EROSION AROUND KRALENDIJK, BONAIRE

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Fig. 1: Saliña di Vlijt, Kaya Amsterdam, Klein Bonaire 2017. (Photo by N. Roos)

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Abstract

On Bonaire, special municipality of the Netherlands, there is a big problem with erosion. In and around the capital Kralendijk, most areas have sparse vegetation and/or are paved. Intense rainfall events (such as those occurring on Bonaire) can loosen the soil material, after which it is transported away towards the ocean by (rain)water flowing over the surface (Koster, 2013). Not only causes this a loss of fertile soil, it also has consequences for aquatic life and plants along the coast, such as the coral reefs of Bonaire and the species which depend on them (Bak et al, 2005).

An erosion (hotspot) map could be a start to determine why, where and how action could be taken to reduce erosion and gives input for the type of measure that may be suited for such an area.

Using the model of Borselli, an hotspot map reckoning factors such as hydrologic and soil properties, land use, landcover and connectivity is created. Critical erosion areas (including urban/paved areas) are now imaged and measures can be undertaken or improved to enhance erosion management.

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1 Introduction

1.1 Background

Bonaire is an Island located North of Venezuela. It is part of the Lesser Antilles and a special municipality of the Netherlands. The capital of Bonaire is Kralendijk and is the most populated area of the Island (§2.1). Tourists attractions are mainly situated in and around this city.

A combination of natural and anthropogenic factors (Bak et al, 2005) causes large percentages of rainfall to run off as surface runoff (L. Borst and S.A. de Haas, 2005). The clayey top soil, (low)vegetation cover and intense rainfall contribute to low infiltration rates (J.H. Gregory, M.D. Dukes, P.H. Jones, and G.L. Miller, (2006). Also, lack of spatial planning and low capacity of the current (urban)drainage system in Kralendijk, means this storm water runoff causes floods (L.Hoang & R.A. Fenner (2015), R. C. AGNIHOTRI & R. C. YADAV (1995)).

Large amounts of surface runoff together with low vegetation are probably a cause of high erosion rates (R. C. AGNIHOTRI & R. C. YADAV (1995). Another problem associated with the deposition of eroded sediments are the coral reefs (L.Borst and S.A. de Haas, 2005). During the last 40 years, coral colonies along the coast of Bonaire have been decreasing in numbers fast (DCNA.org. Status of Bonaire coral reef (2017)).

1.2 Problem statement

Research done on rainfall-runoff relationships show that an increase in surface runoff is a problem in many catchments around the world (Foley et al., 2005)[1]. The main reasons for this increase are anthropogenic activities such as deforestation, overgrazing and urbanization.
Decrease in vegetation cover often leads to a decrease in interception and a change of the soil structure (Feng Qian, Dongbing Cheng and Jingjun Liu, (2014)). These factors reduce infiltration capacity and urbanization leads to an increase in the impermeable surface area. In arid and semi-arid areas the vegetation is naturally low while rainfall events can be intense (Ieke Wulan Ayu, Sugeng Prijono, Soemarno (2013)). Areas that are mainly used for urban, agriculture or natural vegetation, could see an increase in erosion due to increased surface runoff (R. C. Agnihotri & R. C. Yadav (1995)). The clearest effect of erosion is possibly the loss of soil nutrients. The reduction of the water holding capacity/potential of the soil is another huge effect caused by the removal of organic matter and finer soil particles (Jagdale Satyawan Dagadu1 , Nimbalkar P. T. (2012)) Thinning of the top soil also means that the rooting depth of vegetation and crops become limited (Foley, (2005)). Sedimentation is one of the two main causes that affect coral reefs (Koster, 2013). The first one being (long-therm) temperature rise (Bak et al, 2005). And sedimentation, on land is often prosperous (Koster, (2013)). However, fine sediment entering the nearshore ocean during runoff events affect coral colonies in two ways: The main problem with sedimentation in water bodies is the increase in turbidity. Turbidity reduces the amount of light that reaches lower water depths (Bolton, (2001)). This can have consequences for aquatic life and plants and therefore also for the species which are dependent upon them (Bolton, (2001)). Secondly as the sediment settles, it causes corals to expend a large amount of energy keeping their surfaces clean or it can bury corals (Boer, Dirk de, (2012)). These effects are seen to be a very serious threat for coral reefs located near Bonaire (L.Borst and S.A. de Haas, 2005). An increase in precipitation means more runoff. More runoff means less water infiltrates into the soil (October 1954, K.G. Reinhart and R.E. Taylor). A decrease in infiltration leads to less percolation and therefore also to a decrease in aquifer recharge. Agricultural and vegetated areas

[1] Foley, et al. 2005. Global Consequences of Land Use

will become less resistant to droughts as the soil retains less soil moisture after rainfall events (Foley et al. (2005)).

1.3 Goal

The aim of this research is to map different land types in and around Kralendijk and to determine the most important soil and hydrologic characteristics of these land types. From this, a hotspot map indicating which areas probably constitute most to the erosion is developed.
This project is a start to determine where action could be taken to reduce erosion and gives input for the type of measure that may be suited for such an area. Over the next two years, more students from universities of Amsterdam will come to Bonaire to investigate concrete measures to reduce erosion.

Overall research question: What are the soil and hydrologic characteristics in the Kralendijk catchment(s) and where are hotspots of erosion located?

The research is divided into sub-questions to answer the main question addressed above. The sub-questions are:

1. What type of regions can be distinguised in the Kralendijk catchment? [gis analyse in advance]
2. What are the soil properties in these areas? [Fieldwork]
3. What are the hydrologic properties in these areas? [Fieldwork]
4. Is there a correlation between discharge of water to sea and erosion hotspots in the Kralendijk catchment? [Fieldwork]
5. Where are the hotspot areas in terms of erosion, which contribute much sediment [Borselli-method[
6. What kind of measures can be taken in these hotspot areas? [Literature]

2 Study area and previous research

2.1 Study area

The island Bonaire is situated in the Caribbean, North of Venezuela. Bonaire is a part of the ABC (Aruba, Curacao and Bonaire) Island group, also known as the Lesser Antilles. The Island covers an area of approximately 291 km2 and has nowadays around 17000 inhabitants (CBS.nl), mainly situated in the two largest cities: the capital Kralendijk and Rincon. The elevation on the Island varies from 216 meter above sea-level in the north at Mt. Brandaris to 25 meters in the south (and outer parts of the Island (fig. 2.1 DEM)).

The (hydro)geology (fig. 2.2) of this Caribbean Island consists mainly out of two types: the first being volcanic Cretaceous (145-65 Ma B.C.) (faulted rock) dolomite in the centre and western part of the island and the second being karstified limestone (Quaternary (1.8 Ma B.C.)(Hobbelt, 2014).

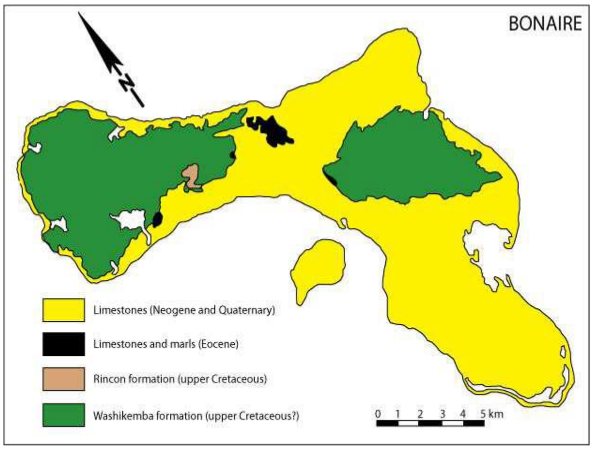


Fig. 2.2: Hydrogeology of the Island Bonaire (Hobbeltin, 2014)

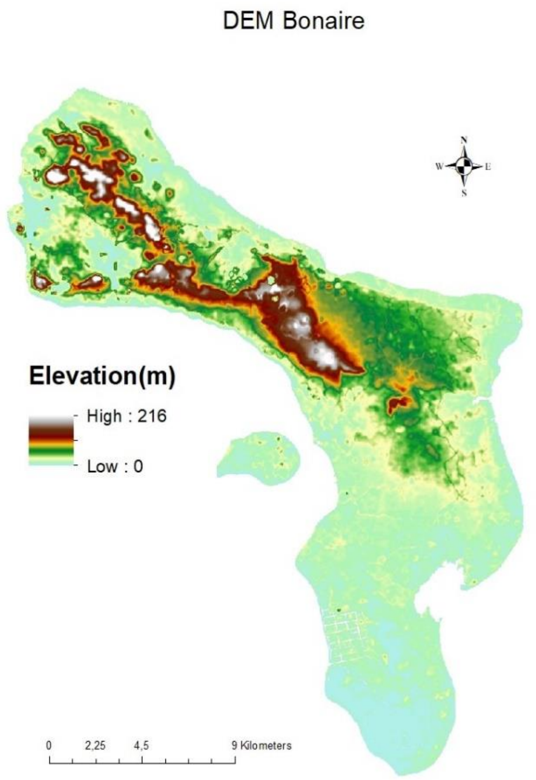


Fig. 2.1: Digital elevation map (DEM) Bonaire. Verweij, Peter (2014) dcbd.nl

Furthermore, Bonaire has a steppe climate (semi-arid) and an average rainfall of 470 mm/yr, mostly falling in the period from October- January. In 2005, Borst and De Haas formed a water-balance of the Island Bonaire. An averaged five percent of the total annual precipitation of 470 mm (135 million m3/year) recharges groundwater. With a potential evaporation of 2600 mm and an actual evaporation of 400 mm (115 million m3/year), an average of ten percent of the total annual precipitation runs off towards sea. Nothing can grow on the island itself because it is to dry.Rainfall water is the only fresh water source. Most of the rainfall water that reaches the surface evaporates before it can infiltrate into the soil. Therefore only plant species that have adapted to low water availability survive here.

Nowadays there are around 500 different species on Bonaire, with the cactus being the most diverse. Cactuses are well represented in Bonaire. They occur in various species and sizes. The two main species that occur the most in this research area are the boll(sphere) and tree cactus. The 'boll' cactuses has large red/blackish spines and fulfill a permanent roll concerning the characteristic landscape. Cactuses have the ability to store large amounts of water, what makes them able to sustain during a dry period.

Fauna has a large influence on Bonaire (Hobbeltin, (2014). Especially related to erosion and the extermination of plant species/vegetation. On the island a large community of wild goats, sheeps and donkeys become a problem. Although people are used to the animals and cope with them, the animals have a large stomach. This means they will eat anything on their path.
This causes the extermination of endangered plant species. Young plants do not get the chance to reach full growth causing large areas to become bare/erosive land. As a result (together with rainfall) the upper layer of the soil, which is the most organic part, flows into the Saliñas by erosion during the rainy season.

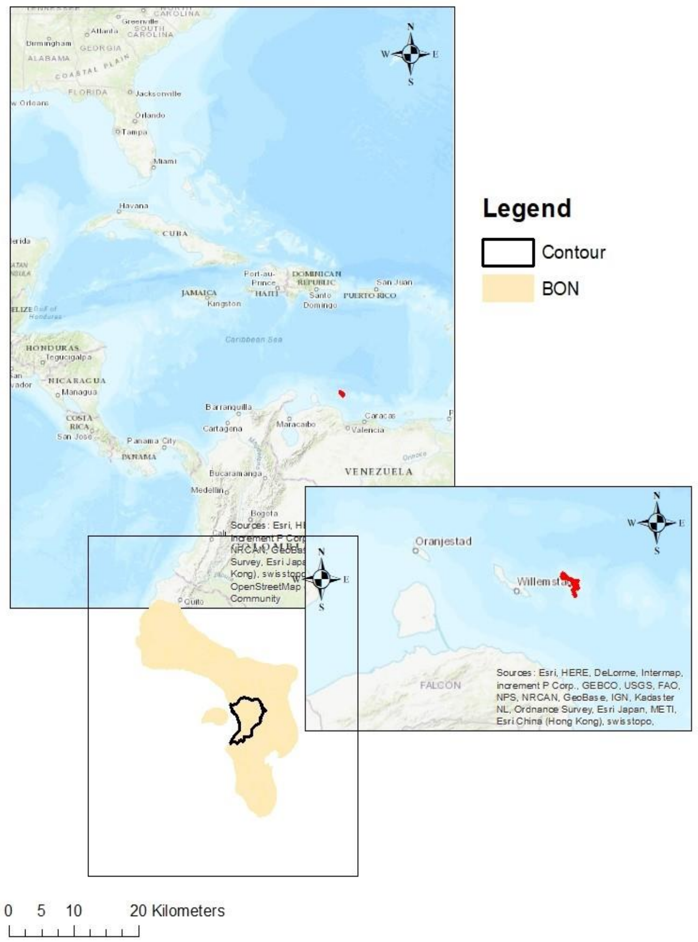


Fig. 2.3: Study area: Kralendijk catchment

The study area itself is located in and around the Capital, Kralendijk. The study area (fig. 2.3) covers approximately an area of 2084 ha and is situated in the middle part of the Island Bonaire. The whole catchment could be divided into two large parts being the western part mostly urban (Kralendijk) and the eastern part rangeland with moderate to light shrub-lands. These lands are grazed by goats and donkeys. The difference in elevation varies from 80 meters above sea-level (north-east) to sea-level.

The catchment drains towards the ocean on the west side of the island.

In this research two more sub-catchments have been added when compared to the study of Koster (2013), to cover a larger area around 'Kralendijk'. This because an important impact of soil erosion is on coral reefs (status of Bonaire coral reef, dcnanature.org (2017)), therefore two sub-catchments at '5' and '6' (fig. 2.4) have been added as they also drain into the sea on the west of Kralendijk. In this research, all these sub-catchments combined are referred to as the Kralendijk catchment.

The Kralendijk catchment is divided into six large sub-catchments (fig. 2.4). The first sub-catchment (green coloured) is also the largest sub-catchment. This is a catchment area with a lot of variations in elevation. The water in this area is not stored but discharged through the outlet to the south of this catchment (fig. 2.5 & 2.6). This sub-catchment contains several reservoirs that are important for sediment deposition but water is not stored (Koster, 2013).

Sub-catchment two is a small catchment that mainly consists of drains in the centre of Kralendijk (Koster, Geert 2013). It is situated near the stadium and ends around the hospital.

Sub-catchment three is actually based on elevation in Kralendijk (Koster, Geert 2013). From the Kaya Grandu there is a relatively steep decline towards the ocean. There are also many drains present in this area draining water (fast) towards sea.

The fourth sub-catchment (Koster, Geert 2013) is situated in the southern part of Kralendijk and is bordered by the Merriot Courtyard complex (fig. 2.4).

Several Salinas present in the western part of sub- catchments four and five influence the flow of water. *A Saliña is a flat area where water is easily is collected. In the Saliña several coral dams were built to maintain water.* In sub-catchment five, most of the water reaches the ocean through the outlet at the Merriot complex (fig. 2.6). The borders of this catchment are based on elevation levels towards the ocean. Although the ocean is the lowest point, it is reached by water that flows from the landing strip of the airport, situated south of the Merriot complex. The landing strip is the lowest point of the catchment.

Sub-catchment six is more complicated. This catchment is an area where a lot of water can flow from higher levels into the Saliña di Vlijt. Saliña di Vlijt is on of the largest salt buffers and very important for holding sediments mixed in (rain)water. The surrounding area is higher in all directions which means water, due to formed streams, flows into this Saliña (fig. 2.5, blue line indicates Saliña di Vlijt).

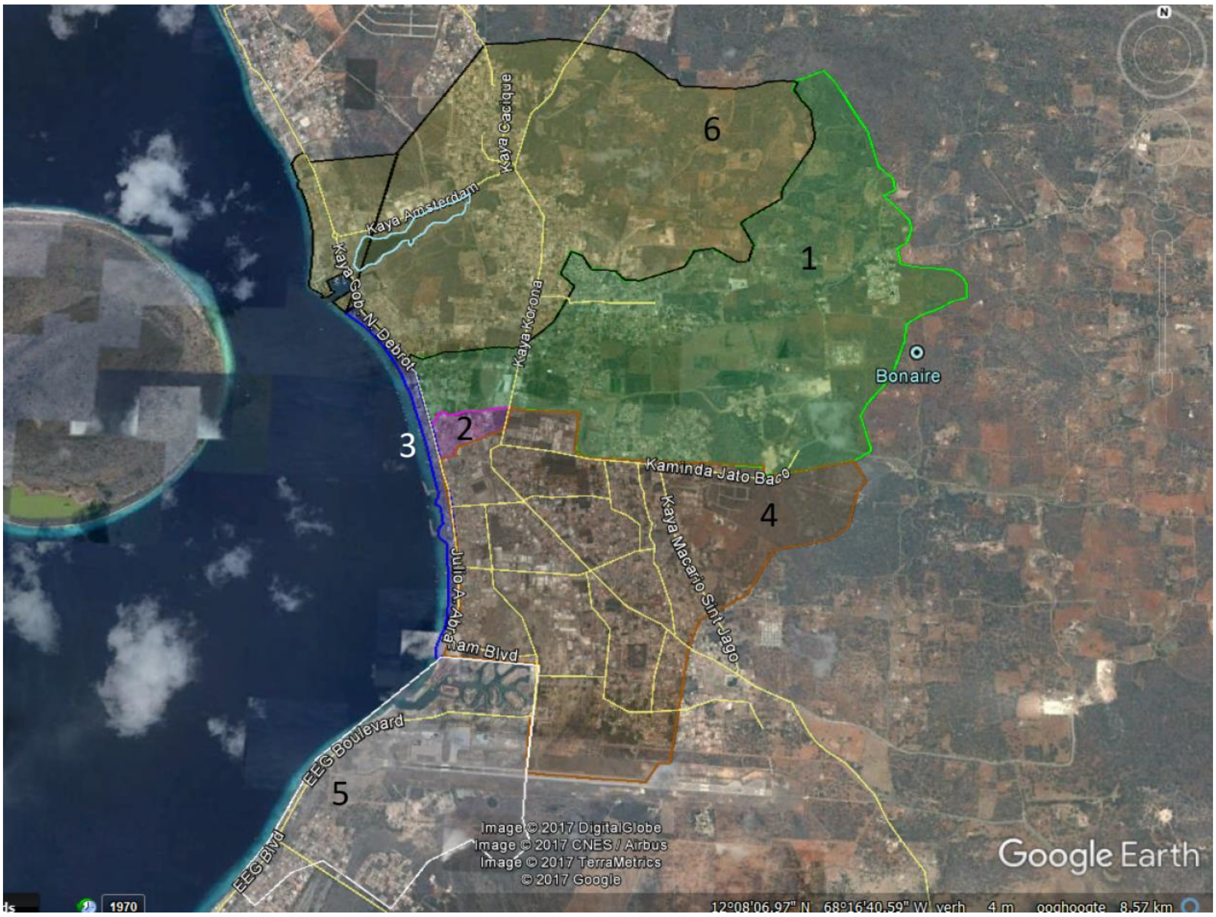


Fig. 2.4: Sub-Catchments in Kralendijk Catchment, Bonaire (Google Earth, 2017). Catchments 1-4 Koster, Geert (2013). The blue encircles the Saliña di Vlijt in northern Kralendijk.

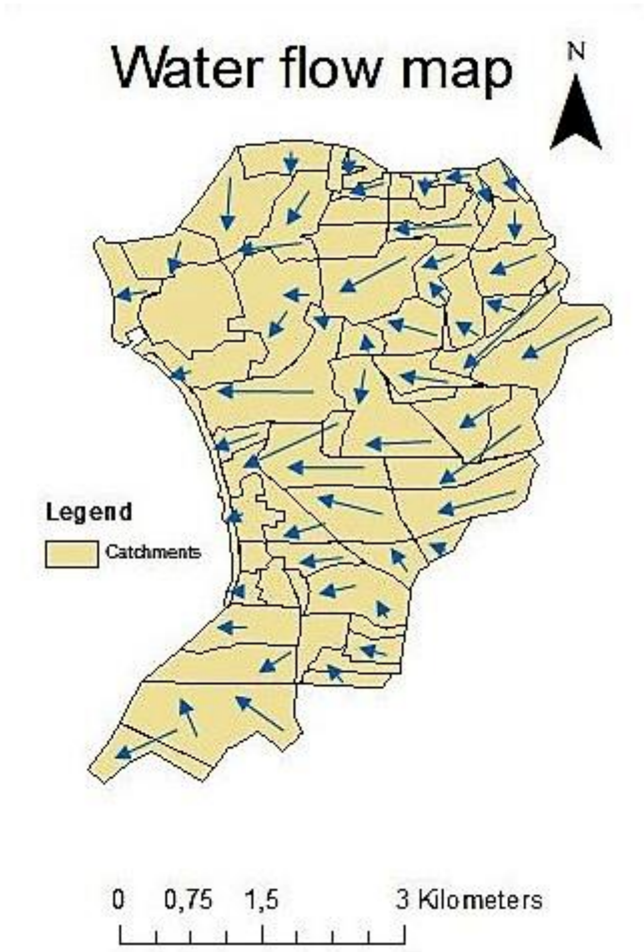


Fig. 2.5: Water flow/catchment map

2.2 Previous research

Research on Bonaire is important to understand the situation as it is. To start a research project, some basic knowledge and previous research on the Island is necessary.
For starters, (geo)hydrological research (Borst and Haas (2005)) helped to understand the water balance of the whole Island (Input, output. evaporation, recharge and leakage included) and a geological description of the formation/creation of Bonaire. Their aim was to store water on the Island (in for example dams or basins) to reduce the transport of sediment towards the reefs, which is similar to this research. Borst and Haas formed a water-balance of the whole Island (that is shortly discussed in (§2.1)), while other research (Hobbeltin, (2014)) focuses more on the dynamics between fresh water fluxes, vegetation and sediment transport. The most important foundings used in this research are for example, the expectation that rain falls in short duration showers with high intensities during rain events with high intensities cannot be proven. Around 2% of the rainfall was transported by surface runoff towards the mangroves in both catchments. This means runoff brought a minor quantity of fresh water to Lac Bay during the research period (October-January 2012).

Low sediment amounts (0.1 m3) are transported into the mangrove system, associated with the low runoff amounts. Surface runoff occurred due to (rain) events that exceed the infiltration capacity. This precipitation sum had a less than 30 year average. In relatively wet periods, the soil profile can be wet prior to rain events that cause saturation and runoff during small events. This means more fresh water will runoff due to higher rainfall amounts, but it will also response faster to relatively low rainfall intensity events.

Extreme rainfall sums might have caused extreme sediment load transports towards the mangrove system. Along with the deterioration of the channels and water circulation, this might causes root smothering and mangrove die off. This 'mangrove die off', is probably strengthened by a dry period with less fresh water transport by surface runoff towards the mangrove system which enhances saline waters in the back of the system.

Significant amount of water is stored behind a dam. This dam overlaps both catchment 1 and 2 in the research area (Hobbeltin, 2014). Removal of dams would cause an increase in surface runoff towards the magrove system. Approximately 2/3 of the water stored behind the dam will infiltrate and, depending on the direction of the groundwaterflow, flow towards the mangrove system.

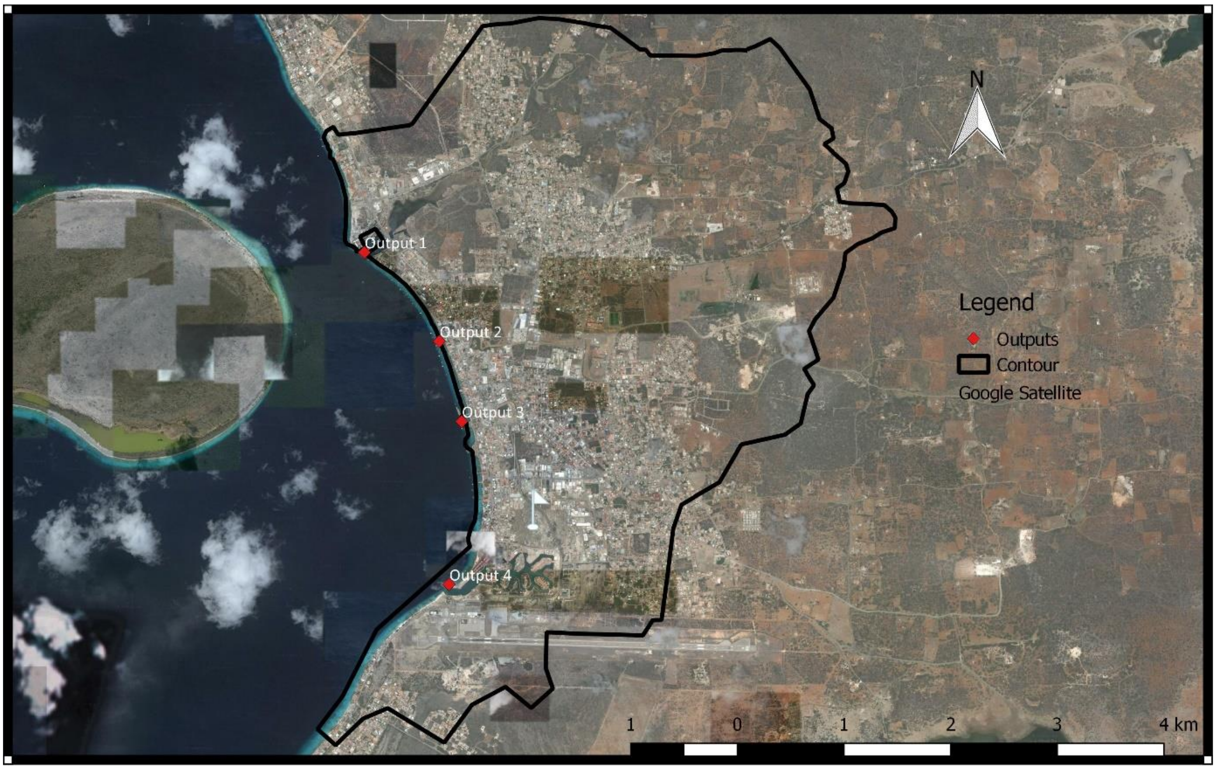
This project serves as a good first impression of the effects that rain events (fresh water fluxes), deterioration of vegetation, fauna and associated sediment transport in combination with the hydrogeology could have on Bonaire. However, this research is more or less focused on the southern part of the Island.

Together with information gathered from studies mentioned above, catchment based research in the capital Kralendijk had been done in 2013 (Koster, (2013)).

This is a case study in the Playa catchment situated in Kralendijk, Bonaire. His research used a spatially event-based distributed erosion and runoff model named Kineros2. Kineros2 is used to map sources and routing of runoff and sediment. Together with factors such as: rainfall intensity, vegeation cover, rainfall duration and soil moisture content, several managemant scenarios were simulated to come up with multiple measures.

In central Kralendijk, large amounts of surface runoff are both produced in the most densely paved areas and in the uplands due to relatively steep slopes. Slope steepness mainly affects erodibility and causes soil loss in (steep) shrub lands to the East.
While comparing rainfall duration and intensity data, it is found that intensity had large effect on runoff and more so on erosion. If a soil is initially moist, the runoff and soil loss increases. Most rainfall events fall when soils are relatively dry. However, Vegetation cover doesn't have a great impact on surface runoff as aspected. Vegetation cover plays a greater roll in erosion rates. In areas with less to none vegetation, erosion rates are larger.

Concerning the sediment budget, the high simulated trapping efficiency of the reservoirs up in the catchment (85-99%) is striking. The Saliña (fig. 2.6) in front of the outlet of sub-catchment 4 (fig. 2.4) has an even higher efficiency of 99%. This, because the Salina agrees with conditions such as large area, shallow dept and an abrupt change in slope (Brune, 1953).
Outlet 1 (fig. 2.6) is the main source of the sediment load towards the ocean. Interestingly, most of the sediment does not come from the eroded uplands but from the area that it drains near the coast. The composition of sediment from outlet 1 and 4 (fig. 2.6) differs. Discharge of outlet 1 contains more fine sand particles than the discharge of outlet 4. These are sediments with a high settling velocity and therefore will easily be trapped by any reservoir.



Outputs/Outlets

Fig. 2.6: Outlets catchment. The outlets are numbered from 1 to 4. Outlet 1 is the harbor, 2 & 3 are situated in front of the boulevard and output 4 is created together with the Merriot Complex. The white flag above the Merriot Complex indicates the Saliña in front of the outlet in sub-catchment 4.

Even though (often) soil loss come from the (upland) planes, most soil loss is discharged through channels and gullies. Channel and gully erosion is the main source of soil loss in catchments where channelling occurs (Osborn and Simanton, (1989), Prosser et al (2001)). An option to reduce channel and gully erosion is to stabilisize both walls and floors of channels and gullies. To allow infiltration, retain soil, halt further erosion and enhance further deposition. Planting vegetation would help (Moline et al (2009)).

Koster, 2013 was one of the first studies that actually did research to the effects and relation between runoff, erosion and sediment flow towards thesea and it applied as an inspiration for the current more extensive research.

3 Methodology

The methodology used for this research is explained in the flow diagram below (fig. 3.1). At first, LandSat remote sensing data from USGS (U.S. geology Survey Earth Explorer) was used in QGIS to classify the research area in several (unsupervised) land use types (April, 2017).

During the actual fieldwork on Bonaire (May-July), together with assisting literature (Koster, Geert 2013), the unsupervised landuse classes were classified into supervised landuse classes as imaged in table 1.

The components (fig. 3.1) consist of several (field) methods that are used in conjunction with nine land uses (§3.1). By sampling (§3.1), soil and hydrological properties are determined. Dry/wet weighing, vegetation records and sampling soil were done on site, while the sampled soil aggregates were saved for accurate measurements (water-drop method, TGA and Grain size) in lab spaces at both the VU and UvA.

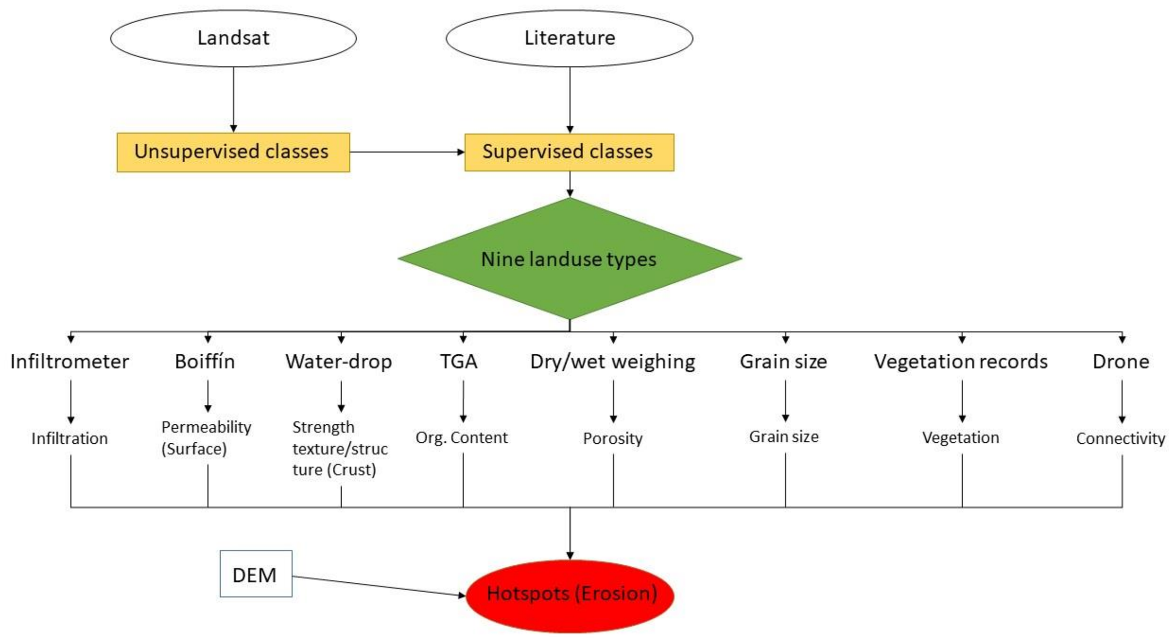


Fig. 3.1: Flow diagram of erosion research

3.1 Land use types

According to Koster (2013), nine types of land use can be identified in the research area (fig. 2.3): (mainly) Urban, green urban, bare land, agricultural land, vegetation and rangeland (table 1). The Rangeland landuse classes are separated into a medium and light (vegetation cover)classes to get a better impression in the difference in landcover. The area mainly consists out of urban/bare land and rangeland landuse classes, though the other landuse classes were also located.

Table 1: LU (Landuse classes)

Main LU (unsupervised)	Supervised LU classes	Code
Urban/green urban	Urban/living areas(buildings)	C1
	Bare land	C2
Vegetation/shrubs	Dense Shrubbery	C3
	Medium Shrubbery	C4
	Light Shrubbery	C5
Agricultural land/Cultivated land/meadow	Dense grass	C6
	Rangeland (medium cover)	C7
	Rangeland (light cover)	C8
	Agricultural field	C9
	Saliñas	C10

The whole project area is divided into six large sub-catchments, which are further explained in §2.1, based on elevation. Along with the nine landuse types (table 1), multiple (field)methods are applied to gather useful data.

In image 3.2, the numbers represent sub-catchments ranged from one to six. Each colored square stands for a method applied in that specific sub-catchment. Beige stands for soil aggregate sampling, brown for soil bags sampling, green for vegetation records, blue for the Boiffin method, light blue for the infiltrometer test and (broken) white pencils connectivity research by drone (also portrayed in legend fig. 3.2). It was not possible to do apply all methods in each sub-catchment. Some areas in sub-catchments 2, 3 and 5 are not accessible and/or suited. Both sub-catchments 2 and 3 are situated in or close to central Kralendijk. This means a high quantity of paved areas and not suited for methods such as Boiffin or Infiltrometer.

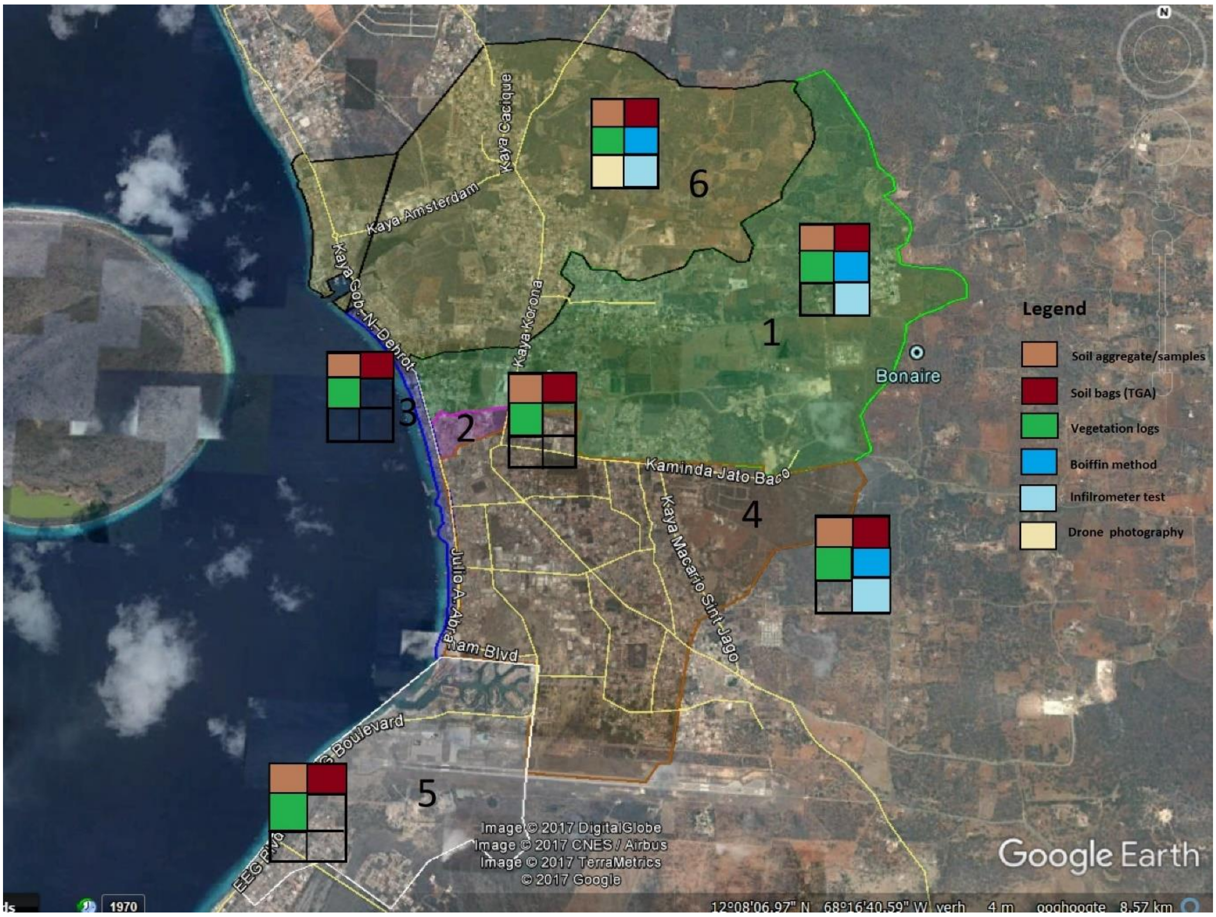


Fig. 3.2: Methods applied in each specific sub-catchment.

The information/results gathered from these methods (fig. 3.1 & 3.2) were combined, together with a 1 arc resolution SRTM (Shuttle Radiation Topography Map) of Bonaire, to create a final (Hotspot) erosion map agreeing with the Borselli method (Borselli, 2008).

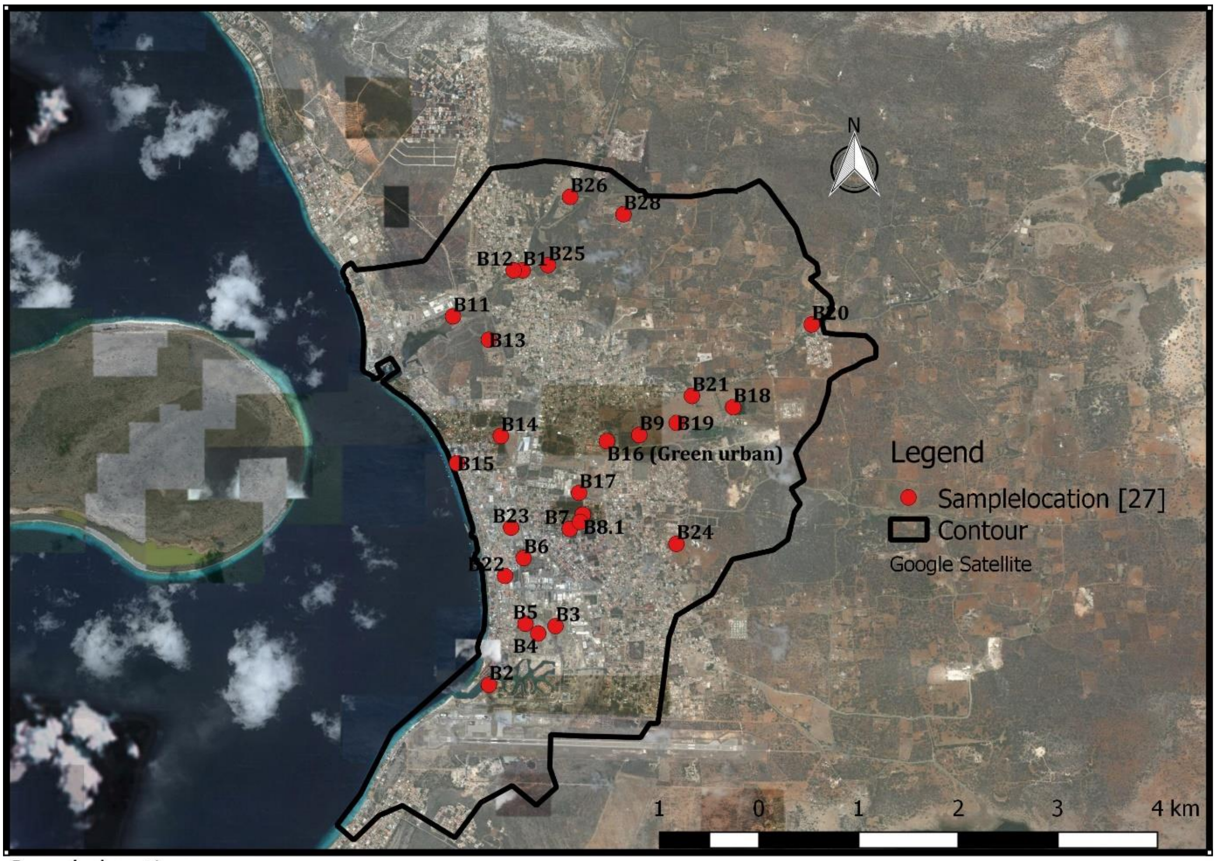


Fig. 3.3: Soil aggregate locations research area

The soil and hydrological characteristics of different land types are determined by soil sampling at multiple sites. Soil (aggregate) locations (fig 3.3) are based on soil type, location and landuse, instead of a geographically correct dispersion as in (Koster, geert (2013)). The red dots represent the sampling locations. Each site has been given a code ranging from B1-B28. The sampling of aggregates was a succes. However, I would have taken more samples but at some (interesting) sites/locations it was not aloud to take samples or not accessible.

At each location (fig. 3.3) soil aggregates and soil material (in a soil bag) was collected, soil and hydrologic properties determined while the environment and vegetation were described.
For the sampling of soil aggregates (fig. 3.4) and material a garden shuffle was used. Further important information such as the envirionment, particularities and landcover were noted in a field book.

Fig. 3.4: Sample at location B8.2

3.2 Infiltrometer-test

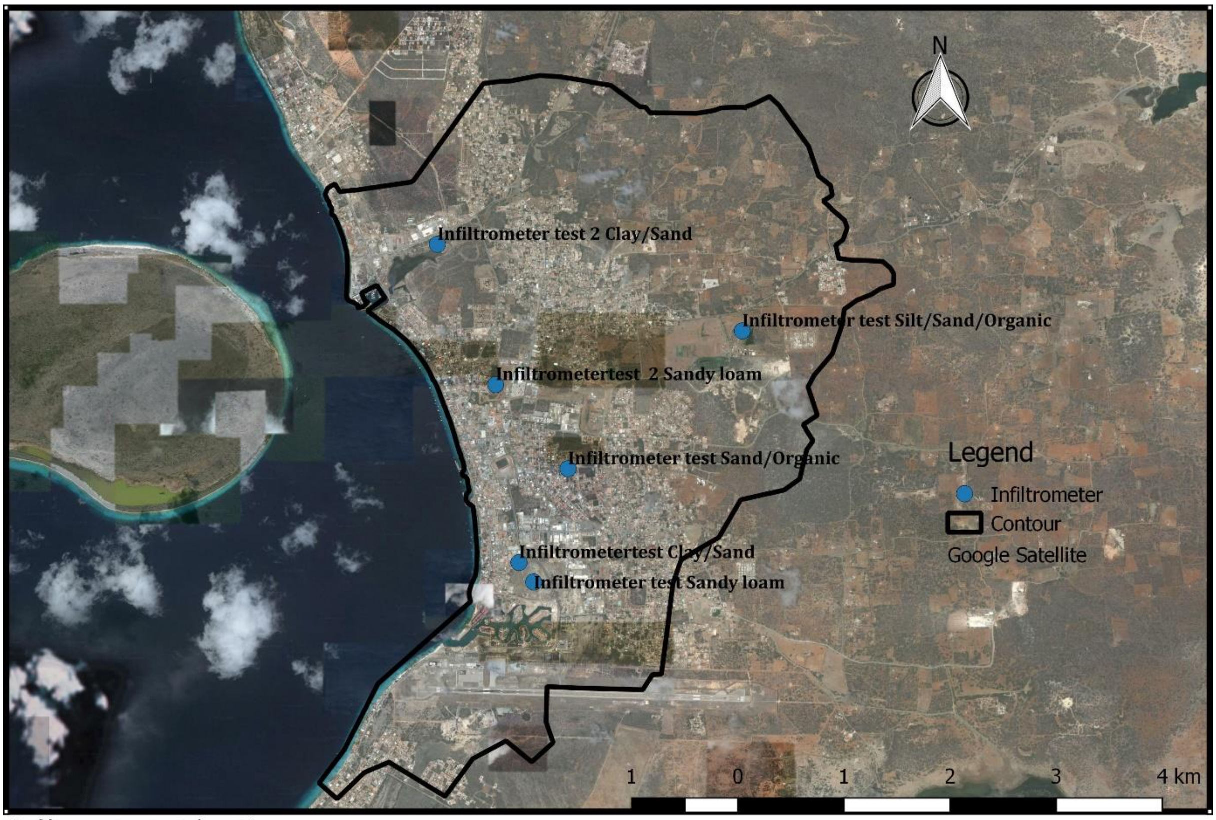


Fig. 3.5: Infiltrometer test locations

Fig. 3.6: Infiltrometer (double) ring. Infiltrometer specifications:Diameter: 0.15m. Surface area: Πr^2: 0.0176m2. Content: 1L = 0.001 m3. Source: Jenny, L.K. Vestin et al. 2009.

The Infiltrometer (double) ring is mainly used to measure infiltration capacity of the soil. A similar type of infiltrometer shown in figure 3.6 is used for this research. The rings are (partially) inserted into the soil and filled with water. Then the speed of the infiltration is measured by the use of a stopwatch. The (outer) double ring has the important function to limit the lateral spread of water during and after infiltration. The downward speed of water that infiltrates depends on for example texture, structure and stratification of the soil. Eventually Ksat (Saturated hydraulic conductivity and infiltration rate can be calculated according to (1).

$$K = V / At \qquad (1)$$

K is the saturated hydraulic conductivity (cm/s). The saturated hydraulic conductivity is a measure to explain the transmittance of water when the soil is saturated. In other words, it refers to the ease with whoich pores of a saturated soil permit water movement. V (m3) stands for the volume of water and A(t) is the surface area with time. Because the infiltrometer is a ring the diameter and the formula Πr^2 are necessary to calculate the surface area of the infiltrometer. (J. Lewis, A Simple Field Method for Assessing Near-Surface Saturated Hydraulic Conductivity, *Groundwater*, 54, 5, (740-744), (2016)).

Infiltration rates are linked to overland flow during/following a rainfall event because the infiltration capacity of a soil decreases exponentially over time when water infiltrates (ref), which can result in overland flow. Two types of overland flow can be distinguished: Hortonian and saturated overland flow. Hortonian overland flow is formed due to a low infiltration rate and/or capacity of the soil As the (rain)water infiltrates at a slow rate (slower than the supply of water), part of the water will remain on the surface and forms overland flow. Saturated overland flow occurs when a soil is fully saturated and cannot absorb any more water. In this case all excess water will turn into overland flow.

3.3 Boiffin-method

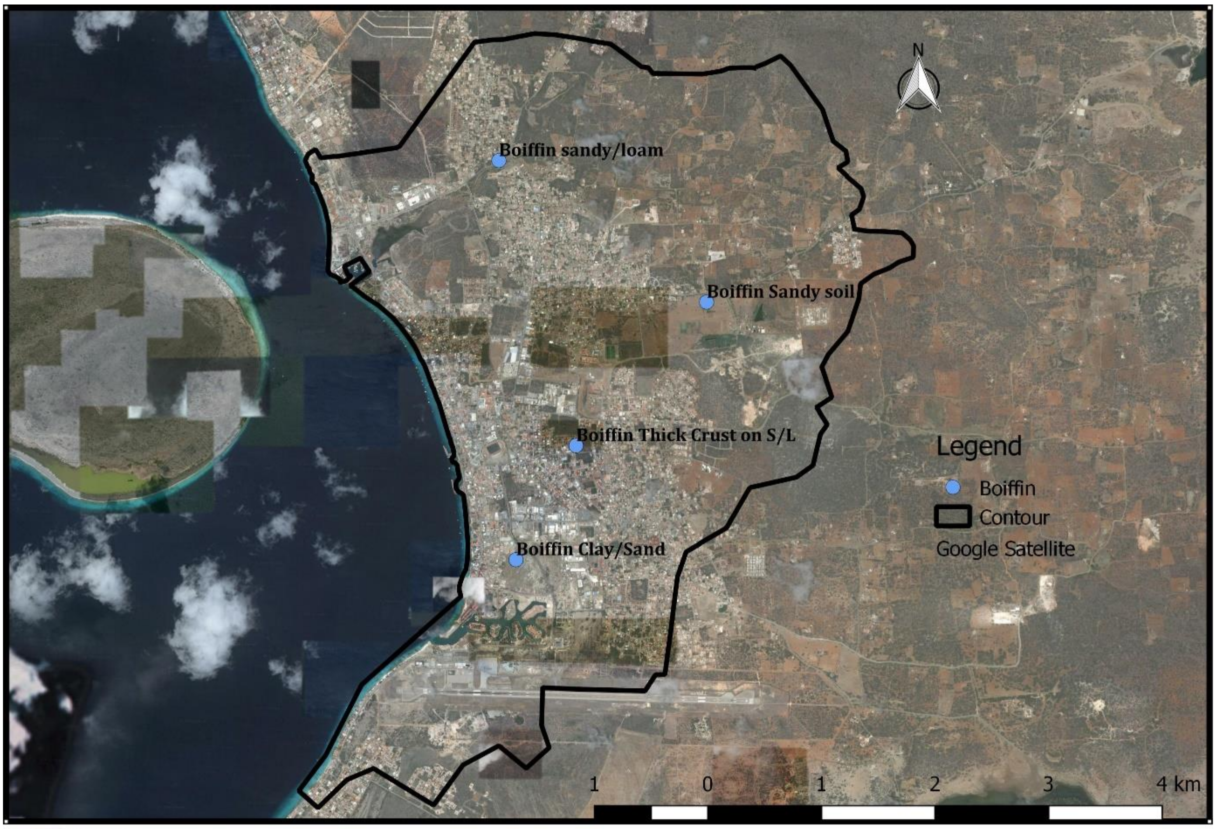


Fig. 3.7: Boiffín test locations

The determination of crust permeability can be obtained by the trickle irrigation method as described by Boiffin and Monnier (1985). The method is briefly described below:

Equipment

Capillary tube with a small aperture, constant water level tank, measurement tape (mm-scale!), small needles, paper, pencil.

Methodology

The Boiffin method (fig. 3.7) is an irrigation method to determine the permeability of the top soil layer (crust). This method basically measures permeability by trickling water on the surface. Eventually droplets that reached the surface form a saturated patch, from which the permeability can be calculated. The trickling speed of the method can be altered.

Permeability is measured by the use of large buret and a (small) reservoir. a capillary tube with a small aperture, constant water level tank, measurement tape (mm-scale!), small needles, paper and pencils (fig. 3.8).

During this method several conditions should be met in order to measure accurately as possible. Firstly, evaporation is disregarded. Secondly, the measurement takes place at undisturbed sites in the field and needs to be repeated several times. Also should the falling height of the water droplets be as small as possible. The soil should already have high moisture levels (saturation), which prevents lateral flow of water and the influence of matrix suction (fig. 3.9).

To calculate crust permeability (infiltration flux qi) water needs to be supplied at a constant rate to the capillary tube and the aperture close to the surface. As mentioned earlier, water applied to the soil will cause a semi-circular saturated patch which eventually reach an equilibrium size. The size of the patch needs to be marked with (for example) needles with a similar color. If the patch does not increase in size, the diameter of this patch is measured.
Then the flux of water from the capillary tube is decreased to cause a new (equilibrium) saturated patch to form. And again marked its surroundings with needles of a different color. In order to for this method to work this procedure needs to be repeated at least three times per site.

Thereafter, both the surface area (1) and source discharge rate (Q) are calculated for each measurement (2).

$A = \Pi\ r^2$ 1

A being the surface area (cm^2), Π (3,14159) and r is the radius (cm).

$Q = V/T$ 2

Q is the source discharge rate (m^3/s), V is the water used in ml and needs to be converted to m^3, T is the time used in seconds.

The relation between source discharge rate (Q) and the surface area (A) of the saturated patch is:

$Q = \Pi\ D^2\ q_i / 4$ 3

Q is the source discharge rate (m^3/s), Π (3,14159), D^2 is the (square) diameter in cm, qi is the infiltration flux (cm/s).

$Qi = (Q / (\Pi\ D^2\ q_i / 4)) * 10^6$ 4

To get the infiltration flux in (cm/s) it is multiplied by 10^6.

From equation (3) qi could already be derived (4), but by using several drip sources at the site, with stabilized patches and assuming qi is constant, the following relations are now valid: $D = u.\ Q^{1/2}$ or $u = D / \sqrt{Q}$ with $q_i = 4/\Pi u^2$. Also some variable need to be adjusted to get the desired unit.

U (rate (m/s)) can also be determined by statistical curve fitting, given a low residual variance. If this is not the case, a rougher estimation of q_i can be obtained from the individual measurements.
The individual measurement to obtain the infiltration flux q_i through a crusted topsoil is expressed as in equation 5, assuming steady-state flow in the crust and a transmission zone below the crust with constant moisture content:

$q_i = K_{CS}\ (h0+hi+zi)/zi = Ku$ 5

with K_{CS} = the saturated hydraulic conductivity of the crust; Ku the saturated hydraulic conductivity of the transmission zone; h0 = the hydrostatic pressure due to ponding; hi = the matric suction at the bottom of the crust; zi = the distance from the crust bottom to the surface.

In this research hi is set to zero (no matrix suction) and zi is the crust thickness, which should be measured after the test. For a complete more detailed description is referred to Boiffin and Monnier (1985).

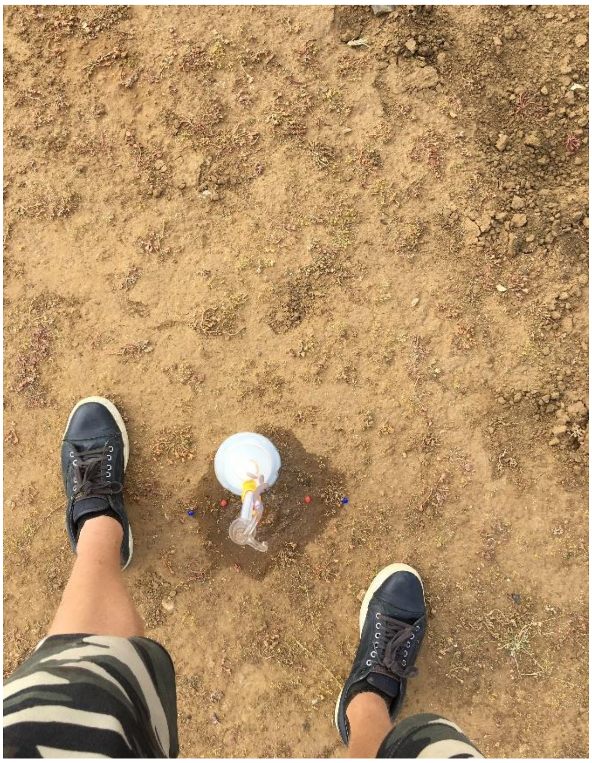


Fig. 3.8: Boiffin method (in action)

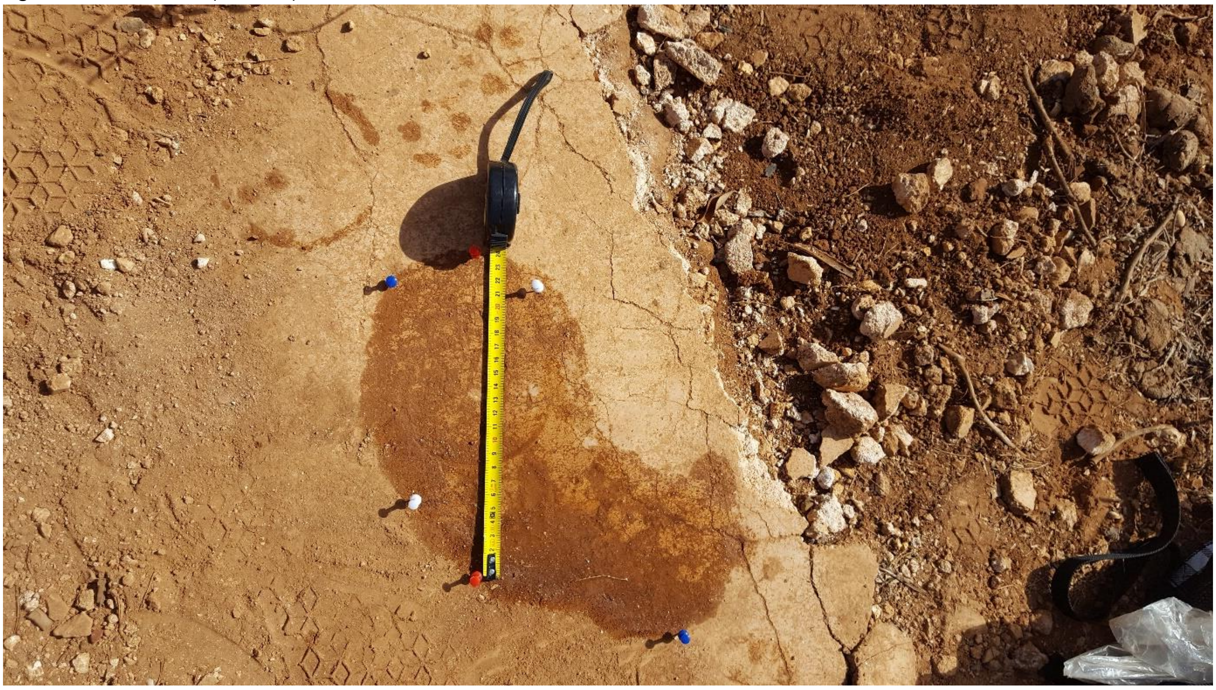


Fig. 3.9: Boiffin method (Measure the results)

3.4 Water-drop method

The water-drop method is mainly used for assessing soil aggregate stability. The test involves counting water-drop impacts of known force required to break down soil aggregates to a certain state of an erosive mechanism (A.C. Imeson and M. Vis, 1984).

The method requires a pre-treatment of the soil aggregates sampled. This involves gently sieving the 4-4.8 mm fraction of soil aggregates from bulk samples in the lab and if necessary, moistening these at pF 1 for 24h with distilled water (fig. 3.11).

For the water-drop test itself, a supply system with a constant head is needed. This system is fitted to a burette. Water droplets falling through a 15 cm diameter polythene pipe (figure 3.10) have a weight around 0.1 g and a diameter of 5.8 mm. These droplets are obtained by fitting silicon tubing to the burette nozzle. The water droplets fall 1 m through the pipe on different aggregates placed on a 2.8 mm metal sieve (fig. 3.10).

The test further simply involves counting the number of water droplet impacts to disrupt the aggregate sufficiently for it to pass through the 2.8 mm sieve. This is repeated for at least 20 aggregates per sample to ensure accuracy.

Fig. 3.10: Water-drop impact system at Universiteit van Amsterdam (UvA).

Fig. 3.11: Pre-treatment equipment: Sieves, sample tubes, forcet, collection tray and a brush (Photo by Nick Roos)

3.5 TGA (Thermogravimetric analysis)

Thermogravimatric analysis is a method to analyse the collected soil samples). The TGA measures soil organic matter, texture and carbonate content for each sample (24 samples in total). It calculates annealing losses relative to the dry weight as a function of the temperature 330, 550 and 1000 degrees Celsius. This method is fully automatic. First the program creates a sample table and loads it with the TGA empty crucibles. Then the empty crucibles are weighted. Meanwhile, the collected samples are crushed to very fine material in a pounder. It is important that all organic matter and gravel is crushed. Thereafter the cricibles are filled with 1-2 grams of each sample (table 7, §4.5). After 2-3 hours the analysis is complete. The results are added to the sample table (and the data will be saved). (Robert, R. et al, (2001).

3.6 Grain size

The determine grain size of the collected soil material each oil bag, collected from the various sampling locations, need to be dried for a couple of days with the cap off or the samples are dried in an oven. After drying all of the samples are preparated in the laboratory before these are suitable for entering the particle sizer machine. Depending on the amount of samples, this procedure is a timeconsuming proces.

When each sample bag is pre-dried, a small sample is taken with the aid of a spatula. If its finer material, clay and/or silt, a smaller scoop is used. For sand samples the big scoop of the spatual is used. Then in total 24 samples are disposed in a 800 ml beaker and 10 ml of H_2O_2 30% (Peroxide) and 25 ml of demi water is added (fig. 3.12). All the beakers are brought to boil on a hot plate making sure the samples do not dry out. Add water to do so again. If the peroxide is developed and organic material can still be seen, add more peroxide in portions of 5 ml. (Eventually the excess peroxide will boil) The peroxide dissovles coarse organic material such as twigs. After all organic material is dissolved, the walls of the beaker glass is cooled and cleaned with demi water and the suspension is made up to 100 ml. When the beaker is filled up to 100 ml, 5 ml of HCl 10% is added and heated to boil. Then the boiling beakers are removed and placed on a bench to cool down. Subsequently all beakers are supplemented to the brim with (normal) water. The samples settle until the following day. Then the following day, all beakers contain a clear liquid with material sanked to the bottom. The beakers are drained until all most all water is removed. Than all suspensions are filled to 100 ml with demi water and a small scoop of sodium pyrophosphate. Heat the suspension till boiling point, let them cool down and transfer to the measuring chamber that measures the grain sizes with a alser particle sizer Helos KR. (Robert, R. et al, (2001).

Fig. 3.12: In total 24 samples are disposed in 800 ml beakers. Including pre-dried sample bag material on the left.

3.7 Porosity

In order to measure porosity, soil material is collected in a sample tube (§3.1 sampling) and weighted atlocation. This is the wet weighting. Samples are weighed including tube and cap. Then the samples must dry for at least 24 hours. After the fieldwork the dried samples are weighed again(soil material, cap and tube) in the lab. To define the dry weight, the weight of the cap and tube need to be distracted from the total weight. The weight difference between the wet and dry weight is the amount of water which is still present in the sample. This is called the pore volume. Together with a caliper, the dimension of the insert tube, diameter and height is measured. Now the volume V can be derived and the porosity is calculated according to Ms/Md = p. (minus the weight of cap and tube). (Robert, R. et al, (2001).

3.8 Vegetation logs

In general there is a lack of fresh water (rain) on Bonaire. Therefore only plant species that have adapted to low water availability will survive. Nowadays there are approximately 500 different species on Bonaire, with the cactus being the most diverse. There are no plant species which only occurs on Bonaire, but for example an Agave species named Agave Boldinghiana only occurs on the ABC (Aruba, Bonaire and Curacao) Islands.

Every vegetation type has its own soil preference. Most vegetation prefers the limestone terraces, while others the volcanic (Dolomite) areas of the Island (fig. 2.2). The project area, situated in the limestone terraces, can in general be divided into a sandy/clayey, sandy/loam soil. The soil often differs in ratio silt/sand/clay (table 8). Therefore vegetation types that occur in the various (sub)-catchments are congregated in logs.

The vegetation logs are based on vegetation occurring on a soil type coherent with nine landuse types (See landuse classification fig. 3.1). In every sub-catchment (fig. 2.4) at each aggregate location, types and differences in vegetation are observed and noted. The outcomes are together with the landuse types combined in table 9. The types of vegetation were analyzed by using a flora guide and previous research sources (§2.2).

3.9 Connectivity

Drones are unmanned aerial vehicles which often are equipped with a (photo)camera. Using a drone is a very easyand relatively cheap way to survey large areas from above.
Together with a drone photograph specialist who lives on the Island, air-photos of large areas were taken in order to determine connectivity of (rain)water on the surface in the study area. The photographed area is mostly situated in sub-catchment six, in and around Saliña di Vlijt. This area covers about 4-5 km2. Other areas or sub-catchments are not scanned by drone (due to lack of time and funding). To estimate the connectivity in these areas results of the scanned area, (Google Satellite/Google Earth) images, vegetation logs and soil information are combined and compared.

The camera-drone (fig. 3.13) used in this research was the DJI Phantom 4+, with the following specifications:

1. 20 MP Camera
2. 7000 m
3. 30 min record
4. 60 FPS


Fig. 3.13: Drone is ready for take-off (Photo taken by Nick Roos)

3.10 Soil crust

Fig. 3.14: Example of a soil crust (B25)

Most soil types on Bonaire and especially in the project area have a crust on the surface (fig. 3.14). This process of crust formation is called surface/soil crusting. There are two types of soil crusting to distinguish, biological formed by micro-organisms) and physical crusting. Physically formed soil crusts mainly occur on Bonaire. They are formed by physical impact such as Drying/raindrops/runoff and (wind) erosion. Surface crusting mainly occurs in arid and semi-arid areas.

At every sampling site in the project area, various layers of the soil were un covered by digging a relatively large hole in the ground using a small shovel and measuring tape, to determine the thickness of the layers. With the use of Casenave and Valentin (1989), processes and factors involved the different crusts were studied and classified (table 2)

Table 2: Main features and properties of the different types of surface crust in semi-arid zones

Type	Structure	Thickness (mm)	Strength	Porosity
Drying	Massive single sandy microhorizon	1-2	Very low	High
Structural l	Rough surface made of coalescing partially slaked aggregates	> 10	Low	Moderate
Structural 2	Laminated, a sandy microlayer over a thin seal of finer particles	1-3	Moderate	Moderate
Structural 3	Laminated, coarse sandy layer at the top vesicular fine sandy layer, seal of finer particles at the bottom	I-3	Moderate	Low
Erosion	Smooth surface made of a single seal of fine cemented particles	< 1	High	Very low
Aeolian	Laminated, interbedding of sandy microlayers	2-50	Low	High
Runoff/Depositional	Laminated, interbedding of sandy microlayers and seals of finer particles	2-10	Low/Moderate	Low
Sedimentary	Laminated, larger particles at the top, finer at the bottom	2-50	Moderate	Low
Gravel	Laminated, similar to structural 3, including coarse fragments	2-30	High	Very low

Source: Casenave, A. and Valentin, C., 1992. A runoff capability classification system based on surface features criteria in semi-arid areas of West Africa. J. Hydrol., 130: 231-249.

3.11 Hotspot determination (Borselli method)

To determine high erosion areas, a map based on multiple properties of the catchment is created. The aim of this method is to predict by means of combining the soil and hydrologic properties of the catchment (§3.1-3.4) with connectivity (§3.9). To do so, the method described in (Borselli, 2008) is used.

Using the Borselli method the area of interest is divided into (several) flow lines. Those contributing to sediment transport upslope (Upslope oncoming sediment (UOS)) and those carrying the sediment downslope towards a sink/basin. To explain this to a model, one will need a probability mass of sediment upslope is put in motion (Pu) and (Pd) that sediment reaches a certain basin. If both up and downslope transport join, the probability is proportional to the (downslope) distance along a flowline. If more oncoming sediment is transported, the chance this sediment reaches a basin all the way downslope increases, because the chance this amount of sediment is caught before arriving decreases.

To estimate Pu and Pd the down and upslope component must be calculated. Pd, contrariwise relative to segment Ddn, also depends on other factors. It is influenced by the degree to which the segment is able to connect on land use and management and hydrological conditions of the spot. For this, a weight (W) has to be assigned to each flow line segment. The slope gradient (S) of the segment is also relevant because sediment flow will stop when the slope is zero (2). If W and S attain their maximum when for example vegetation orland use and management are poorer or slope gradients are larger, then the ratio d/WS can weight the distance as needed. Summing all the segment along the route from A to B so we can estimate the weighted distance Ddn accordingly to (1).

$Ddn = \sum di/(wi*si)$ **(1)**

Di is the length of the ith cell along the downslope path (m). Wi is the weight of the ith cell (dimensionless) and Si is the slope gradient of the ith cell (m/m).

The upslope component Dup is the potential for downward routing of the sediment produced upslope. It mainly depends on the area draining into A. It is also influenced by the same factors described at the downslope component, but now we have to expanse the analysis to an area. In order to keep the structure of the estimation method as simple as possible, several average values of the two weighing factors can be used over the contributing area. In short, we can use the square root of the upslope area to give Dup the same unit of measure as Ddn. Under such assumptions we can estimate Dup (2).

$Dup = WS\sqrt{A}$ **(2)**

Dup is the upslope component. W representsd the impedence to runoff and sediment fluxes. S is the slope component, it is establkished by S = sin(Alpha) + S0 (=0.005), with alpha being the local gradient. A equals the areaof the reference cell.

The factor W is the most important factor in this case study. It represents the hindrance to runoff and sediment fluxes, due to properties of the local land use and soil surface (Borselli, 2008). It is derived from the surface characteristics that influence runoff and sediment fluxes within a catchment. ‘W’ should be related to vegetation, soil properties and landuse management (specifically related to presence of gullies and rills). In this project ‘W’ represents the impediments to sediment movement. It is explicitly related to observable and measurable characteristics of land use. Several parameters which fit are vegetation cover (land cover), rill and gully presence and soil erodibility and soil permeability (Boiffin and Monnier (1985).

In order to create a map for ‘W’, multiple maps have to be created. First, the entire study area is divided into relatively homogenous areas related to vegetation, urban cover and bare land (fig. 4.6, §4.8.1). For each homogenous area, various soil/vegetation characteristics are determined, based on the field and lab work. Overall, three factores are determined for each area: infiltration , landcover and the categoral value of connectivity (based on gullies and rills) (fig. 4.5, §4.8).

To obtain an asaccurate image as possible of erosion, the amount of paved areas and roads are taken into account for each region Then the quantity paved areas and roads in each region area added to the landcover data map.

In GIS, these factors are analysed and compared with eachother. While analysing for correlations or obvious differences between the maps, the influence on erosion each factor has is determined. As imaged in figure 4.7 (§4.8.2).

4 Results

4.1 Results soil aggregates locations

In table (3) most essential soil properties for this research project are pointed out. An important aspect is the landuse type of each location (fig. 2.3). This again, is being compared to the other properties and features. At some locations the landuse type is a combined version between two types (according to figure 2.1). The landuse type, in most cases, correlates with the (local) landcover and soil type. The soil type is hetergeneous in general. The permeability and porosity of the soil both depend of the type soil at that location. Landcover is more or less the same throughout the whole research area. With percentages varying from 5-10 % in general. Some areas have a higher percentage of vegetation. This means that such an area is at least covered with 15% to 25% with vegetation. These percentages usually occur at higher level locations or areas with an organic rich soil. Interesting fact is that in general, the thickness of the crust on top of the soil, does not varie that much. In the different sample sites, crust thickness varies from 1 to 3 mm. Here and there an outlier as seen at location B1 and B2. Thickness here reaches 5 mm and even 10 mm at location B2. An explanation for the outlier could be long periods of drought in these areas, which causes the formation of a thicker crust. Compared to other sampling locations (B11, B15, B21), these areas were much drier with very clear signs drought (such as mud cracks). Because a crust is formed on most of the soils and the soils are quite dry, water cannot infiltrate (fast). Therefore, most of the (rain)water is discharged as runoff. Usually, rivers are formed to discharge the water toward the coast or a Saliña. Saliñas have no vegetation cover due to the saltiness of the clayey soil. It creates a situation that causes crust formation in the (in general) humid Saliñas (B6, B11).
The sampling of aggregates was a succes. However, I would have taken more samples when possible but at some (interesting) sites/locations it was not aloud or these sites were not accessible.

Table 3: Soil properties

Location	Color	Crust th.(mm)	Crust type	Landuse	LC (%)	Porosity	Soil type
B1	5/3 10 YR	2-5 mm	Runoff/drought	C8	10	0,475403	Sand
B2	4/3 5 YR	2-10 mm	Runoff	C1/C2	0	0,480996	Sand
B3	7/2 5 YR	2 mm	Runoff	C8	10	0,458624	Sand
B4	6/2 5 YR			C8	5	0,464217	Clayey/sand
B5	4/2 5 YR	3 mm	Runoff/drought	C2	5	0,492182	Sandy/loam
B6	2/2 5 YR	1-2 mm	Drying	C3/C6	10	0,447438	Organic/Sandy
B7	4/2 7,5YR			C3/C1	25	0,419473	Organic/Sandy
B8.1	7/3 2,5YR	1-3 cm	erosion	C7/C1	10		Sandy
B8.2	4/4 2,5YR			C7/C1	10	0,41388	Sandy soil/loam
B9	4/3 5 YR			C2/(C5)	5	0,430659	Sand
B11	4/2 5 YR	1-2 mm	Runoff	C8	0	0,52574	Sand/clay
B12	4/3 5 YR	1 mm	Runoff	C7	5	0,447438	Sand (firm)
B13	6/2 7,5YR	2-4 cm	Runoff	C8	5	0,475403	Sand
B14	4/2 7,5 R	1-3 mm		C1/C2	15	0,475403	Sand/clay
B15	5/2 7,5 YR	2-3 cm	Runoff/layered	C1/C2	20	0,492182	Sand/bit clay
B16	5/3 5 YR			C2/C7	10	0,441845	Sand/loam
B17	3/3 10 R	1-4`cm	Erosion	C7/C2	10	0,436252	Sandy loam
B18	5/2 7,5 R			C7/C6/C2	15	0,441845	Sand/silt/clay
B19	5/3 7,5 YR	1-3 mm	Runoff	C9/C8	20	0,46981	Silt/Sand

B20	5/2 10 R	1-3 mm	Runoff	C1	25	0,408287	Sand/clay
B21	5/3 7,5YR	1-2 cm	Runoff/erosion	C7	10	0,458624	Sand/silt/clay
B22	4/2 2,5YR	1-3 mm	Runoff	C6	5	0,41388	Sandy soil/loam
B23	6/2 5 YR			C2/C1	0	0,430659	Sand/clay
B24	6/2 10 R			C4/C1/C2	5	0,447438	Sandy soil/loam
B25.1	5/2 7,5 R			C7	0		Sand/silt/clay
B25.2	4/2 5 YR	5 cm	Erosion	C3	5	0,425066	Clayey/organic
B26	5/2 7,5 R			C8	10	0,441845	Sand
B28	5/2 7,5 R			C7	15	0,447438	Sand/clayey

4.2 Boiffin method

The permeability of soil depends on several factors such as: Structure,texture, roughness, type of crust and soil type etc. With the (for me experimental) Boiffin method (Boiffin and Monnier (1985)) the permeability of the topsoil has been determined on four sites: The results are shown in (table 4) (per location). Each location in table 4, includes a different type of soil which results in a different permeability. For all locations, the Boiffin tests relatively show low permeability. This is related to the presence of a crust. Also the quantity of clay present in the soil could influence permeability. Because clay percentages at locations B5/B6 and B8.2 are higher compared to locations B12 and B21 (table 8). Comparing results of all four locations (table 4), indicates a higher percentage of clay present in the soil causes lower permeability
Permeability is measured by the use of large buret and a (small) reservoir (§3.3). Little to none vegetation and strong winds at the locations sites made it difficult to measure accurately. Therefore some measurements had to be done several times to gather reliable data.

Table 4: Boiffin method results

Location	Soil permeability (cm/s)
SdV(B12)	0,000201
LVV(B21)	0,000142
B5/6	0,0000553
B8.2	0,0000339

4.3 Infiltrometer

The results of the infiltration capacity differ per soil type (table 5). A clay(ey) top soil together with a low vegetation cover causes lower infiltration rates. Thus a lower saturated hydraulic conductivity (Ksat), which corresponds with a lower infiltration rate. In table 5, high values represent locations with high sand fractions while locations with more clayey soils have lower values. However, the result of a Clayey soil at location B11 disagrees with the sandy/clayey soil in general. The reason for this could be explained because of the very high Ksat of this sandy/clayey soil and because of the large number of cracks seen in the field (fig. 4.1). Organic material, such as roots, also can have a positive influence on the infiltration rate.

Table 5: Infiltrometer results

Location	Soil type	Ks (mm/hr)
B4	Clay/sandy	39,7
B5	Sandy/loam	62,42
B7	Sandy/Silt	85,2

B11	Clay/Sandy	88,4
B14	Sandy/loam	52,76
B18	Sand/Silt	94,3


Fig. 4.1: large number of (mud) cracks seen in the field. Photo taken at location B1.

4.4 Water-drop method

The water-drop method, which is explained in §3.4, provides useful information about the strength,structure, texture and toughness of each particular aggregate. Especially about the crust formed by drought, runoff and erosion.
In the colorscale table 6 from dark green to dark red, represent the DF (drop frequency = amount of drops needed to disperse aggregate). High values are coloured green and lower values are coloured red. The values in between these lowest and highest values have been given a colour, depending on the gathered value, nearest to the minimum or maximum DF. Aggregates which mostly contain a high clay and silt percentage, are situated near the ocean or in the midlands (locations B1, B5, B22 etc. Fig. 3.3 p.16) and are less resistent compared to aggregates from the more sandy uplands (for instance locations B14, B18, B25 in fig. 3.3, p.16). Data found at B6 is not reliable and therefore mentioned but not included in the final results.

Table 6: Water-drop method results

Aggregate	DF	Aggregate	DF
B1	8,43	B16	8
B2	5,17	B17	5,21
B3	3,65	B18	8,63
B4	3,36	B19	10,8
B5	3,48	B20	9,45
B6	20	B21	7,75
B7	4,57	B22	4,63
B8.2	5,17	B23	5,11
B9	5,09	B24	4,68
B11	7,29	B25.1	5,58

B12	3,35	B25.2	8,59
B13	9,95	B26	4,67
B14	8	B28	7,44
B15	5,8	Average	6,66

4.5 Thermogravimetric analysis

It seems that the thermogravimetric analysis (hereafter TGA) results displayed in table 7 confirm that samples taken nearer to the ocean and/or Saliña, contain a higher percentage $CaCO_3$ compared to samples taken more in the uplands (fig. 3.3). Samples taken for example around the Landbouw, veeteelt en visserij (LVV) territory situated in and around sites B18, B19 & B21 (fig. 3.3, p.16), hold a much lower quantity $CaCO_3$.

The amount of moisture measured is more or less the same in each collected sample. As explained in §3.5 (p.23), the samples are heated at different temperatures. In this case at 330 and 550 degrees. This seperates organic matter in two groups: Easy (330) and harder (550) oxidizable organic matter. Locations in the mid- and uplands contain more organic matter compared to the samples in Saliñas, urban or bare land areas. Coming back to the moisture content, locations with higher moisture levels in the samples include higher organic content.

TGA analysis §3.5 (p.23) also gives a good indication of the total carbon content $CaCO_3$. Nevertheless, those values are subject to overestimation because in the range of 550˚C - 1000˚C not only weight loss occurs due to loss of CO_2 but also due to loss of structural bounded water.

Table 7: TGA results

Field code	Initial Mass (gr)	Moisture (%)	LOI330 (%)	LOI550 (%)	CaCO3tot (%)
B1	1,1215	1,845	1,201	3,852	10,34
B4	0,9194	2,603	4,68	12,73	89,4
B5	0,8519	2,931	2,938	14,01	27,55
B6	0,8524	3,374	3,645	11,44	14,04
B7	0,9342	2,069	3,072	7,812	20,06
B8.2	1,0899	3,149	3,219	7,895	6,455
B9	1,065	2,608	1,608	4,513	3,626
B11	0,7905	2,216	2,245	8,45	13,64
B12	1,2829	1,629	0,9749	3,357	10,53
B13	1,083	1,976	0,9881	4,372	23,09
B14	1,1094	2,29	2,305	5,237	2,953
B15	1,2047	1,229	1,569	5,355	52,74
B16	1,2883	1,721	1,382	4,672	10,44
B17	1,2151	1,806	1,634	4,044	2,448
B18	1,0172	2,042	2,573	6,007	1,886
B19	0,9478	1,358	1,789	4,478	5,563
B20	0,8323	1,518	3,665	8,183	29,1
B21	0,8591	2,034	2,235	5,188	2,37
B22	0,9788	2,759	2,507	7,641	5,435
B23	0,9858	1,384	1,255	4,507	39,07
B24	0,8159	2,624	2,646	7,677	23,67
B25.2	0,863	3,738	2,738	6,668	2,536
B26	0,9788	2,219	1,604	4,338	5,922
B28	0,8758	2,96	1,961	4,77	2,576

B5	0,7454	3,041	2,817	13,89	26,56
B15	1,1676	1,142	1,325	4,846	57,84
B11	0,9389	2,578	1,999	8,305	12,76
B11	0,6864	2,538	1,97	8,208	12,8
B1	1,073	1,748	1,248	3,784	11,07
B1	0,8997	1,812	1,339	3,88	11,08
B14	1,1224	2,365	2,23	5,27	2,889
B14	1,0868	2,347	2,252	5,331	2,72
B17	1,0014	1,844	1,561	3,989	2,414
B17	1,0796	1,849	1,603	3,982	2,935
B19	1,209	1,391	1,769	4,492	5,857
B19	0,984	1,397	1,781	4,459	5,445
B21	0,9073	2,078	2,25	5,275	2,573
B21	1,0883	2,096	2,312	5,549	2,403

4.6 Grain size results

The grain size results are more or less as was expected due to a general sandy loamy texture. The samples situated more land inward consist mostly out of sand/fine sand/silt and a lower percentage of clayey material (fig. 4.2). All sample lcations contain an amount of clay (§3.1). Some samples however do contain more 'very' fine silt (table 8). Towards the ocean, the soil becomes more loamy as the ratio between clay and sand changes (fig. 4.2). The content of clay increases, coarser material decreases, while finer material such as silt/very fine silt increases toward the ocean.

The grainsize results from the collected samples, as shown in table 8, are classified according to grainsize. The grainsize classes start at from < 8 µm and run up to 1000-2000 µm. The horizonatal numbers (percentages) in the different columns and rows, give an overview of the presence of for example clay, silt or sand found in the sample. The field codes represent the sample locations (fig. 3.3, p.16).

Table 8: Grain size results

Field Code	%Clay	%Silt	%Very Fine Silt	%Fine Silt	%Coarse Silt	%Sand	%Very FS	%Fine Sand	%Middle CS	%CS	%Very CS
	< 8 µm	8-63 µm	8-16 µm	16-32 µm	32-63 µm	63-2000 µm	63-125 µm	125-250 µm	250-500 µm	500-1000 µm	1000-2000 µm
B1	13,39	21,4	4,54	6,17	10,69	65,21	18,09	15,05	8,24	19,09	4,74
B4	55,29	39,7	16,28	14,13	9,29	5,01	4,11	0,9	0	0	0
B5	39,68	52,48	15,93	18,53	18,01	7,84	6,57	1,24	0,04	0	0
B6	44,14	55,28	23,84	21,9	9,55	0,58	0,58	0	0	0	0
B7	20,37	29,75	8,22	9,5	12,02	49,88	14,32	11,67	7,63	13,44	2,83
B8.2	70,23	27,16	14,33	7,7	5,13	2,61	2,56	0,05	0	0	0
B9	32,87	32,15	9,64	10,3	12,2	34,98	12,13	8,57	7,1	7,07	0,11
B11	40,57	51,46	16,96	18,16	16,34	7,97	7,83	0,14	0	0	0
B12	11,94	16,17	3,96	4,57	7,63	71,9	19,33	22,4	10,27	15,4	4,49
B13	22,81	32,01	9,19	10,49	12,33	45,18	13,05	9,61	9,39	12,64	0,49
B14	23,51	16,17	5,36	5,13	5,68	60,32	7,74	8,51	9,55	25,82	8,7
B15	22,48	19,48	6,65	5,69	7,14	58,05	10,07	8,28	9,93	22,66	7,11
B16	20,14	22,97	7,37	7,3	8,3	56,88	8,68	7,37	8,06	22,41	10,37
B17	19,98	18,36	4,95	5,49	7,91	61,66	14,29	16,88	10,84	16,07	3,59
B18	22,68	26,74	7,16	9,21	10,37	50,59	9,1	6,12	5,9	19,79	9,67
B19	25,13	30,63	9,28	9,17	12,17	44,25	16,52	11,29	6,08	9,78	0,58
B20	15,91	31,9	6,41	10,19	15,3	52,19	12,35	5,24	5,76	21,27	7,57
B21	34,95	26,66	8,79	8,44	9,43	38,39	9,41	6,16	7,03	13,85	1,94
B22	52,21	44,06	19,63	15,87	8,56	3,73	3,57	0,16	0	0	0
B23	14,55	19,95	4,93	5,85	9,18	65,49	16,24	17,4	13,63	15,96	2,26
B24	61,42	29,16	12,97	8,47	7,72	9,42	8,04	1,39	0	0	0
B25.2	29,28	33,66	9,25	10,53	13,87	37,06	15,03	12,56	8,12	1,36	0
B26	16,08	23,07	5,49	6,99	10,6	60,85	14,96	13,69	8,65	16,85	6,7
B28	17,01	27,55	7,76	8,66	11,13	55,44	13,83	11,7	8,24	16,01	5,66

The results of table 8 are presented in a 100% stacked column. To create a complete picture of all grain size ratios, samples on the x-axis are ordered from coast to inland (fig 4.3). In general most samples are sandy with varying quantities of clay. Sampling sites near Saliñas and towards the coast have a higher clay and silt content. Striking is the high(er) quantity of coarse sand in Saliñas compared to elsewhere. Lower clay content and an increase in (fine) silt, sand and coarser sand describe the samples in higher areas in the research area (fig. 4.2).

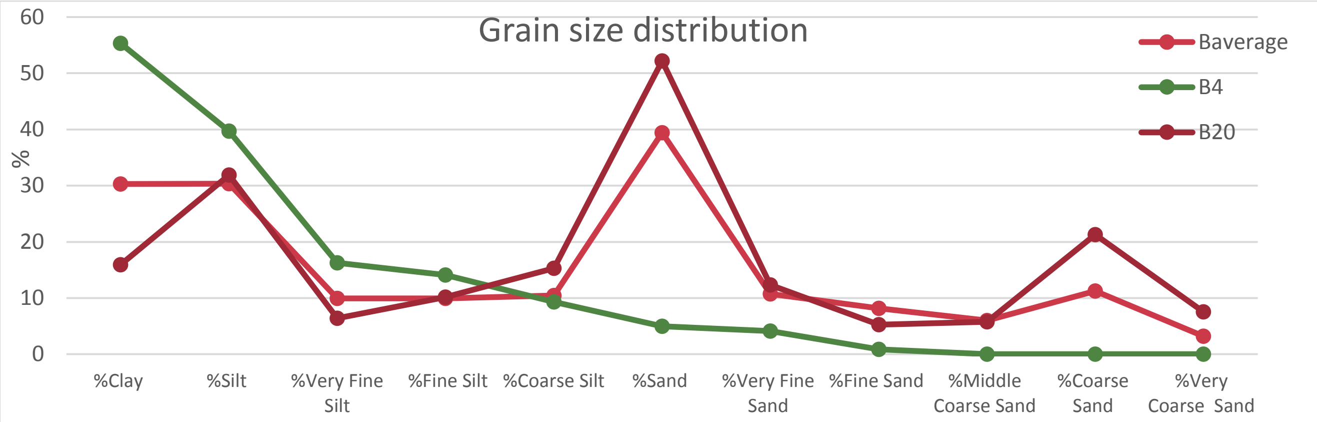


Fig. 4.2: Grain size distribution inland and towards the coast.

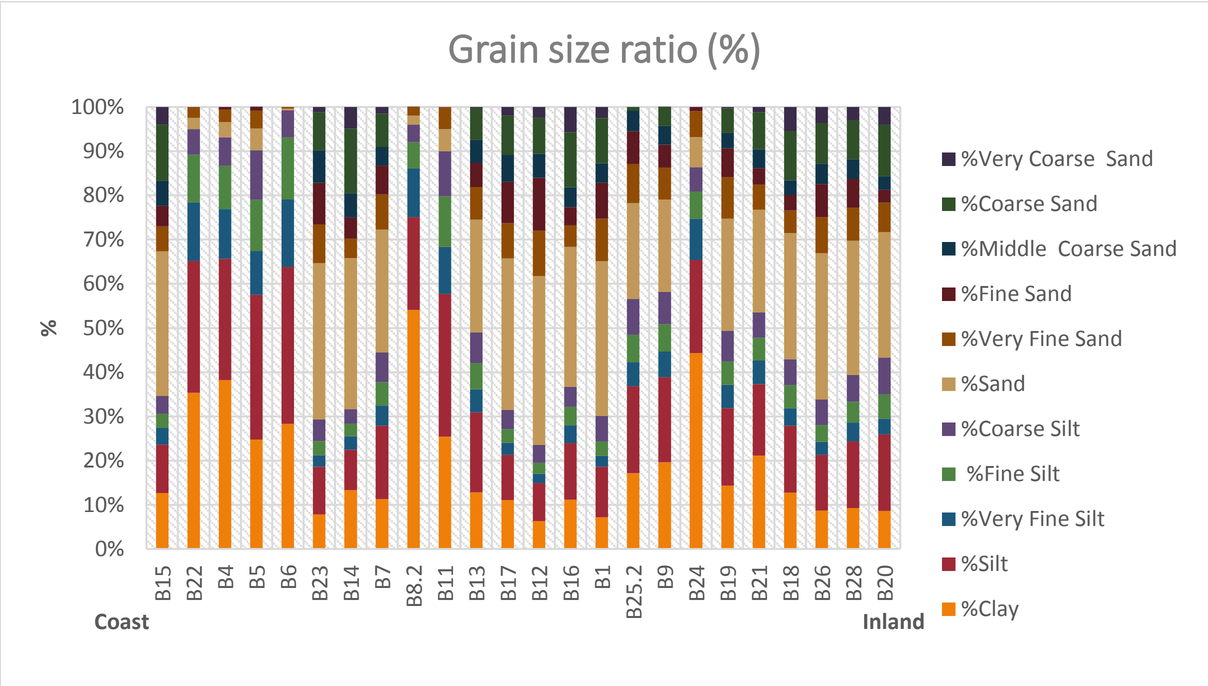


Fig. 4.3: Grain size ratio in a 100% stacked column.

4.7 Vegetation

For each landuse type the vegetation is described. Differences between vegetation are pointed out (§3.8, p.24). In general most vegetation occurring are bushes, grass, shrubs, cactuses and (small) trees. Differences are mainly caused by a difference in vegetation density. Because of this landuse types are divided into classes with light, medium and dense cover (table 9, C3-C8). However, in some landuse types vegetation is not that common. In for example bare lands (C2), the only kind of vegetation that appears is an occasional grass 'spot' or in the Saliñas (C10), where most plant species can't endure the salinity except for a fat plant. All vegetation in urban areas are (garden) planted. Beautiful Sabal palm trees occur in these areas but are neatly arranged. Still not all living areas contain plants or trees. Lot of gardens and streets are bare or contain only grass. Agricultural fields are situated more inland near sampling location B19 (fig. 3.3). These fields contain pastures on which vegetables are being cultivated. All results from the vegetation logs (§3.8, p.24) are presented in table 9.

Table 9: Results of vegetation logs (2.9) for each landuse type

Code:	Landuse type:	Vegetation:
C1	Urban/living areas (buildings)	All vegetation in these areas are planted in (urban) gardens. Main flora are: Grass, garden plants such as: Different kinds of flowers such as the oleander, orchids and the Sabal palm tree. In short: (Green) Urban vegetation
C2	Bare land	The occasionally grass ‘spots’. Usually bare land
C3	Dense Shrubbery	Mixed shrubs and trees/cactuses
C4	Medium Shrubbery	Thorn bushes, cactuses, (long)grass,
C5	Light Shrubbery	Mainly small shrubs occur here such as:
C6	Dense grass	In these areas grass is the main and only vegetation.
C7	Rangeland (medium cover)	These are (rangeland) areas that are more fertile. More water available, which means larger trees (Kubra Hacha, Divi-Divi tree, pokhoutboom, mispelboom), more dense shrubs and larger cactuses. Less influence of animals
C8	Rangeland (light cover)	The Saliña areas are classified in this type of landuse. With no growth of plants/trees/shrubs on the Saliña area but some small trees, cactuses and needle bushes grow along the sides (salinity). More influence of animals
C9	Agricultural field	Grass ‘spots’ are common in these types of fields. Vegetables are being cultivated on these pastures.
C10	Saliñas	Most plants species can’t tolerate/endure the salinity of the soil in these areas. Locally a type of fat plant occurs.

Fig. 4.4: Collage of the different landuse types along with vegetation. The order is as presented in table 9 from C1-C10.

4.8 Hotspots of erosion

The input data required is obtained by using the Borselli method and displayed in figures 4.5A-4.5D. After converting the three maps from figures 4.5B-4.5D into one W-factor map, the map gives a first indication that high 'W' values occur near urban areas and sites with higher vegetation cover (fig. 4.6). Furthermore, the Borselli method is used to create an erosion map (fig. 4.7) with the use of important calculations and methods, mentioned in §4.8.1.

4.8.1 W-factor map

The W-factor is derived in Excel according to the following calculation (3):

1. Infiltration cm/s * 500.000	+[0-100]-	(weighs 2x)	
2. Vegetation = %	+[0-100]-	(weighs 1x)	**(3)**
3. Gullies/rills = CPV	+[0/20/40/60/80/100] –	(weighs 2x)	
		/5	

+ means high connectivity and - a low connectivity.

This calculation results from several field data sources that had to be converted. The data from vegetation (%) and gullies and rills are ranging from 0-100. Though, the Boiffin field data, which is given in (cm/s), had to be multiplied by 500000 to convert the data in numbers ranging from 0-100 (§3.4). After consideration both Boiffin and the categorical presence values (CPV) of gullies and rills in each area, weigh heavier in relation to erosion. All data is merged and divided by a total weight of 5. The average score results in the W-map (fig. 4.6).

4.8.2 Erosion map

The erosion map results from the steps described in (Borselli, 2008) and gives a good indication of where çrucial or 'hotspot' areas are situated. Figure 4.7 points out that erosion is indeed an important proces to take into account. According to figure 4.7, erosion occurs throughout the whole research area.

Especially in the upland, bare and paved areas erosion is high (fig. 4.7). Low vegetation cover, steepness and (low) permeability perform crucial roles in erosion (§3.3 and §3.8). A lot of (sedimental) material in these areas could be transported. Therefore, areas with low vegetation cover and a low(er) permeability are critical locations that qualify for or improvement of measures (§5.2).

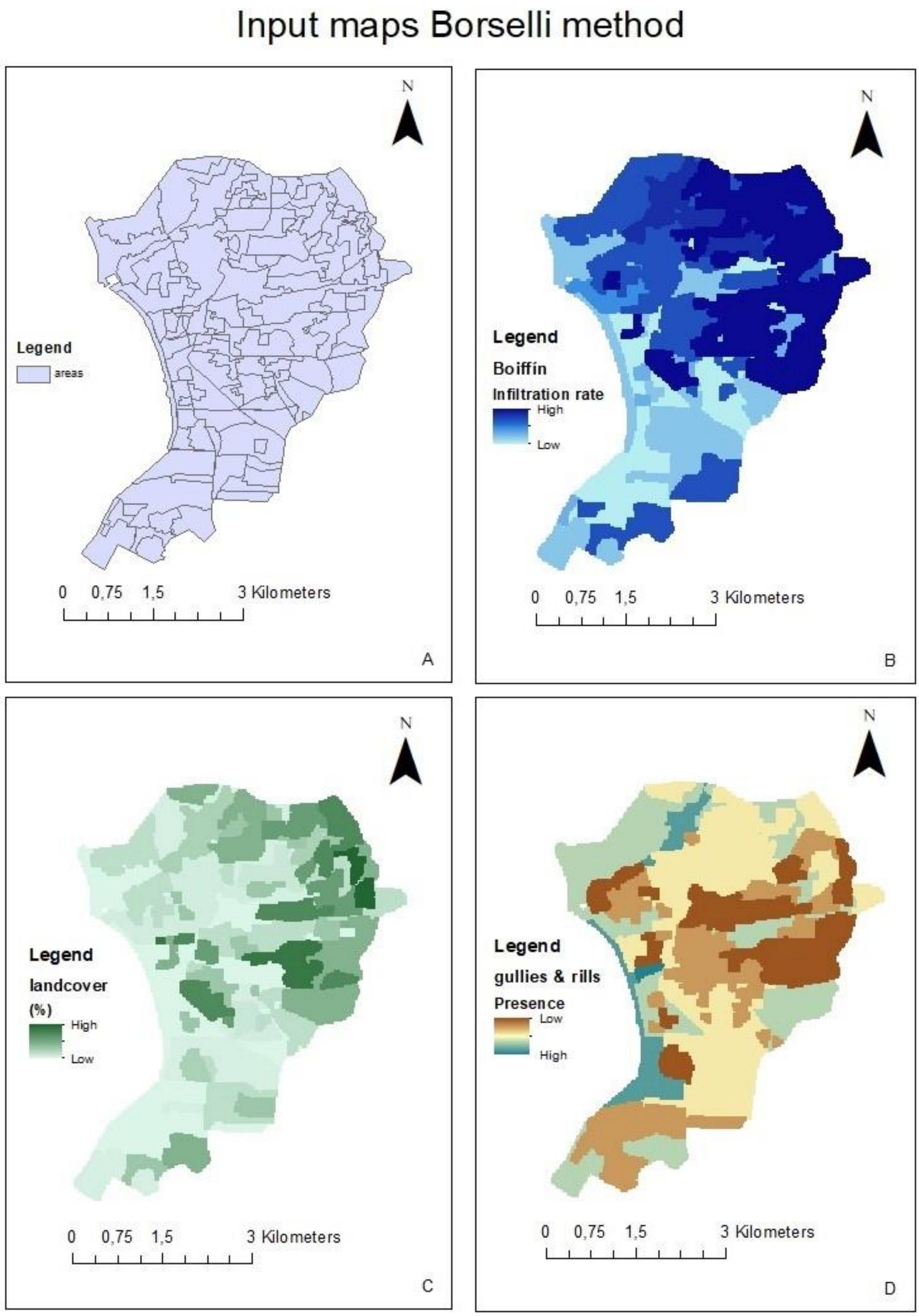


Fig. 4.5: Input maps Borselli method. A presents the entire area divided into homogeneous araes related to vegetation, urban cover and bare land. Maps B-D are the three factors that are determined for each (homogeneous) area. B is the infiltration, C the vegetation cover and D images the categoral value of connectivity (based on gullies & rills).

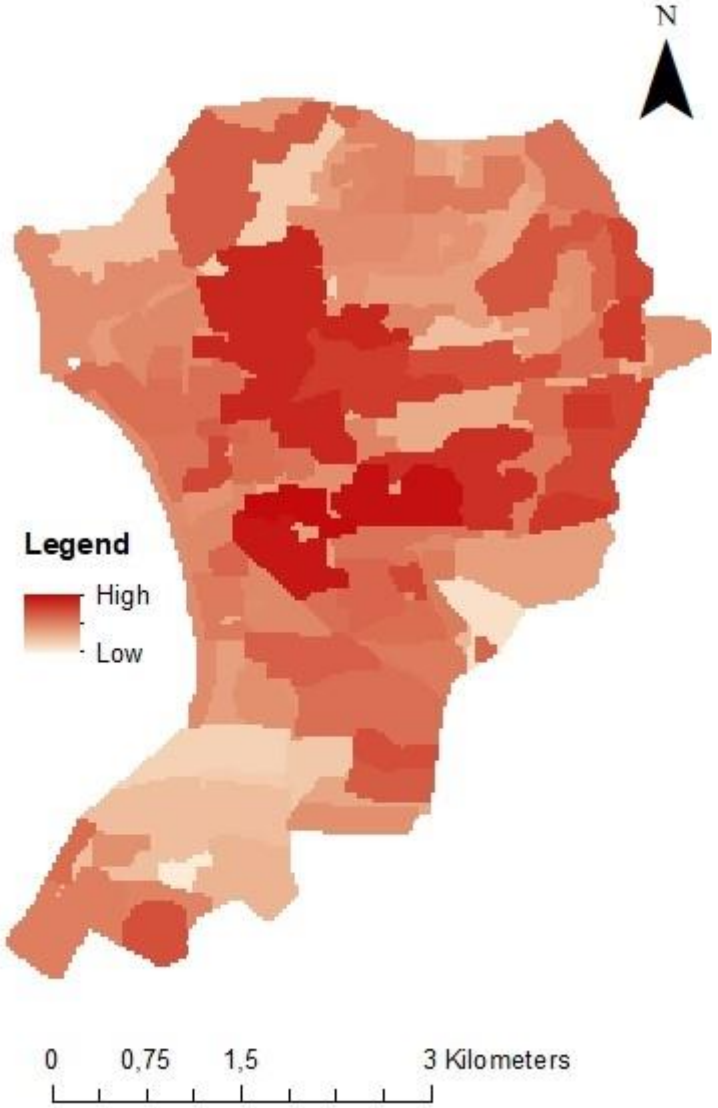


Fig. 4.6: W-factor (Input Borselli method)

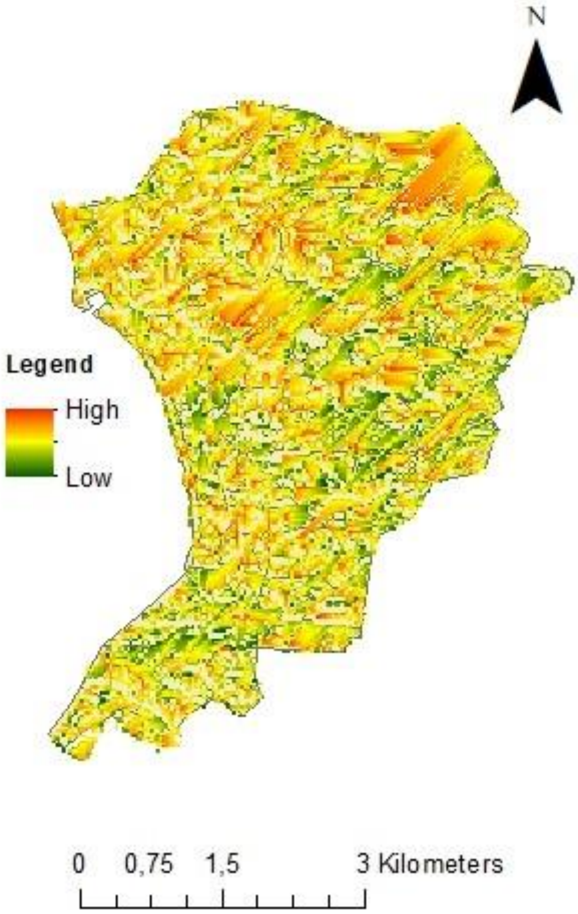


Fig. 4.7: Final (Hotspot) erosion map

5 Discussion

Sensitivity to erosion differ per landuse type (table 10). Therefore, the sensitivity to erosion for each landuse type is discussed and most critical landuse types are pointed out. In §5.2, several important measures to reduce erosion are listed. This paragraph discusses the problems which enhance erosion and the necessity to improve or start these measures.

5.1 Erosion sensitivity

On Bonaire erosion occurs on each land-use type, as imaged in the erosion map (fig. 4.7). Some landuse types are much more sensitive to erosion. The lack of vegetation, dry surface, loose material and in general low infiltration rate in these areas, all enhance erosion.

As seen in table 10 below, land-uses such as: Urban areas, bare land and saliñas are the most sensitive to erosion. These could be classified as qaulifying the most for taking measures. Areas situated more upland are also sensitive to erosion due to steep slopes, relatively low infiltration, loose dry material and high presence of gullies and rills. These critical upland areas therefore also need to be taken into account for (extra) measures (§5.2). Most material deposited in Saliñas and transported towards the ocean, is comes from higher levels inland.

Table 10: Erosion sensitivity per land-use type

Code:	Landuse type (Fig. 4.3)	Erosion (sensitivity) Fig.4.5
C1	Urban/living areas (buildings)	Urban areas are quite sensitive for erosion. Especially in highly paved areas and low vegetation cover. Living areas usually exists out of a house surrounded by (bare) land. With the Boiffin results in mind (table 3), erosion is taken place. Water transports and/or affects these areas.
C2	Bare land	Bare land is the landuse type that occurs the most. As mentioned in the urban section, bare lands are affected by erosion. This is due to low vegetation cover and slow (or none) infiltration of rain(water). The low infiltration is caused by a sturdy soil with a (very) low permeability. Water, which does not infiltrate into the ground, form into (sediment)streams. Bare lands are perfect areas to observe crusts fromation (due to long droughts or runoff).
C3	Dense Shrubbery	These areas are more resistent to erosion. Due to a (relatively) high vegetation cover. The vegetation - existng mostly out of dense shrubs and small trees (table 9)- enlarges the (root)

		space in the soil and therefore increasing infiltration. Less water remain on the surface and less erosion will take place. These are (together with light and medium landuses) the yellow to green regions in Fig. 4.5. Also in these dense shrubbery areas is not being build.
C4	Medium Shrubbery	Medium shrubbery means less land cover and smaller bushes, less cactussen compared to dense shrubbery landuse. Land is at these places somewhat bare and more influnced by erosion.
C5	Light Shrubbery	With no trees and mainly small bushes, light shrubbery areas are more influenced by erosion. The small bushes only have a small root network comapred to larger bushes and trees. This decreases the organic matter content and root space created by roots, which increase infiltration rates.
C6	Dense grass	Mainly grass occurs here (table 9). Duet o lack of water the only type of vegetation which can suruvue out here is or are grass species. It is a sign that he soil (surface) is still rooted and still better in absorbing water compared to rangeland or bare land areas.
C7	Rangeland (medium cover)	Rangelands are complicated regions to describe the relation (sensitivity) to erosion. Rangeland with medium cover can be found in the mid and uplands and are semi-occupied by vegetation. But on the other hand does this vegetation not really cover the land. So the soil and especially the surface (top soil) can be eroded. This whole layer can be transported by for example runoff.
C8	Rangeland (light cover)	As explained in table 9, the line between Saliña and light cover areas is thin. However there is a small difference in grain size ratio and vegetation. Areas closest to saliña areas mostly meet this cirteria.
C9	Agricultural field	LVV territory -in the upland area- is the only region in my research that's classified as agricultural area. Tjis lands are mostly cultivated and roamed by animals. The LVV territory is an area with a lot of loose material (loose topsoil). More urban or habitats downslope are protected by several dams and reservoirs. To store sediment,

C10	Saliñas	Saliñas are: *'flat areas where water is easily collected' (3.1).* In the Saliña (di Vlijt) several coral dams were built to maintain the water. There is almost no vegetation. Saliñas situated in catchment 5 (Saliña di Vlijt) and close to the Merriot Courtyard complex, are pretty much bare. These areas the lowest points in the areas and most of the (transported) sediment by erosion is deposited. Although the Saliñas perform an important role in the (whole research) area, it is highly sensitive for further erosion. Especially in the rainy season. Due to very low infiltration and none landcover, sediment deposie in these flat areas, are somewhat taken easily towards the ocean.

5.2 Management scenarios/Measures

Measures are needed to control and/or solve the present situation and/or problems caused by the effects of and originating from erosion. Measures discussed in these paragraphs are mostly determined to, for example, reduce the sensitivity to erosion of land-use types and/or decrease the influences critical areas cause to erosion/sedimentation transport. Some of these measures are already in progress but need to be improved or expand.

5.2.1 Reservoirs

Sediment removal in reservoirs (especially on governmental territory) is not a priority at the moment. Especially reservoirs closest to Kralendijk have a legal status and are in the Bonaire Development Plan (Beek, I.J.M. et al, 2015 & DRO, 2010), registered as freshwater areas.

Because reservoirs are important in the prevention of floods in residential areas, they are maintained and cleaned whenever it is considered necessary. According to the DRO (Dienst Ruimtelijke Ordening) (Pers. Com. Jeroen Meuleman, 2012) every 1 to 5 years.

The reservoirs on Landbouw, Veeteelt en Visserij (LVV) territory are on occasion maintained by LVV. The governmental reservoirs in the uplands are maintained by the DRO when funding permits it. The importance of the reservoirs in the Playa catchment and the effect of losing 'tankis' ((small) reservoirs/tanks) can be understood due to lack of maintenance. If these reservoirs aren't maintained more often, rainfall events of different intensities will cause reservoirs to overflow more often with the risk losing the reservoirs totally. This means a decrease in storage capacity of 20600 m3. In other words: A small issue could become a large problem.

5.2.2 Overgrazing

Reduced grazing will increase vegetation cover. Overgrazing is a known problem on Bonaire. It was estimated that around 25000 goats, 5000 sheeps and unknown number of donkeys are present on the Island (Nolet and Veen, 2009). This means 4 goats per hectare (Nolet and Veen, 2009). During the dry season the carrying capacity of Bonaire is estimated at 1 goat per hectare whereas 14 goats per hectare during the wet season. This means the carrying capacity is being exceeded for the largest part of the year. (Koster, Geert 2013). Thereafter, goats can freely wander over the Island. Feeding them is unnecessary. This saves money and allows the owners to keep more goats (Debrot et al., 2012).

The main problem overgrazing is causing is reduced vegetation cover. Rate of succession for plants to mature and decline in grazing sensitive species, while grazing resistant species (often thorny) are given a competitive release (De Freitas et al., 2005). The decrease in vegetation cover has lead to increased soil erosion due to a reduction in root cover, organic matter, surface roughness and rainfall interception. For this reason plans are (still being) made to reduce the grazing pressure of goats. It is believed that if the grazing pressure reduces, vegetation cover between the start and end of the rainy season increases. The reason for this is that mainly the grazers are to blame for bare soils in the dry season (Pers. Com Jan-Jaap van Almenkerk, 2012). Areas which have been 24/7 fenced for a number of years show a healthy ground cover both in the dry and wet season.

5.2.3 Reducing paved surface area

Another option for reducing soil erosion-runoff is to change the percentage of paved areas. In densely built areas such as central Kralendijk there is not enough space to reduce the amount of pavement but there are other indirect methods which can have positive effects on improving infiltration. Some improvents are for example permeable asphalt, “swells” (gravel beds below a lawn), ifiltration wells, more vegetation and increase of green urban areas. To estimate the effect of reducing the amount of pavement (especially in central Kralendijk), runoff and erosion was modelled for a rainfall event with a return period of five years when paved area is reduced by 10% and 20% respectively (Koster, 2013).

Construction of(more) reservoirs in the uplands governmental (LVV and governmental (DRO) territory) to reduce the chance for (surface) runoff, overflow and decrease pressure on the reservoirs closest to Kralendijk. Especially in (sub) catchment 1, 4 and 5 (fig. 3.4).

Fig 5.1: Water overflow in Kralendijk (photo Antoin, 2004). L.Borst and S.A. de Haas, 2005.

5.2.4 Fertile soil

The Vrije Universiteit (VU) and Universiteit van Amsterdam (UvA) are teaming up with partners from Bonaire (Wayaká Advies BV and local authorities) to do research into these erosion issues. This research is an example of that cooperation and herein the causes of erosion by determining the most important soil and hydrologic characteristics of different land types around the capital of Kralendijk are mapped. Also the layer thickness of deposited soil in the Salina di Vlijt is determined. This appears to be up to 50 cm in some areas. This is fertile soil that flows down from higher areas into the Saliña during heavy rainfall. Although this 50 cm layer is testimony to the magnitude of the erosion issues in the area, it could have a second function. Emptying the Saliñas, fertile soil can be used for farming and this will give renewed fulfillment to the Saliña(s).

6 Conclusion

To be able to answer the main research question: ''Is there a correlaton between discharge of water and erosion in the 'Kralendijk' catchment?'' This research shows that there is in fact a correllation between the two processes. Both soil and hydrological properties of each soil type influence the extent of impact. Especially, when soils hardens during the dry season with little to no rain and less chance of vegetation growth due to trampling cattle (goats, sheeps,dokeys), the top soil becomes at some places water repellent. Extreme rainfall events, during the wet season, forms rivers and water flows –transporting the upper soil layer from higher areas– towards the ocean until sediment is deposited (fig. 6.1). Saliñas are important flat areas where soil material is deposited to prevent this material to runoff into the sea. The (upper) soil layer in Saliña di Vlijt is fertile soil (§5.2.4) transported by erosion from higher areas (fig. 4.7). To measure the soil layer thickness in Saliña di Vlijt, several soil drillings were done. It turns out to be 40-55 cm at some points. A plan to scrape off the upper layer, 40-50 cm, has got a green light and will start in 2018. If further measures are not taken, even in the nearby future, Saliñas could quickly fill up and (brown) sediment loaded water will be deposited in the ocean. This has a great impact on the corals (L.Borst and S.A. de Haas, 2005).

Fig 6.1: Water flowing from Saliña into the harbour (photo Antoin, 2004). L.Borst and S.A. de Haas, 2005.

Most of the critical (erosion) areas are situated in the uplands and urban areas. Steep slopes in the uplands easily discharge (coarse) loose sandy material downslope. Figure 4.7 (p.40) clearly shows a high erosion levels in the upland areas of all catchments, but the highest values are situated in the north-eastern part of catchment 1 and 5. The southern part of the research area is still influenced by erosion yet much less compared to the northern part. Obviously the reason for this is less urbanization and more vegetation. The soil is in general quite heterogeneous, so measures need to be well fitted locally.

Measures to reduce erosion in and around Kralendijk, are discussed in paragraphs (§5.2.1-5.2.4, p.42-44) have been formulated to the (erosion) situation. All measures described contribute in reducing erosion. Most promising measures though, are the reducement of paved areas and overgrazing. Realising and expantion of these plans can be achieved in a short term. For instance, the measure to reduce paved areas could be adjusted to new building sites. However, as mentioned in the paragraph, Kralendijk (and especially central Kralendijk) is to dense to change the percentage of paved area. New methods (permeable asphalt, more vegetation etc) are doable and cost friendly ideas to achieve the goal of increasing infiltration in paved areas. Overgazing is a problem that could easily be solved by controlling areas for grazing. By fencing off more areas from goats, sheeps and donkeys, grazing pressure on multiple areas is reduced. Therefore allowing vegetation to grow and reduce soil erosion.

Although the plan to increase the frequency in maintenance (dredging and cleaning) of reservoirs is very helpful to prevent natural disasters (floods, flows etc), reservoirs on the Island (especialy those maintained by the government) are maintained and cleaned whenever funding permits it. It is very difficult to pursuade local authorities to increase maintenance, because the governmental budget for an Island as Bonaire is not unlimited (Beek, I.J.M. et al, 2015. Structure and financing of nature management costs in Caribbean Netherlands, (2015).

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