors, such as Bonaire's arid climate, past deforestation and overgrazing by feral animals have left the island bare which furtherly increases erosion and sediment rich runoff towards the bay. To come up with interventions to reduce mangrove mortality quantitative and qualitative data on the erosion potential and on the rainfall runoff relationship is required. This research provides information on spatial distribution of potential erosion rates in the catchment of Lac Bay, using the RUSLE equation. Moreover, a portable mini rainfall simulator is used to estimate the surface runoff coefficient and to validate RUSLEs potential erosion rates. Unfortunately, no correlation has been found between the measured data and the estimated soil erosion rates. Median annual potential soil loss is $19,3 \text{ t ha}^{-1}$ corresponding to annual soil loss of 41678 t. Spatial variation of potential erosion rates is homogeneous, implying catchment wide conservation measures. Measures such as reduced grazing could decrease the potential erosion rates in Lac Bay up to 5%, by increasing vegetation cover in the catchment. Structural measures such as earth dams could furtherly reduce sedimentation at the point of deposition, however before implementation further research needs to be conducted on the impact of such structures on freshwater inflow to the bay. The median runoff coefficient is 0,24 with 76% of the catchment having runoff coefficients between 0,16 and 0,33.

Keywords: Lac Bay Catchment, Bonaire; Mangroves; Mangrove mortality; Potential erosion assessment; Soil erosion; Soil loss; Surface runoff; RUSLE; Rainfall simulator; GIS

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I. INTRODUCTION

Coastal zones are one of the most important areas in the world's oceans from the human perspective, due to their diversity and provisioning of a large variety of goods and ecosystem services (Bijlsma et al., 1995). They include areas of complex and specialised ecosystems, such as mangroves, coral reefs, seagrasses, and salt marshes, all of which are highly sensitive to human influence.

These zones contribute significantly to the proportion of global food production, in the form of fisheries and aquaculture, while also being important ports of commerce. They protect coastal communities from natural disasters, such as storms and flooding, improve resilience to coastal erosion and capture and store large quantities of atmospheric carbon (Bijlsma et al., 1995; Luisetti et al., 2014; Turner & Schaafsma, 2016). Duarte et al. (2005) suggests that coastal ecosystems, despite occupying only 5% of the global land area and 2% of the ocean, store up to 55% of all carbon in the ocean sediment.

These areas have been able to capture an enormous economic value, estimated to around \$6.000 - \$19.000 ha⁻¹ annually (compared to a tropical forest, estimated to supply \$2,000 ha⁻¹), making them the centre of human activity for millennia. Studies by NRC (1990) and Cohen et al. (1997) have shown that around 37% of the human population lives within 100km of the coastline, while LOICZ (2002) indicated that around 70% of the world's megacities (cities with more than 1,6 million inhabitants) are located in coastal zones.

This increased human population and its adverse effects have led to a sustained loss of these ecosystems globally. The rate at which these ecosystems are threatened ranges from a minimum of 1-2% annually for salt marshes and 1-3% for mangroves to 2-5% for seagrass meadows and 4-9% for corals (Duarte et al., 2008). These rapid losses have been attributed to several mechanisms present in these zones, such as reclamation of land for aquaculture and coastal development, excess sediment, and nutrient inflow, overfishing and mechanical damage by boats and fishing gear, intensive aquaculture, impacts of invasive species and finally climate change (Duarte et al., 2008 from Jackson et al. 2001; Adam 2002; Duarte 2002; Bellwood et al. 2004; Lotze et al. 2006; Orth et al. 2006). Without drastic changes in the coming years, the total area of these habitats could decline to less than 15% of the area present in 1950 (Duarte et al., 2008).

One of the important ecosystems in the coastal zones are mangroves. Despite their importance, there is significantly less research conducted on these ecosystems (only 11% compared to 60% of published papers on coral reefs) (Duarte et al., 2008). The word mangroves, refer to both the trees and the communities they form. There are around 35 – 60 species worldwide (Engel, *personal communication*) covering more than 152.000 km², which makes them a relatively rare forest type globally (FAO, 2007). This is due to the harsh environment in which they thrive, defined by regular inundations of the soil and variable salinities.

Mangrove forests provide a large variety of ecosystem services, that include coastal protection (Alongi, 2008; Sheng & Zou, 2017) and water quality improvement (Warren-Rhodes et al., 2011). They promote biodiversity and fisheries and act as the main nursery biotope for juvenile fish (Nagelkerken et al., 2000; Benzeev et al., 2017). Like a terrestrial forest, mangroves are efficient in storing carbon dioxide (Yando et al., 2016), but also work as a buffer for rising sea levels and protect the coast from storm surges. Therefore, conservation and restoration of such biomes can play a crucial role in climate change mitigation (Warren-Rhodes et al., 2011).

Over the past decades, mangrove populations are being increasingly threatened and have been reducing at alarming rates (Nagelkerken et al., 2000). Studies by Spalding (2010) and FAO (2007) have shown a net loss of around 30.000 km² in the past 30 years, which is 20% of the existing habitat. One of the main reasons for this rapid deforestation are anthropogenic pressures on coastal ecosystems leading to competition for land for aquaculture, agriculture, infrastructure, tourism as well as pollution (Forestry Economics and Policy Division, 2007).

Similar can be observed on the island of Bonaire, where urbanization and nature tourism together with ecological threats such as overgrazing and sargassum inflict pressure on the wide variety of islands habitats. From dry tropical forest, to caves, beaches, saltpans, mangrove forests and seagrass beds, as well as coral reefs and the deep sea. Combined, these habitats provide home to around 130 endemic species and provide a large variety of ecosystem services to humans (Slijkerman et al., 2019).

Nature tourism is the biggest economic sector of Bonaire (Rijksdienst Caribisch Nederland, 2020) therefore it is of great importance to research and preserve these habitats as the tourism sector is dependent on the health and quality of Bonaire's ecosystems. However, analysing potential threats to all of these would be expensive and time consuming, therefore this research has focused on a case study of Lac Bay and its mangrove forest.

Problem Statement

There are approximately 365 ha of mangrove forest on Bonaire, most of which are located on the South-East of the island in a shallow non-estuarine lagoon called Lac Bay. In the past decades, catchment of the Lac Bay has been under increasing anthropogenic pressure from free roaming grazers, resulting in a seaward shift (*figure 2*) and a long-term decline in mangrove cover (*figure 1*) (Debrot et al., 2010). This seawards shift is highly unfavourable since the expansion of the mangroves happens at the expanse of the open bay and the seagrass and algal ecosystem located there. Seagrass beds are ecologically very important, since they provide a habitat for the endangered queen conch (*Lobatus gigas*) and are grazing areas of the green sea turtles (*Chelonia mydas*) (Wösten, 2013). Moreover, Lac Bay is an important hotspot for tourism and windsurfing and contributes immensely to the economy of Bonaire. This dynamic limits the options for nature conservationists, as preservation of both mangrove forest and the services of bay itself are important.



Figure 1: Dry and dead mangroves of the backwaters of Lac Bay. Photo by: Rik van der Meulen.

Wösten (2013) reported three main causes for the mangrove mortality in the backwaters of the Lac Bay. First, reduction of freshwater inflow during the rainy season, due to blockage of the surface runoff. Second, reduced tidal interaction between seaside and landside because of blocked feeder channels, which leads to an increase in salinity and insufficient flushing with seawater. This build-up of salts in the back of mangrove forest, is resulting in a hypersaline environment, which is causing the mangrove die-off (Debrot et al., 2010). Finally, increased sedimentation in the Bay, due to terrigenous water borne sediments from inland (*figure 4*) was pointed out as a big cause for the mangrove mortality, as it enhances the process of salinization (Wösten, 2013; Debrot et al., 2010). Summarized, the causes of the seawards shift of the mangrove forest and increased salinity in the backwaters are:

- a) Increased sediment transport towards the Lac Bac.
- b) Reduced tidal interaction between the sea and the land side.
- c) Reduced freshwater inflow during the rainy season.

This study will focus only on the causes a) and c), since they are being influenced by similar mechanisms, which are described below and visualised in *figure 3*.

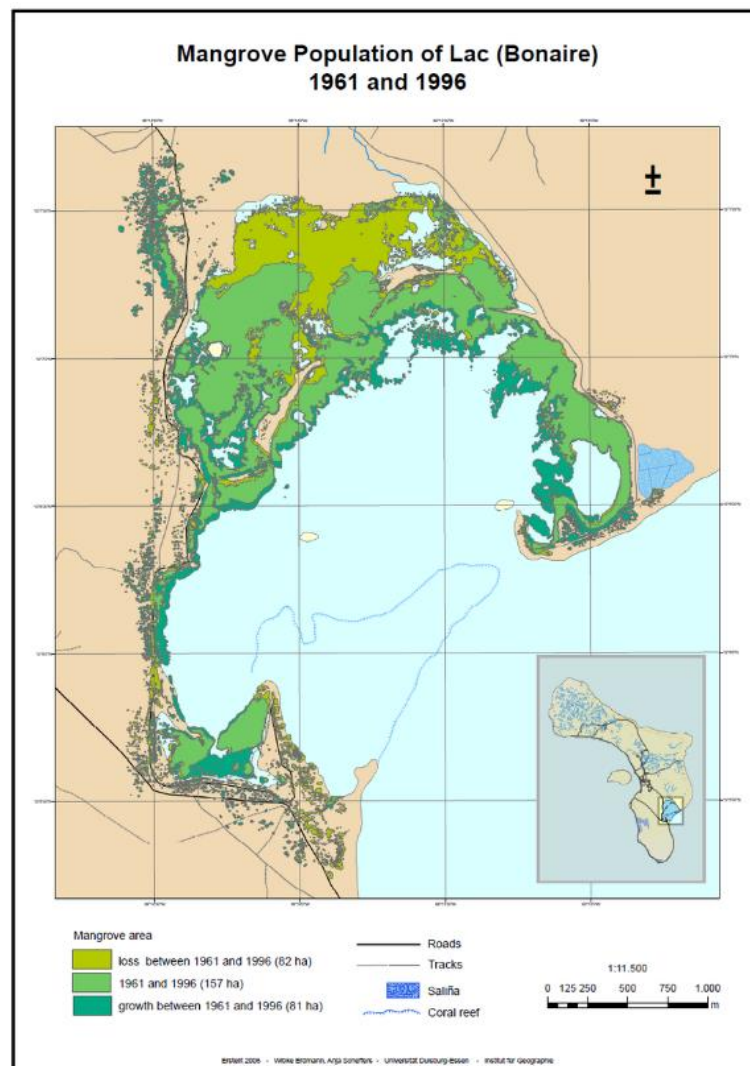


Figure 2: Seaward shift of the mangrove forest in Lac Bay since 1961. The loss of mangroves has been balanced by new growth during this period (Erdmann and Scheffers, 2006).

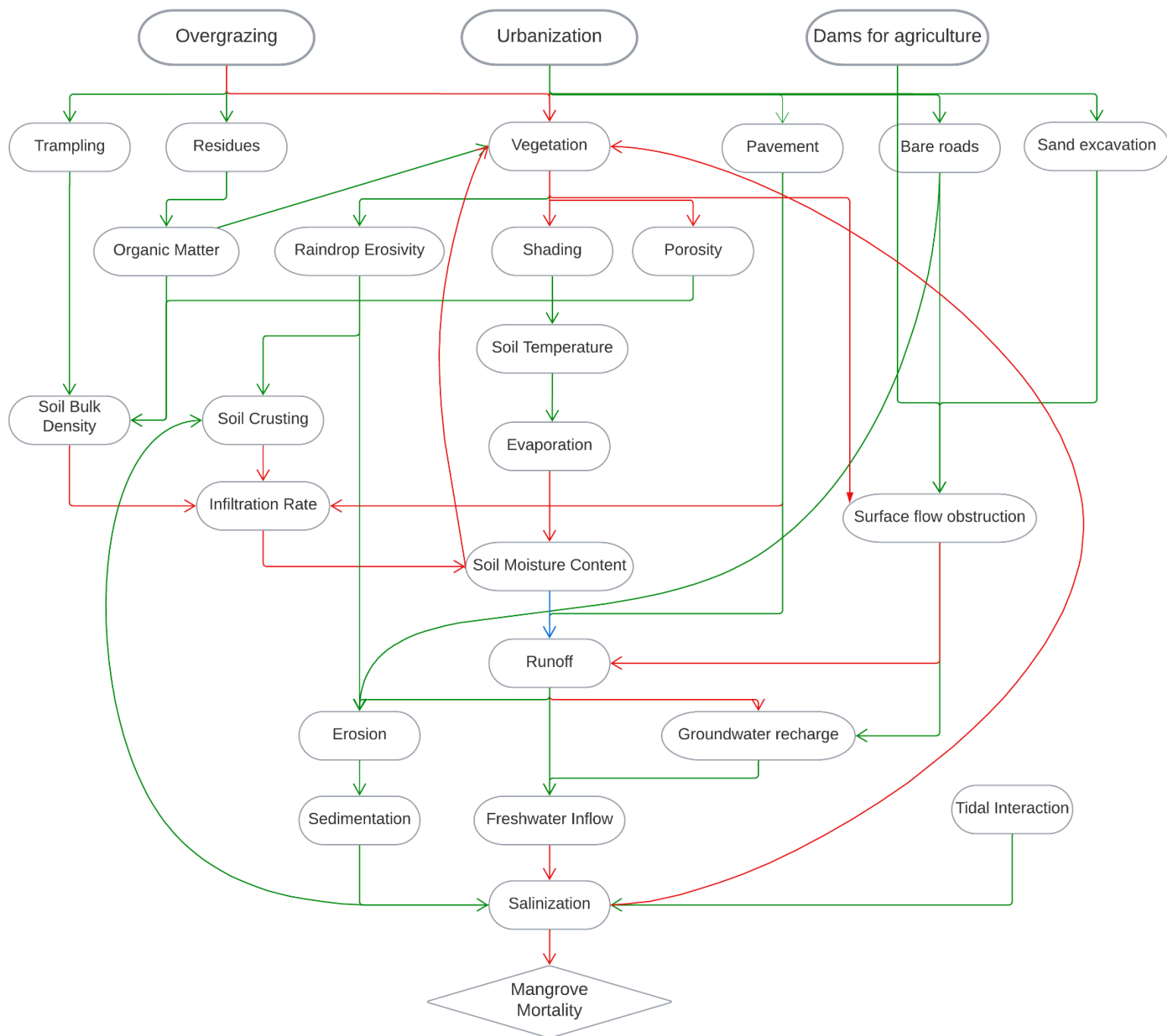


Figure 3: Conceptual model. Overgrazing, urbanization, dams for agriculture affecting soil hydrological properties and the effect they have on mangrove mortality. The green lines indicate a positive relationship or an increase in the terms and the red lines are indicating a negative relationship or a decrease in the terms in the model. The blue lines indicate processes that can have both positive and negative relationships.

Increased sediment transport towards the bay, is a result of a combination of past deforestation on the island for the purpose of exporting dye-wood and later charcoal production and overgrazing by feral goats. This idea is supported by studies from Liu et al. (2013); Coolen (2015); Geest et al. (2020) that have shown that feral goats (*Capra hircus*) are important contributors to destruction of the natural habitat and species alteration on the island. Goats were introduced to the island by Spanish settlers in 16th century for the purpose of livestock breeding (Hartog, 1978). Now it is estimated that there are more than 30.000 head scattered across the island, or 4 goats per hectare (Geest & Slijkerman, 2019). This means that the carrying capacity of the ecosystem, which is around 1 goat per hectare during the dry season, is being exceeded for the most part of the year (Debrot, 2016). Many are free roaming, as it is cheaper for the owners, who do not require to provide feed enabling them to own more goats. On Bonaire it is illegal to have free roaming animals, however with strong roots in the local culture, authorities are struggling to enforce any kind of restrictions (Eckrich, *personal communication*).

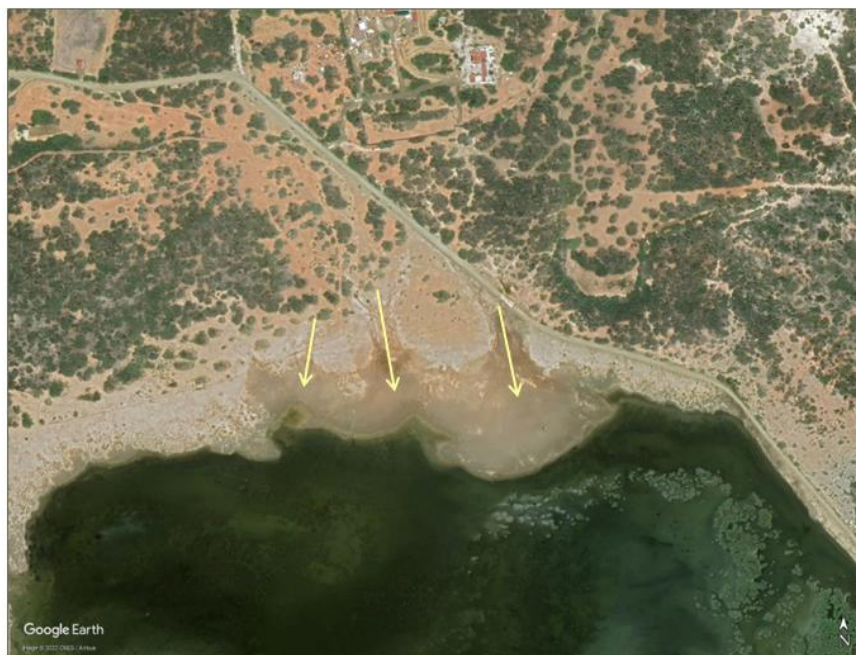


Figure 4: Satellite image of the sediment plume where sediment rich surface runoff enters the Lac Bay. Three separate flows can be identified that add to the sediment accumulation in the backlands. Retrieved from: Google Earth, 2022

Overgrazing is responsible for loss of vegetation cover on the island, reduction in succession of mature forest, change in vegetation type and impeded rejuvenation where vegetation cover is still present. Moreover, in areas with high grazing pressure trampling is also known to compact the upper soil layer and thus increase the bulk density of the soil (Warren et al. 1986). Removal of vegetation and trampling have negative consequences for soil structure and soil moisture content, resulting in increased erosion and surface runoff towards the bay (*figure 4*), which are the main causes of mangrove mortality. Finally, overgrazing on Bonaire has a significant effect on the health of coral reefs, due to sedimentation (Geest & Slijkerman, 2019).

Furthermore, land use change is another processes contributing to runoff and erosion. With expansion of the tourism sector and increase in population, which is expected to reach 24.000 inhabitants by 2030 (CBS, 2022) Bonaire is becoming increasingly urbanized (Verweij et al., 2020). Urbanization leads to removal of vegetation for road development and construction, increasing the amount of bare soil and enhancing soil erosion.

Low inflow of freshwater into the bay is mainly the result of the arid climate, as there are only a few months where precipitation exceeds evapotranspiration (November- January) (Wösten, 2013). In the past freshwater could enter the mangrove forest from the North and West, but after 1960 this inflow has been decreased, as freshwater is being blocked by small dams and/or roads (Wösten, 2013). Moreover, in the past decade there has been an increase in the sand excavation activity in the catchment, where large mining pits are diverting the freshwater flow and preventing it from entering the bay (Eckrich, *personal communication*).

To mitigate and prevent the die-off of mangroves and improve the health of Bonaire's ecosystems conservation measures should be implemented. Based on the literature (Geest et al., 2020; Debrot et al., 2010) salinity and sedimentation are influencing the health of the mangroves the most, therefore further research should be conducted on the causes of these processes. To come up with interventions to reduce the mangrove mortality and their seaward shift quantitative and qualitative data on the sensitivity of the area to erosion and on the rainfall-runoff relationship is required.

Research Objective

The main objective of this research is to execute a case study of the Lac Bay Catchment in relation to mangrove mortality in the bay by looking at the spatial distribution of the rainfall-runoff and erosion relationships in the catchment and quantifying them. Mapping these relationships will give useful information to ecologist and policy makers and assist them in their conservation initiatives. Finally, advice will be given on possible conservation measures, with two scenarios being discussed in detail.

Therefore, a main research questions and several specific research questions were formulated as follows:

“How is the rainfall-runoff and erosion relationship spatially distributed in the catchment of the Lac Bay lagoon?”

1. *Which are the areas with the highest potential erosion risk in the catchment of Lac Bay?*
2. *Which are the areas with the highest runoff potential in the catchment of Lac Bay?*
3. *What is the annual soil loss of the Lac Bay catchment?*
4. *Which soil and water conservation measures can be implemented to reduce the potential erosion rate in the catchment of Lac Bay?*

Study Area

Bonaire is a Dutch island located in the Leeward Antilles in the south-east region of the Caribbean Sea, around 80km north of Venezuela (*figure 4*). With an area of around 288km² it is home to 22.573 inhabitants (CBS, 2022), most of them living in the capital Kralendijk or in Rincon.



Figure 5: Location of Bonaire in the Caribbean Sea. Adapted from: Google Earth, 2022

In contrast to most of the islands in the Caribbean, the climate of Bonaire is a relatively dry tropical climate with average annual precipitation of 463 mm (KNMI, 2017). Much of the precipitation falls over a period of 4 months, starting in October/November and ending in January, marking the rainy season. Moreover, there is a big inter-annual variation (de Freitas et al. 2005) but also spatial variation in precipitation amounts (Engel, *personal communication*; “Local Weather Forecast, News and Conditions | Weather Underground,” 2022). The warmest month is September with maximum temperatures reaching 32°C, while January and February are the coldest with temperatures around 27 °C. The average annual temperature is around 28 °C (KNMI, 2017).

Being positioned in the intertropical convergence zone, a zone of low pressure around equator, Bonaire receives just enough precipitation to sustain a semi-arid ecosystem (Verweij et al., 2020). Therefore, the vegetation is mostly xerophytic (de Mayer, 1998) and is described as dry evergreen woodland, dominated by columnar cacti and low shrubs (de Freitas et al. 2005). In the past, a large part of the island has likely been covered by a dry tropical forest, which has been degraded and heavily altered by human activity (Hartog, 1978). Large parts of the island are bare, due to the combination of low precipitation and grazing by feral goats, moreover in some parts on the lower terrace vegetation can only be found in small erosional pits or in otherwise shallow soils (de Freitas et al. 2005).

Bonaire is a flat island. Elevated areas are only found in the north, reaching the height of 238m, while the southern parts rarely exceed 2m above the sea level (de Mayer, 1998) (*figure 7*). The geology is complex. Due to the islands’ volcanic origin, two main rock formations can be distinguished, as seen in *figure 6*. First is the volcanic Washikemba Formation, covering around 31% of the island dominant in the north-west (from Slagbaai to Rincon) and east Bonaire (Bolivia to Seru Largu) appearing as elevated areas with high relief. Second, are the quaternary limestone terraces overlaying the Washikemba formations and covering 58% of the island (de Freitas, 2005). These coral limestone terraces differ in age, thickness, and elevation, due to sea-level fluctuations and slow tectonic uplift. The oldest are forming low limestone cliffs, while the youngest shape the coral-rubble beaches, (de Mayer, 1998).

Geological Units of Bonaire

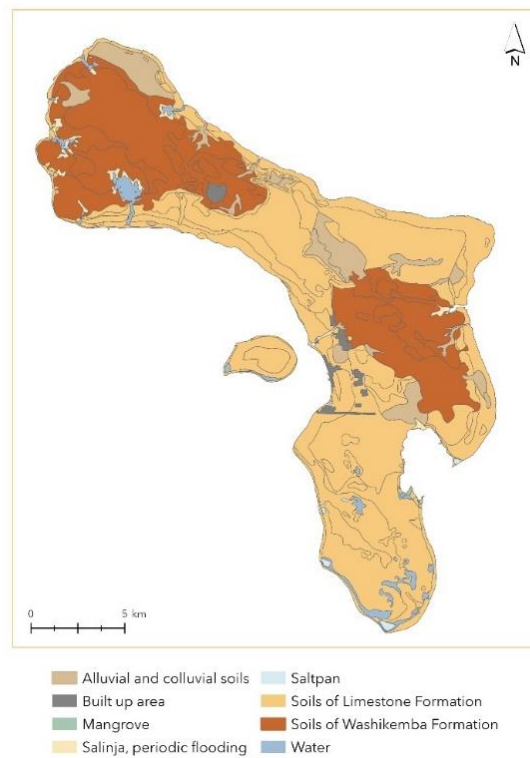


Figure 6: Map of soils and geological units of Bonaire. Adapted from: (Soil Map of Bonaire | Dutch Caribbean Biodiversity Database, n.d.)

Digital Elevation Model of Bonaire

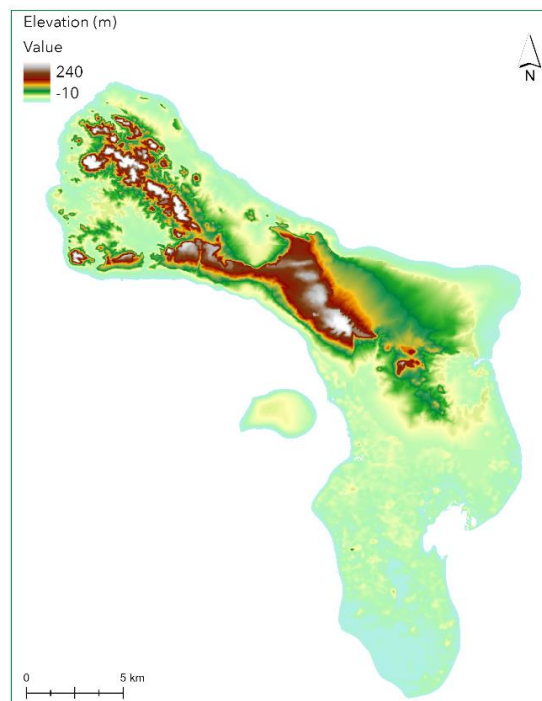


Figure 7: Improved ASTER Digital elevation model (DEM) of Bonaire, with a 10-meter spatial resolution and 1-meter height resolution. Adapted from: (Improved ASTER Elevation Model for Bonaire | Dutch Caribbean Biodiversity Database, n.d.)

Case study area – Lac Bay Catchment



Figure 8: The case study area of Lac Bay catchment. Retrieved from: Google Earth, 2022

The case study area is the catchment of Lac Bay, located in the South-eastern part of the island (figure 8). With an area of 1600 ha it is covering roughly 6% of the island and is draining towards the Lac Bay. Lac Bay (figure 10) covers an area of 700 ha (Wösten, 2013) providing an important habitat for island's mangroves (figure 9), and communities of seagrass beds (*Thalassia testudinum*) and macro-algae (*Avrainvillea nigricans*). The mangroves of Lac show clear zonation and succession with principal seaward zone of *Rhizophora*, and principal landward zone of *Avicennia* and depending on the location, an intermediate mixed transitional zone (Appendix A) (Davaasuren and Meesters 2012). The northern part of the bay is characterised by dry and dead mangroves. Due to its important natural value the lagoon has been identified and assigned a legally protected RAMSAR site, as well as IUCN IBA (Important Bird Area) (Delannoy, 2010). Moreover, the southern part of the bay is used extensively for recreational use, such as windsurfing, canoeing, swimming, and sunbathing. There are a few resorts and restaurants adding economic value to the bay.



Figure 9: Left: Red mangroves (*Rhizophora mangle*) (fisherbay, 2020). Right: Black mangroves (*Avicennia germinans*) (Black Mangrove Pneumatophores, 2022). The main differences can be observed in their leaf structure, specialized root structure and propagules.

The topology of the catchment is flat (*figure 15*). In the North the landscape is dominated by isolated medium high and low hills elevated 50m above sea level, which are sloping south towards shallow loamy plains in the centre of the catchment (de Mayer, 1998). Areas close to the bay are characterized by nearly flat erosional and depositional limestone terraces. On the east coast, the lower terrace is exposed as a flat rock-land with very shallow soil found only in few places (de Freitas, 2005). The limestone terraces are overlain with shallow to moderately deep loamy soils. Due to karstification, the hydraulic conductivity is heterogeneous making the groundwater flow hard to predict. Since there are no perennial streams in the area the inflow of freshwater is dependent on the groundwater flow and precipitation runoff. It is estimated that 10% of the precipitation runs off via the surface, 5% infiltrates into the groundwater and 85% evaporates (Grontmij & Sogreah, 1968). During the rainy season, the basin is drained by a system of rooien or ephemeral streams (*figure 19*)

Most of the area is undeveloped and is vegetated by low and high shrubs or by communities of shrubs and cacti. Urbanized parts in the west, like Flamingo Airport and barrio Tera Kora are the only exceptions. However, with the high rates of urbanization Bonaire is facing, this could change in the coming years. Moreover, there are several Kunukus or typical agricultural plots located in the area. 20% are inactive or abandoned creating a perfect habitat for feral goats (Lazebnik et al., 2022).

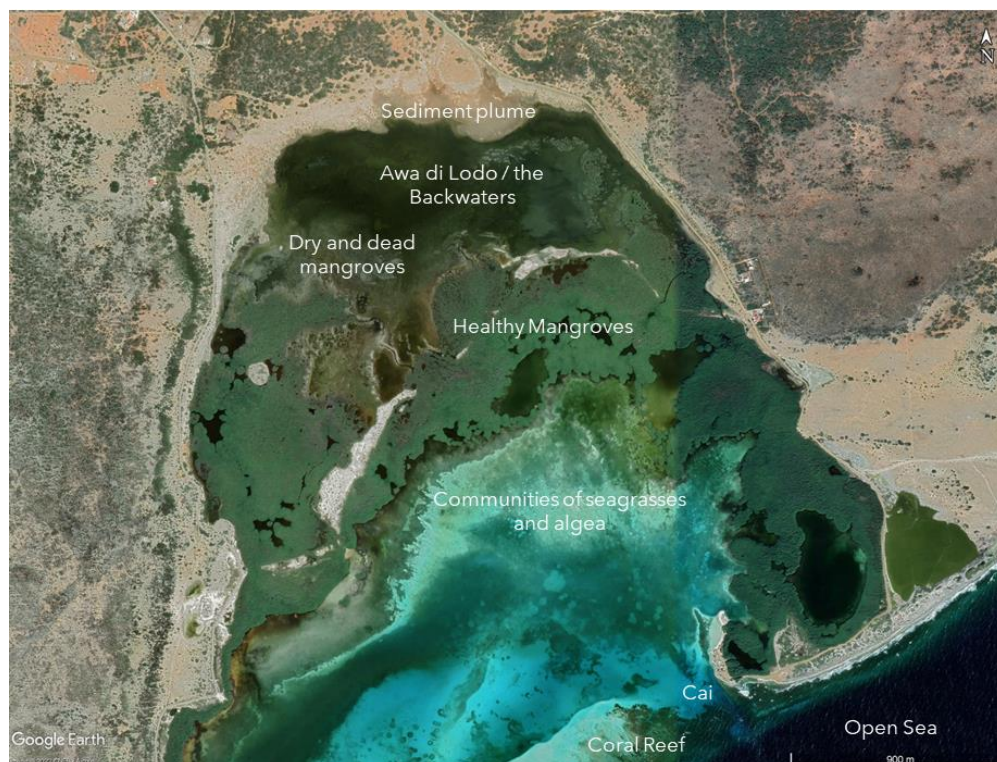


Figure 10: Important areas of Lac Bay. Retrieved from: Google Earth, 2022

II. METHODOLOGY

RUSLE model

One of the most widely used soil loss models is the Universal Soil Loss Equation (USLE) (Wischmeier & Smith, 1978) and its revised version, the RUSLE (Renard et al., 1997). The USLE equation was initially developed for estimating potential soil losses on gently sloping croplands, while the applicability of the RUSLE has been expanded to a range of different situations including forests, rangelands and disturbed areas (Renard et al., 1997). For this reason, the RUSLE equation was used to estimate the potential soil losses in the Lac Bay catchment (*equation 1*):

$$E = R * K * LS * C * P \quad (1)$$

The RUSLE model is an empirical model for estimating potential sheet and rill erosion from the field measurements. It is based on erosion measurements on clean-tilled fallow plots, 22,1m long with slopes of 9% (Renard et al., 1997). The benefit of this equation is that it does not require intensive data as some of the other models (USPED, WEPP or SWAT model) and can be easily implemented within a GIS for spatial analysis. Moreover, certain parameter such as slope, aspect, vegetation cover, etc. can be easily derived from satellite data and integrated in the model (Ganasri & Ramesh, 2016).

Therefore, the aim of this study is to combine the RUSLE equation with GIS and remote sensing to assess the potential erosion risk in Lac Bay catchment, Bonaire and compare it with *in-situ* measured sediment loss. The factors used in the RUSLE equation are given in *table 1*. Each of these factors will be determined separately. Finally, a map of each factor will be combined in ArcGIS Pro to generate a map of potential erosion.

Symbol	Meaning	Unit
E	The annual soil loss rate	t ha ⁻¹ year ⁻¹
R	The rainfall-runoff erosivity factor	MJ mm ha ⁻¹ h ⁻¹ yr ⁻¹
K	The soil erodibility factor	t ha ⁻¹
L	The slope length factor	ranging from 0 to 1
S	The slope steepness factor	ranging from 0 to 1
C	The cover management factor	ranging from 0 to 1
P	The erosion control practice factor	ranging from 0 to 1

Table 1: Explanation of the factors from the RUSLE equation.

The rainfall erosivity factor (R)

The rainfall erosivity factor (the R-factor) is defined as the kinetic energy of a raindrop hitting the soil surface and the rate of associated runoff (Wischmeier and Smith, 1978). The R factor reflects the rainfall capacity to cause sheet and rill erosion (Toy et al., 2002) and is defined as product of the long-term annual rainfall kinetic energy (ΣKE) and the maximum intensity of a 30-minute rainfall event (I_{30}) *equation 2*:

$$R = \Sigma KE * I_{30} \quad (2)$$

In this study the empirical formula (*equation 3*) of Wischmeier and Smith (1960) was used to calculate the R factor, based on the data received from the Royal Netherlands Meteorological Institute (KNMI). Finally, the R factor map was assumed to be homogeneous within the catchment due to the unavailability of long-term data on spatial distribution of precipitation. The calculated R factor was 1163.

$$R = 1,11 * 10^{-3} * a * b * c + 660 \quad (3)$$

where:

a = Average annual Precipitation (mm)	= 456 mm
b = Max 24-hour precipitation, return period 2 years (mm)	= 45 mm
c = Max hourly precipitation, return period 2 years (mm)	= 22 mm
Period 2016 -2022	

The soil erodibility factor (K)

The soil erodibility factor (the K factor) of a particular soil is defined as the rate of soil loss per erosivity of the rainfall as measured on a unit plot (Renard & Foster, 1997; Wang et al., 2013). It quantifies the susceptibility of soil particles to detachment and transport by rainfall, runoff and infiltration, accounting for the properties of the soil (Renard et al., 1997). Soil texture is one of the principal factors affecting the erodibility factor, but organic matter content, structure and permeability also contribute (Stone and Hilborn, 2012).

The K-factor was estimated using the nomograph by Wischmeier et. al. (1971) and its algebraic approximation proposed by Wischmeier and Smith (1978) and Renard et al. (1997), as given by *equation 4*:

$$K = [2,1 * 10^{-4} * M^{1,14} * (12 - OM) + 3.25 * (s - 2) + 2,5 * (p - 3)]/100 * 0,1317 \quad (4)$$

where K is the soil erodibility factor, expressed in $t * ha * h * ha^{-1} * MJ^{-1} * mm^{-1}$. M is the soil texture, collected from the first 15 cm of the soil and was calculated using *equation 5*. OM is % of organic matter. S is the soil structure code and P is the soil permeability. This erodibility equation is only applicable when organic matter content is known, and the silt content does not exceed 70% (Panagos et al., 2014).

$$M = (\%silt + \%fine\ sand) * (100 - \%clay) \quad (5)$$

Jar method

Soil texture was estimated using the jar method. This method is not most accurate, but it gives a general idea about the soil texture (Jaja, 2016). First, a soil sample of about 15 cm depth was collected at sample sites. Second, soil was crushed to get rid of lumps and put in the jar, so that about 1/3 of the jar was filled. Third, the jar was covered and shaken vigorously for about 5 minutes and placed on a shelf and left undisturbed for 48 hours. Fourth, after one minute of settling, the separation between the particles was marked, indicating the sand. This was repeated after two hours for silt particles and after 48 hours for clay particles. Finally, the OM content was calculated using the formula bellow (equation 6) and soil texture was determined using the soil texture triangle in figure 11.

$$\frac{\text{sand (or silt or clay) thickness}}{\text{total thickness of the sediment}} = \% \text{ sand (or silt or clay)} \quad (6)$$

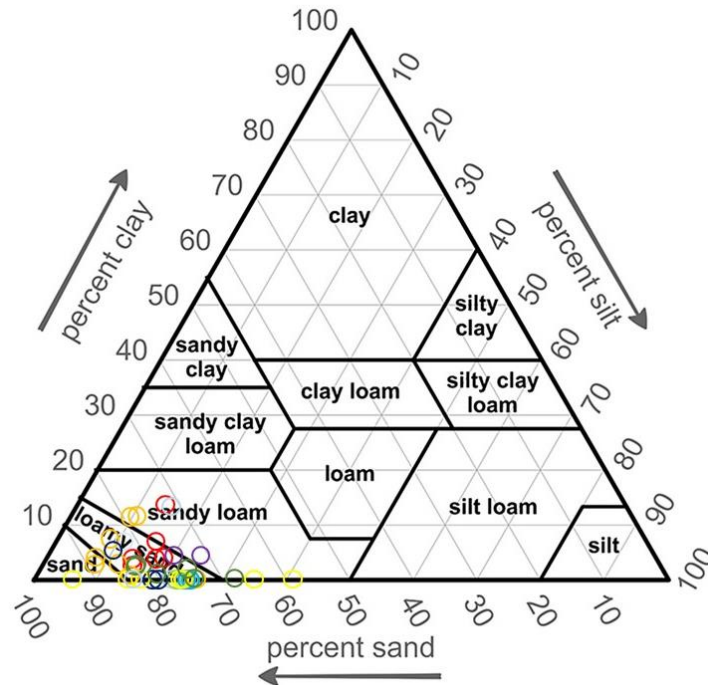


Figure 11: Soil texture triangle, showing the soil types of 41 sampling locations.

Loss on ignition method

Organic matter content was determined using one of the most widely used methods called *Loss on ignition* (LOI) method. It does not have a universal standard protocol, but in this study, soil samples that were collected at sample sites, were first placed in a pizza oven at 100°C to dry the samples. After 90 minutes, the samples were taken out to determine their dry weight. Samples were then placed in the pizza oven at 550°C for another 270 minutes to combust the SOM. Finally, sample weight was determined again and %OM was calculated using the formula bellow (equation 7):

$$\frac{m(100^{\circ}\text{C}) - m(500^{\circ}\text{C})}{m(100^{\circ}\text{C})} / 100 = \text{OM}\% \quad (7)$$

Soil Structure and Soil Permeability

Soil structure was assigned based on the soil structure classes developed by the Food and Agriculture Organization (FAO) (*table 2*) and field observations. Similarly, soil permeability was estimated based on the soil permeability classes described in the US Department of Agriculture's National Soils Handbook No. 430, considering the soil texture (*table 2*).

Permeability class (p)	Texture	Saturated hydraulic conductivity, mm h ⁻¹	Class	Percentage of stones	Value (%) used for the St calculation	Number of samples and proportion (%)	St (correction factor)
1 (fast and very fast)	Sand	>61.0	0	0%	0.0%	95 (0.48%)	1
2 (moderate fast)	Loamy sand, sandy loam	20.3–61.0	1	Stones ≤ 10%	5.0%	14,585 (73.37%)	1
3 (moderate)	Loam, silty loam	5.1–20.3	2	10% < Stones < 25%	17.5%	3114 (15.66%)	0.740
4 (moderate low)	Sandy clay loam, clay loam	2.0–5.1	3	25% ≤ Stones < 50%	37.5%	1442 (7.25%)	0.332
5 (slow)	Silty clay loam, sand clay	1.0–2.0	4	Stones ≥ 50	75.0%	643 (3.23%)	0.074
6 (very slow)	Silty clay, clay	<1.0					

Table 2: Left: Soil permeability class based on the soil texture. Right: soil structure code based on the percentage of stones. Both retrieved from Panagos et al. (2014)

Finally, a K-factor map was generated from soil erodibility values calculated for each sample location and interpolated using inverse distance weighted (IDW) interpolation (*How IDW Works—ArcGIS Pro / Documentation*, 2020) in ArcGIS Pro, to create a map of soil erodibility seen in *figure 12*.

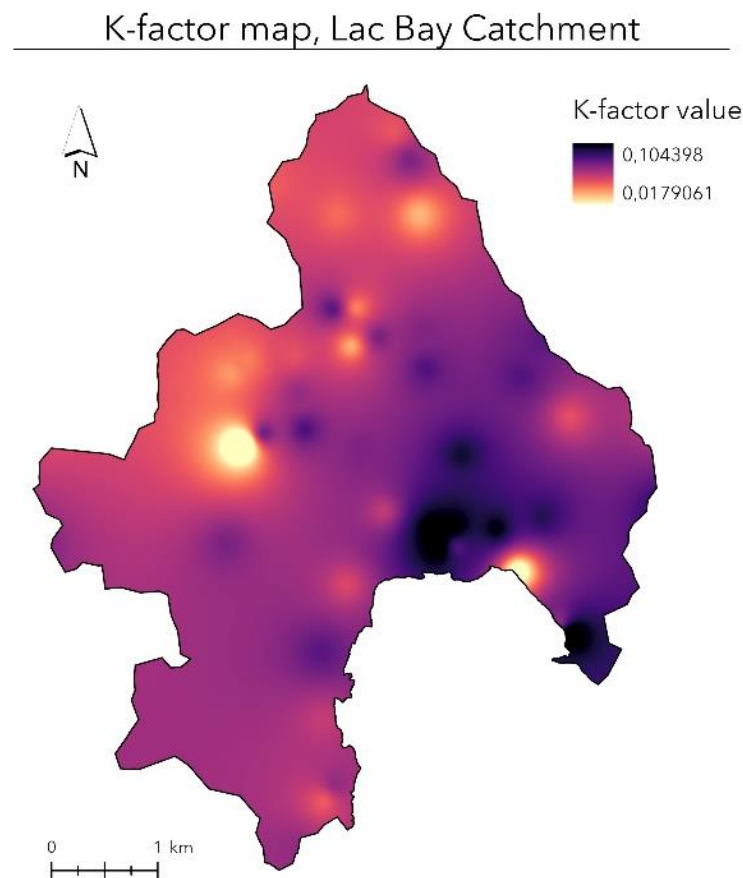


Figure 12: Soil erodibility map of the Lac Bay catchment, based on equation 4 and interpolated using IDW interpolation.

The cover management factor (C)

The C-factor is one of the most important values for potential erosion modelling. It reflects the effect land cover, cropping and management practices have on the soil erosion rates in agricultural lands and the effects vegetation canopy and ground cover have on reducing soil erosion in forested areas. (Lu et al., 2004 from Renard et al., 1997). Moreover, it provides insight on how management plans, such as crop rotations, construction activities or reforestation can affect the average annual soil loss (Van der Knijff et al., 2000).

Usually the C-factor is calculated using empirical equations, based on the measurement of ground cover variables collected over the growing season in a sample plot. Measurements should be repeated frequently, since vegetation cover is dynamic. The C-factor is later interpolated through spatial techniques. However, since satellite imagery became so readily available and can provide up to date information on land cover, new approaches have been developed.

To determine the C-factor, a widely used method based on the Normalized difference vegetation index (NDVI) was used. NDVI is a widely used indicator which measures the amount of green vegetation through calculation of spectral reflectance differences between reflectances in the red (R) and near-infrared bands (NIR) of the satellite image (Gamon et al., 1995; Carlson & Ripley, 1997):

$$NDVI = \frac{(NIR - R)}{(NIR + R)} \quad (8)$$

The NDVI values range from -1 to 1, where higher values indicate areas with higher vegetation cover while low values indicate areas with no vegetation, such as bare soil (NDVI = 0) and water bodies (NDVI = -1). Although similar, NDVI should not be interpreted as the C-factor. The two can be linked through the *linear least square method* (de Jong, 1994) or using an *exponential function* (Van der Knijff et al., 2000).

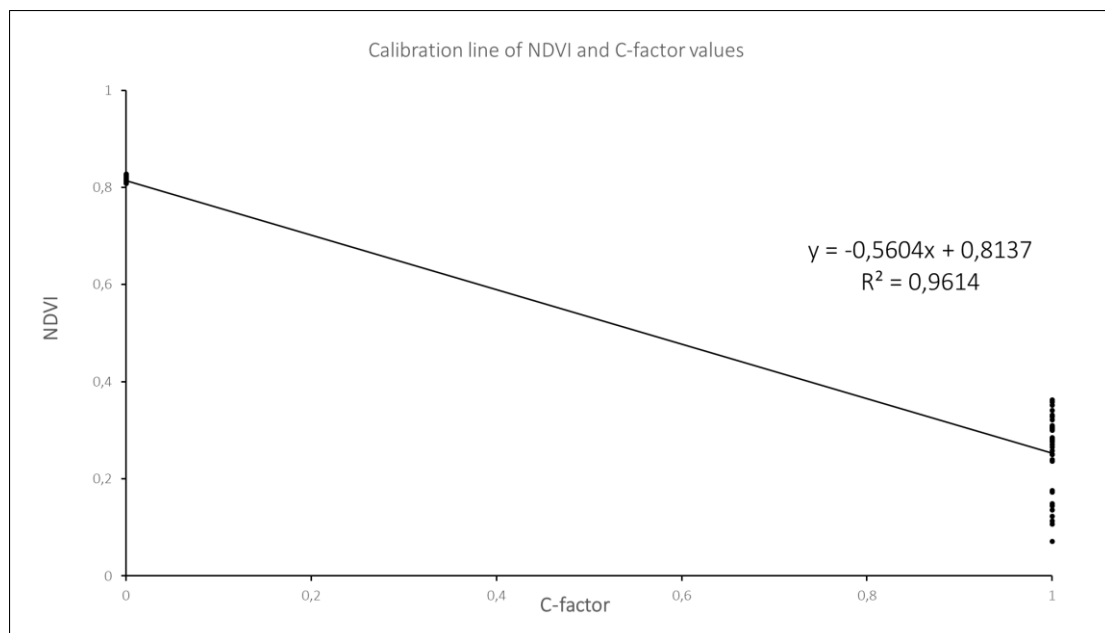


Figure 13: Graph of the calibration line with NDVI values plotted against C-factor values. A relatively large scatter in the NDVI values for the bare soil explains the relatively low R^2 ($n=70$).

In this study the C values were estimated using a calibration line with an R^2 of 0,96, cf. *figure 13*. The regression equation below (*equation 9*) was then used to estimate the C values in other locations.

$$C = \frac{NDVI - 0,8137}{-0,5604} \quad (9)$$

To obtain the NDVI values, atmospherically corrected PlanetScope 4 OLI, surface reflectance imagery with spatial resolution of 3 meters was downloaded from Planet Explorer. Moreover, a temporal analysis from April 2021 to February 2022 was conducted, to reduce the seasonal differences in vegetation cover and obtain mean (*figure 14*), max and min NDVI images (*Appendix B*) of the study area. Finally, a C-factor map was generated using the raster calculator and the equation above in ArcGIS Pro (*figure 14*).

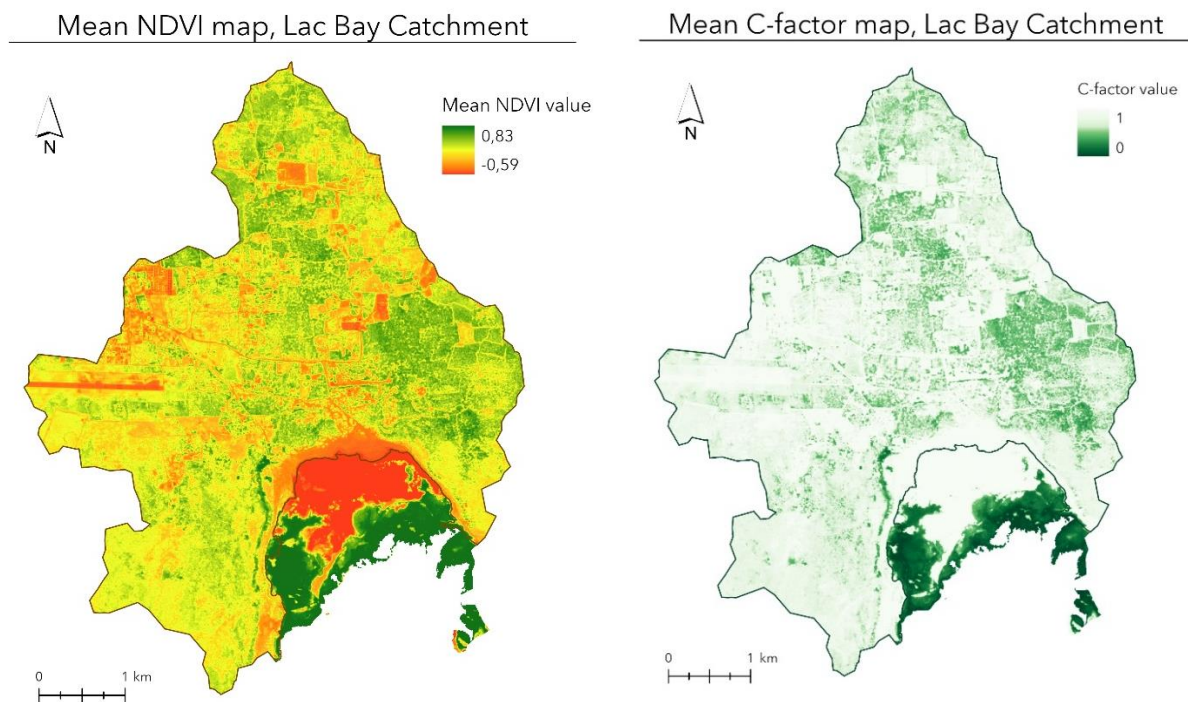


Figure 14: Left: Mean NDVI map of the Lac Bay catchment Right: Cover Management factor map of the Lac Bay Catchment. A relatively high C value can be observed throughout the catchment, except in the mangrove forest where dense canopy results in high NDVI values.

The support practice factor (P)

The support practice factor (P) expresses the control practices, that reduce and affect the surface runoff and therefore the erosion potential, by influencing drainage patterns, runoff concentration, runoff velocity and hydraulic forces on the soil surface (Renard et al., 1997). These practices can range from contour farming and strip cropping to terracing and subsurface drainage, meaning any practice that modifies the flow pattern, grade or direction of the surface flow (Renard et al., 1997) which makes this factor uncertain (Morgan & Nearing, 2011). It is a fraction, that decreases with adoption of these conservation practices, as they reduce the runoff and promote sedimentation on the hill slope surface (Panagos et al., 2015). In this study the P-factor was fixed at 1 since such practices are absent in the catchment.

The slope steepness factor (LS)

The slope-steepness factor (the LS factor) describes the effect of topography on soil erosion. It is a dimensionless factor, consisting of two factors, slope length (L) and slope steepness (S) that account for the topography of an area in the RUSLE model (Zhang et al., 2017). The slope length factor (L) represents the impact of the slope length and is defined as the ratio of soil loss from the field slope length to that from a slope length of 22,1 meters with the same conditions. For the purpose of GIS application, it can be defined as the distance from the point of origin of the overland flow to the point where deposition begins, or runoff enters a well-defined channel. Slope steepness factor (S) is defined as the ratio of soil loss from the field slope gradient to that from a 9% slope, under same conditions (Zhang et al., 2013 from Wischmeier & Smith, 1978). Combined, the LS factor is a measure of the velocity of the surface runoff because of the slope and distance the water travels. The faster water flows the more kinetic energy it can impart on the soil surface, resulting in higher erosion rates (Artiola et al., 2019). The LS factor in this study was calculated using the *equation 10* proposed by Stone and Hilborn (2012).

$$LS = \left(\frac{\text{slope length}}{22,13} \right)^m * (0.065 + (0.0456 * \theta) + (0.006541 * \theta^2)) \quad (10)$$

slope length = slope length (m)

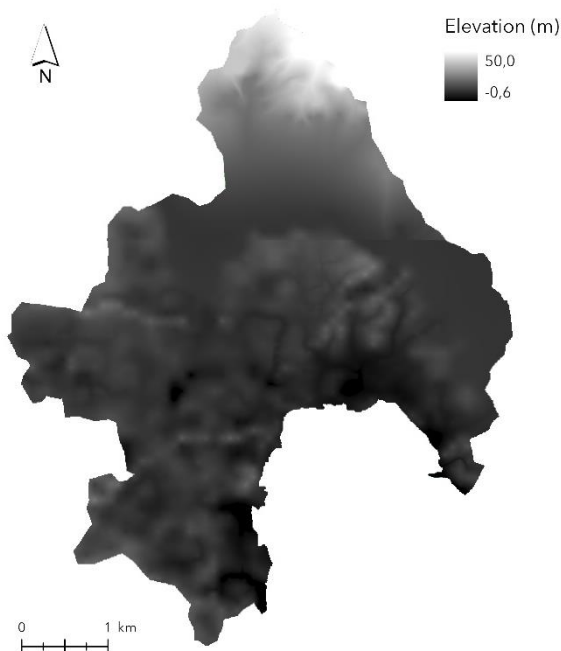
θ = slope steepness in %

m = factor based on the slope steepness

θ (%)	<1	1 < 3	3 < 5	5 \geq
m	0,2	0,3	0,4	0,5

Using the *equation 10*, the LS map (*figure 15*) was generated using ArcGIS Pro spatial analyst extension. An improved AsterDEM for Bonaire with a 10m spatial resolution and 1 m height resolution was used, created by Mucher & Stuiver (2017). The unit contributing area was defined as the accumulated flow for a given cell multiplied by the cell size, while slope steepness was extracted from the DEM.

Improved AsterDEM, Lac Bay Catchment



LS -factor map, Lac Bay Catchment

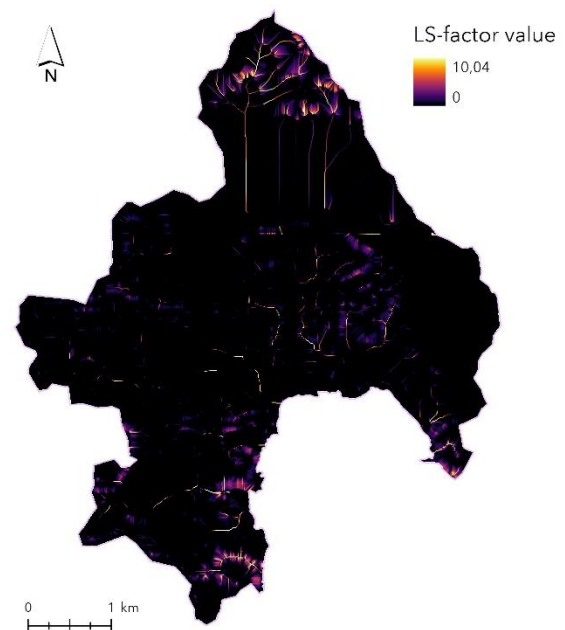


Figure 15: Left: Improved ASTER DEM of Lac Bay Catchment (Mucher & Stuiver, 2017). Right: generated LS factor map of the Lac Bay Catchment

Rainfall Simulator

As rainfall events on Bonaire are scarce, have often low intensity and are unpredictable, the mini rainfall simulator by Eijkelkamp Agrisearch was used to simulate erosion processes to gather data on actual erosion and runoff rates and validate the accuracy of the RUSLE model for local conditions. Advantage of this simulator is that the recorded runoff and soil loss reflect the integrated effect of all the processes occurring during sheet erosion, i.e., splash, swelling, slaking, crusting, and sealing, infiltration and runoff, particle detachment and to an extent sediment transport (Terzaghi, 1996).

With this device runoff and soil loss is generated by a standard rain shower on a plot with standard slope and surface area. For our experiment a heavy shower with intensity of 6 mm/min was simulated for 3 minutes to expose the soil to 1125 ml of water, during which sediment rich runoff was collected. Although such a high precipitation is uncommon for Bonaire, this intensity is proven to be useful for comparison of soil erodibility values (Eijkelkamp Agrisearch Equipment, 2014).

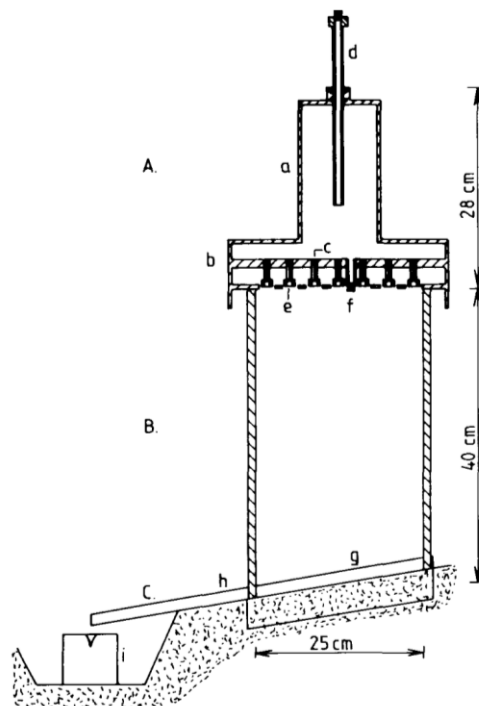


Figure 16: Left: Setup of the rainfall simulator in the field. Photo: L. Remeta. Right: Schematic side view of the set up. A indicating the shower head, B indicating the frame, C indicating the ground frame. Quoted from: Kamphorst, 1987.

Rainfall simulation was conducted once on each sampling location, 41 times in total. To produce promising results a slope of 20% is proposed by Kamphorst (1987), which was often not feasible due to the topology of the study area. Therefore, the steepest slope in the area was chosen, averaging between 3-4%. Moreover, only bare plots were selected, to eliminate the effect of vegetation.

After finding the bare spot at the steepest location, the plot was prepared by digging the 25x25 cm frame (figure 16 g) into the ground to remove the effect of lateral flow and removing large pebbles and stones (>2cm in diameter). A gutter is then installed, as seen in figure 16 C to collect the water and sediment and funnel them into the collection pot. The shower head (figure 16 A) is placed horizontally on the frame using the spirit level. The height of the frame legs (figure 16 B) is measured to calculate the slope. The shower head is filled with water and calibrated, to secure even outflow and

rainfall intensity during every simulation. During the 3-minute simulation, the collection pots were replaced every 30 seconds. In the end the runoff volume in each pot is noted and stored in a container for further analysis. Sediments stuck on the nozzle were brushed into the container.

To determine the soil loss of the simulation, the runoff samples were brought home and placed on a shelf for 24-48 hours for the sediments to settle completely. After the sample had stood overnight the clear water was siphoned out, leaving the sediment and a small quantity of water. The containers were then placed outside to be sun-dried. After 24 hours the weight of the container and the remaining sediment was measured and noted down.

Potential Erosion Map, Lac Bay Catchment

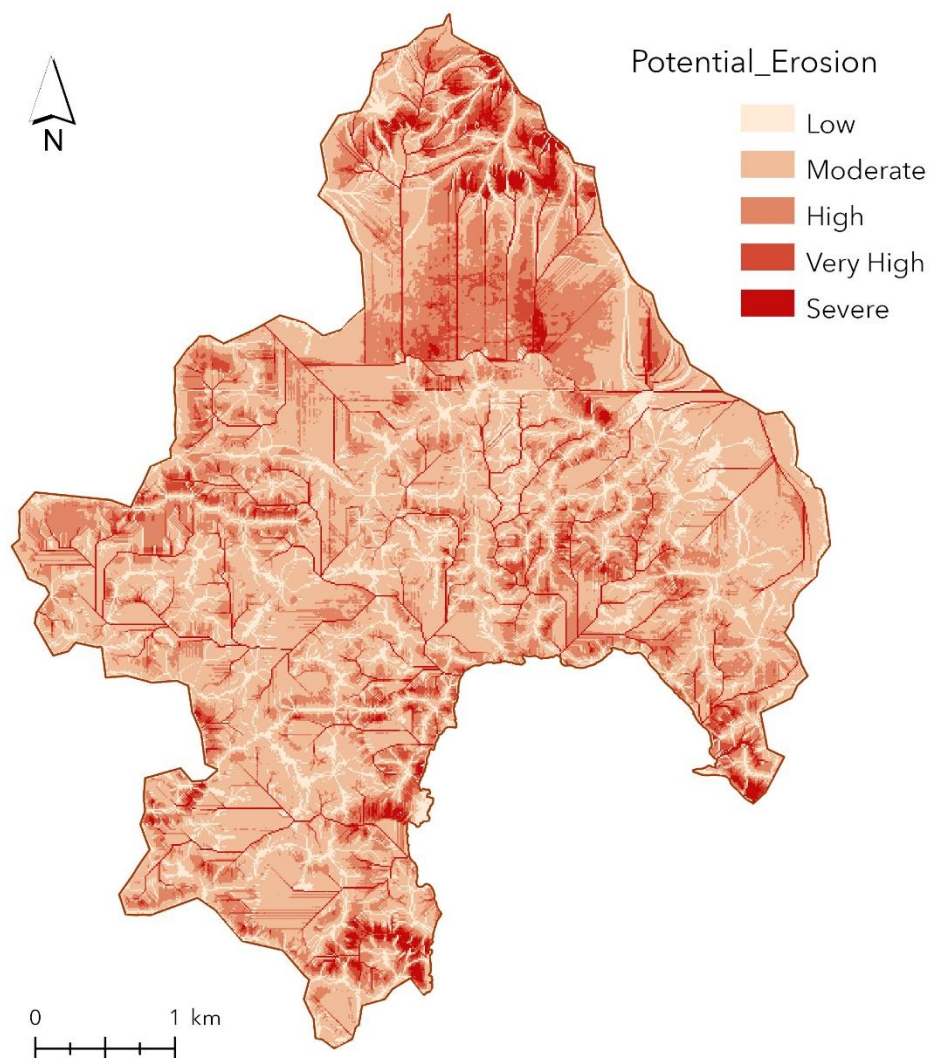


Figure 17: Potential Erosion Map of Lac Bay Catchment, based on the erosion severity classes defined by Derks & Nicolai (2021).

III. RESULTS

Both sediment yield and runoff rates were measured in all 41 study sites and later analysed to generate runoff coefficient map and to calculate the potential water recharge of the bay. Moreover, the sediment yield was analysed and compared to the potential erosion results from the RUSLE model.

the RUSLE model

The potential erosion map based on the RUSLE model (*figure 17*), displays annual erosion rates from low to severe. For easier comparison, the classification was based on the classes proposed by Derks & Nicolai (2021). As seen in *table 3*, 51% of the area is characterized with moderate erosion rates, ($5\text{--}25 \text{ t ha}^{-1} \text{ year}^{-1}$) reserved for areas high in vegetation cover, but even more for areas with slopes between 0 and 3%. High to very high erosion ($25\text{--}80 \text{ t ha}^{-1} \text{ year}^{-1}$) can be found in 30% of the catchment, mostly in areas contributing to flow accumulation where slopes exceed 3%. Finally, areas considered to have severe erosion ($> 80 \text{ t ha}^{-1} \text{ year}^{-1}$) amount only to about 5% of the catchment but contribute almost as much as the areas with moderate erosion, even though the area is significantly smaller. Severe erosion is characteristic for the most northern part of the catchment, where topology shifts to a higher elevation, in south of the catchment close to the bay and around flow accumulation zones.

Using the median rate of erosion per class as displayed in table 3, the annual amount of soil loss was calculated for each severity class and finally the total annual soil loss for the entire catchment was found to be $41678 \text{ t year}^{-1}$. The overall area weighed median erosion of the catchment is $19,3 \text{ t ha}^{-1} \text{ year}^{-1}$, with 1st quartile being $9,6 \text{ t ha}^{-1} \text{ year}^{-1}$ and the 3rd quartile being $32 \text{ t ha}^{-1} \text{ year}^{-1}$.

Table 3: Median rate of erosion, contributing area and the total soil loss per soil erosion severity class as defined by Derks & Nicolai (2021).

Severity class	Rate of Erosion ($\text{t ha}^{-1} \text{ year}^{-1}$)	Median Rate of Erosion ($\text{t ha}^{-1} \text{ year}^{-1}$)	Area (ha)	Area (%)	Total Soil Loss (t/year)
Low	0-5	0	223,4	14	0,0
Moderate	5-25	14,8	813,4	51	12038,9
High	25-50	33,4	379,3	24	12669,5
Very High	50-80	59,8	101,4	6	6064,0
Severe	> 80	132,24	82,5	5	10906,0
Total		19,3			41678,4

Interpretation of the potential erosion map

Observing the spatial distribution of the potential erosion in the catchment there are certain areas that stand out. In this section different areas of interest will be discussed.

Location 1 (*figure 18*), the most northern part of the catchment is characterized by very high to severe erosion rates, as a result of the steep slopes in this part of the catchment. However, there is a relatively large homogeneous area with high to very high erosion rates and lines of severe erosion flowing vertically towards the middle of the study area. In nature water rarely flows in a straight line, therefore this location is most probably the result of the DEM which is later discussed in more detail.

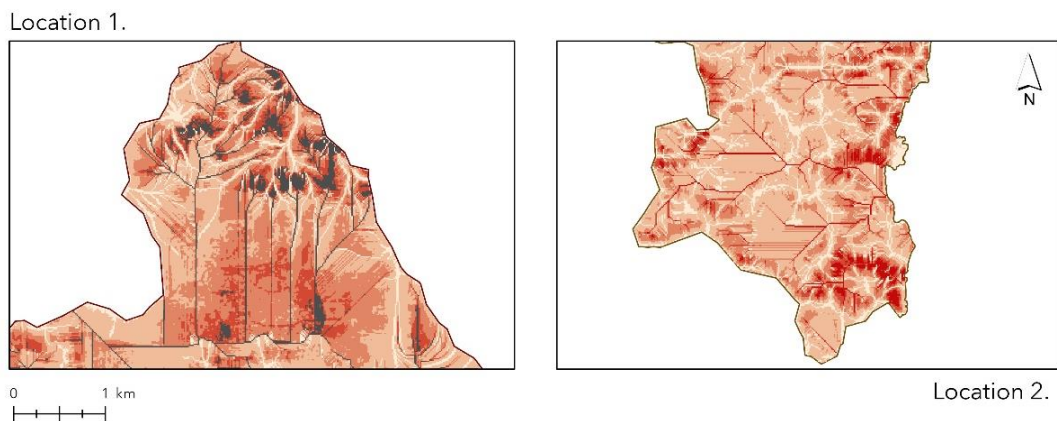


Figure 18: Left: Location 1, where severe erosion lines, displayed as grey are flowing from north to south. Right: Location 2 in the southeast of the catchment characterized by calcareous bedrock and shallow soils but displaying high and severe erosion rates.

Similarly straight lines can be observed in other locations i.e. location 2 (*figure 18*). Location 2, located in the southeast of the catchment is showing a large area with heterogeneous soil erosion levels which is conflicting the observations made in the field. This entire area is characterized by calcareous bedrock as part of the lower limestone terrace. Soil is mostly absent or very shallow and was only found in local depressions, which means that the actual erosion in this area is very low or absent. This points to another limitation of the RUSLE model, that is discussed later.

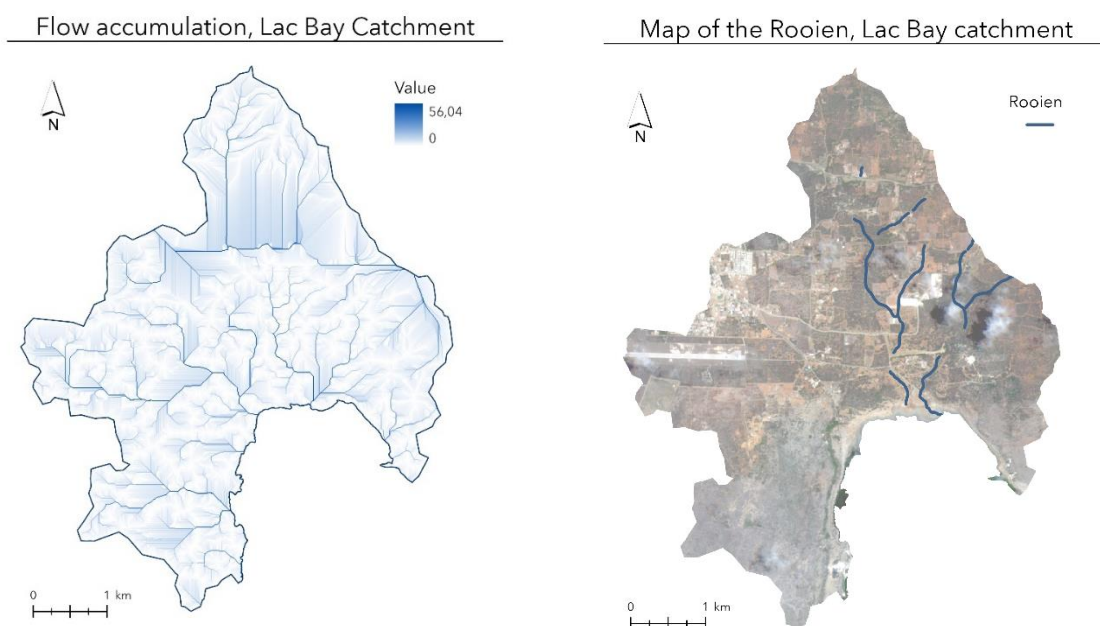
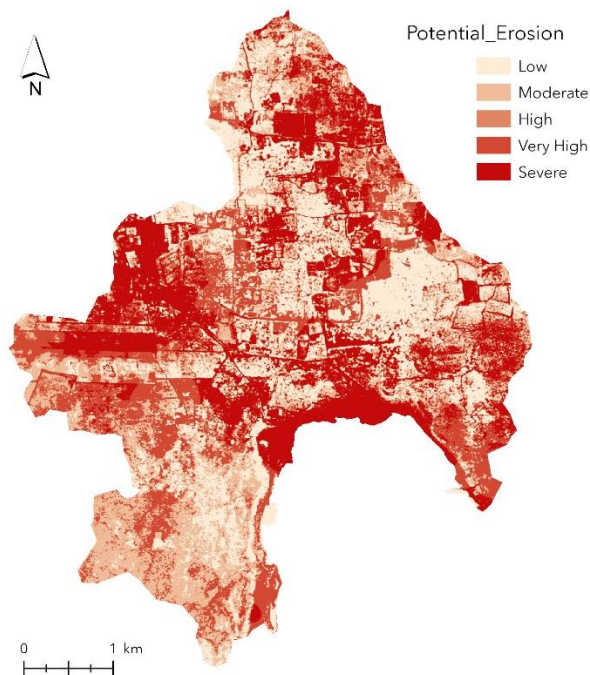


Figure 19: Left: Map of the flow accumulation paths (L-factor). Right: Map of the intermittent rivers (rooien). It can be observed that the flow accumulation paths in some places correlate with the rooien.

Location 3 is the L factor map of the catchment, that is clearly reflected in the potential erosion map as lines with severe erosion rates throughout the catchment. L factor is based on the accumulated flow, calculated with ArcGis pro (*figure 19*). Based on field observations, the actual flow accumulation is better reflected by the intermittent rivers (rooien) (*figure 19*), that were observed and mapped over the years which in some parts do correlate with the accumulated flow generated by ArcGis. Due to the coarse resolution of the used DEM, the ArcGis software probably underestimates the volume of water that can be stored on the surface and therefore overestimates the accumulated flow. Meaning that the severe erosion rates in the catchment are probably overestimated and limited to the areas in the north, which is later elaborated on.

Potential Erosion Map 2, Lac Bay Catchment



Roads in the catchment of Lac Bay

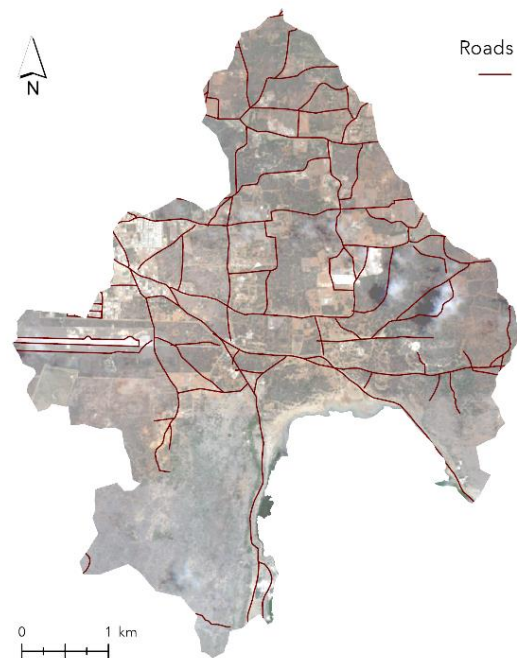


Figure 20: Left: Map of potential erosion rates (excluding the LS factor), with a relative scale. Right: Roads in the catchment of Lac Bay. Roads in the west of the catchment are paved, while the rest are bare and constructed of loose material.

In location 4, the roads in the Lac Bay catchment are displayed. Most of the roads in the catchment are bare, unpaved and constructed from loose sediment excavated in the area, which makes them prone to erosion (*figure 20*). Heavy trucks use them regularly to transport the sand that is excavated for construction in the east side of the catchment, which in combination with heavy rain during the rainy season results in sheet erosion. On Bonaire, roads are fixed twice per year after every rainy season by depositing a new layer of sediment. Since most roads are flat the RUSLE model does not assign them a severe erosion risk, while comparing the map to the one generated without the LS factor, the roads are clearly displayed with severe erosion rates.

Rainfall simulator

Evaluation of the potential erosion values was performed using the measured soil loss data, adjusted to fit the model. The measured sediment yield ranges from 0 g to 40,52 g per simulation, with a mean of 10,16 g and standard deviation of 8,32 g as seen in *figure 21*. Quantities are randomly distributed over the catchment, with no significant differences between the sampling areas (*figure 21*).

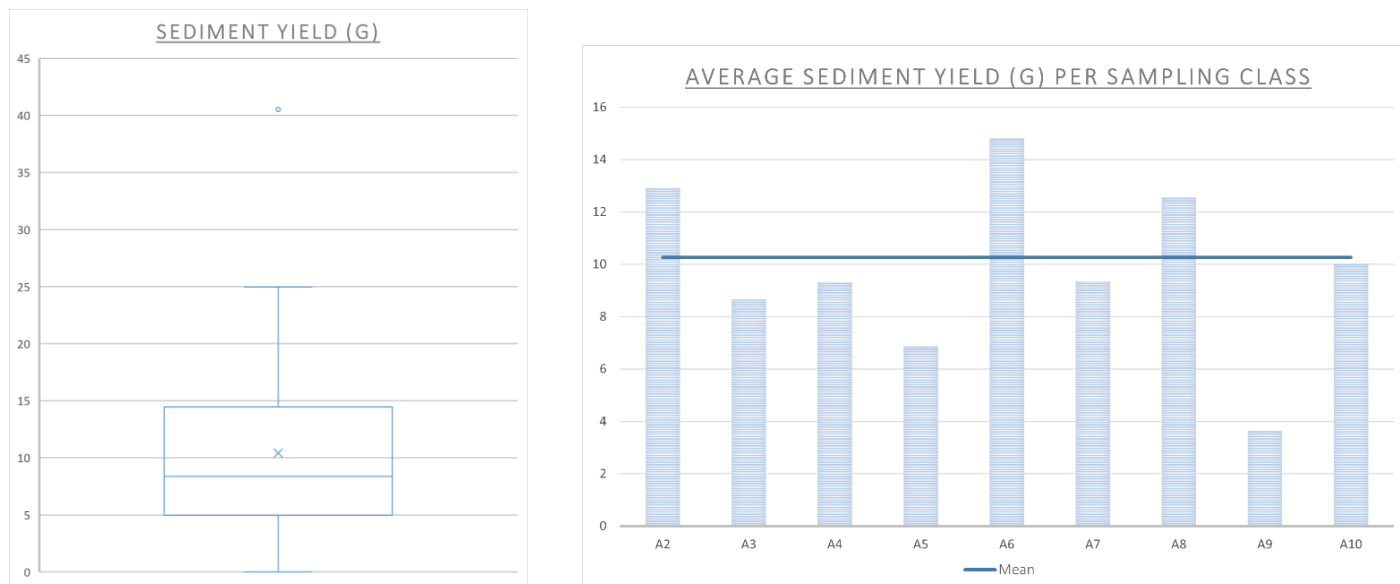


Figure 21: Left: Boxplot of the sediment yield from the rainfall simulations. Right: Average sediment yield (g) per sampling class.

Validation of the RUSLE model

To compare measured soil loss to the potential soil loss predicted by the RUSLE model, measured soil loss was adjusted for the plot size and erosivity of the event (R) (*Appendix C*). The adjusted data (A_m) now represents the annual soil loss in tons per hectare. Statistical analysis was performed after the data was cleared of outliers (3 data points., 7%).

	A_m (tons/ha year)		A_{RUSLE} (tons/ha year)	
Min	0		0	
Max	28,27	45,87*	49,36	239,22*
Mean	10,76		11,19	
Median	8,75		8,14	
SE	1,27		1,94	
RMSE	13,05			
R^2	0,15			

*Data before outliers were removed

Table 4: Comparison between the measured soil erosion and predicted soil erosion at sampling locations.

Data points in *figure 22* are distributed around the line ($y=x$) in a random manner. A linear regression between measured and potential soil loss has an R^2 of 0,15 which suggests that the RUSLE can not predict erosion with high spatial accuracy. Approximately the same number of points lay above and below the line, which means that the model does not over nor under-estimate the actual erosion rates. Mean, and median values of the measured soil loss do not differ much from the predicted values by the RUSLE, as seen in *figure 22* and *table 4*.

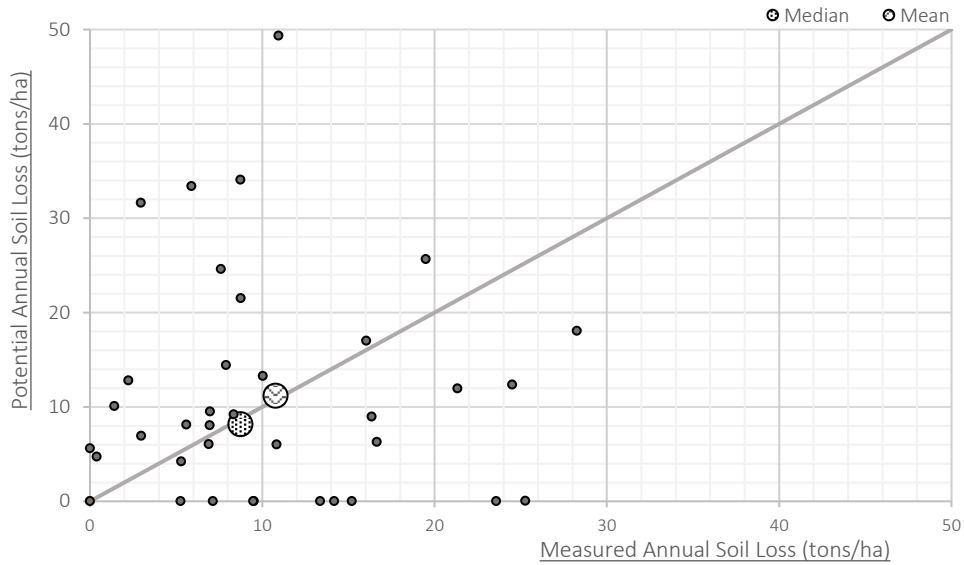


Figure 22: Graph of the correlation between the potential annual soil loss, based on the RUSLE model (y-axis) and the measured and corrected annual soil loss based on the rainfall simulator data (x-axis).

Surface Runoff

The runoff coefficient map (*figure 23*) displays both measured runoff coefficient and the measured runoff fraction, as well as the potential runoff coefficient. It was generated using the measured runoff fraction from rainfall simulator data, that was interpolated using the IDW spatial interpolation method in ArcGIS Pro and overlayed over the C-factor map, to account for the vegetation cover. The slope of the area was not considered, due to several reasons. First, no correlation was found between the measured runoff and the slope, at which the experiment was performed (*Appendix E*). Second, the average slope in the catchment (1,5 %) does not differ much from the measured slope (3,7%). Finally, the analysis of the DEM showed inconsistencies, which will later be discussed more fully.

The calculated runoff coefficient, displayed in *table 5* ranges from 0 to 0,8 with median value of 0,24. Mean runoff coefficient of the catchment is 0,25 with the standard variation of 0,09. Most of the catchment (68%) has runoff coefficients between 0,16 and 0,33. Around 12% of the area has coefficients lower than 0,16, while only 2% exceeds 0,81, i.e., the coastline east of the bay and some isolated areas in the centre of the catchment. Using the median runoff coefficient, the total annual runoff of 112 mm for this scenario was calculated. Moreover, the potential water discharge, that is the maximum volume of water that can be discharged to the Lac Bay was estimated to be 1.806.912 m³/year. These runoff coefficients are applicable only for rainfall events with rainfall intensities higher than 6mm/min, meaning that the median runoff coefficient would in reality be lower.

	Min	Median	Max
Runoff Coefficient	0	0,24	0,80
Total Annual Runoff (mm)	0	112	370
Potential Water Recharge (m ³ /year)		1.806.912	

Table 5: Runoff coefficient and the potential water recharge of the Lac Bay, for the maximum rainfall intensity scenario

Runoff Coefficient map, Lac Bay Catchment

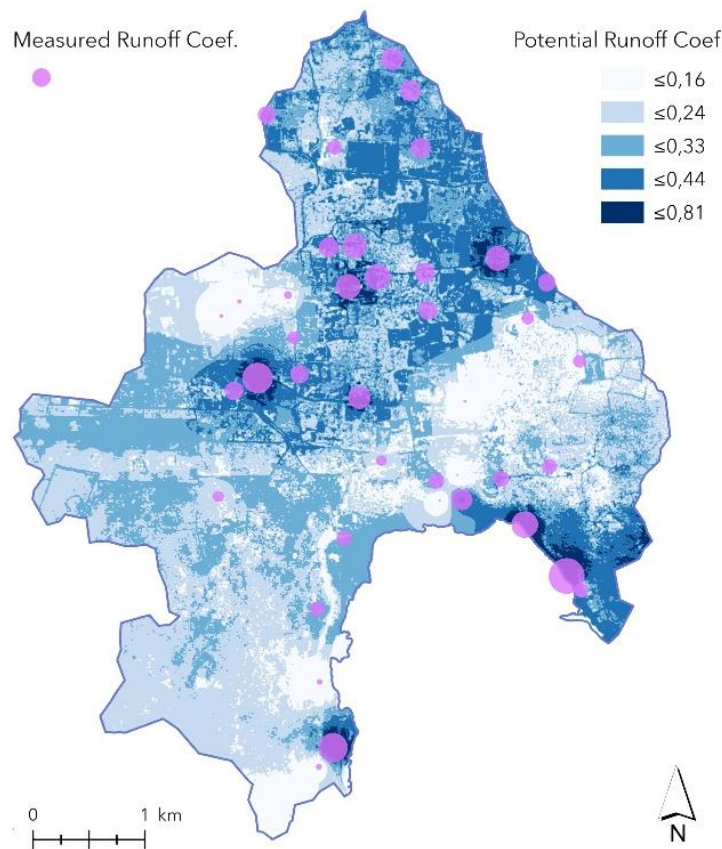


Figure 23: Runoff Coefficient map of the Lac Bay Catchment.

Interpretation of the runoff coefficient map

Observing the runoff coefficient map, we can see that it strongly reflects the vegetation map of the catchment, as it is the only factor in our “model”, next to the measured runoff coefficient. There are a few areas that stand out and are highlighted in *figure 24*.

Location 1, in the east side of the catchment indicates a big area with a very low runoff rate, due to low measured runoff and high vegetation cover in this area. Compared to the rest of the catchment, this part is mostly undeveloped and covered with communities of shrubs and cacti. With increased urbanization of Bonaire, there is a risk for a potential urban sprawl towards the east of the island, which will likely lead to removal of vegetation in the area and will therefore decrease the infiltration and increase the runoff rate.

Location 2, in the northeast of the catchment is characterized by high runoff rate, due to high measured runoff and low vegetation cover which is the result of the high density of overly grazed Kunukus. High runoff rates and favourable topology might explain the formation of the two large intermittent rivers (*figure 24*) in the catchment also known as the rooien. These two rivers occur only in the rainy season and convey the major part of the runoff from this part of the catchment towards the bay, resulting in high erosion rates. The bigger rooi ends at the Mona Passage dam (*figure 26*), which was constructed for agricultural purposes in the area, but is nowadays abandoned and serves mostly as a measure that strongly reduces the sediment transport to the bay.

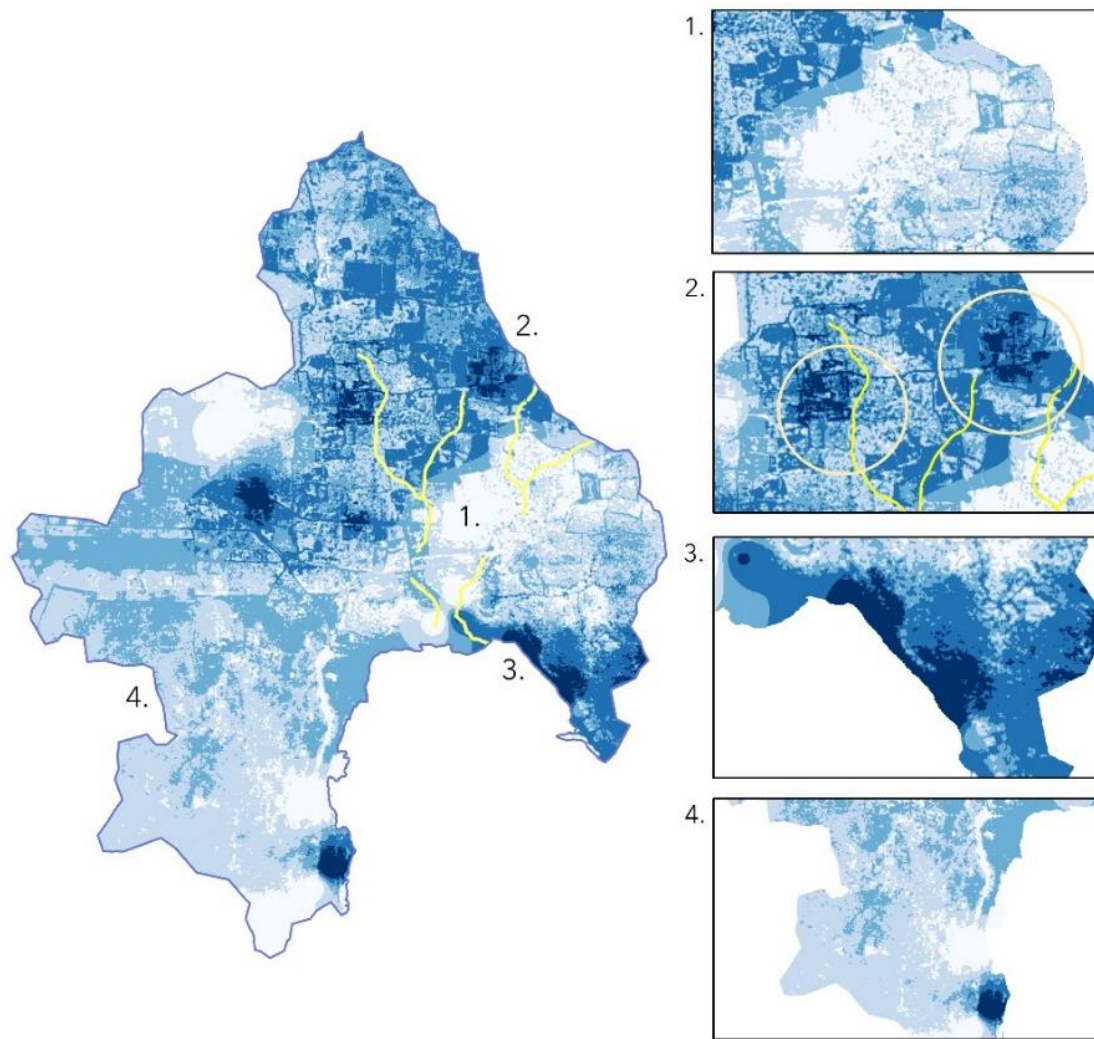


Figure 24: Runoff coefficient map of the Lac Bay catchment, with areas of interest shown on the right and the intermittent rivers indicated in yellow.

Location 3, in the southeast is showing a very high runoff rate, as it is very close to the Kaminda Lac and the bay itself, where almost no vegetation grows.

Location 4 is a homogeneous area with low to moderate runoff rates generated by the model, which is similar to location 2 on *figure 18*, and contradicts observations made in the field. As explained before the soil here is mostly absent or very shallow. The measurements were conducted on small patches of soil, found in depressions, which could mean that the actual runoff coefficient is probably much higher in this area, depending on the available depression storage.

Soil and water conservation measures

Measures are needed to control and solve the present situation, in which mangrove population in Lac Bay is steadily declining due to the effects caused by erosion and reduced freshwater recharge of the bay. Measures discussed below are intended to reduce the sensitivity of critical areas to erosion and to decrease the influences these areas have on sediment transport. Some of these measures are already implemented, however improvements are needed to conserve this ecosystem.

Management Measures – Reduced Grazing

As explained before, free roaming goats and donkeys in combination with arid climate and historical deforestation of the island are responsible for loss of vegetation cover on Bonaire, leading to increased surface runoff and potential erosion. Therefore, to reduce the pressure of the goats on the ecosystems two things can be suggested:

- A) Reduce the number of free-roaming goats on Bonaire
- B) Enclose the areas that are threatened by overgrazing

It is estimated that the economic costs of fencing would be around 2,5 million dollars with a lifespan of approximately 10 years, while costs of eradication are estimated to around 8,8 – 12,9 million dollars with a permanent effect on the ecosystem (Roberts, 2017).

There are around 30.000 goats on the island, 1/3 of which are located at Washington-Slagbaai National Park and the rest are owned by kunukeros, who only rarely keep them fenced (Geurts, 2015). Free roaming is seen by many as part of the “tradition”, but is also financially beneficial for the owner, therefore eradication and fencing is strongly opposed by the local community (Engel, *personal communication*). This suggests that the goat problem on Bonaire is an ecological problem with strong cultural roots, meaning that culling the number of free roaming goats is not a suitable solution.

Therefore, the preferred solution is enclosure of areas threatened by overgrazing. In the catchment these areas can either be agricultural plots such as Kunukus or areas designed as nature. There are a few locations where reduced grazing is already taking place, such as San Jose and Fofoti, as indicated in *Appendix F*. These are reforestation areas just north of Lac Bay, 38 hectares in size, with the purpose of restoring and planting the indigenous flora and fauna of the island (Engel, *personal communication*; Coolen, *personal communication*), improving water infiltration and reducing soil erosion.

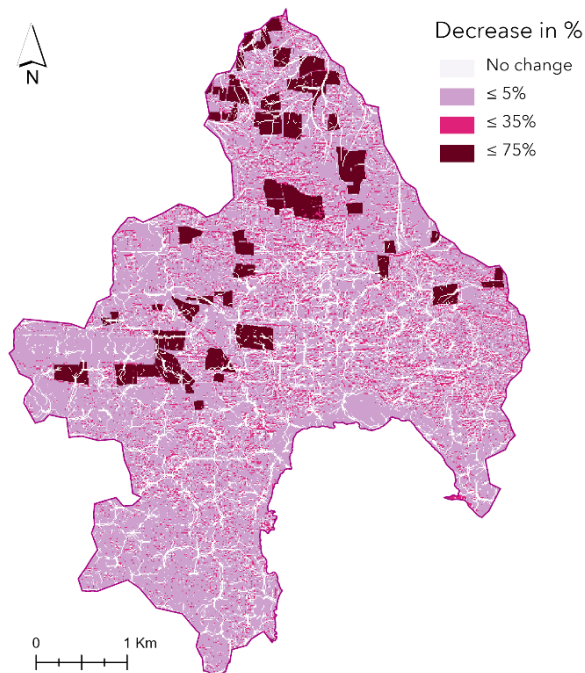
Areas are first chosen and fenced, after which capturing of goats begins until most goats are removed from the fenced areas. The remaining goats are culled. When building fences, it is advised that cacti fences are used, as they have multiple benefits. First, they prevent feral livestock from damaging the fence, ie. donkeys like to rub their backs on the fences causing structural damage (Engel, *personal communication*). Second, there have been cases in the past when parts of fences were stolen, which can not happen with cacti fences (Coolen, *personal communication*).

Moreover, there are multiple associated benefits of these measures as they promote biodiversity and allow restoration of indigenous flora and fauna, increase water infiltration and groundwater recharge, could increase organic matter content and finally decrease erosion and runoff which has a positive effect downstream (Eckrich, *personal communication*).

It is estimated that fencing vulnerable areas could increase ground cover from around 4% (currently) to 14% (Roberts, 2017) and therefore reduce erosion.

Moreover, fencing *Kunukus* that have been inactive since 2003 (*figure 25*) (“Agricultural Fields (Kunuku) Bonaire | Dutch Caribbean Biodiversity Database,” n.d.) and increasing the ground cover to that of the average vegetated Kunuku (C factor = 0,25) could yield a decrease in median erosion rates of about 5,7%. Such decrease in the potential erosion rates could prevent 1996 tons of soil from being eroded annually. As seen in *figure 25*, decrease in the erosion rates does not only occur in the fenced area, but around the entire catchment, however changes in the erosion rates there are relatively small (< 5%) compared to the fenced areas (from 35% to 75%).

Decrease in the potential erosion rates when inactive Kunukus are fenced



Map of inactive Kunukus in Lac Bay

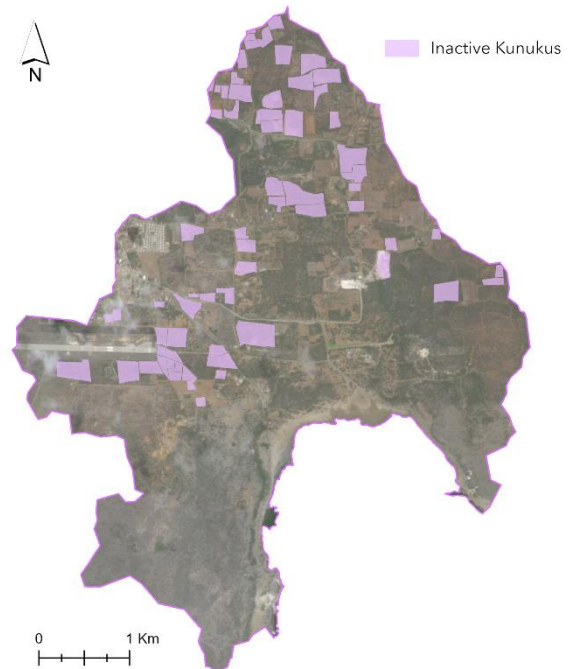


Figure 25: Left: Spatial representation of decrease in potential erosion rates when inactive Kunkus are fenced. Right: Map of inactive Kunukus (Kunukus that were in use in 2003 but not in 2019) in Lac Bay Catchment.

Structural Measures – Earthen Dam and Sediment traps

Structural measures are permanent or long duration measures typically used to control runoff, wind velocity and erosion. They are often aligned along the contour or perpendicular to the prevailing wind direction and spaced according to the slope. Their disadvantage is that they are relatively costly and labour intensive as they involve major earth movements or construction with wood, stone or concrete (United Nations, 2007).

In the catchment of Lac Bay, the proposed structural measures are earth bunds or small earthen dams. Such structures are already in place in the catchment, as seen in *figure 26*, with Mona Passage and the Dam in San Jose being the most important ones. Looking at the remote sensed images and supported by Hobbelt (2014), we can conclude that the Mona Passage acts as an effective measure against runoff and sedimentation in the bay, while the dam in San Jose is relatively new and the effect is still unknown.

It can be argued that such structures would drastically decrease the sedimentation in the backlands by catching the sediments uphill, but also decrease the surface runoff towards the bay, which might enhance the salinity. However, Hobbelt (2014) found by looking at the decrease in water levels of Mona Passage that around 31% of the water evaporates, while around 69% infiltrates in the soil and flows as groundwater towards the bay.

To really prevent sediment rich water from entering the bay, another dam/earth bund would need to be constructed in Fofoti. As seen in *figure 26*, that is the area where one of the major rooien enters the bay. This would not only help decrease sedimentation in the bay, but it would also increase water

infiltration in the area and improve the reforestation initiatives. Before implementation, additional research should be done on the effect of current dams on the groundwater recharge and flow towards the bay.



Figure 26: Earth dams and sediment traps close to the Lac Bay that are affecting the surface flow and sedimentation in the bay.

Moreover, another important measure in the catchment is the sediment trap also indicated in *figure 27*. Sediment traps (ST) are great at slowing down sediment transport when soil erosion is difficult to control. The challenge of ST is to create sinks in the catchment where surface flow and sediment can be trapped. These sinks can take the form of vegetative strips along the contour, shrub and tree buffers, ponds, or concrete traps, such as one near Lac (*figure 27*). To maximise the effectiveness of the ST measures, regular maintenance is needed to avoid structural failure and overfilling. Unfortunately, latter was the case with the sediment trap on Bonaire, which was not maintained for a duration of 3 months (based on the observations in the field).

Finally, a vegetative strip of native Buttonwood tree (*Conocarpus Erectus*), together with Sea purslane (*Sesuvium portulacastrum*) is being grown in Fofoti, along the road with the purpose of catching sediment rich runoff before entering the bay. A study by Yan et al. (2021) has showed that surface runoff and soil loss can be reduced by 15% - 62% and 79%- 94%, respectively, when earth bunds are covered by vegetation, depending on the type of vegetation. Since conditions in Fofoti are not suitable for most plants (high temperature, low precipitation, brackish groundwater) only selected native species can be introduced. Therefore, further research should be conducted on effectiveness of different native species to control erosion.



Figure 27: Left: Earthen dam of San Jose with local vegetation. Right: Existing sediment trap next to kaminda Lac, showing the lack of maintenance.

IV. DISCUSSION

Rainfall-runoff-erosion relationship is a function of the climatic variables such as precipitation, soil properties, topology, vegetation cover and the management practices. In this study these relationships are displayed in the form of a potential erosion and surface runoff coefficient map of the Lac Bay catchment. Median erosion potential in the catchment has been identified as moderate (19,3), which is of concern as rates higher than $2 \text{ t ha}^{-1} \text{ y}^{-1}$ are already above the recommended sustainable threshold and call for implementation of conservation measures (Verheijen et. al, 2009). Moreover, there are no clear patterns in the spatial distribution of the potential erosion. Areas in the north and in the south are showing severe potential erosion risk, while most of the catchment has moderate risk of potential erosion.

This creates a hard environment for policy makers and conservationists to come up with solutions for the mangrove mortality and the mangrove seawards shift. Implementing management measures at watershed level, such as reduced grazing could reduce the potential erosion in the catchment by 5%, while also improving vegetation cover. Structural measures close to the bay, such as the earth dams and the sediment trap are already effective at capturing the runoff and sediments before entering the bay but could be improved by further construction of an earth dam in Fofoti and maintenance of the existing sediment trap.

It was expected that the potential erosion will be mostly affected by differences in the soil type and the absence of vegetation cover, while the topological factor will not contribute much, since the topology of the catchment is flat. However, this is not true as it seems that the RUSLE model gave considerable weight to the topological factor, which is reflected in the potential erosion map. This leaves us questioning the usefulness of the RUSLE model for erosion assessments in gently sloping areas.

Moreover, based on the literature study of the geological background (de Freitas, 2005) and the soil map by Koomen et al (2012), bigger heterogeneity in the soil type through the catchment was expected, that would cause differences in the K value and therefore affect the potential erosion. Each of the sampling areas was expected to have slightly different soil type and therefore the erodibility values. Ground observations and later soil texture analysis disproved that and showed that soil in the catchment is rather homogeneous, varying between sandy loam and loamy sand. This can be explained by the lack of in-depth soil studies on Bonaire and more precisely lack of spatial studies on soils.

Looking at the rainfall simulator, it was expected that the measured sediment yield within the sampling areas will reflect the slope on which the simulation was performed, since soil type is the same and vegetation is absent. This was not true, as no correlation was found between the measured sediment yield and slopes (*Appendix E*). This could be explained by lack of variables, that influence erosion rates, measured in the field, such as the soil moisture content, temperature, salinity and crusting of the soil.

Finally, it was expected that the potential erosion values based on the RUSLE model will be validated by the rainfall simulator measurements, which was also not true. No correlation was found between the measured erosion and the predicted erosion, which limits the validity of our study. Differences between the actual measured and the potential erosion might be the result of the shortcomings and limitations of the RUSLE model and the rainfall simulation measurements, which are later discussed in detail.

Other studies

Studies on mangroves in arid climate worldwide agree that salinity is the main cause for mangrove die-off, which is a result of a reduced groundwater recharge and surface runoff (Adame et al., 2021). Similarly, Fromard, (1998) and Ellison (1999) claim that burial of mangroves roots by sediment causes degradation and death.

However, the study by Lovelock et al. (2015), argues that a heavy sediment supply is crucial for survival of mangrove forests in context of climate change. With a relatively low productivity in arid regions, sediment accumulation is necessary to keep pace with rising sea levels. Moreover, blocking the sediment streams reduces surface flow and recharge of the bay, which furtherly enhances the salinity. This might be the case in the Indo-Pacific region, where this study was conducted. In Lac bay however, the infilling of the sediments causes the seaward shift of the mangroves. The sediment supply allows the mangroves to grow into Lac Bay, but the area in which the shift of the forest can take place is limited by the size of the bay and important ecosystem of seagrass beds.

No case studies have been found that analyse runoff and erosion risks in relation to mangrove conservation. On Bonaire however terrestrial runoff and erosion have been studied in several contexts related to nature and urban development (Derks & Nicolai, 2021), coral reef conservation (Geest et al., 2020) and flooding (Koster, 2013) showing comparable results.

Derks & Nicolai (2021), who used the RUSLE model to assess the potential erosion in the catchment of Bolivia have found comparable results. Their study looked at the Bolivia catchment in the North-East of Bonaire, covering an area of 3500 ha with similar hydro-geological properties. Differences between the studies can be found in the estimation of the RUSLE model factors. For example, soil erodibility was estimated based on K factor values by Stone & Hilborn (2012), rather than quantified through an empirical equation. Moreover, the C factor was estimated based on the land use and land

cover map by Múcher & Verweij (2020) and combined with literature values, while this study estimated the cover factor on the basis of NDVI values from remote sensed data.

Their study uses a similar methodology and has same climatic, geological and hydrological properties allowing comparison and evaluation of the results. The differences in methodology did not yield big differences in erosion estimation. Mean erosion rates for Bolivia catchment were estimated to 18 t/ha y, comparable to the median erosion rates of 19,3 t/ha y found in the Lac Bay Catchment. Equally, over 80% of their catchment is considered to have very low to low erosion rates, which corresponds to the erosion rates found in 65% of my studied area. Severe erosion was found in 4% of their catchment, close to 5% threatening the catchment of Lac Bay. These differences in the erosion rates might be explained by the differences in the topology and/or vegetation cover. The rainfall-runoff relationship is similar as well. Surface runoff in their study was estimated using the curve number method, which yielded mean runoff coefficient of 0,16 for the maximum runoff scenario, which is comparable to our estimation of 0,25. Due to lack of data, runoff coefficients for other scenarios were not calculated and can therefore not be compared.

Based on these findings, it can be argued that the validity of the RUSLE methodology to estimate the potential erosion on Bonaire is high. However, Derks & Nicolai (2021) pointed out the same limitations of the RUSLE model as found during my research, namely limited resources and quality of the existing data, unreliability of the LS factor, and the models inherent inability to account for the soil depth, which questions the validity of the absolute values calculated in our research.

Limitations

Below shortcomings, and limitations mentioned before, and others will be discussed in detail.

Field work

Sampling locations were chosen in areas where soil was bare to reduce the number of variables that could influence the rainfall simulator measurements. This resulted in first, having soil samples with considerably lower organic matter content, due to the absence of vegetation and consequently plant litter and humus. Second, absence of vegetation might result in lower infiltration capacity of the soil, due to the absence of roots and therefore reduced soil porosity, both affecting soil erodibility. This has likely influenced my rainfall simulator measurements as well determination of OM from soil samples and potentially led to overestimation of the potential erosion and surface runoff.

Studies have shown that environmental factors, such as soil moisture content (Bushueva et al., 2014; Qianjin et al., 2019), soil temperature (Al-Ali, 2016), soil salinity and crusting influence (Baumhardt & Schwartz, 2005) the surface runoff and potential erosion rates as well but were not accounted for during the fieldwork. This might have added to the unreliability of the rainfall simulator measurements, but their relative contribution to the soil erosion processes is also hard to quantify.

Data

One thing that limits the validity of our results the most is the availability and quality of the data. When quantifying the erosivity factor for the RUSLE model, rainfall data from Flamingo Airport Bonaire was used. It was assumed that the erosivity factor in the catchment is constant and that the spatial differences in the erosivity are negligible. Even though, the island of Bonaire is relatively small there are differences in precipitation amounts (Engel, personal communication; "Local Weather Forecast, News and Conditions | Weather Underground," 2022; *Appendix G*) but due to lack of rainfall data these differences can not be quantified without additional precipitation measurements. Even, if precipitation measurements were performed there is a need for historical precipitation data, due to

the high annual and interannual variability. All this results in questioning the validity of the erosivity factor and therefore the outputs of the RUSLE.

Other data that affects validity is the DEM data used for calculation of the LS factor. First, the spatial accuracy of the Improved ASTER DEM has a resolution of 10m with 1m height resolution, which translates to a spatial accuracy of 10%. Moreover, due to the low vertical resolution of the DEM, quantification of the LS factor often resulted in a value of 0, which yielded a potential erosion rate of 0, meaning that more precise DEM would be needed for potential erosion estimates. Finally, there is an error in the DEM, due to the integration of various sources of DEMs used in creating the improved ASTER DEM (Mucher, personal communication, 2022). The error occurs as a line with questionable DEM values that is separating the northern and southern part of the catchment. This limits further analysis such as flow accumulation and puts the validity of the LS factor and the outputs of the RUSLE in question. The low accuracy of the DEM could have also contributed to the lack of correlation between the measured and potential erosion. The values of the potential erosion could deviate up to 10% from the actual values, resulting in a different correlation.

Soil analysis

On Bonaire limited resources are available for soil analysis. Absence of a soil laboratory lead to the use of less accurate methods for analysis of soil properties. Estimation of soil texture using the jar method is prone to biases and human errors as separation between different soil particle layers is often undistinguishable. Moreover, organic matter estimation using a pizza oven with a maximum temperature of 500°C and the short amount of time the samples were drying for could also contribute to inaccuracies of the results. In their study Hoogsteen et al. (2015) have shown that temperatures above 550°C are needed to fully combust the organic matter present in the soil. This could mean that the combustion of organic matter was incomplete, and that organic matter content was overestimated, leading to overestimation of soil erodibility values and potential erosion rates in the catchment.

Model validation and results of the study

One of the main limitations for ground truth validation of the RUSLE model, is that it is not aimed at simulating single events. It is expected to provide potential gross yearly erosion rates, while rainfall simulator refers to net erosion rate for the single rainfall event, making this data hard to compare. Differences in values may be a result of low validity of the measurements, as described in previous paragraphs and/or tendency of erosion measurements being prone to errors (Alewell et al., 2019), but could also be the result of shortcomings of the RUSLE model.

The RUSLE model is limited in only accounting for soil loss through sheet and rill erosion and ignores the effects of gully erosion. As it is unclear how much soil is lost through gully erosion in the catchment it is possible that the annual soil loss in the catchment is higher than estimated. Moreover, RUSLE models predictions will be most accurate for medium-textured soils, slope lengths less than 120 m, gradients between 3% and 18%, and cropping and management systems represented in the erosion studies used to develop the model (Wischmeier and Smith, 1978). Therefore, applying it to conditions, such as the ones in Lac Bay may increase uncertainties. The model also fails to account for important factors that reflect the reality but are not included in the model. For example, soil depth is one that puts the validity of our results in question. Soil depth is a crucial factor when looking at the potential erosion since soil loss can not occur without sufficient soil amounts. Finally, a big limitation of the study is the inability of the RUSLE model to include a sediment transport, delivery, or deposition module. This means that the actu

al amount of surface runoff and sediment that ends up in the Lac Bay is unknown. Finally, as mentioned before the validity of the results is limited by RUSLE models sensitivity to the topological LS factor. LS factor is “in my opinion” often underestimated since the model assigns LS values of 0 where there is no difference in elevation of the surrounding pixels and overestimated in case of the flow accumulation. Consequently, potential erosion is often under and over-estimated.

When using the absolute results of these studies, one should pay attention to the limitations discussed above. Shortcomings of the field work like the unequal distribution of the sampling locations and limitations due to the quality of data, like the quality of the DEM and limited precipitation data and the inherent limitation of the RUSLE model increase the uncertainty of the results. Nevertheless, the simplicity of the model to communicate the findings and transparency and objectivity of the model, can be considered an advantage. Even though, the validity of the absolute potential erosion rates for Bonaire is questionable, the relative rates are important for large scale erosion assessment of Bonaire. The model is good at sufficiently identifying the areas prone to erosion, enabling comparison of different land use scenarios, and planning of the conservation measures.

Therefore, to build upon my findings it is first advised to improve on the quality of existing data and improving the measurements of the current research. First, improving on the understanding of the spatial distribution of precipitation on Bonaire by conducting precipitation research (rain gauges, tipping buckets) in different parts of the catchment for a longer period. Second, a higher quality DEM model of Bonaire is needed to improve the results of this study. For example, using LIDAR to scan the surface of Bonaire would significantly improve the resolution of the current DEMs.

To increase the accuracy of rainfall simulation measurements, in the future I would suggest measuring the soil moisture content with a simple soil moisture sensor and performing a pre-wetting treatment to reach field capacity and account for differences in soil moisture. Moreover, I would suggest using a soil laboratory for soil analysis. Soil texture analysis could be improved by using sieve analysis for larger particles and hydrometer analysis for smaller particles. A laboratory quality oven could be used for better estimation of organic matter content.

Finally, to build on the existing knowledge on rainfall-runoff and erosion relationships, I would advise further studies on surface runoff and groundwater flow, sediment transport, sediment delivery and rate of the sedimentation in the bay. Moreover, monitoring of these parameters over several years and the corresponding health of the mangrove forest could give insight on how such systems react to hydrogeological changes.

V. CONCLUSION

This research was aimed at providing information on the spatial distribution of the rainfall-runoff and erosion relationship in the catchment of Lac Bay and serve as a baseline for mangrove conservation in Lac. Potential erosion rates were estimated using the RUSLE, while surface runoff coefficients were estimated using the mini rainfall simulator. Moreover, the RUSLE model was validated using in-situ erosion measurements from the rainfall simulator, finding no correlation between the data. The median annual potential soil erosion rates were estimated to $19,3 \text{ t ha}^{-1} \text{ year}^{-1}$ with annual soil loss of $41678 \text{ t year}^{-1}$ over the entire catchment. Most of the catchment (51%) has moderate erosion rates ($5\text{--}25 \text{ t ha}^{-1} \text{ year}^{-1}$) and only 5% has severe erosion rates ($>80 \text{ t ha}^{-1} \text{ year}^{-1}$). Similar is observed for the runoff coefficient. The median runoff coefficient was estimated to 0,24 with 76% of the catchment having runoff coefficients between 0,16 and 0,33.

It can be concluded that the spatial variation in the potential erosion rates and surface runoff coefficient is rather homogeneous. This creates a complicated environment for conservation since there are no distinct erosion prone areas where measures could be implemented but calls for catchment wide conservation. Reduced grazing is one such measure that could reduce the annual soil loss by up 5%. Moreover, sedimentation could be tackled at the point of deposition using structural measures, such as earthen dams and sediment traps. Such measures, however, could reduce the freshwater inflow to the bay and furtherly increasing the salinity concentration.

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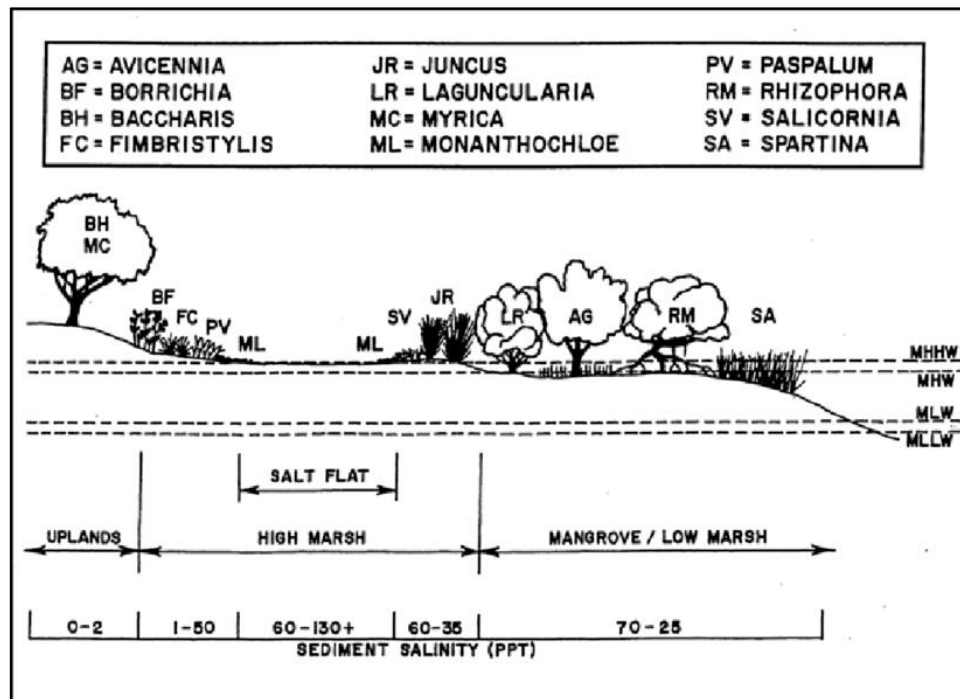
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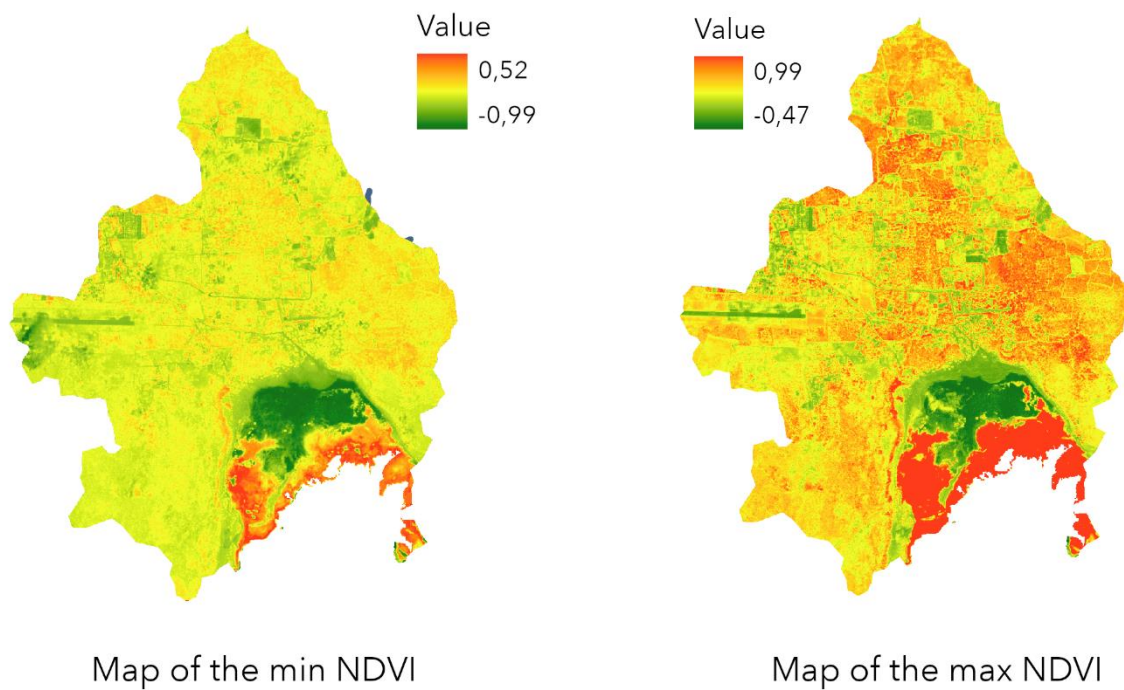
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Appendix A- Zonation diagram of the mangrove ecosystem of Lac Bay. Retrieved from Debrot et al. (2010).



Appendix B- Minimum and maximum NDVI values retrieved from the satellite imagery from the period between



Map of the min NDVI

Map of the max NDVI

Materials:

- 10 L water
- Portable rainfall simulator
- TDR – Stopwatch
- Small shovel
- Spirit level
- Knife
- Folding ruler
- Funnel
- Notebook and pencil

Rainfall simulator set up and simulation.

1. Installation of the ground frame using the four nails (A).
2. Trench is dug under the frame for the collection box (A).
3. Gutter is installed (A).
4. Installation of the adjustable support on the ground frame. Frame is levelled using a level and four knobs (B).
5. Aeration pipe is closed with a plug.
6. The sprinkler is placed upside down on the support to fill it with water (C).
7. Plug is removed and water from the tank is filled in the sprinkler using a funnel (C).
8. Sprinkler is placed on the support and rainfall intensity is adjusted using the aeration pipe. Rainfall intensity should always be calibrated and tested to achieve the 375 ml/min (D).
9. Water level in the reservoir is noted (D).
10. Stopwatch is tested and reset.
11. The plug from the aeration pipe is removed and the simulation starts. Simultaneously the stopwatch is started.
12. Every 30 seconds the water level in the reservoir is noted and the collection cup is replaced.
13. After three minutes, the simulation is stopped by placing the plug back on the aeration pipe. The water level is noted and the amount of water in each collection cup is measured. Water and sediment is stored in a collection container (E).
14. Rainfall simulator and other material is cleaned and stored in the box (E).
15. Samples are air dried and sediment is weighted (F).

A



B



C



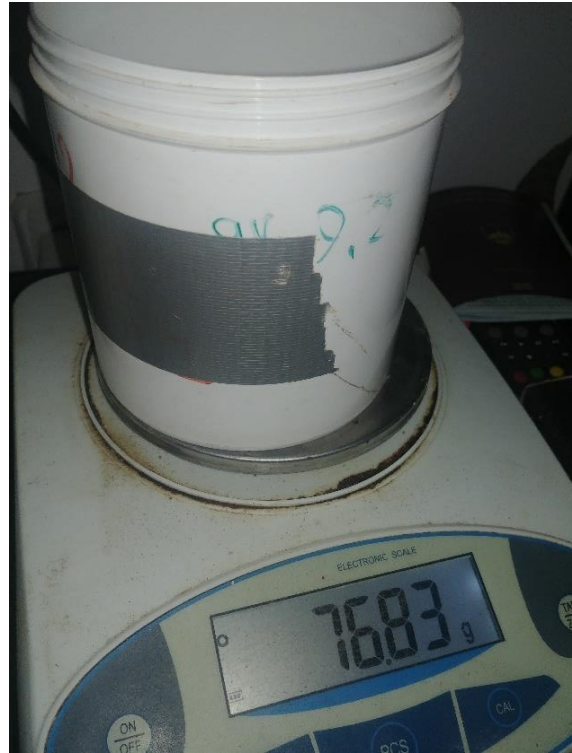
D



E

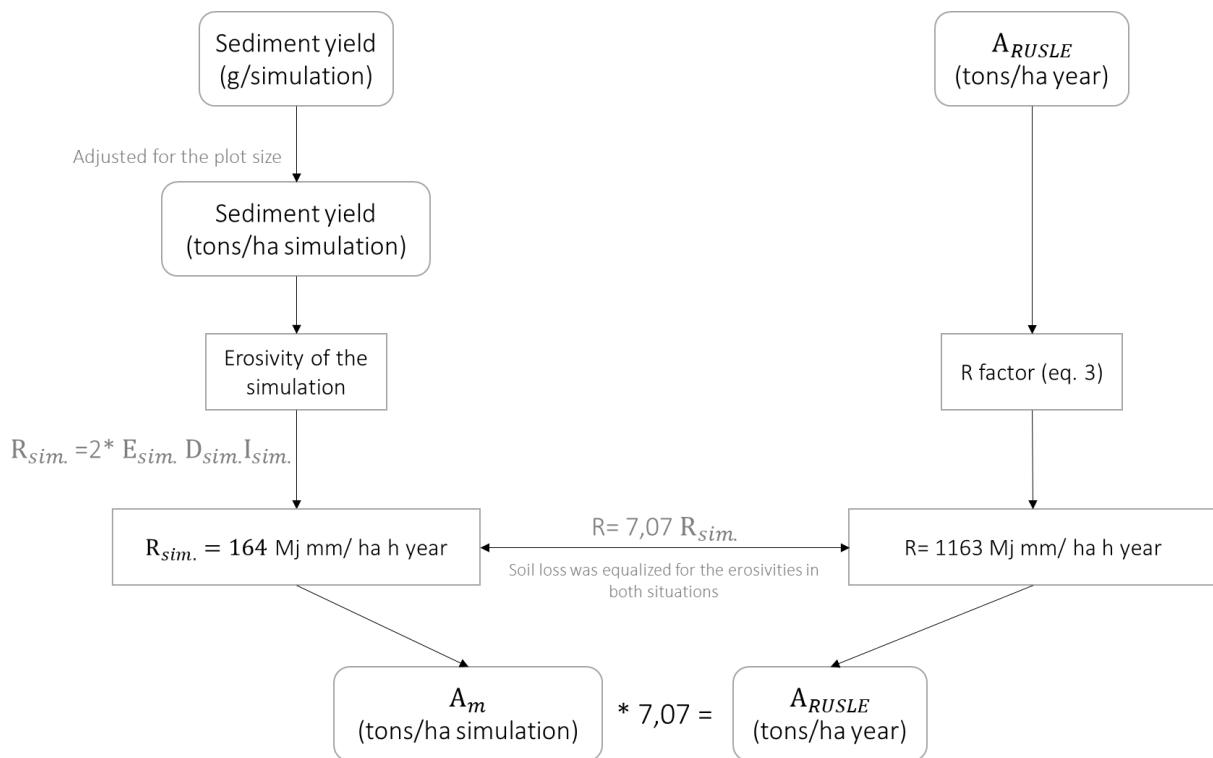


F



Appendix D- Sediment yield data from rainfall simulations was adjusted for the plot size and compared to the point values extracted from the potential erosion map. The adjusted sediment yield data were also adjusted for the erosivity of the event by factor 7,08.

BJECTID	Name	Sediment yield (g/simulaton)	Am (Tons/ha 3 min)	A_RUSLE(tons/ha*Year)	R_measured	R_RUSLE	R_m:R_rusle
1	A9_02	6,10	6,91	5,62	164,34	1163,00	7,08
2	A9_01	14,71	16,66	8,14	164,34	1163,00	7,08
3	A5_03	24,84	28,13	33,39	164,34	1163,00	7,08
4	A5_02	0,00	0,00	6,95	164,34	1163,00	7,08
5	A5_01	4,95	5,60	0,00	164,34	1163,00	7,08
6	A6_02	9,57	10,84	9,21	164,34	1163,00	7,08
7	A8_08	14,17	16,04	49,36	164,34	1163,00	7,08
8	A4_07	9,67	10,95	0,00	164,34	1163,00	7,08
9	A4_06	6,15	6,96	21,54	164,34	1163,00	7,08
10	A4_08	21,65	24,51	24,62	164,34	1163,00	7,08
11	A3_06	6,30	7,13	0,00	164,34	1163,00	7,08
12	A3_05	10,06	11,39	34,09	164,34	1163,00	7,08
13	A8_07	11,81	13,37	0,00	164,34	1163,00	7,08
14	A8_06	8,41	9,52	4,23	164,34	1163,00	7,08
15	A3_03	6,71	7,60	0,00	164,34	1163,00	7,08
16	A8_05	20,82	23,57	17,01	164,34	1163,00	7,08
17	A3_01	8,38	9,49	0,00	164,34	1163,00	7,08
18	A7_02	6,98	7,90	13,28	164,34	1163,00	7,08
19	A7_01	0,00	0,00	66,62	164,34	1163,00	7,08
20	A8_01	7,73	8,75	9,50	164,34	1163,00	7,08
21	A4_05	17,21	19,49	0,00	164,34	1163,00	7,08
22	A4_04	0,00	0,00	8,98	164,34	1163,00	7,08
23	A4_03	13,43	15,21	31,63	164,34	1163,00	7,08
24	A4_02	5,20	5,89	68,22	164,34	1163,00	7,08
25	A4_01	1,97	2,23	6,31	164,34	1163,00	7,08
26	A10_06	14,45	16,36	0,00	164,34	1163,00	7,08
27	A10_05	4,69	5,31	0,05	164,34	1163,00	7,08
28	A10_04	24,97	28,27	12,81	164,34	1163,00	7,08
29	A3_02	18,84	21,33	239,22	164,34	1163,00	7,08
30	A10_03	8,86	10,03	14,44	164,34	1163,00	7,08
31	A10_02	0,35	0,40	8,06	164,34	1163,00	7,08
32	A10_01	7,38	8,36	25,67	164,34	1163,00	7,08
33	A8_02	1,25	1,42	6,01	164,34	1163,00	7,08
34	A2_04	6,16	6,97	12,36	164,34	1163,00	7,08
35	A2_03	7,71	8,73	11,94	164,34	1163,00	7,08
36	A2_02	40,52	45,88	0,00	164,34	1163,00	7,08
37	A2_01	2,61	2,96		164,34	1163,00	7,08
38	A6_01	22,32	25,27	18,06	164,34	1163,00	7,08
39	A8_04	12,52	14,18	4,75	164,34	1163,00	7,08
40	A7_03	2,63	2,98	10,08	164,34	1163,00	7,08
41	A8_03	4,65	5,26	6,06	164,34	1163,00	7,08



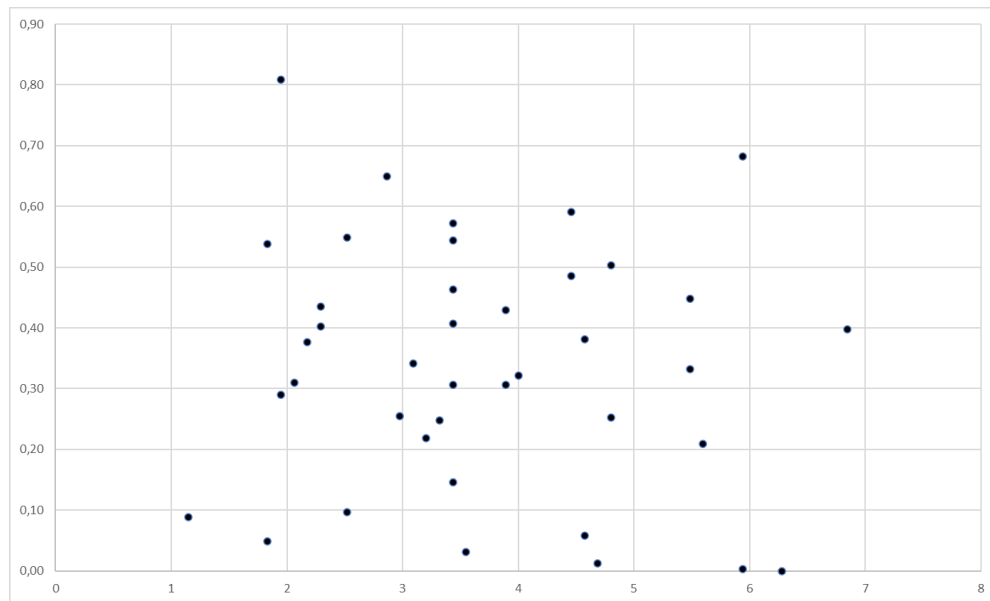
$$R_{sim.} = 2 * E_{sim.} D_{sim.} I_{sim.}$$

$E_{sim.}$ = kinetic energy of the event

$D_{sim.}$ = duration of the event

$I_{sim.}$ = rainfall intensity of the event

Appendix E- Absence of correlation between the surface runoff depth and the slope on which rainfall simulations were performed.



Appendix F – The reforestation areas of San Jose and Fofoti, north of Lac Bay.



Appendix G – Precipitation amount on 4 different location on Bonaire. Variation in monthly precipitation amounts can be observed. Retrieved from (“Local Weather Forecast, News and Conditions | Weather Underground,” 2022)

Precipitation amount 2022 (ml)				
	Cadushy Distillery Rincon	Nikiboko	Oranje Pad	Belnem
January	17	34	/	26
February	30	33	/	96
March	43	42	/	106
April	33	80	/	74
May	2	/	5	13
June	81	/	65	145
July	24	/	32	61
August	58	/	39	41