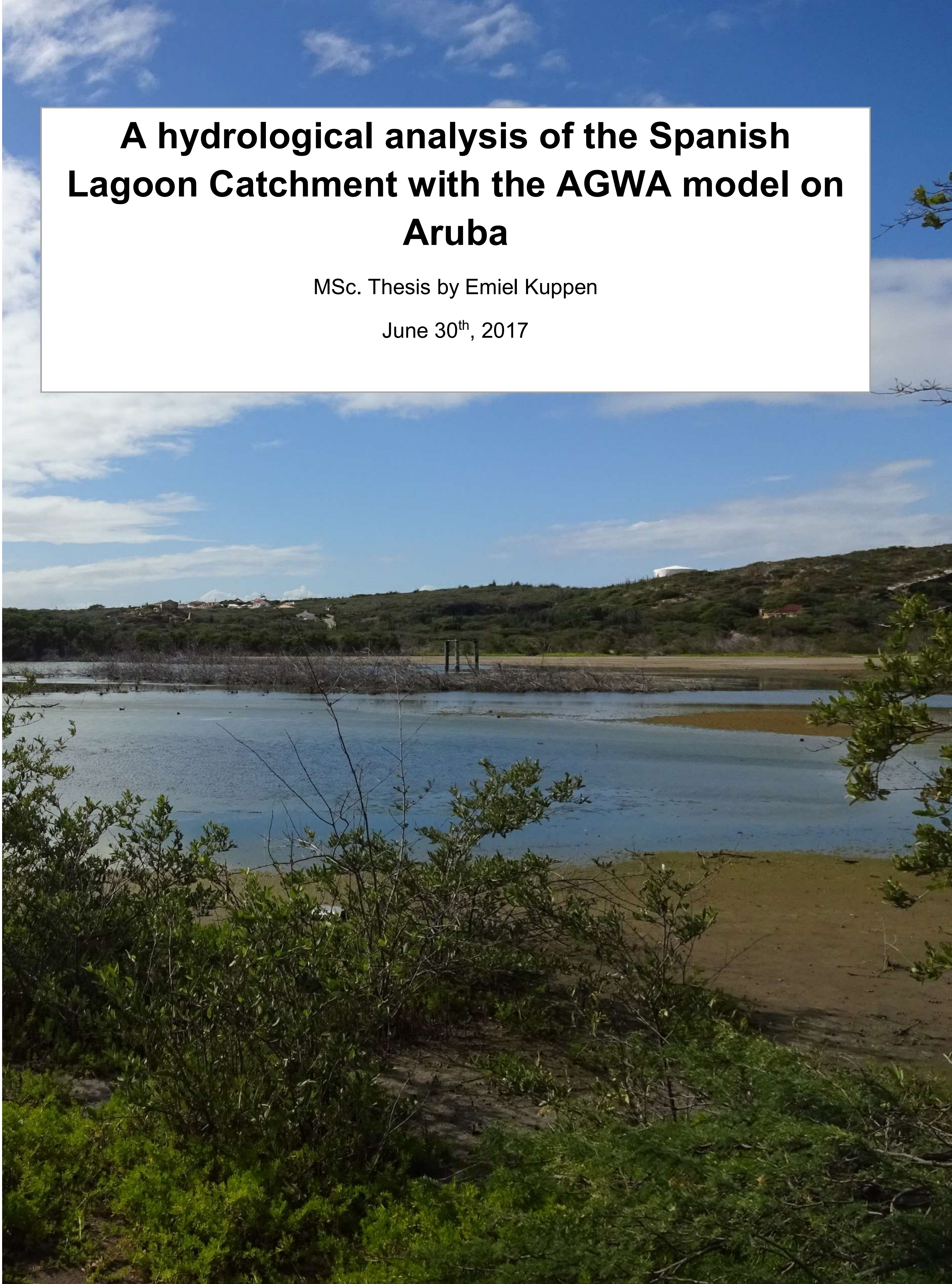
A hydrological analysis of the Spanish Lagoon Catchment with the AGWA model on Aruba

MSc. Thesis by Emiel Kuppen

June 30th, 2017



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Fieldwork has been carried out to be able to create a soil- and land use map of the catchment to set up and run a AGWA model. Simulations are done with Kineros2 (for one extreme rainfall event) and SWAT (until 2070) for the current situation and possible future scenarios, to get insight into the infiltration, runoff and sediment transport.

MSc. Thesis by Emiel Kuppen

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ABSTRACT

A HYDROLOGICAL ANALYSIS OF THE SPANISH LAGOON CATCHMENT WITH THE AGWA MODEL ON ARUBA

Mangrove forests are important ecosystems with a large biodiversity. This study focuses on a catchment in Aruba in which the Spanish Lagoon mangrove forest is located. The area is protected since 1980, and was added to the Arikok National park in 2017. The managing board of the park decided to excavate a channel to create new mangrove forest at the head of the lagoon. This study analyses the influence of the runoff and sediment on the lagoon. This has been done by executing field measurement to determine soil parameters and interviews and observation to create a land-use map. Those are used to model the hydrologic situation of the catchment with the AGWA model. This includes a simulation of a single extreme precipitation event with Kineros2 and a year-round simulation of the catchment with SWAT. The results show that deposition of sediment is a threat for the lifespan of the channel that has been excavated. For the long term, the analysis of the SWAT model gives an indication for the situation of the catchment until 2070. The outcomes show that further reduction of the amount of precipitation can have widespread consequences for the catchment.

PREFACE AND AKNOWLEDGEMENT

This is my MSc Thesis for the study International Land and Water Management at the Wageningen University. The thesis has been written under supervision of Klaas Metselaar from the Soil Physics and Land Management Group. It was my wish to go abroad for this research and Klaas helped me a lot to find a good place for me to do this. I want to thank you for the possibility you gave me to do this research and the inexhaustible will to help me whenever I need help.

The data collection of for this study has been done on Aruba which was accompanied by Emil ter Horst. I want to thank Emil for the possibility he gave me to come to Aruba and the hospitality he offered by letting me live and work in his house. I also appreciate it a lot that Emil was willing to show the island to my father when I had to go home earlier than expected. I hope that you can use this study as well as the studies of the other students you accompanied for further development and research on Aruba.

The last person that I want to thank is Anouk Horn. Anouk is a fellow student who did research that was comparable to mine using the same model and fieldwork strategy. Already on the first days after I arrived on Aruba she helped me to explain everything she did so far and helped me with my fieldwork. The methods that I have used are mainly adopted from Anouk’s research and this saved me lots of time and struggling. Because she started about 2 months earlier with her research Anouk has always been ahead of me. This meant that I could always ask her for help about the fieldwork or the model that we both used.

Next to the fact that Anouk helped me with the fieldwork and the model it was also very nice to have another student on the same subject to be able to have in depth conversations and discussions about everything that had to do with the study. Lastly, I want to thank Anouk once more for showing me island, introducing me to local people who became friends and enjoying the good life of Aruba together.

This research will also be shared with the people I spoke with on the island from different authorities and organizations. I hope that those people will look at this report and support future research on the island. I think that there is much more interesting research to do in the area of environmental science on Aruba, but more collaboration with the authorities and data exchange between them would help further research.

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1. INTRODUCTION

Mangrove forests occupied about 140.000 km2 of the coastline of tropical areas in 2000 (Giri et al., 2011) but this area is rapidly decreasing because of agriculture, aquaculture, tourism and urban development (Alongi, 2002; Giri et al., 2008). Next to clearing of the trees also relative sea level rise is a major threat for mangroves and a prediction by Duke et al. (2007) concludes that there will be no mangrove forest left 100 years from now, when the present rate of loss continues. These alarming conclusions resulted in growing concern about the loss of a highly productive ecosystem that is rich in biodiversity and contributes to livelihoods by providing forest resources (Spalding, 2010). Mangroves are also recognized as carbon sinks (Alongi, 2012) and protective areas for natural disasters such as tsunamis and cyclones, especially in small island countries (Spalding et al., 1997).

The Caribbean area consists of many islands with a total of 28 different independent counties. The mangrove forests in the Caribbean are characterized by a micro-tidal regime and a highly seasonal climate (Lambs et al., 2015). These are perfect conditions for mangrove plants who are adapted to salt water because of the year-round availability of sea water. The Caribbean region has the second highest mangrove area loss relative to other global regions, with approximately 24% of mangrove area lost over the past quarter-century (FAO, 2007). Several studies to Caribbean mangroves report many threats including coastal development, upland runoff of pollutants, sewage and sediments, petroleum pollution, storms and hurricanes, small-scale or minor clearcutting, conversion to aqua- or agriculture, tourism and prospecting for pharmaceuticals (Ellison and Farnsworth, 1996; Duke et al., 1997; Polidoro et al., 2010). This study will investigate the runoff and sediment transport towards the biggest mangrove forest of Aruba.

Aruba is a small island in the Caribbean that accommodates a wide range of different landscapes, some of which have high nature value areas such as the Arikok National Park, but also coastal lagoons with mangrove forests (DCNA, n.d.). The value of these areas is not always considered when it comes to decision making because of the economic value of tourism. This leads to the implementation of large scale development of the island without an environmental impact assessment (Becker, p.c., 2017). The effect of land-use changes and urbanisation on the nature areas are unknown. To support future decision making, it is important to get insight into the current situation of the nature areas and analyse the possible influence of changes within their catchments. This research focuses on the hydrological situation of the Spanish Lagoon catchment on Aruba. This is the most significant coastal lagoon of the island and one of the largest natural lagoons in the Caribbean (DCNA, Spanish Lagoon). The lagoon is a protected area designated by RAMSAR[1] in 1980 which describes it as follows (RAMSAR Site Information Service);

"Het Spaans Lagoen is a narrow coastal inlet, fringed by tidal mudflats and mangrove swamps. An important feeding and breeding area for water birds, and nursery area for various species of fish and crustaceans. Ramsar site no. 198."

[1] The Convention on Wetlands, called the RAMSAR Convention, is an intergovernmental treaty that provides the framework for national action and international cooperation for the conservation and wise use of wetlands and their resources (http://www.ramsar.org/).

From 1980 until 2017 the area was protected, but hardly any management, monitoring or research took place in the area (G. Boekhoudt p.c., 2017). Since March 31st, 2017 Spanish Lagoon is part of National Park Arikok and management strategies will be implemented to protect the mangrove forest. The risk of implementing measures is that the situation of the Spanish Lagoon is uncertain and the effect of the measures is unclear (F. Franken, G. Boekhoudt and T. Becker, p.c., 2017). The aim of this research is to describe and analyse the hydrological situation of the catchment of the Spanish Lagoon and parameterize and use a model to quantify runoff, infiltration and sedimentation towards the mangrove forest.

1.1 STUDY AREA

Aruba is a small Caribbean island located 25 km before the Venezuelan coast and forming the “Benedenwindse” islands with Curacao and Bonaire. The total land surface of the island is approximately 180 km^2 which makes it the smallest of the three islands. Aruba is a constituent country of the Kingdom of The Netherlands, with their own parliament and cabinet. Although Aruba is not an official member of the EU, they receive money from the European Development Fund. With more than 100.000 inhabitants the island is densely populated (559 persons per km2) with the capital Oranjestad at the centre (ROP, 2009).

The island is located in the tropics, and has a tropical steppe, semiarid hot climate (Ridderstaat et al., 2014). The average temperatures are between 25,6 and 28,8 Celsius with only little difference between winter and summer (Departemento Meteorologico Aruba, 2012) The rain season is from October through December and on a yearly basis the annual rainfall is approximately 470 mm, measured in a period from 1981 to 2010. During this same period, the average amount of days with thunderstorms was 17,9 per year. This is relatively low as compared to the rest of the tropics but still has a major impact on the water management on the island (Ridderstaat et al., 2014).

This study focusses on the catchment of the Spanish Lagoon, located in the centre of the island. Aruba consists of about 10 catchments. Out of these 10 this catchment is relatively big, but still only 13,7 km^2. The catchment is located at the northern side of Santa Cruz and covers a part of National Park Arikok, including Jamanota, Aruba’s highest mountain (188m). The outlet of the catchment is located a few hundred meters inland, at the head of the lagoon (Figure 1).

Figure 1; Study area, the location of the Spanish Lagoon and the outline of the catchment (Google Earth)

The core of Aruba consists of an old lava formation with a combination of conglomerates, dolerite and tuft which has partly been covered by younger sediments. The south coast is located on a limestone area while most of the northern and central part are covered by the tonalite batholite formation (ROP, 2009). Westermann (1932) presents a geological map for the island. Figure 2 shows the part of the map in which the Spanish Lagoon is located.

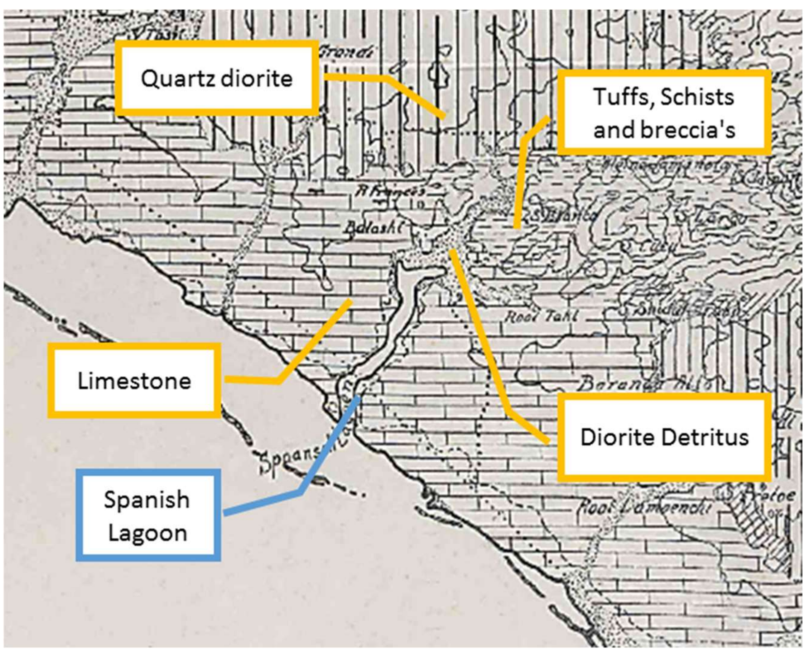


Figure 2; Geology of the area around the Spanish Lagoon (Westermann, 1932)

1.2 BACKGROUND

Aruba has been inhabited for thousands of years by Indian tribes and was discovered around 1500 by the colonists. In 1636 the island was taken by the Dutch but remained uninhabited until 1754 when the first western colonists started to live on the island. They started with equestrian farms and the production of Aloe Vera but this was all small scaled and the landscape remained in its natural shape until around 1900 (ROP, 2009).

During the 20th century the land-use of Aruba will drastically change and as described in the ROP (2009) this has the following reasons: the first reason is that around 1900 the mining of gold and phosphorus started, leading to immigration of former slaves from Curacao. In 1929 the second immigration impulse was the opening of the Lago oil refinery in San Nicolas which was needed to ship the Venezuelan oil to the US. Aruba benefited in an early stage of the worlds dependency of oil and this created large transformations for the landscape of the island. In the first place, the imagery of the imposing oil refinery but also urbanisation of the southern part of the island.

From 1953 onward the economic focus was more and more on tourism, because the oil refinery stopped growing while the population kept increasing. While the southern part of the island was already urbanised and industrialised, now also the northern part of the island started to develop. The number of tourists kept growing and when the Lago oil refinery closed in 1983 the economy of Aruba depended fully on tourism. The number of tourists is still growing with over 850.000, mostly American, visitors in 2011 (Ridderstraat et al., 2014).

The downside of this rapid growth of economy and inhabitants on Aruba is the impact of those transformations on the landscape of the island. Especially in the 1980s when the economic hart of the island moved from south to north, a dense network of roads started to develop and this created a highly fragmented landscape. Together with the high rate of urbanisation the landscape of the island changed almost entirely during the past century and only small parts of the island remained in a natural state.

The Spanish Lagoon is one of those parts of the island that remained in a relatively natural state and because it is one of the last natural wetlands, it is also increasingly important to birds, fish and other species as an area to live and breed. As also mentioned in the ROP of Aruba (2009) the fragmentation of the island is affecting the entire island. With this study, insight will be gained into the impact of the current stage of the catchment on the mangrove forest and how possible future scenarios can change this.

1.3 SCIENTIFIC BACKGROUND

Very limited scientific research has been done on Aruba and even less is available online or in libraries. The only study that has been found about the Spanish Lagoon is about bird species in the forest (Mlodiinow, 2006; Mlodiinow, 2015), but nothing that has to do with the hydrology of the area. An important base study for the entire island has been done by Grontmij and Sogreah (1968) who made a water and land resources development plan that gives an overview of the geology, climate, hydrology and soils of Aruba. In addition to this study Van Belle and Strijker (year unknown) from the University of Groningen preformed an inventory into the terrestrial environment of Aruba. The focus of this report is on flora and fauna, but also a landscape analysis is done. As mentioned before, the landscape on Aruba is highly influenced and fragmented by human influence. This report states that Aruba was forested completely before the colonists arrived but now the island turned into a semi-desert.

The flora on Aruba is more intensively documented, among others about the native species (Freitas, 1996; Perk, 1997) on protection and spatial variation. Other research focussed more on a detailed vegetation map for the island (Beers et al., 1997). The most complete and detailed work on flora on Aruba is Arnoldo's Zakflora (Proosdij, 1954) which was updated in 2001. During the 1990s more researchers from o.a. Wageningen, Utrecht and Groningen University had research projects on Aruba, but this stopped because of a lack of funding that came with declining political interest (F. Franken, p.c., 2017). An example of a study was on erosion and sedimentation on the island (Geelhoedt, 1997) but these reports are only available at Santa Rosa (ministry of agriculture).

On a world wide scale there is scientific research on situations which are like the situation in the Spanish Lagoon, i.e. research about the influence of the soil and land-use in the catchment on a mangrove forest at the outlet. In a study by Neil et al. (2002) the effect of changing land-use from natural area to cropland in the catchment behind the Great Barrier reef is modelled. The sediments load is quantified and it turned out that the sediment load will increase with a factor four. For the Great Barrier reef the main threat is that this increasing amount of sediment will also increase the potential transport rates of nutrients and other pollutants, but stronger empirical support is needed draw conclusions on this. A field study by Williams et al. (2012) measured and modelled the influence of agricultural land close to a mangrove forest in Puerto Rico. Combining runoff measurements with groundwater depths to calibrate the field hydrology the APEX model was used to simulate the hydrology and water quality of the fields. The outcome of the model was that a field managed as described in the Riparian Ecosystem Management Model (REMM) reduced the sediment load with 24% in comparison to the non-managed field. Another outcome is that tropical storms have huge impact on the sediment load, about 63% of the total amount. Since Puerto Rico is also an island in the Caribbean Sea, the effect of those storms is important to consider for this research as well. A difference between the islands is that Aruba is located more in the south of the Caribbean, and the number of hurricanes and tropical storms is less in this part (NASA earth observations, n.d.).

1.4 PROBLEM STATEMENT

The Spanish Lagoon has been a protected RAMSAR area since 1980 and has most recently been adopted as part of the Arikok National Park. This means that the area has been protected for 37 years, but hardly any kind of management, monitoring or research has taken place. According to interviews and personal observations the mangrove forest is threatened by siltation at the head of the lagoon by sediment coming from the catchment. Sedimentation of the back of a mangrove forest is a natural process, but in this case, it is a problem because the forest is also unable to grow seaward.

Currently there is a lack of knowledge on the hydrological situation of the catchment. |The rainfall-runoff relation and the sediment-runoff relations are unknown for a single rainfall event or on the longer timescale. This is a problem because during large rainfall events flooding occurs in the catchment which lead to damage on houses and infrastructure, like in November 2016. This study aims to use information on the soil type and land use in the catchment and provide insights on runoff, infiltration and sediment flows. This knowledge can be used to manage the catchment and protect the mangrove forest.

1.5 RESEARCH QUESTIONS

The main research question of this study is;

- What is the influence of the soil and land-use in the catchment on the runoff, infiltration and sediment load that enters the Spanish Lagoon for current and future situations?

To be able to answer the main question the following sub-questions need to be answered;

1. What is the current hydrological status of the catchment?
2. How much sediment will be deposited in the recently excavated channel during an extreme precipitation event
3. What are possible future scenarios for the Spanish Lagoon catchment?
4. What are the effects for the different scenarios compared to the current situation?

2. RESEARCH METHODOLOGY

2.1 FIELDWORK

The fieldwork focused on the collection of soil samples and their analysis to determine the soil type. Next to the sampling of the soil measurements were done to determine top soil parameters. The outcomes of the samples and measurements are used as input for the AGWA model.

2.1.1 Soil Samples

Soil samples have been taken over the catchment to get insight into the different soils in the area. The figure below shows an overview of the catchment and the locations of the soil samples (Figure 3). The samples are taken all over the catchment to cover the area as much as possible. Most samples are taken about 5 to 10 meters off the route on a spot with bear soil, often under the vegetation. There are also soil sample taken during different hikes through Arikok National Park or around the Spanish Lagoon to get a complete picture of the catchment.

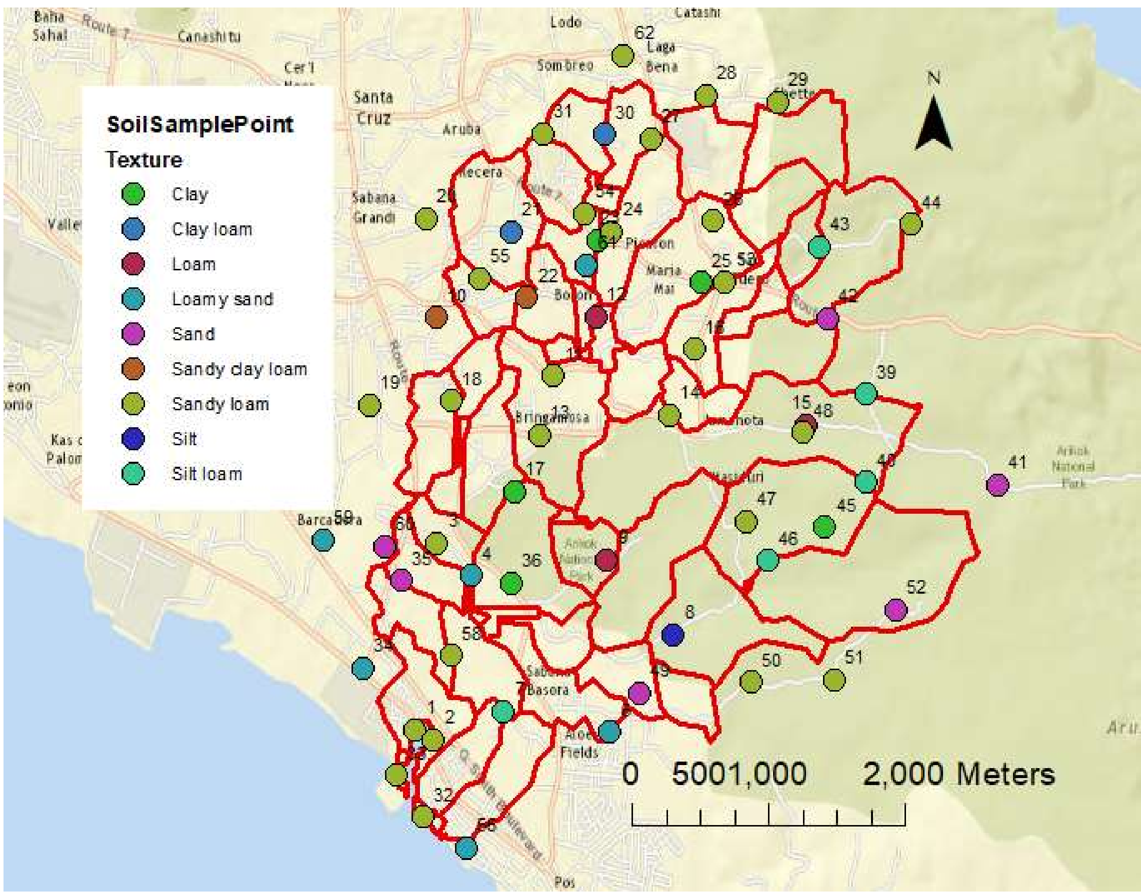


Figure 3; Overview of the catchment with the soil sample points

All the locations are visited and a sample between 250 to 500 grams of topsoil was taken for analysis. The following measurements were done to determine the soil type of the samples;

- The first step after drying the sample is weighing the total volume and determining the rock content of the sample. This is done by sieving the sample and weighing the amount of the soil that is bigger than 2 mm.

- To determine the ratio of the different particles in the soil a simple method, the so-called sedimentation method, has been used (Taubner et al., 2009). The basic principle is that the sedimentation velocity of the different particles is different because of the difference in size. The soil is mixed with water in a cup and the next day the amount of sand, silt and clay can be measured (Rowell, 2014; Michigan State University, Bio-energy Sustainability Project, n.d.). Figure 4 shows an example of the cups one day after the sediments are mixed with water.

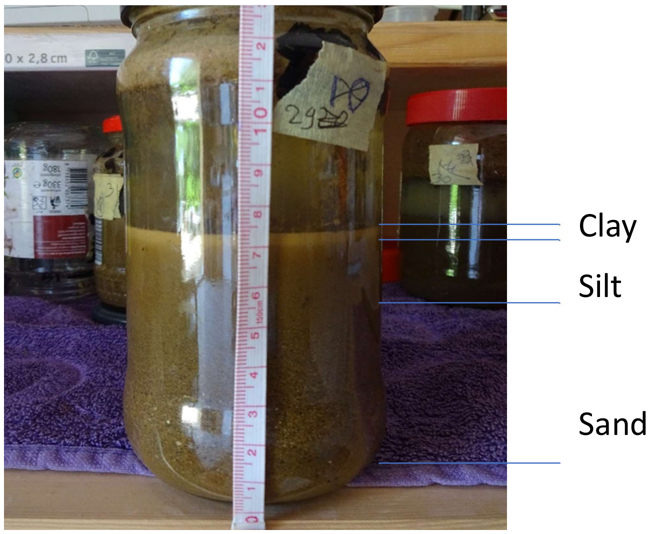


Figure 4; Soil Sample after the sedimentation method with a clear clay layer on top, a silt layer underneath and a sand layer on the bottom.

When the percentages of clay, silt and sand are determined the soil type can be defined by using the soil triangle (USDA). More details about this in Appendix 1.

2.1.2 Field measurements

In addition to determining soil texture, a map is created with the different soil sample points and the corresponding soil type. On a location on every single soil type additional measurements are done:

- Soil samples to determine the bulk density and porosity of the soil using 100cc rings. For the bulk density, the sample was dried in the sum. The samples were weighed at least once a day until the weight was steady. To determine the porosity the sample is wetted again until all the pores are filled with water.
- The infiltration of the soil was measured with an infiltrometer. This is a small device with a porous plate that is put on the soil. The rate at which the water level drops indicates the hydraulic conductivity of the soil (Decagon Devices, Inc., 2014).

2.1.3 Rainfall simulator

In addition to the measurements that are needed to adjust the input for the AGWA model the amount of erodible sediment was measured with a small rainfall simulator. This method is used because during the campaign period (the dry season on Aruba) there were no actual sediment flows to measure. By simulating an intense rainfall event for a small plot of bare soil and a gradual slope the amount of sediment and runoff are measured. This method of using a small and portable rainfall simulator has been used e.g. by Zemke (2016) who made a comparison between bare and vegetated soils. A study by Cerda, et al. (1996) describes the usage and practices of a small rainfall simulator in more detail. Both studies mention the importance of calibrating the desired rainfall intensity by choosing a constant pressure head. This was tested before going into the field and the simulations were all executed with the same rainfall intensity of 250ml per minute.

2.2 MODELING WITH AGWA

The model that has been chosen is AGWA, which includes both Kineros2 and SWAT. The different parts of the model are described below;

- Kineros2 model; the model was developed at the US Department of Agriculture in the 1960s. The latest version of the model is now distributed freely via internet (Semmens et al., 2007; Smith et al., 1995). Semmers et al. (2007) give the following description of the Kineros2 model; "Kineros2 is a distributed, physically based, event model describing the processes of interception, dynamic infiltration, surface runoff, and erosion from watersheds characterized by predominantly overland flow. The watershed is conceptualized as a cascade of planes and channels, over which flow is routed in a top-down approach using a finite difference solution of the one-dimensional kinematic wave equation (Figure 6 gives an example of the conceptualization). Kineros2 may be used to evaluate the effects of various artificial features such as urban developments, detention reservoirs, circular conduits, or lined channels of flood hydrographs and sediment yield". The input of the model will be established as explained before and the model will be used to get insights into the runoff, infiltration and sediment yield of the catchment.

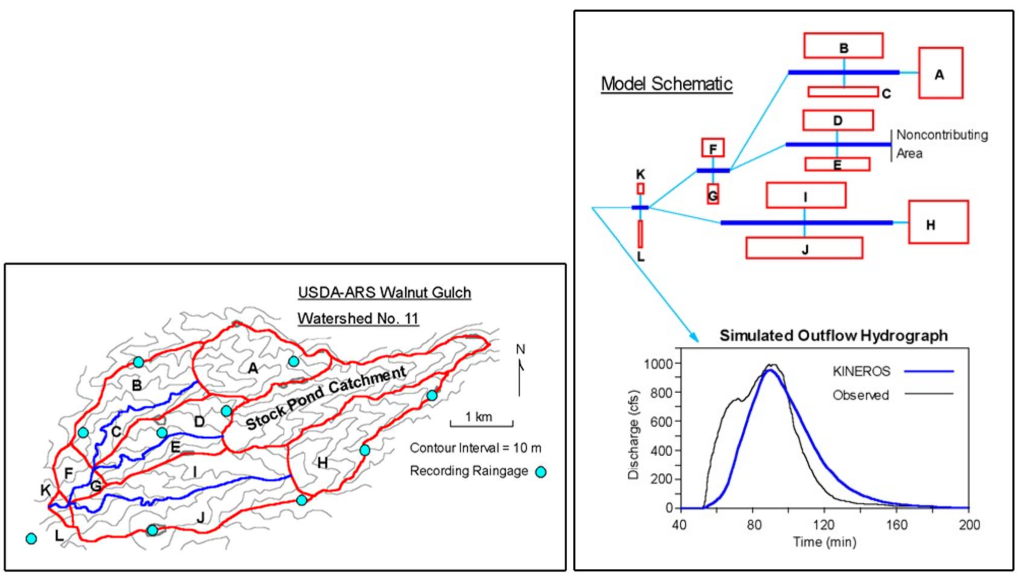


Figure 5; Example of Kineros2 model conceptualization (http://www.tucson.ars.ag.gov/kineros/)

The model has been used and tested in a few other studies, one of which is a study by Al-Qurashi et al. (2008). He concludes that the factors that mostly affect the peak discharge are infiltration, Manning's roughness of hillslopes and channels and the rainfall parameter. The model is validated for different rainfall events, but Al-Qurashi et al. (2008) only looked at the discharge and runoff. Another study by Ziegler et al. (2001) also included sediment movement. This study is very critical regarding the possibilities of the model as they had to make some major adjustments to get the same outcomes from the model as they got from field measurement. For this study, this leads us to conclude that it will not be possible to provide the tons per year of sediment that flow towards the mangrove forest. The goal is to provide insight in sediment flows and locations of detachment, transport and deposition.

- The Soil and Water Assessment Tool (SWAT) is the second model that is used in this study. The version of that has been used is SWAT 2005. On the website of SWAT (swat.tamu.edu) the following description of the model is given. “SWAT is a public domain model jointly developed by Texas A&M and AgriLife Research. SWAT is a small watershed to river basin-scale model to simulate the quality and quantity of surface and ground water and predict the environmental impact of land use, land management practices, and climate change. SWAT is widely used in assessing soil erosion prevention and control, non-point source pollution control and regional management in watersheds”. The most important difference between SWAT and Kineros2 is that SWAT is a continuous-time model which means that long term effects can be calculated. A study by Arnold et al. (2012) is giving an extensive and complete overview of the model possibilities the model has also been validated to prove the accuracy and calibrated to improve the software.
  The way SWAT is used during this research is through the interface of AGWA. This strongly limits the number of parameters that had to be set and almost all the input that had been used for Kineros2 could be used for SWAT as well.

- AGWA (The Automated Geospatial Watershed Assessment tool) is a tool that is developed by Miller et al. (2007) to link Kineros2 and SWAT to GIS. Miller et al. (2007) describes the model as follows; “AGWA uses commonly available GIS data layers to fully parameterize, execute, and visualize results from both the Soil and Water Assessment Tool (SWAT) and Kinematic Runoff and Erosion model (KINEROS2)”. In a paper by Goodrich et al. (2012) a detailed description is given about the use of the model and its calibration and validation. The input that is needed to be able to simulate a catchment is limited. A DEM (Digital Elevation Model) is used to calculate the external borders of the catchment and the location of the streams. The DEM is also necessary to discretize the catchment into smaller watersheds with the corresponding topographic data. The second inputs are a soil- and land-use map of the area. These are uploaded or created in GIS and then linked to the available databases integrated in AGWA. These inputs are identical for SWAT and Kineros2.
  The AGWA tool in combination with Kineros2 has not much been used yet in published science. Currently only some specific cases like post-wildfire response (Sidman et al., 2016) has been published There are a few studies that use the combination of SWAT and AGWA, like a study by Abdulla and Eshtawi (2007) to calculate the sediment yield for a catchment in Jordan. In this study, the calibration of the model with measured data was very important, but unfortunately this was not possible for the study about the Spanish Lagoon Catchment because data for calibration were not available.

Figure 6 gives an overview of the different processing steps that need to be done before a simulation with Kineros2 or SWAT can be run. For both models a catchment is generated from the DEM and this is discretized into watersheds and streams. For both models the parameterization also uses the same soil and land-use data. The main difference of the two models is the climate data that is needed for the simulation. For Kineros2 the only data that is needed is the amount of rain and the duration of the event. For SWAT, the daily mean maximal and minimal temperature per month are needed, but also data about windspeed, mm of rain and days of rain as average values per month are needed.

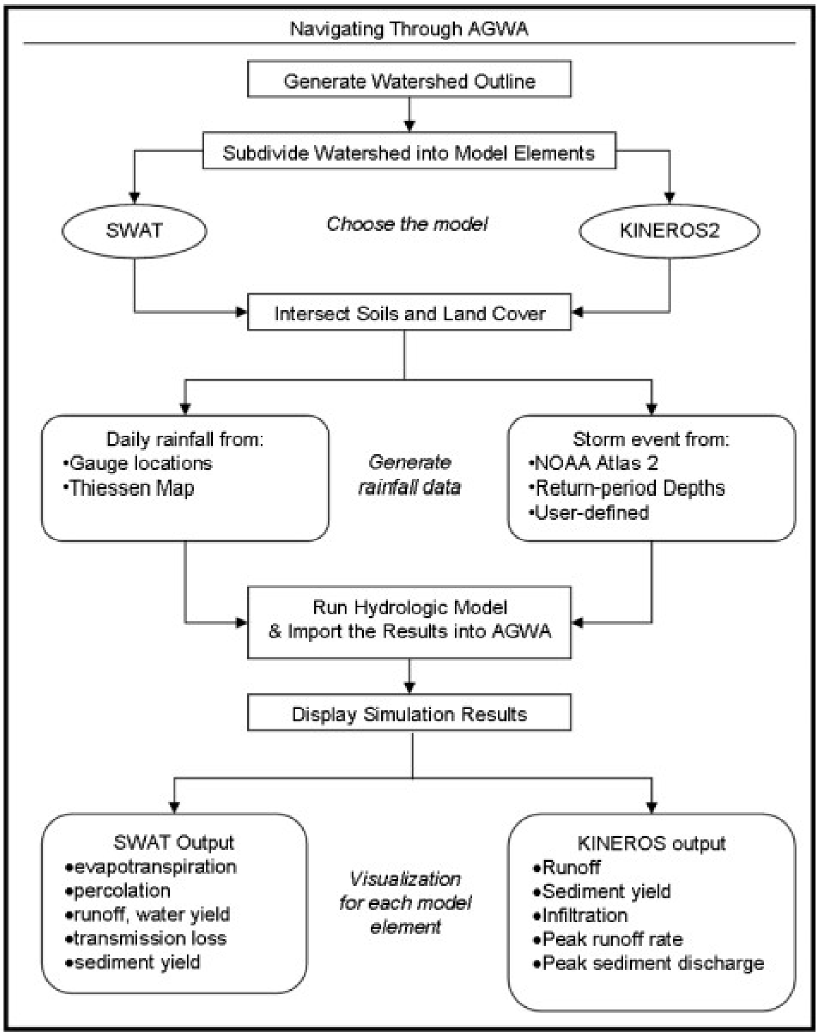


Figure 6; Basic processing steps for AGWA, from the AGWA user guide (https://www.tucson.ars.ag.gov/agwa/download/documentation/agwa_3.x_user_guide.pdf).

3. SCENARIOS FOR THE CATCHMENT

In addition to the calculations and modelling of the current situation, as explained in the previous chapter, the data that is collected also will be used to analyse the impact of different possible future scenarios.

3.1 CHANNEL AT THE HEAD OF THE LAGOON

The first scenario that will be explained is a management practice that has already been started at the head of the Spanish Lagoon. The intention of the project is to extend the mangrove forest by about 90 meters by excavating a channel and creating slopes on which the mangrove trees can start growing. The figure below gives an overview of the location of the project and some information regarding the shape of the channel (Figure 3).

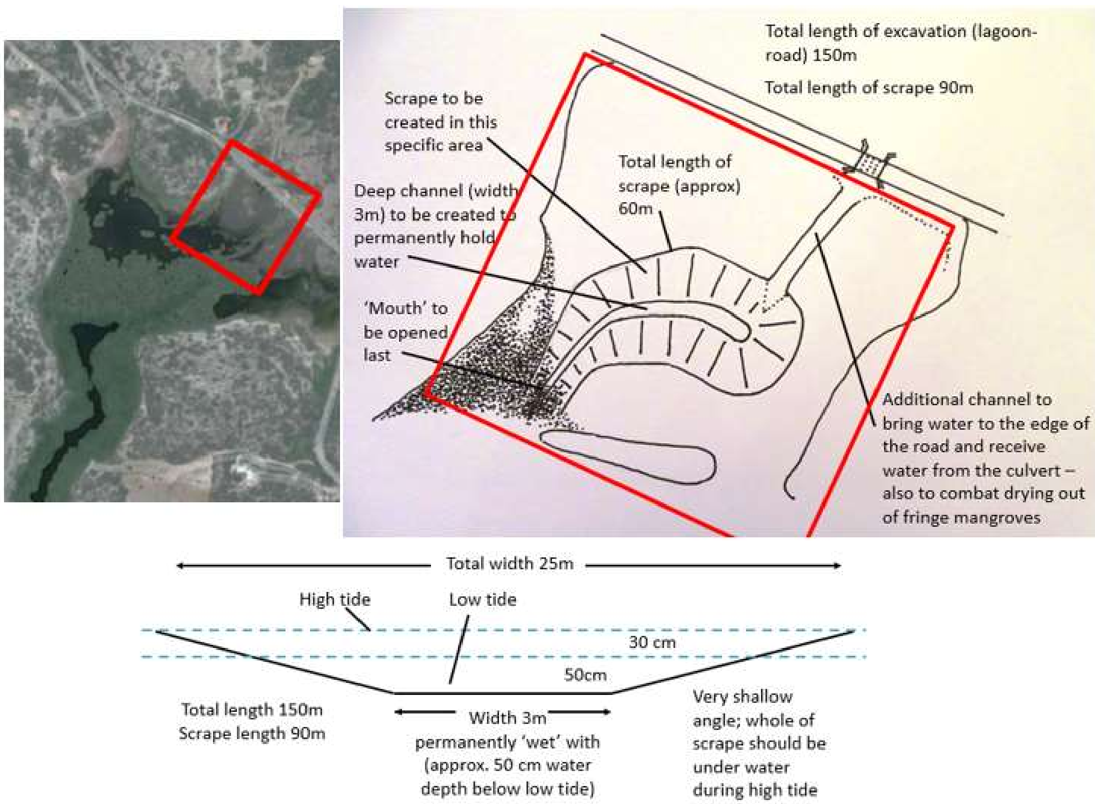


Figure 7; Overview of project based on presentation (Jones-Walters, 2017), showing the location and a cross section of the channel.

The reason that this project is now started is to compensate for the mangrove forest that has been lost during building activities in the lagoon towards the sea. A bridge over the lagoon has been build and because of the protected status of the lagoon the area that has been lost during this work needs to be replaced. The project started directly after the official allocation of the area to Arikok National Park, in March 2017. The research plan is made by ALTERRA Wageningen with Lawrence Jones-Walters as the project manager. In a news article (Intranet WUR, 2017) Jones-Walters mentions the project and says that everyone hopes that the project will be successful, but that this is dependent on the weather conditions and the siltation of the area. As to my knowledge no research has been done to calculate the amount of sediment that is transported towards the lagoon. This is the focus of this scenario.

A concern about the project that came up during all the interviews and conservations about the project is that the channel is located in a floodplain that is filled with sediment and that this also will happen with the new channel. It is unclear how the location is chosen for this project, but it seems like only little research has been done on this matter.

3.1.1 Amount of sediment replaced

The main goal of this scenario is to predict how resistant the channel is for erosion that will flow towards the area during extreme weather events. The rainfall event that occurred in November 2016 with 70 mm of rain in one single day will be the starting point of the analysis. To be able to give an indication of the resilience level of the channel the amount of sediment that has been replaced needs to be calculated and this will be compared with the outcome of the model.

Unfortunately, the detailed excavation plans are not public and therefore the cross-section and dimensions that are given in Figure 5 will be used. By calculation the area of the cross-section and multiply this with the length of the channel the total amount of soil that will be excavated will be around 1200m3, approximately 1800 tons. After the results of the model are known this amount will be compared with the amount of sediment transported towards the channel mouth from the catchment during an extreme rainfall event.

3.2 FURTHER URBANIZATION AND DEVELOPMENT OF THE ISLAND

The second scenario that will be looked at is a scenario in which the residential area will be developed more. The percentage of urbanized area is expected to grow from 50% in 2000 to 65% in 2030 (UN social development, 2002). Although most of the area in which the Spanish Lagoon is located is protected, this scenario will consider the change of current residential area from low to high intensity. For the model, this means that the land-use map will be changed and that “low intensity residential” will be transformed into “high intensity residential”.

Another aspect of the development of the island is that de streams will be developed more to be able to increase the rainwater runoff velocity. The idea is that this will reduce the flooding in the catchment. The DOW (Dienst Openbare Werken/ Department of Public Works) has decided to manage the streams more intensely which means that the area direct above or next to the stream will be cleaned to make room for the water (Boekhoudt, p.c., 2017). The locations at which the water was led over the roads will be changed and culverts will be constructed. This will protect the houses around the streams because the water will flow to designated areas. For the model, this means that the channel type that has be chosen will change from natural to developed. The results for this scenario will be given for Kineros2 and will be compared with the current situation and the other scenario.

3.3 VEGETATION COVER DEGRADATION SCENARIO

This study has been done during the first months of 2017, after a very intense and wet rain season in November and December 2016. The maximum precipitation event had an intensity of 70 mm within 24 hours on November 20th. This is an exceptional amount of rain and the people of the island where surprised by the amount of green on the island this year. The maximum amount of precipitation in 2014 was 18 mm on a single day. For 2015 this was 28 mm (The Weather Company, 2017). This scenario will simulate the situation of the catchment after a drier season when the island will be covered with less vegetation. For this scenario, the same precipitation event will be used, but the land-use map will be changed to create a degraded vegetation cover. This means that the vegetation that is indicated on the map will change to a less densely vegetated shrubland. This means that the soil becomes more vulnerable to erosion and the N (Manning's coefficient) will decrease strongly. The results of the simulation with Kineros2 for this scenario will be compared with the results of the current situation.

3.4 THE IMPACT OF CLIMATE CHANGE ON THE CATCHMENT

The fourth and last scenario that will be modelled characterizes the influence that CC will have on the runoff, infiltration and sediment load of the catchment. This scenario will be executed in SWAT because this makes it possible to see the influence of a changing climate over a long period of years. The climate input of the model will be changed according to the A1B scenario (IPCC, 2007b). This scenario is also chosen by Debrot and Bugter (2010) in a study about the influence of CC on the biodiversity on the Dutch Antilles. The A1B scenarios is described by the IPCC as follows;

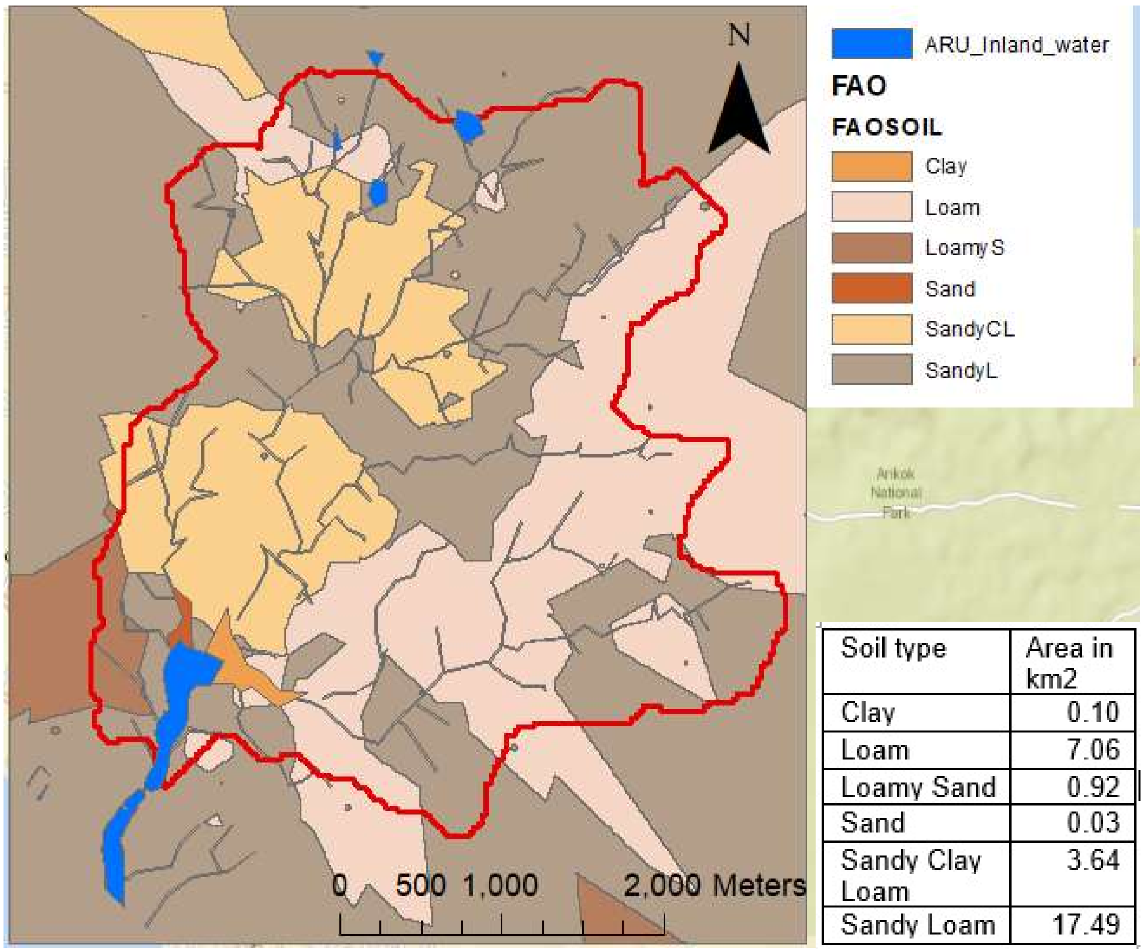
"The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. A1B is defined as not relying too heavily on one particular energy source but a combination between fossil fuels and non- fossil energy sources."

Within the scenario the average temperature is predicted to increase between 1.4 and 3.2 degrees for air and sea surface temperature. The sea level rise will be up to 1,3 meters at the end of the century (Deltacommissie, 2008). The most important factor for the simulation of SWAT is the change in precipitation, but unfortunately there are no clear predictions for the region of Aruba (Debrot and Bugter, 2010). In a study by Kunkel et al. (2013) an effort is made to predict global maximal precipitation for 2070. The study shows the outcomes in maps of fractional changes of maximum precipitation for seven climate models. The difference between the predictions for Aruba are that big that a dry and wet scenario are simulated. The percentages that are shown on the map range from about +30% to -30% and therefore both scenarios will be modelled.

4. RESULTS

4.1 SOIL MAP

In Figure 8 the final soil map is shown with the corresponding areas in km^2. The dominant soil type is Sandy Loam (17,49 km2). This is also the soil type that is found in the stream beds. In addition to Sandy Loam, Loam (7,06 km2) and Sandy Clay Loam (3,64 km2) are the most common soil types. The soil types Sand (0,03 km2) and Loamy Sand (0,92 km2) are only located in the south-western part of the catchment. Clay (0,10 km2) is located at the sediment body at the head of the Spanish Lagoon. The map is created by interpolating the percentages of clay, silt and sand for the soil samples. In GIS, the map below is created and can be read by AGWA.



Soil type	Area in km2
Clay	0.10
Loam	7.06
Loamy Sand	0.92
Sand	0.03
Sandy Clay Loam	3.64
Sandy Loam	17.49

Figure 8; Overview of the different soils in the catchment and the area in km2

For the different soil types, a SNUM code is created and added to the FAO soil database. SNUM codes are used by the FAO to specify the soil type, the slope on which the slope is located and the texture of the soil. In this database, the outcomes of the measurements are added and those are used to calculate the infiltration, runoff and sediment load. A more detailed explanation of the SNUM codes is given in Appendix 1.

During the fieldwork, a difference between the sediment body on the western side of the Spanish Lagoon and the one on the eastern side was observed. The western deposit consists of sand, with big fractions, while the sediment deposit on the other side is filled with clay. There are two reasons that explain the difference between the sediment deposits. The first reason is the different soil types located in the catchment behind the deposits. The map shows that an area of loamy sand is located behind the sand body, while this is not the case for the other part of the catchment. The second reason has to do with the use of the area in the past. According to Emil ter Horst (p.c., 2017) the area with the sandy sediment deposition used to be a more industrialized area with a gold melting plant, a railway and probably a harbour to transport the gold.

Figure 9; Picture taken from the ruins of the gold melting plant with a view on the Spanish Lagoon and the sediment body between the two.

Uphill straight next to the sediment body the ruins of the gold melting plant are still in place. The area is part of the national monuments agency (Monumentenfonds Aruba) who could give some more information about the history of the area. The most important information was that it was one of the two big gold melting plants on Aruba during the gold rush. The construction was built in 1899 and has been used until 1915 when operation ceased and was returned to the colonial government. The monuments agency could confirm that there used to be a railroad, but there was no information about a harbour in the Spanish Lagoon.

It is possible that the excavations that were needed to build the gold melting plant or the railway created an overload of sand on the western side of the Spanish Lagoon. It is also possible that sand was one of the waste products during the washing and melting of the soil to get out the gold. Unfortunately, there is too little information available about the amount of sand that was used or replaced by the gold industry. Besides that, it is also unknown how much sand is in the sediment body and what the age of this sand is.

4.2 LAND-USE MAP

In addition to the soil map a land-use map has been created in GIS. A raster has been created in which the different land-use types are drawn. The different types correspond to the MRLC1992 (Multi-Resolution Land Characteristics Consortium) that is part of the National Land Cover Dataset. This is a group of federal agencies who coordinate and generate consistent and relevant land cover information for the US (NLCD, 2016). The land-use types that are drawn are linked to the database and the standard values are used to simulate the infiltration, runoff and sediment load in the catchment.

Figure 10 is the land-use map as it is created and used during this study. What is clear to see is that the biggest part of the area is covered in Mixed Forest (22,40 km2). This is also visible in Figure 9 which almost only shows forested area. The second biggest area is the Low Intensity Residential (4,98 km2) but the given areas are specified for the entire map. The residential area is mostly located outside the catchment area. The other land-use areas are all relatively small.

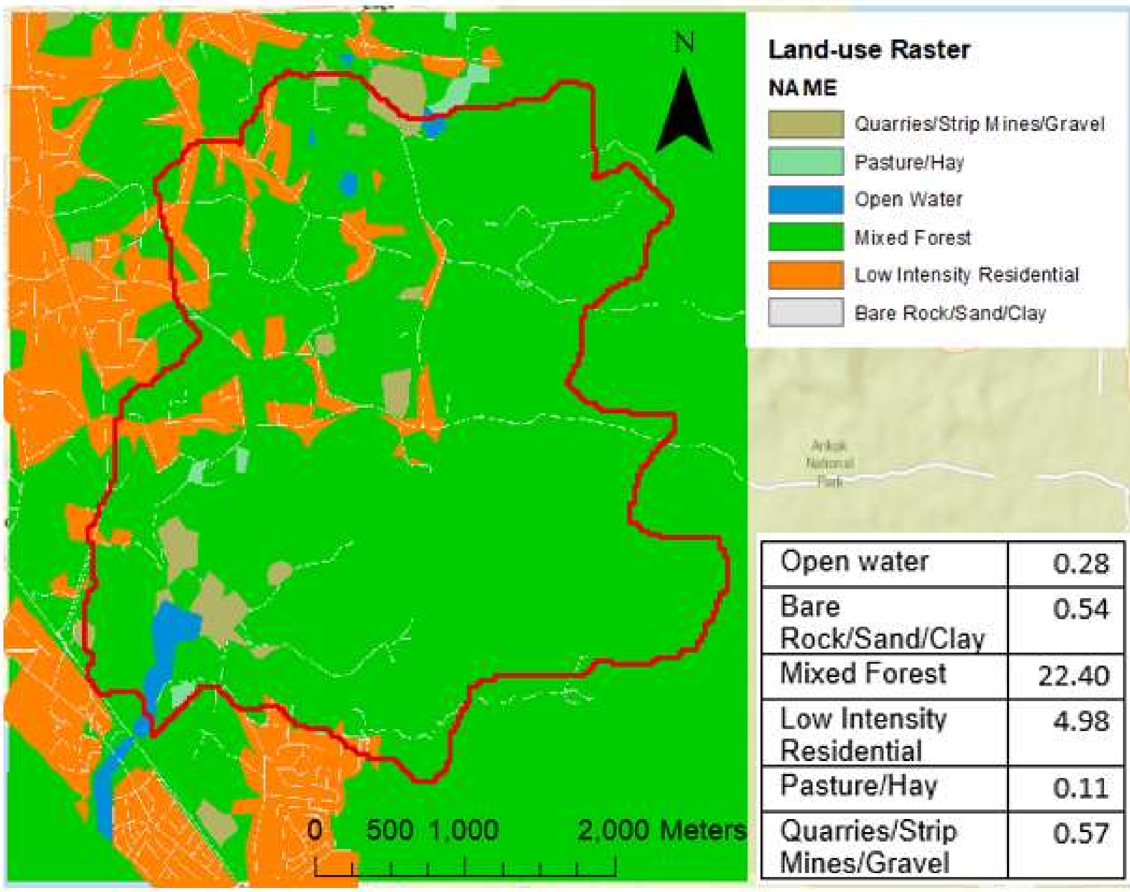


Figure 10;Overview of the land-use types in the catchment and the area in km2

The names of the land-use types correspond to the mrlc1992 database and the raster map is input to AGWA. The map will be used to model the catchment and adapted for the urbanization and vegetation cover degradation scenarios.

4.3 RESULTS FOR CURRENT SITUATION

When the soil- and land-use map are created and linked to the AGWA database files it is possible to start modelling. Below an overview is given of the input for the model for the current situation. A detailed version of the explanation of the model is given in Appendix 1. For the scenarios that follow the input will be the same, exceptions will be mentioned explicitly.

- The first step of the model is to define the outline of the catchment (delineation). The only input required for this step is the DEM of the area from which also a Flow Accumulation Map and a Flow Direction Map are created. The outline of the catchment is visible in Figure 10 on the previous page.
- The second step is the discretization of the catchment into much smaller watersheds. This is the first step in which a choice between Kineros2 or SWAT needs to be made. For both models a threshold of 1000 meters was chosen for the maximum stream length. For the Kineros2 model the catchment is divided into 67 different watersheds. For the SWAT model, the number of watersheds is 41. The reason that the number of watersheds is different is because for the calculation method of SWAT it is possible to have a stream going through a watershed, while in the Kineros2 model the stream will divide this watershed into two different watersheds.
- The third step is the parameterization of the model elements. For the streams, there was chosen to work with a “natural stream” for the current situation. In this step, also the maps that are discussed previously in this chapter are linked to the database. This is the model step in which the fieldwork is integrated into the model.
- The fourth step is to write a precipitation file which differs between Kineros2 and SWAT;
    - The Kineros2 model is a single event based model where the event has been specified in a precipitation file. The depth of the event was 70 mm in 6 hours, like the event of November 20th, 2016. This event is applied to the entire watershed.
    - SWAT is a continuous time model which means that the climate data for a longer period is used to do the calculations. The climate data that is usually used to run the model comes from a wgn. file that is part of the AGWA database (Neitsch et al., 2011). This file gives an overview of more than 700 weather stations with the monthly average data. Unfortunately, the file only contains US data. In GIS data and location for one of the weather stations has been replaced by those of Aruba. This file with averages of temperatures, wind speed, amount of rain days, amount of rain etc. per month has been used for the SWAT simulations.
- The fifth and last step of the AGWA model is to write the simulation file and run the model. Again, this is different for Kineros2 and SWAT;
    - For the Kineros2 model the only step that is needed is to choose the right parameterization – and precipitation file. Then if everything is corrected the model can be run. For SWAT, the step of writing the simulation file is also straight forward when all the steps before are done.

4.3.1 Kineros2 results current situation

The current scenario for the Kineros2 model means that the precipitation event from November 2016 will be executed by the model. For the current situation, the soil- and land-use map as presented previously in the chapter will be used. The precipitation event of 70 mm for the entire watershed has been used for all different scenarios. The total amount of water that falls on the catchment is 910.000 m^3, uniformly distributed. The values that are used for the simulation are based in majority on the field measurements. The only measurements that have not been used are the infiltration capacities of the different soils. Those values differed too much from the FAO values of the AGWA database. In Appendix 2 the current Kineros2 model has been executed with the measured values. For this scenario, the infiltration capacity of the standard AGWA database are used.

Figure 11 gives and overview of the amount of infiltration for the streams and the planes. For the planes where the topography is limited and the soil is Loamy Sand or Sandy Loam almost all water will infiltrate within the watershed. Less water infiltrates on the watersheds with steeper slopes or on Loam or Sandy Clay Loam. From the total 70 mm or rain 62 mm will infiltrate into the soil and another 4,98 mm will infiltrate in the channels. This means that only 3 mm of the total rainfall will reach the outlet.

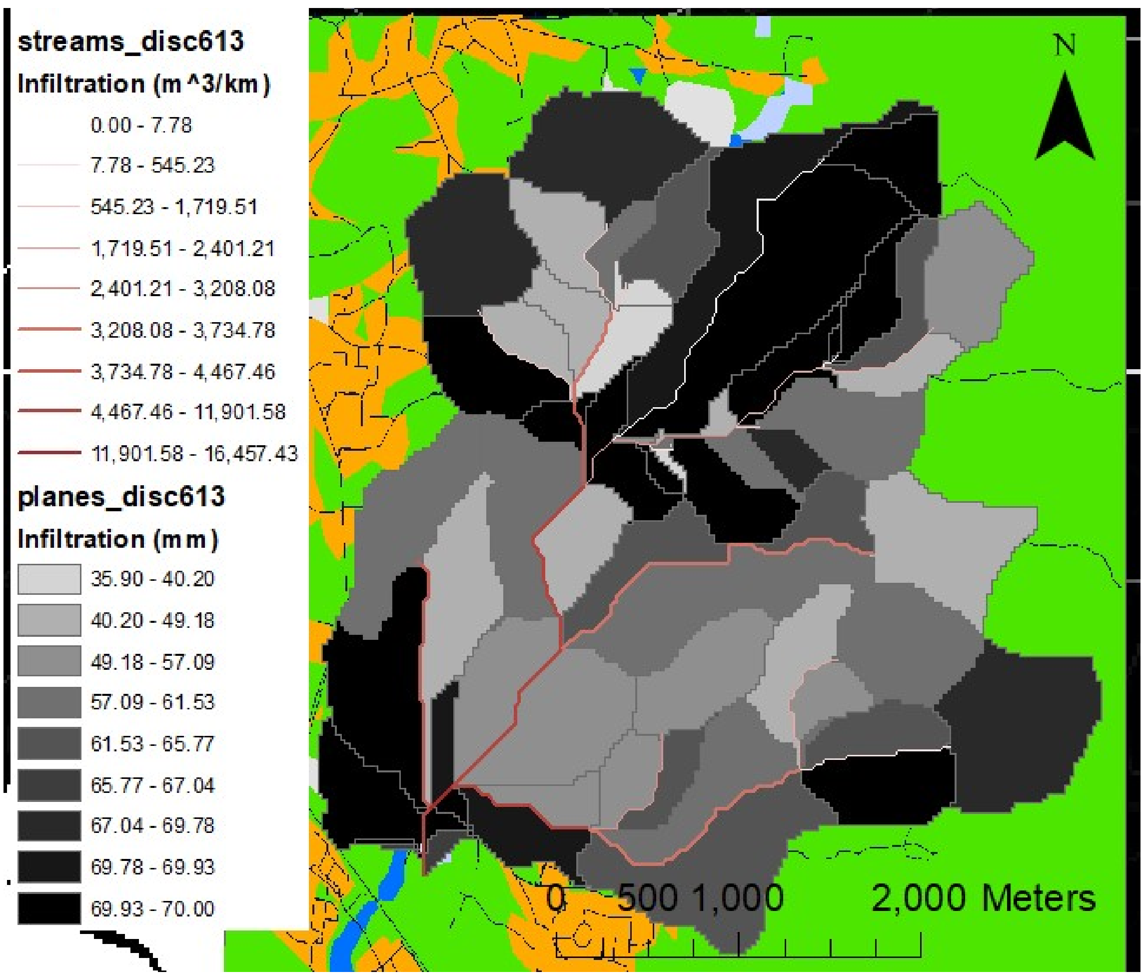


Figure 11; Overview of the infiltration in the catchment for the current situation with the Kineros2 model

The total amount of runoff that will flow towards the Spanish Lagoon is 39.800 m3 in 6 hours. The watersheds that mostly contribute to this runoff are the watersheds with a relatively high slope. In the next paragraph, more detail will be discussed about the areas with the highest runoff levels.

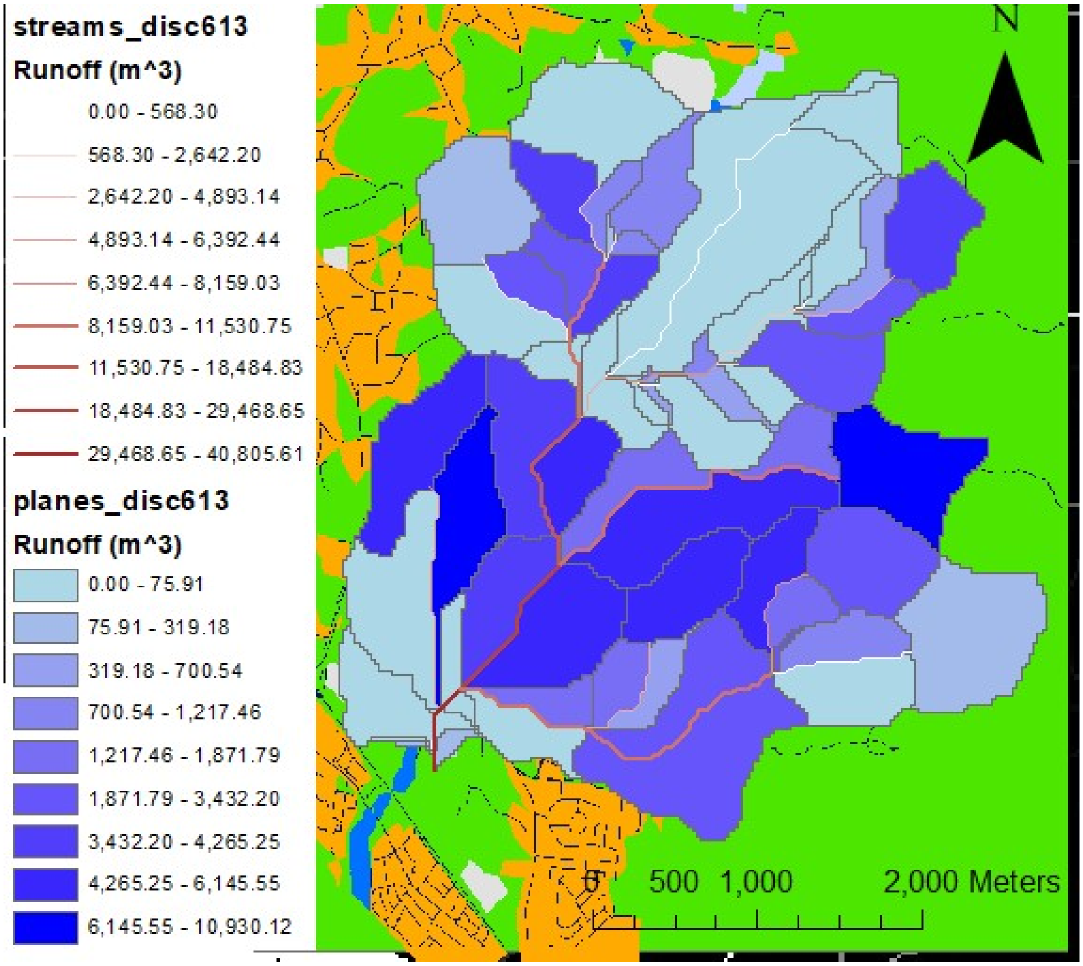


Figure 12; The amount of Runoff during a precipitation event of 6 hours as calculated with the Kineros2 model.

The third and last outcome of the model that will be shown is the amount of sediment that will be moved during this precipitation event. The total amount of sediment that leaves the catchment is 246 kg of soil per hectare. This is a total of 338 ton of soil loss. Figure 13 shows the maximum amount of sediment that flows outside the planes and through the streams during the event. The image looks like Figure 12 because the amount of sediment is obviously very closely related to the amount of runoff from the planes. A difference between the two maps is the influence of the east and west side on the total amount of runoff and sediment flow. The influence of the east side is relatively bigger for sediment than for the runoff. This indicates that Loam is more sensitive to erosion than Sandy Clay Loam and Loamy Sand.

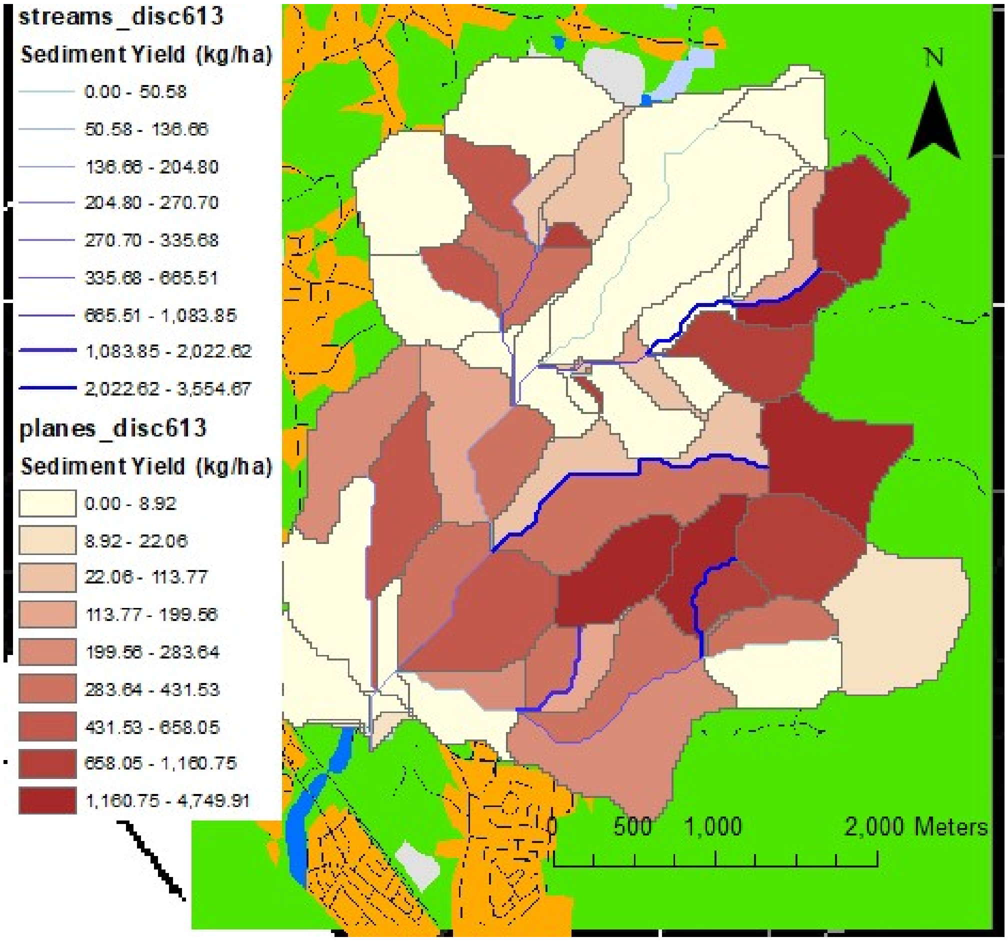


Figure 13; Overview of the maximum sediment flow from the planes and through the streams.

4.3.2 SWAT results current situation

For SWAT, the period that has been chosen to simulate the watershed is from 2017 to 2070, a total of 53 years. This period has been chosen because it is the same Kunkel et al. (2013) use in the study of precipitation and climate change. The yearly average that SWAT used is 291 mm of precipitation. This has been calculated for the average rainfall of the past from each month. This is the same for the entire watershed and for this run there is assumed that this will not change. In Figure 14 the maps are shown for the most important outcomes of the model.

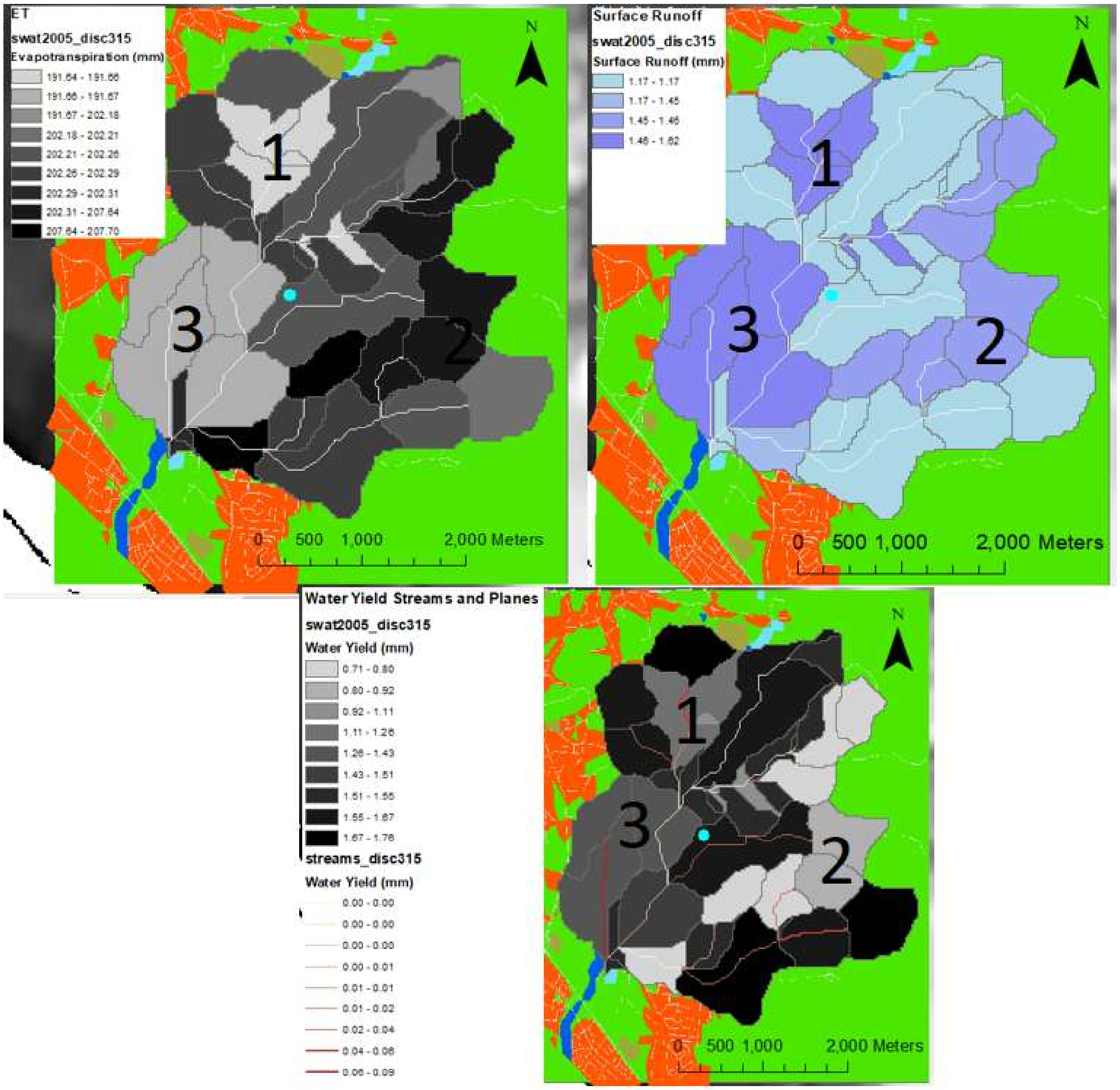


Figure 14; Overview of the results for SWAT of the current situation. The results are presented for Evapotranspiration, Surface Runoff and Water Yield per year.

As mentioned before the precipitation per year is 291 mm for the entire watershed. The model shows that most of the rainwater will evaporate, between 191 and 207 mm per year. Another large amount of water will percolate into the soil and only a small fraction of water will runoff over land. The total amount of water that will flow towards the Spanish Lagoon is about 1000 litres of water per day. This is a very small volume of water because almost all the precipitation will evaporate of percolate into the soil. On the map on which the runoff is presented, three "hotspots" are visible. These locations are also indicated on the ET and water yield map for the lower values. Below an explanation is given why those three locations are notable.

- Most runoff will occur in the centre of the catchment at the north side. In these planes, the amount of land-use other than vegetation is relatively big. Besides that, the topography shows some steep slopes on a hill on which the Urataka Water Tower is located.
- The second location are the planes on the most eastern side of the catchment. This is the location that is entirely located in Arikok National park and includes Mount

Jamanota, the highest point of Aruba. Despite the vegetation on this part of the catchment the topography creates high amounts of runoff.
- The third area is located on the west side, relatively close to the head of the Spanish Lagoon. The reason that more runoff occurs here is because this area is densely urbanized. This does also include many roads on which the water can be transported easily.

The SWAT model for the current situation calculates that there will be no sediment flow towards the Spanish Lagoon. This is because the model works with monthly averages for climate. This creates very high ET rates because of the high temperatures and the intensity of the sun.

4.3.3 Influence of the outcomes for the channel

The current situation of the Spanish Lagoon also includes the channel that has been excavated recently. Both models do not work on a scale that can give clear estimates about the amount of sediment that will be deposited in the channel. SWAT has no results for the sediment yield but with the precipitation event that has been modelled with Kineros2 the total sediment outflow is 337 ton in 6 hours.

The Kineros2 model calculates a water- and sediment balance for every different element of the model. This can be used to get an indication of the amount of sediment that will be deposited in the stream that flows through the channel. The stream that is situated at the location of the channel is stream 184 (Figure 15).

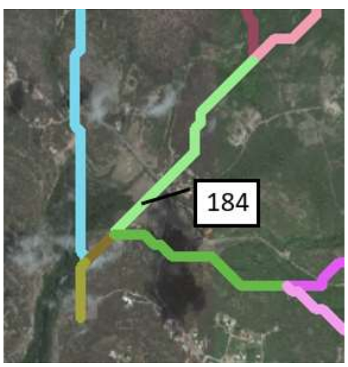


Figure 15; Location of stream number 184 which is in the area where the channel will be excavated.

Table 1 gives an overview of the water- and sediment balance for the stream. The total area that contributes to this stream is 842 ha, 61% of the total area of the catchment. The peak flow that will occur is 3m3 per second at 361.5 minutes. This is 1.5 minute after the event and the peak sediment discharge at this moment is 28,8 kg/s.

Table 1; Water- and sediment balance for stream 184 for the current situation as calculated with the Kineros2 model

Water balance		Sediment balance	
Rain:	0.00 cu m	In:	629284.2 kg
Inflow:	39174.24 cu m	Deposited:	346847.2 kg
Infilt:	9702.82 cu m	Soil Loss:	0.0 kg
Stored:	0.00 cu m	Out:	282623.3 kg
Out:	29468.65 cu m		

The total sediment deposition for the channel is 346 ton of soil as shown in the table. This means that the amount of soil deposited in this channel is slightly bigger than the amount of sediment that will flow outside the catchment. The total amount of soil that has been excavated to create the channel was approximately 1200 m3, about 1800 ton. This means that almost 20% of the excavated soil would be deposited again after this 70mm rainfall event. The actual deposition in the channel will be less, because the deposition is based on the entire length of stream 184 which is almost 1km. Although this will reduce the deposition in the channel it is still clear that the sediment load can be a threat for the lifespan and sustainability of the channel.

4.4 FURTHER URBANIZATION AND DEVELOPMENT

In this scenario, the land-use map has been changed from an urban area with “low-intensity residential” into “high-intensity residential” area. Besides this change the channel type has been changed from natural to developed. This means that water can no longer infiltrate in the streambed.

The amount of outflow towards the Spanish Lagoon will increase from 2,9 mm (39.840 m3) to 4.96 mm (68.150 m3). This is logical because in the current scenario the infiltration in the residential area was bigger. Also, part of the precipitation infiltrated in the channel but this is not possible in the developed channel.

Another more remarkable result is that the amount of sediment that will reach the output of the catchment will be strongly reduced. The sediment yield will be 93 kg/ha for the urbanized and developed scenarios while it was 247 kg/ha for the current situation. The total amount of sediment has been reduced with 62%. This indicates that a very large portion of the sediment yield for the scenario of the current situation comes from the streams. This is something that can be considered by policy makers when there is a wish to reduce the sediment yield for the Spanish Lagoon.

The simulation has also been done for the SWAT model, but these results were almost similar to the simulation of the current situation. This is also the case for the next scenario.

4.5 INFLUENCE OF A DEGRATED VEGETATION COVER

The last scenario that will be considered with Kineros2 is the scenario in which the rain season will bring less precipitation. This will lead to a further degradation of the vegetation cover on the island. The change in the model that has been done to simulate this is a modification of the land-use map where mixed forest has been changed to shrubland. The most important influence of this is the difference of the Manning’s coefficient. This was 0,6 and is now only 0,055. A study by Goodrich et al. (2012) describes a sensitivity analysis of the model and in this study the Manning’s coefficient was one of the factors that had an important influence on the results.

In Figure 16 the differences in percentages of the sediment yield are shown between the simulation of the current situation and the situation of with less vegetation. The differences between the watersheds are big but for most watersheds there is an increase for the sediment yield. A few watersheds have a decreased amount of runoff and sediment loss, this will be discussed below.

The total amount of outflow has decreased a little from 39.800m3 to 38.100m3, i.e. by 4.3%. This means also that the amount of infiltration has increased. Also, the total amount of sediment that will flow into the Spanish Lagoon has increased from 338 ton to 369 ton. This is an increase of 9,2% and this indicates that the soil has a higher infiltration capacity but at the same time it has also become more vulnerable to erosion.

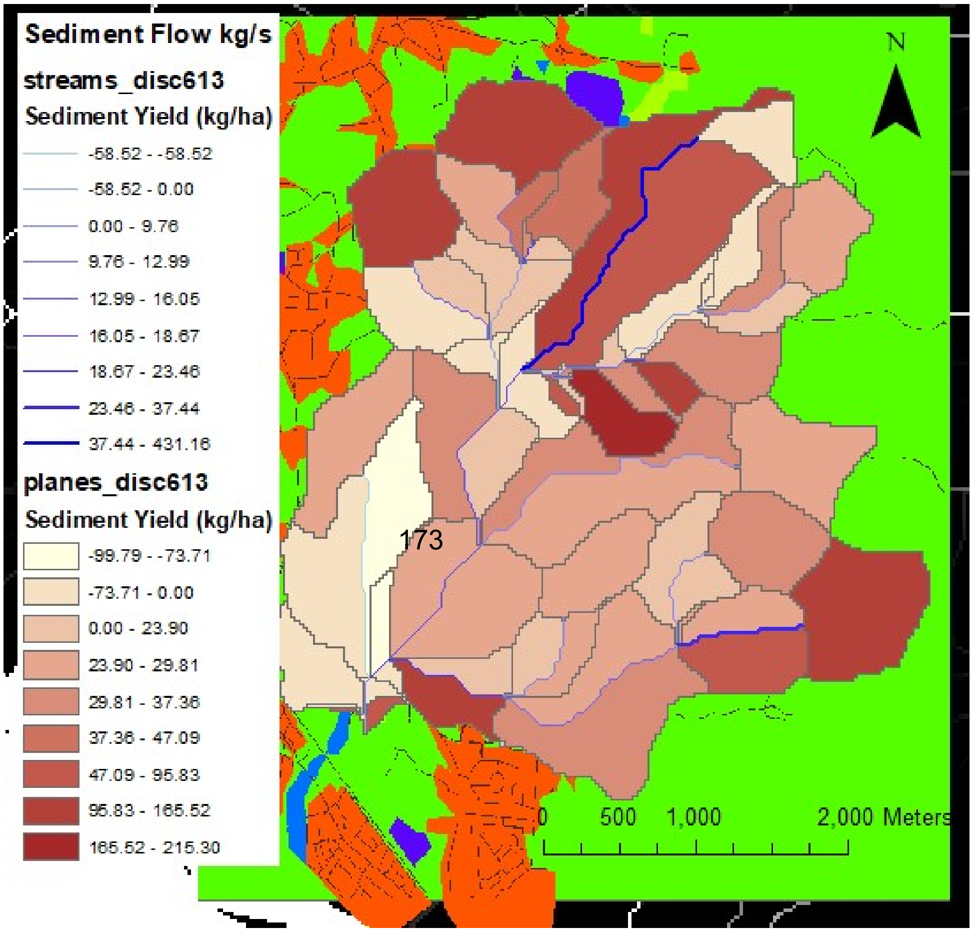


Figure 16; Overview of the difference in percent between the sediment yield for the current situation and the situation with less vegetation.

It was noticed that in general the amount of sediment yields increased, but for plane 173 the opposite happened. The watershed has been highlighted in Figure 16 and it is located at the west side of the watershed close to the head of the Spanish Lagoon. The watershed consists of two parts, the upper part of the watershed is located on a hill with a steep slope. At the bottom of this slope the Frenchman's Pass is located i.e. the road that runs through the sediment body at the head of the lagoon. The lower part of watershed 173 is located on the sandy sediment body at the head of the lagoon. Table 2 shows the water- and sediment balance for the two simulations. Comparison of the tables shows that the infiltration increased strongly for the dry scenario. The decrease of runoff from 24.5mm to 7.26mmalso decreases erosion from 19.600 kg to 5200 kg. The reason for this is the combination of a vegetated slope with a flat plane below, because the flow over the sand plane will start earlier during the event. This makes is possible for more water to infiltrate in the sand body which has a high K value of 210m/d. This is the only location in the catchment with such a high K value which makes the response to a less vegetated area different from the rest of the watersheds.

Table 2; The outcomes of the Kineros2 calculation for the water- and sediment balance. The upper table represents the simulation of the current situation and the table below gives an overview for a dry situation.

Water balance			Sediment balance	
Rain:	26012.35 cu m	70.00000 mm	In:	0.00 kg
Inflow:	0.00 cu m	0.00000 mm	Deposited:	0.00 kg
Infilt:	16895.82 cu m	45.46714 mm	Soil Loss:	19618.40 kg
Stored:	0.00 cu m	0.00000 mm	Out:	19613.09 kg
Out:	9095.64 cu m	24.47663 mm		

Water balance			Sediment balance	
Rain:	26012.35 cu m	70.00000 mm	In:	0.000 kg
Inflow:	0.00 cu m	0.00000 mm	Deposited:	0.000 kg
Infilt:	23262.32 cu m	62.59959 mm	Soil Loss:	5242.349 kg
Stored:	0.00 cu m	0.00000 mm	Out:	5155.910 kg
Out:	2698.07 cu m	7.26058 mm		

4.6 INFLUENCE OF CLIMATE CHANGE

The last scenario assesses the influence of the expected climate change for the catchment. As explained before the prediction of the amount of precipitation is unclear. The SWAT model is run for the current situation with a change of -30% and +30% precipitation.

The amount of precipitation per year changed from 291 mm for the current situation into 368 mm for the wet scenario and 198 mm for the dry scenario.

4.6.1 Increased amount of rainfall

Figure 17 gives an overview of the difference of runoff in percent between the current scenario and the +30% rainfall scenario. The most striking result is that the areas where the most runoff occurs in the current situation change the least when the rainfall intensity rises. For location 1 and 3 the increase of precipitation only gives 2,5% more runoff while surrounding watersheds have an increase of about 40%. This means that although the amount of runoff will increase, this will be spread more evenly over the catchment.

The ET in the catchment also increases when there will be more rain, but it will increase only by 11% to 12%. The amount of percolation of water into the ground will change much more, up to 65%. This means that the climate is still so dry that the soil can take up most of the water that does not evaporate. This will lead to an island with more year-round vegetation.

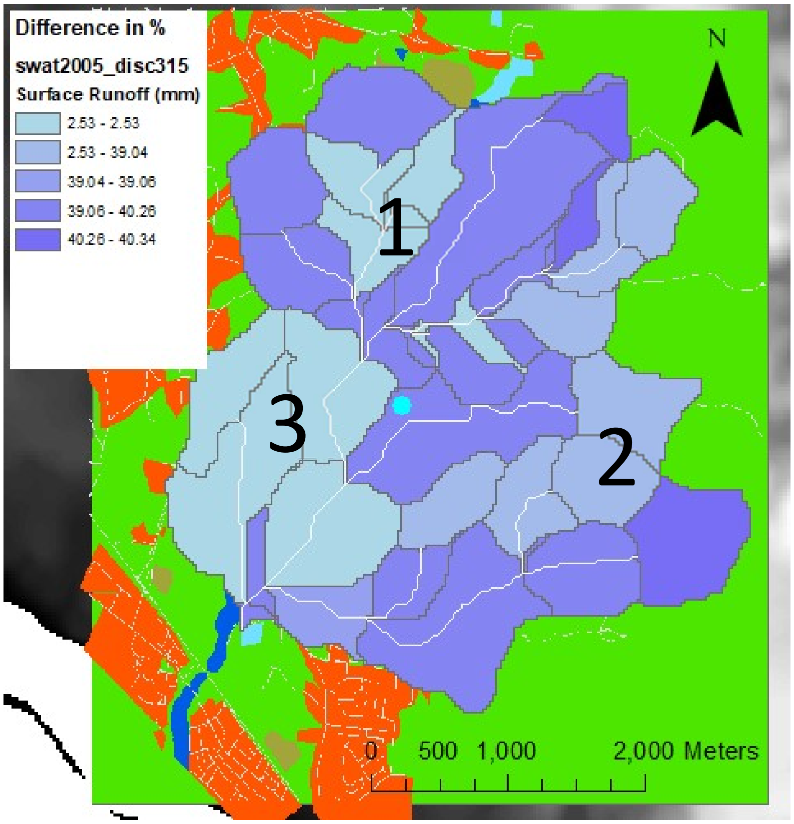


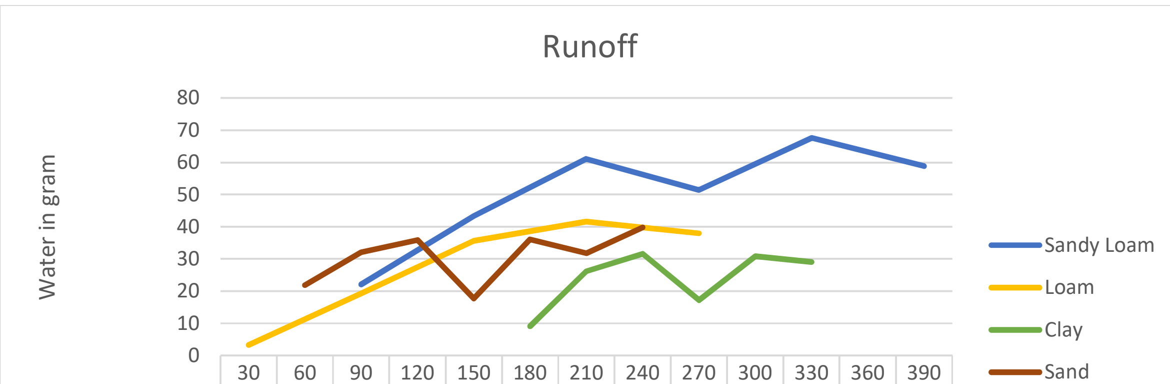
Figure 17; Map that shows the difference in percent between the runoff of the current scenario and the scenario with 30% more precipitation.

4.6.2 Decrease of rainfall

Aruba is already a very dry island and if the amount of precipitation would decrease even further the island would turn into a desert eventually. The modelled result for a decrease of precipitation of 30% would lead to a total amount of 198 mm per year. The outcome for the model is that 162 to 173 mm would evaporate. The rest of the water would percolate into the soil and the amount of runoff would be close to nothing. This would lead to further degradation of the vegetation cover on the island. When there is no runoff towards the Spanish Lagoon there would be a risk of salinization for this area. When the vegetation will die because of the drought this will also influence wind erosion and increase the risk of flash floods.

4.7 SMALL RAINFALL SIMULATOR

In addition to the results of the model for different scenarios there are also results for the measurements with the small rainfall simulator. Figure 18 and 19 show the results of the measurements with the rainfall simulator. The experiment has been done on four different soils, Clay, Sand, Sandy Loam and Loam on the same slope with the same rainfall intensity. The diagram that shows the amount of runoff on the different soils shows that most runoff occurs on the Sandy Loam and the least runoff at the Clay soil. This indicates that more water would infiltrate in the Clay then it does in the other soils. This is strange because in general the K value of clay is much lower than the other soils. A reason for this is that the clay soil was hard with a high percentage of stones which made it difficult to install the rainfall simulator. This is a big disadvantage of the experiment as the water needs to flow from the soil over a collection plate into a cup. It is almost impossible to construct this in such a way that no water will be lost and does not flow next to the collection plate or underneath it.

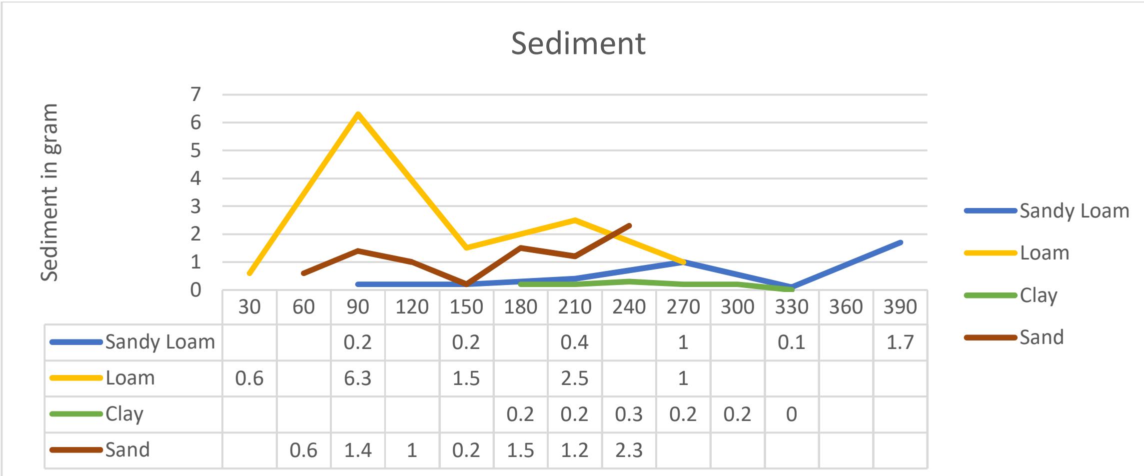


	30	60	90	120	150	180	210	240	270	300	330	360	390
Sandy Loam			22.1		43.3		61.1		51.4		67.6		58.8
Loam	3.3		19.4		35.6		41.6		38				
Clay						9.1	26.2	31.6	17.2	30.9	29.1		
Sand		21.9	32.1	35.9	17.7	36.1	31.8	39.8					

Figure 18; Overview of the measured runoff with the rainfall simulator with the time in second on the x-axis and the amount of water in grams on the y-axis.

Also, the amount of sediment that is collected during the experiment has been determined and is shown in Figure 19. Most sediment came from the Loam soil, especially for one measurement at 90 seconds with 6,3 grams of soil. It is unlikely that this soil has been taken along with the 19,4 grams of water that have been measured at the same timestep. This will probably have to do with soil that fell into the cup during the change of cups because they need to be placed in a hole in the ground underneath the rainfall simulator.

The clay soil generates almost no sediment into the cup which indicates that the clay layer is less erodible. The fact that the amount of total runoff from the clay soil was already low also plays a role. The amount of sediment from the sandy soil as shown in the diagram looks like the line that has been drawn for the runoff. The amount of sediment per gram of water is the most constant for this soil.



	30	60	90	120	150	180	210	240	270	300	330	360	390
Sandy Loam			0.2		0.2		0.4		1		0.1		1.7
Loam	0.6		6.3		1.5		2.5		1				
Clay						0.2	0.2	0.3	0.2	0.2	0		
Sand		0.6	1.4	1	0.2	1.5	1.2	2.3					

Figure 19; Overview of the measured sediment with the rainfall simulator with the time in second on the x-axis and the amount of sediment in grams on the y-axis.

Table 3 gives an overview of the average amount of sediment in grams per gram of water for the different soil types. Also included in the table are the standard deviation per soil type and the difference in percent of this standard deviation and the percentage of sediment per gram of water. As mentioned before the sediment stream of sand is the most constant flow. The biggest variability is found for the loam soil.

Table 3: Average amount of sediment in grams per gram of water for the different soil types

Soil type	% of sediment	Standard dev.	% dist. STDEV
Clay	0.76	0.73	95
Sand	3.809	1.480	39
Loam	8.63	12.64	146
Sandy Loam	1.18	1.16	98

The outcomes of the experiment will not be used furthermore in this research because the uncertainty of the results is too large. The experiment should be done on a prepared soil with the right conditions to dig a hole for the cups. It is also important that the construction is waterproof but this was nearly impossible for the coarse soils on Aruba. Water was constantly leaking during the experiment to other places than the cups. It was also a problem to find a good plot to conduct the experiment because it had to meet a set of different requirements. Therefore, it is uncertain if the values that were found only apply on the plots or for the entire area with the same soil type.

5. DISCUSSION

This research consisted of two different parts that both will be discussed separately. After the discussion of the methods and the model, the results will be discussed.

5.1 DISCUSSION OF FIELDWORK

The fieldwork for this research has been executed on Aruba where the technical methods to do fieldwork are very limited. A disadvantage of working on soil and hydrological science on Aruba is that there is almost no work to compare with. The amount of data is extremely limited since there is hardly any published science about the island. Therefore, the fieldwork was needed to be able to get an indication about the soil and land-use. Because of the limited possibilities of using devices or a laboratory most measurements are done with daily products like jars from the supermarket or plastic bottles. This was the only way to get an indication about the soil and can be considered as a first and rough attempt to map the soil in the catchment. Although the methods that were used to determine the soil type, bulk density and porosity were not done with professional devices, the results where satisfying and therefore used during the research.

The only two actual measuring devices that were used are the infiltrometer and the small rainfall simulator, both products of Eijkelkamp[2]. What is striking, is that both the experiments gave results that were not used during the simulation study. In appendix 2 the situation is shown for the measured infiltration, but those where too low. It is unclear why this experiment did not work because the standard protocol has been followed. Also, the calculations of the translation from the measurements in the field to the final K value are done in a standardized Excel sheet that uses the Van Genuchten parameters (Van Genuchten, 1980). The difference between the standard FAO K value of the soil and the value that has been measured was up to a factor of more than 100. This difference was too big to be realistic and therefore there has been chosen to use the standard FAO values. Although the results of the measurements were too low, it is very well possible that the actual infiltration on Aruba is lower than the one that has been used. Different studies show hydrophobic effects for soils after a dry period that can reduce the infiltration rate up to three times (Burch et al., 1989; Doerr et al., 2000; Farrick and Branfireun, 2014). The infiltration rate will probably be somewhere between the values that have been measured and the standard FAO infiltration rates, but it has not been possible to prove that during this research. This is a major setback in this analysis because Al-Qurashi et al. (2008) already showed that the infiltration rate of the soil is one of the most important parameters of the model that influences the results the most. During further research on soil science on Aruba more emphasis should be put into infiltration rates of the different soils to be able to make the results more reliable.

The other experiment that has been done but not used is the measurement for sediment that will be taken along with the runoff from a small plot during an extreme rainfall event. The small rainfall simulator that has been used during the experiment did not provide any useful results. This is because the selection of the plots was already very challenging, which indicated that it is not representative for the entire area. Additionally, the construction that must be build needs to be waterproof to be able to catch all the water that does not infiltrate. The soil on Aruba is not suitable to allow a good experimental setup, because the soil is in general a very thin, with a high percentage of rock fragments. Water will be leaking underneath the construction and

[2] Eijkelkamp Soil and Water is one of the world leading companies on the supply of innovative soil and water research methods (https://en.eijkelkamp.com/)

pass the cup. The last point is that the amount of sediment that has been captured is very small. With the weighing device that was available during this research it was almost impossible to weigh it. The small rainfall simulator as it has been used during this research is not the right device to work with on Aruba and is not recommended for use in any possible further research on the island.

5.2 DISCUSSION OF THE MODEL

The second part of the research consisted of modelling. The AGWA model that has been used is a model that links between Kineros2 / SWAT to GIS. The model was developed by the US Department of Agriculture and the input data that the model used is also specifically chosen for the situation in the US. The model works with databases from which maps and data are available and can be easily linked to the model. The disadvantage is that those are mostly only available for the US, like the MRLC 1992 land-use database. This is a map for the US with a detailed overview of the land-use that can be linked to GIS and then to AGWA. This map was not available for Aruba and therefore a new one has been created during this research (Figure 10).

For the soil map the AGWA model can be coupled to the FAO Soil Map of The World, which also covers Aruba. This has not been done because the map is not detailed enough and classifies the entire island as just one single soil type. Therefore, also a soil map has been created to get a more detailed image of the catchment (Figure 8).

The calculations that have been done with the Kineros2 model resulted in detailed results for the entire catchment, but also a water- and sediment balance for each element. This made it possible to get detailed information about the influence of the different scenarios on the runoff, infiltration and sediment yield of the catchment. The results also give an indication about the amount of sediment that will be deposited in the recently excavated channel. A disadvantage is that it is not possible to compare the results with measurement from the field or previous data, because that does not exist. For further research, it would be of great help if it would be possible to measure the inflow towards the Spanish Lagoon during an actual precipitation event. This would make it possible to validate the model and start to analyse the impact of possible scenarios for this point.

The second model that has been used during this research is SWAT, to be able to get insights into the long-term effects of climatic changes on the hydraulic situation of the catchment. The main disadvantage of SWAT is that the climatic input that is used consist of monthly average values. The temperatures and windspeed on Aruba are always high and that makes that most of the water will evaporate or infiltrate. According to the model hardly any water will runoff or reach the outlet of the catchment. This is because the intense events that occur a few times a year are averaged out. This makes that the outflow results are not possible to use, but the model can be used to compare the current situation with possible future climate change scenarios. The influence that climate change will have until 2070 is still uncertain, but both a wet and a dry scenario are simulated and compared to the current situation.

A general remark of the AGWA model is that the available information, both scientific as general, is limited. This makes it sometimes difficult to work with the model because errors can occur that are not explained anywhere. Also, the help function of the model does not work which makes it unclear what input the model needs for a specific step.

5.3 DISCUSSION OF RESULTS

With the combination of fieldwork and the model simulations it was possible to get results for different scenarios on different timescales. The current situation modelled with the Kineros2 model shows that a total amount of sediment of 246kg/ha was lost during the event. As mentioned before, there is no previous research on Aruba to compare this number with, but it is possible to compare the number with research for other Caribbean islands. In a study by Ramos-Scharron and MacDonald (2007) a GIS based model has been used to calculate sediment yield per year for three different catchments on the American Virgin Islands. These islands are located much further from Latin Amerika which makes the chances of hurricanes and tropical storms much bigger. The total amount of rain on these islands is over 1000 mm per year, more than three times as much as Aruba. The amount of sediment per hectare per year in this study was 100, 380 and 170 kg/ha/year for the different catchments. This is comparable with the 246 kg/ha for the Spanish Lagoon catchment, but this is in only 6 hours from one single (extreme) precipitation event. This can indicate that the amount of runoff is high, but this can also be because of the differences in land-use and soils. All three catchments in the study are in the Saint John Nation Park, which has a dense vegetation cover. This can work as a protection measure that is not in place on Aruba. Another aspect that can have an influence is the area of the catchment. The catchments in the study on the Virgin Islands had an area differing from 1,5 to 6 km2 and much more steep slopes. This means that sediment will be flowing outside the catchment earlier while more deposition will take place already within bigger catchments with less altitude differences. In another study by Thattai et al. (2003) the sediment yield for a list of catchments have been calculated, with Indian Hill as the smallest one. It has an area of 40 km2 but an annual amount of rain of 3000 mm, which is still one of the least in this study. The annual amount of sediment in total is 3000 tons, while the total amount for the Spanish Lagoon catchment is 338 ton during the single event. This means that the difference between the watershed is a factor 10, but this is also the case for precipitation. After comparing the results to the other studies, the conclusion can be drawn that there is still some uncertainty about the exact numbers, but the magnitude of the results is in line with other research.

A study by A. Horn (2017) has been executed similar to this research for another catchment on Aruba. The same methods and model are used during this study for an urbanized catchment in Paradera. This study looked into the flooding's that occurred in the catchment during different precipitation event with the Kineros2 model. The outflow in total is 72944 m^3, equal to 10,6 mm (Horn, 2017). This means that the outflow is higher than for this study but this can be explained by the difference of land-use in both catchment. The Paradera catchment has much more paved surface which increases the overland flow towards the outlet.

The magnitude of the results from both this study and the study by Horn (2017) are in the same range. This is not surprising because a lot of work has been done together and the same measuring techniques have been used. Unless those similarities it is an important sign that the results are in line with the expectations. Those expectations where that the Paradera catchment would have more runoff because of the urban character of the catchment. More areas of vegetation will decrease the amount of runoff and damage by floods.

For SWAT, the conclusion was already drawn that the only use that the outcomes have is to compare the differences between the simulations. Because of the overly generalised climate data the numbers do not reflect what will happen in the field. Interesting and useful to see is what the influence of the increase and reduction of precipitation will be on the results. The

SWAT model has been used to predict the influence on several places around the world (Sood et al., 2013; Ghaffari et al., 2010). Unfortunately, it is not possible to compare those results, because the predicted climate change differs between every different location. Also the results of this study are not enough to make it possible to make a comparison to other research. The choice to include the SWAT model has only been taken at the very end of the research. When more time and effort will be put into the model it is probably possible to improve the outcomes, but there was no time to do that during this research.

6. CONCLUSION

This research was initiated to find out what the influence is of the soil and land-use in the catchment of the Spanish Lagoon on the infiltration, runoff and sediment yield for a single extreme precipitation event and until 2070. To be able to fill this knowledge gap field research has been done in the catchment on Aruba from which the outcomes are used to set up a catchment hydrological model.

The current hydrological situation of the catchment has been investigated by executing field measurements and experiments in combination with personal observations and interviews which resulted in two maps. The first and most labour-intensive map that has been produced is the soil map. Soil samples are taken throughout the catchment to be able to determine the soil type in the area. The outcomes of this analysis are interpolated in GIS which led to a soil map of the catchment. The area where the streams flow into the Spanish Lagoon has manually been changed to a sand and a clay soil because the sediment deposits are in this area. To get more insight into the properties of the soil, additional experiments are done to determine the most important soil parameters. Unfortunately, the outcomes of the infiltration and erodibility of the soil were not possible to use, but bulk density, porosity and rock fragments are used from the experiments. Remaining soil parameters that were needed to run the model are taken from the FAO database that is part of the AGWA model.

The second map that has been created is the land-use map. The input for this map comes mainly from observation in the field and satellite images in GIS. During the interviews that were held, a few changes and additions came up which were implemented in the map. The different land-use types are linked to the MRLC1992 database where the properties of the different types are incorporated. This map has been adapted to the situation that is described in different scenarios to be able to analyse the impact of a changing land-use on the possible future.

When the maps were finished and correctly linked to the databases that AGWA uses, it was possible to start simulating the model. To be able to get as much information about the hydrological situation as possible the model was run with both Kineros2 and SWAT. For the simulations with Kineros2 an event is used in which 70mm of rain falls in the catchment within 6 hours. SWAT is a continuous time model that shows yearly average values for precipitation, percolation, runoff and sediment yield until 2070.

For the SWAT model it is not possible to give detailed results because the amount of runoff is too small. The SWAT model has only been used to get insight into climatic changes for the future. The influence that climate change will have on the islands is still uncertain but the most relevant change for this study is the amount of rainfall. This change is also very uncertain, but it will probably be in the range between +30% and -30%. Both scenarios are simulated with SWAT. Table 4 gives an overview of the results.

Table 4; Results for the analysis with the SWAT model for the different climate change scenarios.

Scenario	Total amount of precipitation	Percolation	Runoff from planes	Outflow
Current climate	291 mm	82 – 97 mm	1,5 mm	1000 litres/day
+30% precipitation	368 mm	134 – 152 mm	2 mm	1750 litres/day
-30% precipitation	198 mm	25 – 35 mm	0 mm	0 litres/day

The results show that more annual precipitation does not have a big impact on the catchment. The outflow will be bigger towards the Spanish Lagoon which will reduce the salinity in the mangrove. Also, the amount of percolation increases which means that there will be more water available for the plants. From this result, the conclusion can be drawn that an increased amount of rainfall would be positive for the vegetation in the catchment and the mangrove forest in the Spanish Lagoon.

A further reduction of the amount of precipitation would lead to widespread problems in the catchment. If on a yearly basis only about 30mm of the water will percolate into the soil, it is going to be hard for any plant to survive. This means that on the island, which is already dry, desertification will occur more. The model shows that not a single drop of water will reach the mangrove forest.

The Kineros2 model has been used for different analysis of which the first one is about the deposition that is calculated for the recently excavated channel. The channel will be created in a sediment deposition at the head of the lagoon to expand the mangrove area. In total about 1800 tons of soil have been removed, but the model showed that during the event that has been simulated, already 346 ton of soil will deposit in the stream in which the channel is located. The stream as modelled with Kineros2 is longer than just the channel but it gives an indication about the impact that this sediment can have on the lifespan of the channel.

Table 5 shown the results of the current situation as simulated with Kineros2, together with the outcomes of the scenarios on urbanization and a degraded vegetation cover.

Table 5; Results of the Kineros2 model for the different scenarios

Scenario	Infiltration	Total outflow	Outflow in mm	Total sediment loss	Sediment loss in kg/ha
Current situation	62 mm	39800 m3	2,91 mm	338 ton	246 kg/ha
Urbanized	64 mm	68150 m3	4,96 mm	127 ton	93 kg/ha
Degraded vegetation cover	62 mm	38100 m3	2,77 mm	368 ton	268 kg/ha

The results show that the difference between the current situation and the scenario with the degraded vegetation cover are limited. The outflow would be slightly less, but the sediment that this flow takes along would increase. This indicates that the vegetation is important to hold the sediment.

The results of the scenario with the urbanized area and the developed channels differs much more from the current situation. The total outflow will increase strongly because more water will flow downstream from the urbanized area. A factor that is even more important is the fact that water can no longer infiltrate in the riverbed because it has changed to a developed stream. This has even more impact on the amount of sediment that will be lost during the event. This has been reduced because the streams have a big influence on the total amount of sediment. The streams in the area have an important impact on the erosion and deposition of sediments, but this is no longer the case when they will be developed according to the model.

In the current situation, this research has shown that sedimentation will be a major threat for the channel that has been excavated recently. A recommendation that follows from the scenario analysis is that managing the streams can have a major difference on the total sediment load that will flow into the Spanish Lagoon.

REFERENCES

Abdulla, F. A., & Eshtawi, T. (2007). Application of Automated Geospatial Watershed Assessment (AGWA) Tool to Evaluate the Sediment Yield in a Semi-Arid Region: Case Study, Kufranja Basin-Jordan. Jordan Journal of Civil Engineering, 1(3), 234-244.

Alongi, D. M. (2012). Carbon sequestration in mangrove forests. Carbon Management, 3(3), 313-322.

Alongi, D.M. (2002) Present state and future of the world's mangrove forests. Environmental Conservation, 29, 331–349.

Al-Qurashi, A., McIntyre, N., Wheater, H., & Unkrich, C. (2008). Application of the Kineros2 rainfall–runoff model to an arid catchment in Oman. Journal of Hydrology, 355(1), 91-105.

Arnold, J. G., Moriasi, D. N., Gassman, P. W., Abbaspour, K. C., White, M. J., Srinivasan, R., ... & Kannan, N. (2012). SWAT: Model use, calibration, and validation. Transactions of the ASABE, 55(4), 1491-1508.

Beers, C. E., De Freitas, J., & Ketner, P., 1997: Landscape ecological vegetation map of the island of Curaçao, Netherlands Antilles. Uitgaven Natuurwetenschappelijke Studiekring voor het Caraibisch Gebied ,vol. 138(1). Amsterdam

Burch, G. J., Moore, I. D., & Burns, J. (1989). Soil hydrophobic effects on infiltration and catchment runoff. Hydrological Processes, 3(3), 211-222.

DCNA. (n.d.). Aruba. Retrieved from http://www.dcnanature.org/islands/aruba/

DCNA. (n.d.). Spanish Lagoon. August 19th, 2014. Retrieved January 24, 2017, from http://www.dcnanature.org/spanish-lagoon/

Debrot, A. O., & Bugter, R. J. F. (2010). Climate change effects on the biodiversity of the BES islands: Assessment of the possible consequences for the marine and terrestrial ecosystems of the Dutch Antilles and the options for adaptation measures (No. C118/10). Alterra.

Decagon Devices, Inc. (2014, September 10). Mini Disk Infiltrometer [PDF]. 2365 NE Hopkins Court: Decagon Devices, Inc.

Deltacommissie, 2008. Samen werken met water. Een land dat leeft, bouwt aan zijn toekomst. Bevindingen van de Deltacommissie 2008. Secretariat Deltacommissie.

Departamento Meteorologico Aruba 2012: Beknopt Overzicht van het Klimaat van Aruba (2012)

Doerr, S. H., Shakesby, R. A., & Walsh, R. (2000). Soil water repellency: its causes, characteristics and hydro-geomorphological significance. Earth-Science Reviews, 51(1), 33-65.

Duke NC, Pinzon ZS, Prada MCT (1997) Large-scale damage to mangrove forests following two large oil spills in Panama. Biotropica 29: 2–14.NC DukeZS PinzonMCT Prada1997Large-scale damage to mangrove forests following two large oil spills in Panama.Biotropica29214

Duke, N.C., Meynecke, J.-O., Dittmann, S., Ellison, A.M., Anger, K., Berger, U., Cannicci, S., Diele, K., Ewel, K.C., Field, C.D., Koedam, N., Lee, S.Y., Marchand, C., Nordhaus, I. & Dahdouh-Guebas, F. (2007) A world without mangroves? Science, 317, 5834, 41–42.

Ellison AM, Farnsworth EJ (1996) Anthropogenic disturbance of Caribbean mangrove ecosystems: past impacts, present trends, and future predictions. Biotropica 28: 549–565.AM EllisonEJ

Farnsworth1996Anthropogenic disturbance of Caribbean mangrove ecosystems: past impacts, present trends, and future predictions.Biotropica28549565

F. Franken (2017, April 10) Personal interview. Santa Rosa Department of Agriculture, Livestock and Fishery

FAO (2007) The World's Mangroves 1980-2005, FAO Forestry Paper 153. Rome: Forest Resources Division, FAO. 77 p.FAO2007The World's Mangroves 1980-2005, FAO Forestry Paper 153.RomeForest Resources Division, FAO77

Farrick, K. K., & Branfireun, B. A. (2014). Infiltration and soil water dynamics in a tropical dry forest: it may be dry but definitely not arid. Hydrological Processes, 28(14), 4377-4387.

Freitas, J. A. de., 1996: De inheemse bomen van de Benedenwindse Eilanden. Zutphen

G. Boekhoudt (2017, April 11) Personal interview. Directie Natuur en Milieu

Geelhoed, R., 1997: Inventarisatie naar erosie op Aruba. pp. 1-38. Wageningen

Ghaffari, G., Keesstra, S., Ghodousi, J., & Ahmadi, H. (2010). SWAT-simulated hydrological impact of land-use change in the Zanjanrood Basin, Northwest Iran. Hydrological processes, 24(7), 892-903.

Giri, C., Ochieng, E., Tieszen, L. L., Zhu, Z., Singh, A., Loveland, T., ... & Duke, N. (2011). Status and distribution of mangrove forests of the world using earth observation satellite data. Global Ecology and Biogeography, 20(1), 154-159.

Giri, C., Zhu, Z., Tieszen, L.L., Singh, A., Gillette, S. & Kelmelis, J.A. (2008) Mangrove forest distributions and dynamics (1975–2005) of the tsunami-affected region of Asia. Journal of Biogeography, 35, 519–528.

Goodrich, D. C., Bums, I. S., Unkrich, C. L., Semmens, D. J., Guertin, D. P., Hernandez, M., ... & Levick, L. R. (2012). KINEROS 2/AGWA: Model use, calibration, and validation. Transactions of the ASABE, 55(4), 1561-1574.

Grontmij & Sogreah., 1968: Water and land resources development plan for the islands of Aruba, Bonaire en Curaçao. De Bilt

Horn, A. (2017) Modelling urban floods in semiarid environment: a case study in Paradera, Aruba

Intranet WUR. (2017). Beatrix enthousiast over werk ESG op Aruba, Available at: https://www.intranet.wur.nl/nl/home/news/Pages/BeatrixenthousiastoverwerkESGopAruba.aspx, Accessed 17 May 2017.

IPCC 2007b WG1 Science base report

Jones-Walters, L. (2017, March). Restoration Plans Spanish Lagoon. Address presented at Presentation plans Spanish Lagoon, Wageningen.

Kunkel, K. E., Karl, T. R., Easterling, D. R., Redmond, K., Young, J., Yin, X., & Hennon, P. (2013). Probable maximum precipitation and climate change. Geophysical Research Letters, 40(7), 1402-1408.

Lambs, L., Bompy, F., Imbert, D., Corenblit, D., & Dulormne, M. (2015). Seawater and Freshwater Circulations through Coastal Forested Wetlands on a Caribbean Island. Water, 7(8), 4108-4128.

Michigan State University, Bio-energy Sustainability Project. (n.d.). Sedimentation for Soil Texture. Retrieved from http://kbsgk12project.kbs.msu.edu/wp-content/uploads/2011/09/Sedimentation-for-soil-texture.pdf

Miller, S. N., Semmens, D. J., Goodrich, D. C., Hernandez, M., Miller, R. C., Kepner, W. G., & Guertin, D. P. (2007). The automated geospatial watershed assessment tool. Environmental Modelling & Software, 22(3), 365-377.

Mlodiinow, S. G. (2006). Five new species of birds for Aruba, with notes on other significant sightings. Journal of Caribbean Ornithology, 19(1), 31-35.

Mlodinow, S. (2015). Three new species for Aruba, with notes on other significant sightings. Journal of Caribbean Ornithology, 28, 1-5.

NASA Earth Observations. (n.d.). Hurricane Gordon Nears the Azores. Retrieved from http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=6950&eocn=image&eoci=morenh

Neil, D. T., Orpin, A. R., Ridd, P. V., & Yu, B. (2002). Sediment yield and impacts from river catchments to the Great Barrier Reef lagoon: a review. Marine and Freshwater Research, 53(4), 733-752.

Neitsch, S. L., Arnold, J. G., Kiniry, J. R., & Williams, J. R. (2011). Soil and water assessment tool theoretical documentation version 2009. Texas Water Resources Institute.

NLCD. (2016, September 12). About MRLC. Retrieved June 5, 2017, from https://www.mrlc.gov/about.php

Perk, J. P. v. d., 1997: De verspreiding en ecologie van de zeldzame bomen van Aruba. pp. 1-41. Wageningen/Aruba.

Polidoro, B. A., Carpenter, K. E., Collins, L., Duke, N. C., Ellison, A. M., Ellison, J. C., ... & Livingstone, S. R. (2010). The loss of species: mangrove extinction risk and geographic areas of global concern. PloS one, 5(4), e10095.

Proosdij van ASJ (1954), Arnoldo's zakflora. Wat in het wild groeit en bloeit op Aruba, Bonaire en Curaçao, ed. 4, Walburg Pers

Ramos-Scharron, C. E., & MacDonald, L. H. (2007). Development and application of a GIS-based sediment budget model. Journal of environmental management, 84(2), 157-172.

RAMSAR Site Information Service. (1980, May 23). Ramsar Sites Information Service. Retrieved May 9, 2017, from https://rsis.ramsar.org/ris/198

Ridderstaat, J., Oduber, M., Croes, R., Nijkamp, P., & Martens, P. (2014). Impacts of seasonal patterns of climate on recurrent fluctuations in tourism demand: Evidence from Aruba. Tourism Management, 41, 245-256.

Rowell, D. L. (2014). Soil science: Methods & applications. Routledge.

S. Houtsma, fellow student doing research in the Spanish Lagoon

Semmens, D. J., Goodrich, D. C., Unkrich, C. L., Smith, R. E., Woolhiser, D. A., & Miller, S. N. (2007). KINEROS2 and the AGWA modelling framework. Hydrological modelling in arid and semi-arid areas. H. Wheater, S. Sorooshian, and KD Sharma (eds.), Cambridge University Press, Cambridge, 49-68.

Sidman, G., Guertin, D. P., Goodrich, D. C., Unkrich, C. L., & Burns, I. S. (2016). Risk assessment of post-wildfire hydrological response in semiarid basins: the effects of varying rainfall representations in the KINEROS2/AGWA model. International Journal of Wildland Fire, 25(3), 268-278.

Smith, R. E., Goodrich, D. C., Woolhiser, D. A., & Unkrich, C. L. (1995). KINEROS–a kinematic runoff and erosion model. Computer models of watershed hydrology, 20, 627-668.

Sood, A., Muthuwatta, L., & McCartney, M. (2013). A SWAT evaluation of the effect of climate change on the hydrology of the Volta River basin. Water international, 38(3), 297-311.

Spalding, M. (2010). World atlas of mangroves. Routledge.

Spalding, M., Blasco, F., & Field, C. (1997). World mangrove atlas.

T. Becker (2017, April 13) Personal interview. Freelance researcher on Aruba

Taubner, H., Roth, B., & Tippkötter, R. (2009). Determination of soil texture: Comparison of the sedimentation method and the laser-diffraction analysis. Journal of Plant Nutrition and Soil Science, 172(2), 161-171.

Thattai, D., Kjerfve, B., & Heyman, W. D. (2003). Hydrometeorology and variability of water discharge and sediment load in the inner Gulf of Honduras, western Caribbean. Journal of Hydrometeorology, 4(6), 985-995.

UN Social Development. Population Division. (2002). World urbanization prospects: the 2001 revision (Vol. 216). United Nations Publications.

van Belle, J., & Strijker, D. Inventarisatie Terrestrisch Milieu van het Eiland Aruba.

Van Genuchten, M. T. (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil science society of America journal, 44(5), 892-898.

Westermann, J. H. (1932). The geology of Aruba. Oosthoek's Uitgeversmaatij..

Williams, C. O., Lowrance, R., Bosch, D. D., Williams, J. R., Benham, E., Dieppa, A., ... & Steglich, E. M. (2013). Hydrology and water quality of a field and riparian buffer adjacent to a mangrove wetland in Jobos Bay watershed, Puerto Rico. Ecological Engineering, 56, 60-68.

Worldatlas. (n.d.). Aruba. Retrieved from http://www.worldatlas.com/webimage/countrys/namerica/caribb/aw.htm

Zemke, J.J. Runoff and Soil Erosion Assessment on Forest Roads Using a Small Scale Rainfall Simulator. Hydrology 2016, 3, 25.

Ziegler, A. D., Giambelluca, T. W., & Sutherland, R. A. (2001). Erosion prediction on unpaved mountain roads in northern Thailand: validation of dynamic erodibility modelling using KINEROS2. Hydrological Processes, 15(3), 337-358.

APPENDIX 1; DOCUMENTATION OF THE MODELLING PROCESS

In this appendix, the modelling part of the research will be described. The first part is about the creation of the maps that are needed to use the AGWA model. The second part will be on the different steps of the AGWA model.

A.1 Creating the soil- and land-use map

The first map that has been created is the soil map that gives an overview of the different soil types. The map has been created from interpolating the outcome of the soil samples on percentages of clay, silt and sand. The locations of the point with the corresponding values are loaded into GIS and by using the kriging interpolation tool, the maps are created as shown in Figure 20.

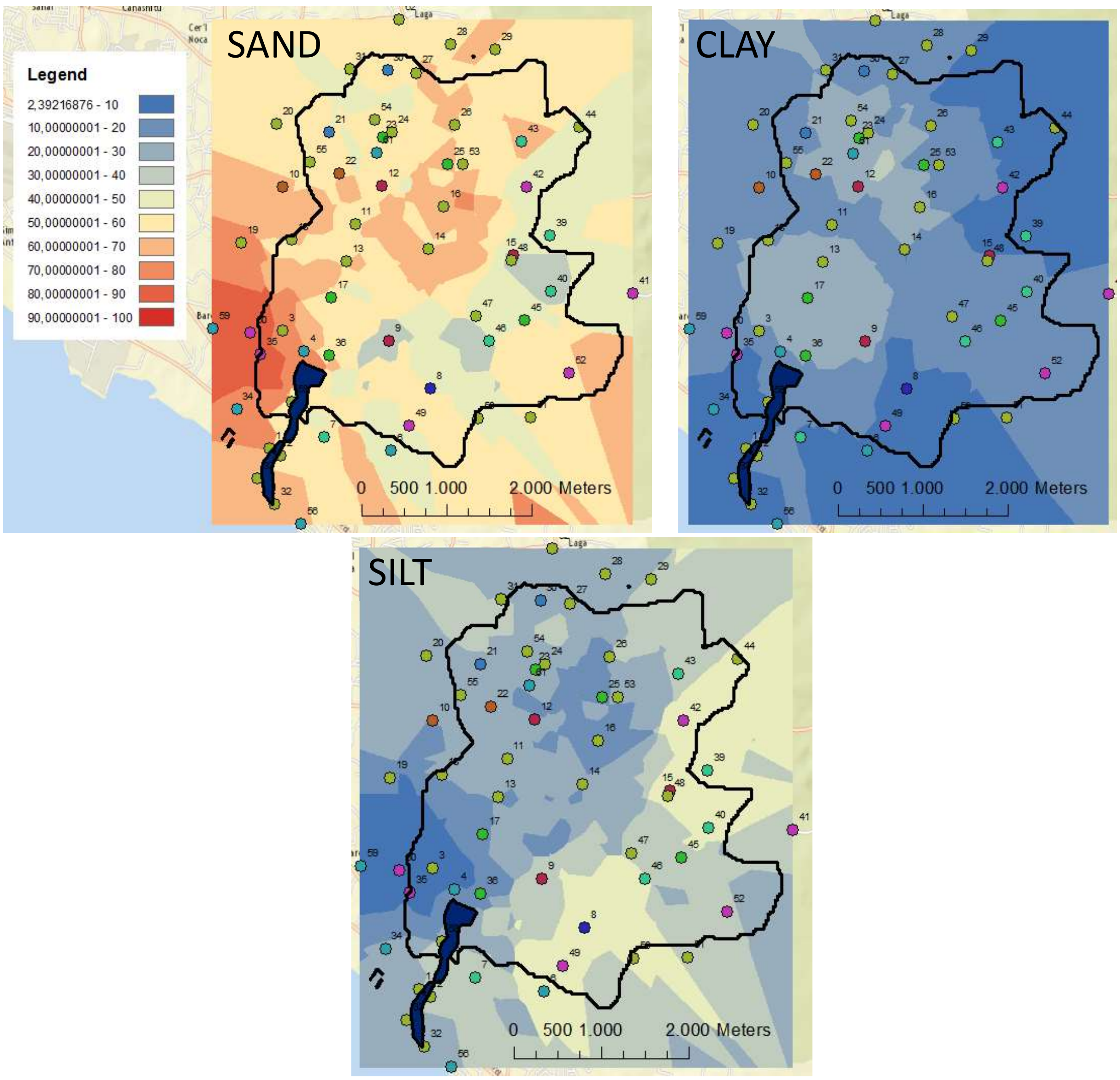


Figure 20; Map of the percentages of sand, clay and silt in the Spanish Lagoon catchment

From these maps, it is clear to see that the percentages of sand are generally high, especially on the west side of the area. For the creation of those maps, the soil samples that where taken in het sediment body at the upper side of the Spanish Lagoon are not considered because they differ to much from the rest of the area. The areas are drawn is a separate GIS file which is added to the final soil map. Those are the sediment bodies located at the head of the Spanish Lagoon consisting of Sand and Clay.

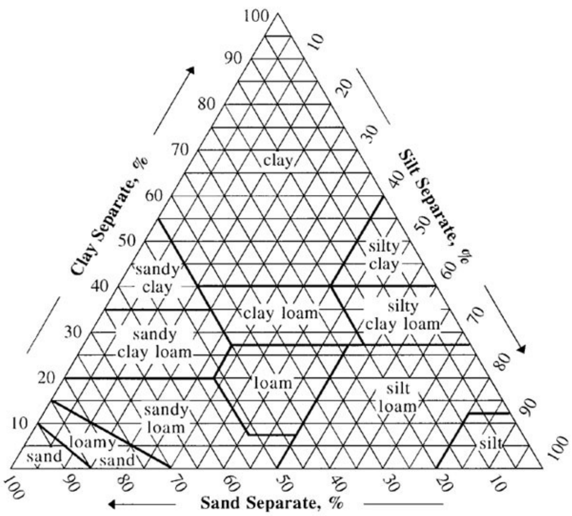


Figure 21; Soil texture triangle that indicates different soil textures by percentages of sand, clay and silt (Soil Texture Calculator USDA).

From the three maps shown in Figure 20, a combined soil map is created in which the soil type is calculated for the entire catchment. The soil types are like the ones that are shown in the soil texture triangle (Figure 21). A combination of the three different percentages determines the soil type. This has been calculated in the GIS model with a raster calculation tool. For each different soil texture, a map is created with the area in this specific class. This has been done by running a whole set of formulas downloaded from the USDA and adjusted to make them useable for GIS (Appendix 3). The formula below equals the area in the soil texture triangle of Sandy Clay Loam.

- Con (("kriging_clay" >=20) & ("kriging_clay" < 35) & ("kriging_silt" <28) & ("kriging_sand" > 45), 6, 99)

The formula starts with CON, which stands for an IF function in GIS. This is followed by the different percentages of clay, silt and sand who form the boundaries of the sandy clay loam part of the triangle. If the location of the map meets the function, it becomes a 6 but if it does not meet it is empty (99).

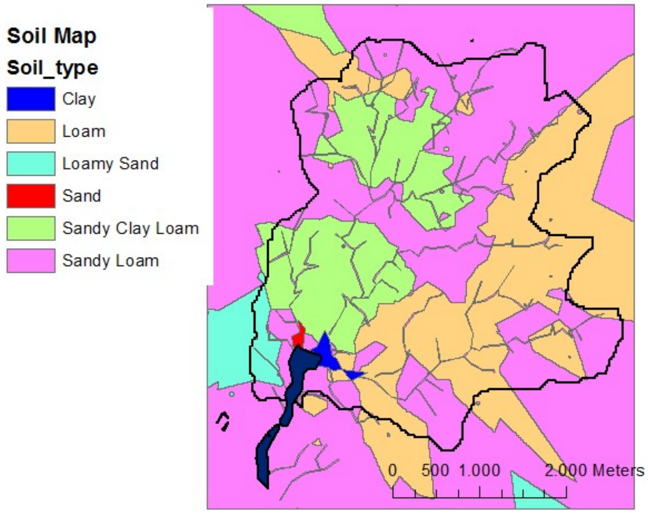


Figure 22; Soil map of the Spanish Lagoon Catchment including sediment body and streams.

Figure 22 shows the soil map of the area with the combined map of the raster calculations, but also the added red and blue parts that indicate the sediment bodies at the head of the Spanish Lagoon. Another adjustment is that the streams are all added with a width of 10 meters and a Sandy Loam soil.

The land-use map

The second map that has been created to analyse the hydraulic situation of the Spanish Lagoon catchment is het land-use map. The map is mainly based on satellite images and in addition to this, field observations, interviews and existing GIS data were used. Clear to see is that most of the area is covered by vegetation. This is because a big part of the catchment is in Arikok National Park, where building is not allowed.

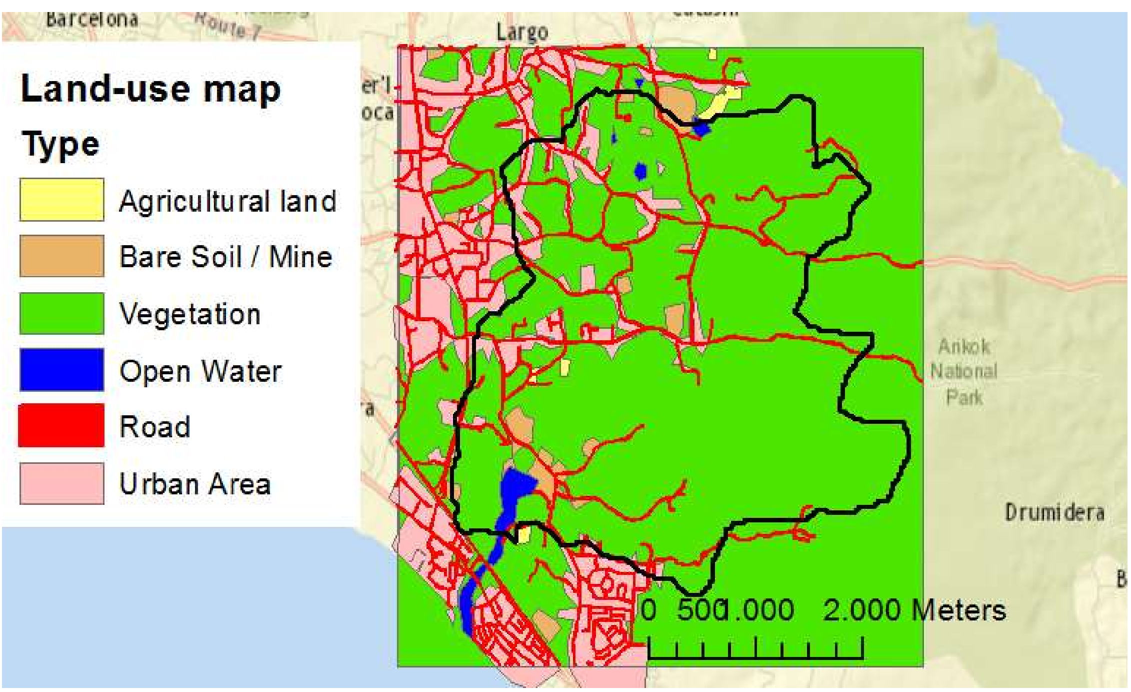


Figure 23; Land-use map of the Spanish Lagoon catchment

The urban areas are located on the North-West side of the catchment (Santa Cruz) and the South-West side (Balashi). Besides that, the area is almost fully covered by vegetation, except from some mines in the Northern part of the area and a few spots of bare soil and agricultural sides.

A.2 Process of modelling with AGWA

AGWA is a model that works step by step, therefore this chapter is following those steps as well. The input of the model consists of the soil – and land-use map as mentioned in the previous chapter, and besides that only the DEM of the area and precipitation data are needed. The steps that are used are according to the AGWA user-guide, in which also additional background information is provided (USDA-ARS TUSCON).

Delineation and discretization of the watershed

The first step of the AGWA model is to delineate the catchment by using the DEM of the area. The model creates a Flow Direction Grid and a Flow Accumulation Grid from the DEM and with those three grids the catchment is delineated. The delineation in AGWA works a bit different from the GIS HYDRO tools because with that method the outlet of the area was located much more towards the sea. The shape and area of the new delineated watershed is slightly different from the one that has been used as starting point during the fieldwork, but the maps still cover the entire catchment.

After delineation, the catchment will be discretised into model specific elements; watersheds. Those watersheds are smaller elements with a single outlet point or stream at one side of the watershed. This is needed because the Kineros2 calculations are based on streams with one watershed at the top, one watershed at each side and a single outlet. For SWAT it is also possible that a stream is going through a watershed. Because of this the map looks the same but the number of watersheds is smaller. Figure 5 gives an overview of the watersheds within the catchment and the streams though the area.

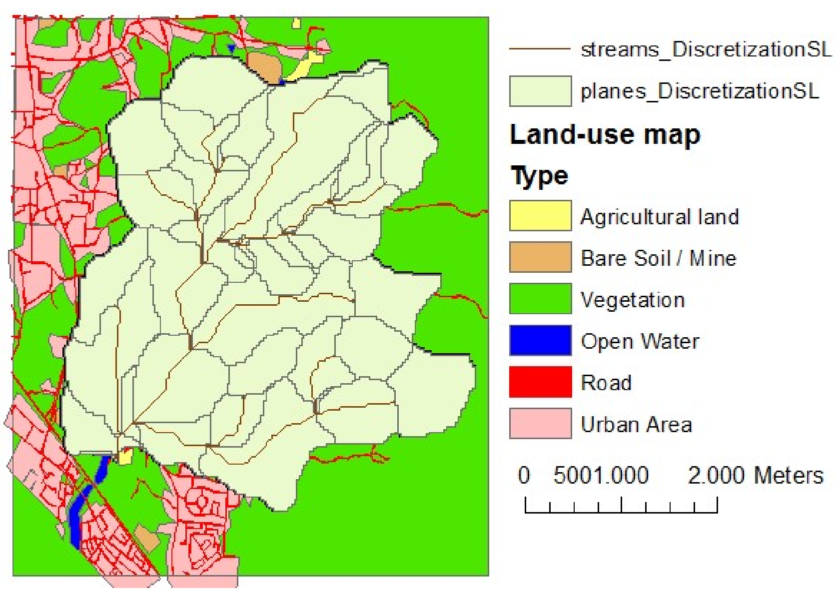


Figure 24; Overview of discretised catchment into watersheds

During the study, it came up that the threshold of the discretization is of great influence of the outcomes of the model. The threshold can be given in different settings but the main options are the maximum area of the watershed as a percentage of the total watershed, or the maximum length of the channels in meters. To be able to choose the optimal threshold for the study, different thresholds are compared and an overview is given in Figure 25.

The threshold is based om the flow length, with a maximum of 300, 750, 1000, 1500 and 3000 meters. As a comparison the stream that are defined in the GIS HYDRO tools are also added to the figure. For the discretisation with a threshold of 300 meters the number of watersheds is to large and the pattern of streams is to dense in comparison to the base version. The stream pattern of the 750-meter threshold looks much more like the one that is shown on the base map, but still the number of watersheds is too big (116). The watersheds in the north-east corner of the catchment are too small, some of them only one raster cell. This level of detail does not match the other aspects of the study.

The map with a threshold of 3000 meter is too imprecise, because a large part of the stream pattern falls away and some important streams are not considered at all.

For the calculation with 1000 meter the pattern of the stream is less detailed, but still every important stream is a separate one in this situation. The number of watersheds is strongly reduced to 53 and all of them consist of at least a few raster cells. The same goes for the discretization with a threshold of 1500 meters in which the number of watersheds is further reduced to 34. The main difference between the two situations is that the stream pattern of the 1500 map is less detailed and some of the streams that are visible in the base map are no longer visible. Therefore, the threshold of 1000-meter maximum stream length is chosen.

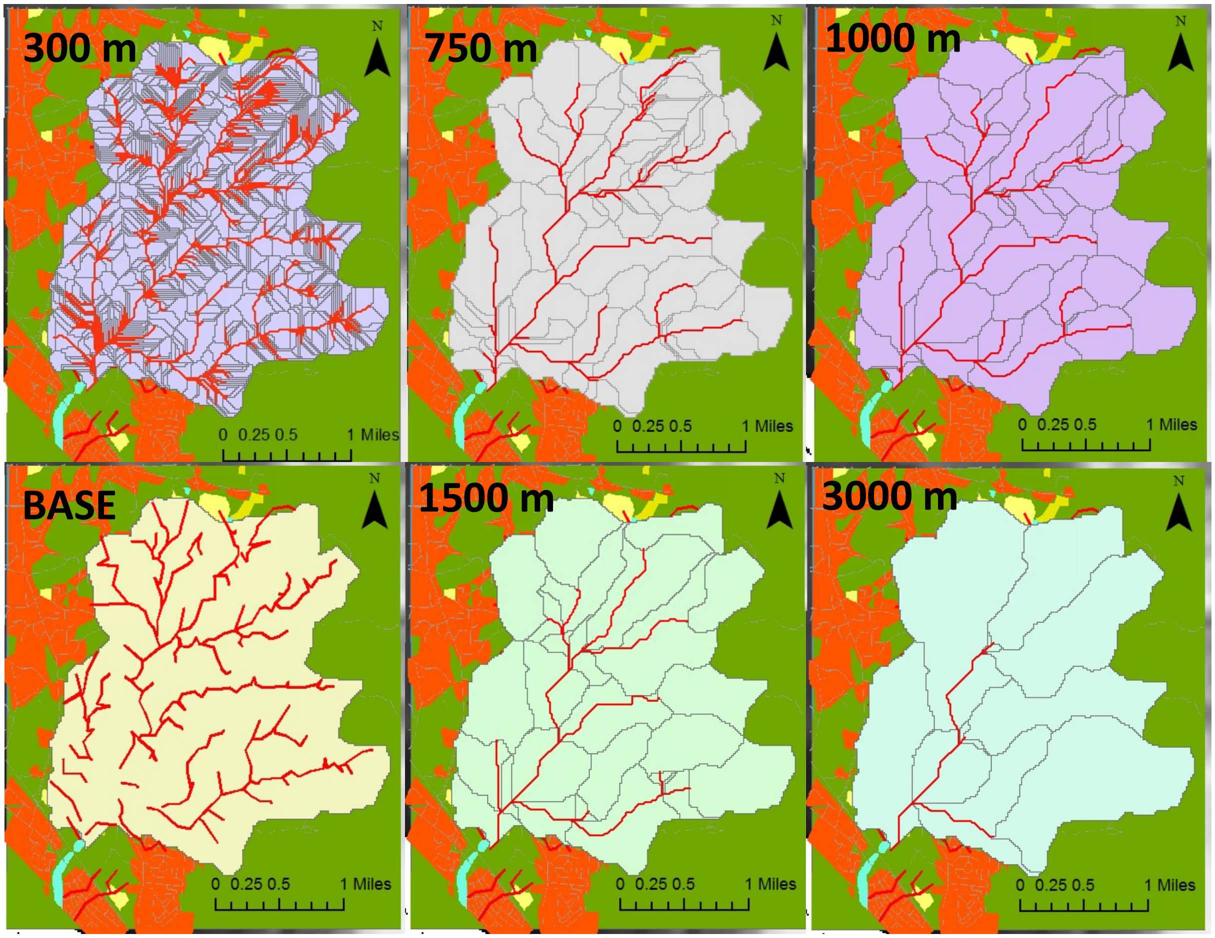


Figure 25; Overview of different thresholds for the discretization of the catchment.

Parameterization

In the parameterization step parameters need to be derived from each model element of the land-use map, the soil map and the different watersheds and streams as determined in the previous step. Parameterization consists of two parts; the first part is to specify the details of the streams and the second part is the coupling of the soil- and land-use map to the AGWA databases. For the first part, the channel type that has been chosen is the “Natural” channel. This has been chosen because in the catchment of the Spanish Lagoon the streams are mostly unaffected by humans and the bottom of the streams are natural.

For the second part, the parameterization is the coupling of the land-use map that has been drawn to one of the standard datasets in which additional parameters are given for different land-use types. For the study of the Spanish Lagoon the dataset *mrlc1992_lut* is used and the only thing that needed to be done was to match the names in the map with the exact same names and classes in the database.

For the parameterization of the soil map the dataset that has been used is the FAO soil dataset but it needed to be adjusted to be able to work with the soils that where found during the fieldwork. The FAO dataset works with SNUM codes and those are a combination of soil texture, slope and FOA soils. The problem of these codes was that during this study it was not possible to determine the FOA soils in the area and if that would be done the list of SNUM codes would still be incomplete.

Table 6; Overview of the SNUM codes and the changed values.

FAO component				FAO properties				FAO_summ	
SNUM	FAOSOIL	SU1	PER1	SANDTOP	SILTTOP	CLAYTOP	BDTOP	FRAG_TOP	POR_TOP
7001	Loam	AL	100	46.60	36.28	17.12	1.20	44	35
7002	LoamyS	ALS	100	79.35	17.68	2.98	1.20	26	34
7003	SandyCL	ASCL	100	55.44	19.89	24.66	1.66	25	25
7004	SandyL	ASL	100	66.30	24.96	8.74	1.49	34	26
7005	Clay	AC	100	25.63	16.23	58.14	1.84	29	15
7006	Sand	AS	100	90.19	7.84	1.96	1.62	35	22

To solve this problem the dataset of SNUM codes has been adjusted and new SNUM codes are added for the soil types that were found in the field (sand, clay, sandy clay loam, loam, loamy sand and sandy loam). The dataset is spread over different files and in every one of them the new codes are added. Table 6 gives an overview of the soil parameters that were changed with the outcomes of the fieldwork. The upper row indicates the file in which the value has been changed and the row below show the meaning of the values, for example the percentage of sand in the top layer (SANDTOP) or the bulk density (BDTOP). The left columns show the “new” SNUM codes, the description of the codes and the abbreviation that is given to the code.

When this was done, the SNUM codes were also added to the soils in the soil map, the parameterization can be done and the parameterization file will be written. This file gives an overview of the different watersheds with the information about the topography, land-use and soil. This step is the same for both Kineros2 and SWAT.

Precipitation

The final step before the model can be executed is to write the precipitation file. It is possible to get precipitation from a database, but unfortunately those are only databases for the US. There is no detailed precipitation data available for Aruba during this research, only daily precipitation rates by the meteorological centre. This is the reason that the precipitation file will be written with limited input only. The data that will be used is the open source daily climate data from The Weather Company (n.d.). The input for precipitations is different between SWAT and Kineros2 but for both models an overview is given below.

Kineros2 is a model that is built for a single precipitation event and the event that has been chosen for this is the extreme event of November 20th, 2016. 70mm of rainfall felt that single day, and this has caused inconvenience on the entire island, including the Spanish Lagoon catchment. Because there is no further detailed information about the event, the precipitation is set as a uniform event over 6 hours.

The climatic input for SWAT is more complicated. To be able to run the model it is necessary to link the map to one or more data stations. Those stations are linked to a database with all the climatic average monthly data per location. Unfortunately, the stations are only located in the US which means that it is not possible to couple this with the map.

To be able to get the SWAT mode running one of the stations have been moved from Florida to Aruba. The file that was part of this station has been changed into the values that belong to the climatic data on Aruba. The most important numbers are the amount of rainfall per month, the number of days it is raining per month, average/minimum/maximum temperature of each month and the average wind speed (Winchell et al., 2007). After the values were changed this was saved over the original file and used by the AGWA model to calculate the climatic data.

Running the model

When all the input parameters and files are correct, the simulation file can be written and executed. The results are described and discussed in the main report Chapter 4.

REFERENCES

Soil Texture Calculator USDA. (n.d.). Natural Resources Conservation Service Soils. Retrieved May 04, 2017, from https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_054167

USDA-ARS TUSCON, US – EPA, & University of WYOMING. (n.d.). AUTOMATED GEOSPATIAL WATERSHED ASSESSMENT (AGWA) (Rep.). Retrieved May 8, 2017, from SOUTHWEST WATERSHED RESEARCH CENTER TUCSON, ARIZONA website: https://www.tucson.ars.ag.gov/agwa/download/documentation/agwa_3.x_user_guide.pdf

The Weather Company. (n.d.). Weather History for ARUBA - 2016. Retrieved May 26, 2017, from https://www.wunderground.com/history/airport/TNCA/2016/1/1/CustomHistory.html?dayend=31&monthend=12&yearend=2016&req_city=&req_state=&req_statename=&reqdb.zip=&reqdb.magic=&reqdb.wmo=&MR=1

Winchell, M., Srinivasan, R., Di Luzio, M., & Arnold, J. (2007). ArcSWAT interface for SWAT2005 User's guide. Texas Agricultural Experiment Station and United States Department of Agriculture, Temple, TX.

APPENDIX 2: RESULTS OF THE MODEL WITH MEASURED INFILTRATION

The infiltration capacity of the soil has been measured with a mini disk infiltrometer, but the results differed too much from the general infiltration capacity of the soil. The infiltration that has been used comes from the standard FAO soil data that comes with AGWA. The table below gives an overview of the differences between the measured K value and the K value that is determined by the FAO.

Table 7; Difference between standard FAO value for K and the measured K value.

Soil Type	K value FAO	K value measured
Sand	210	10.8
Clay	0.6	0.45
Loam	13	0.06
Loamy Sand	61	2.11
Sandy Clay Loam	4.3	0.85
Sandy Loam	26	0.23

The difference between for example the measured K value for loam (0.06) and the value given by the FAO (13) is a factor 216. It is unclear whether this mistake comes from the measuring device, method, the top layer of the soil or some other reason.

To be able to get a clear view on the value of these differences the model has also been executed for the current situations with the measured K values. As one could expect these results differ a lot from the model with the standard K values from the FAO. Figure 26 below gives and overview of the runoff that will occur during a 70mm precipitation event. The amount of runoff is extremely big with a discharge up to more than 500.000 m3 in 6 hours towards the Spanish Lagoon.

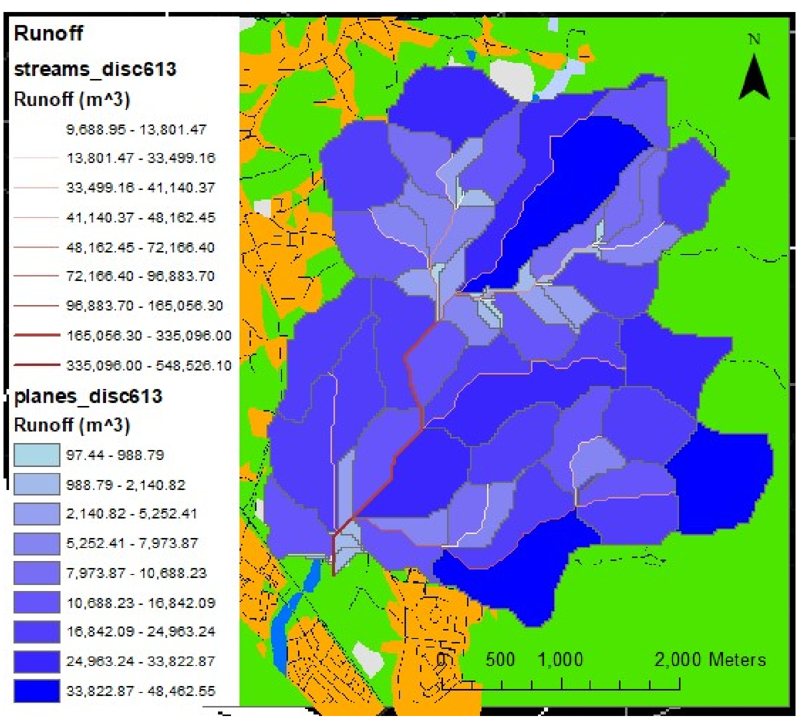


Figure 26;Overview of the amount of runoff in the catchment for the measured K values.

The amount of infiltration in the catchment has been strongly reduced because of the change of the infiltration to the measured values. The results for this model show that the sandy areas in the west of the catchment infiltrate about 15 to 20 mm of water. The parts towards the east with the soil that have lower infiltration levels and more topography show infiltration of only 3 to 5 mm during the event. These values are very low, especially when the initial condition of the soil is dry. The total amount of infiltration in the catchment is 9,65 mm of the total of 70 mm.

Figure 27 shows the amount of sediment that will be moved towards the outlet of the catchment. In the area with the steepest slopes the amount of sediment that is lost every second will be maximum up to 30 kg/sec. For the streams, the flow is even bigger, up to 365 kg of sediment that flows through the stream. In total, the sediment loss of the catchment during this single precipitation event was 2910 kg/ha. This is a total of more than 4000 tons of soil.

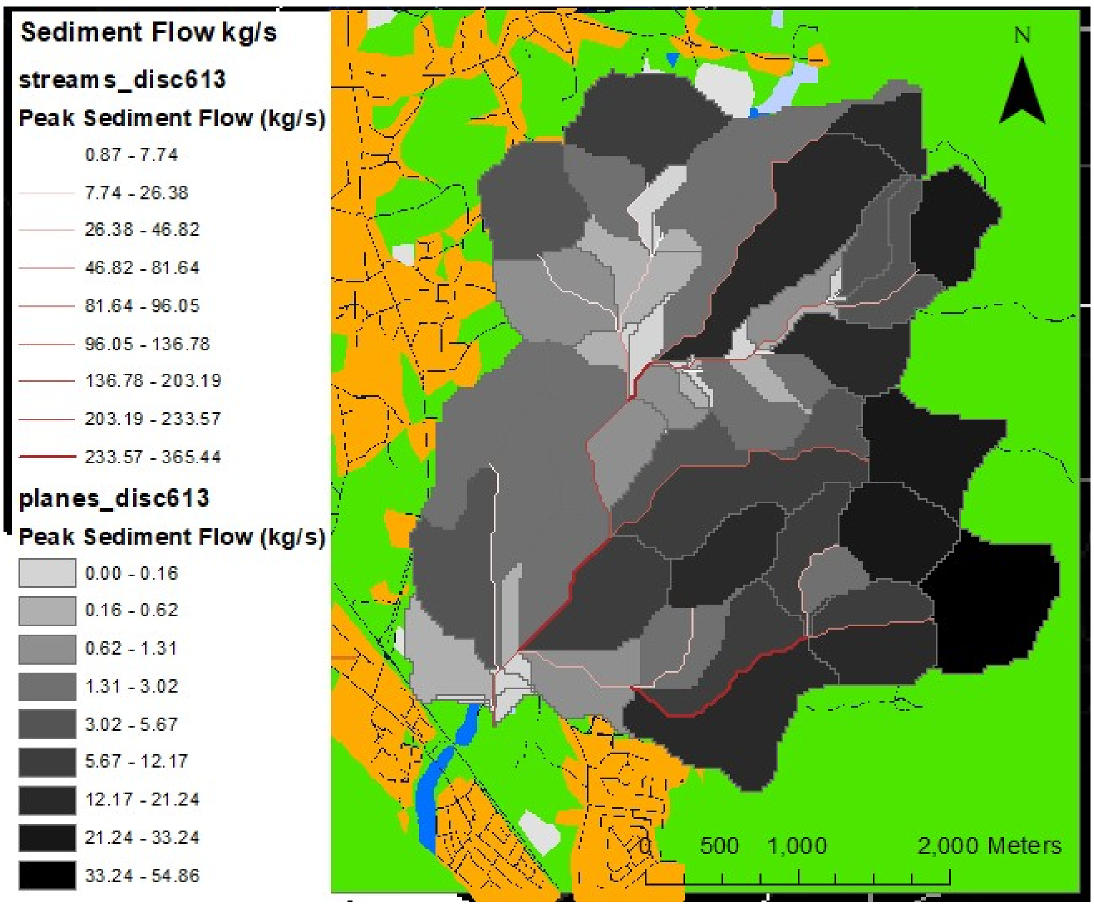


Figure 27; Overview of the sediment flow in the catchment with the measured K values.

APPENDIX 3: FORMULAS TO CALCULATE THE SOIL TYPE

Below an overview is given of the different formulas that were used for the Raster Calculation tool in GIS to be able to create a soil map. The term “kriging” followed by Clay, Sand of Silt indicates the percentage of each of the three soil fractions for all the different locations.

Clay
Con(("kriging_clay" >= 40) & ("kriging_silt" < 40) & ("kriging_sand" <= 45), 1, 99)

Silty Clay
Con (("kriging_clay" >=40) & ("kriging_silt" >=40), 2, 99)

Sandy Clay
Con (("kriging_clay" >=35) & ("kriging_sand" > 45), 3, 99)

Silty Clay Loam
Con (("kriging_clay" >=27) & ("kriging_clay" <40) & ("kriging_sand" <=20), 4, 99)

Clay Loam
Con (("kriging_clay" >=27) & ("kriging_clay" < 40) & ("kriging_sand" >20) & ("kriging_sand" <= 45), 5, 99)

Sandy Clay Loam
Con (("kriging_clay" >=20) & ("kriging_clay" < 35) & ("kriging_silt" <28) & ("kriging_sand" > 45), 6, 99)

Silt
Con (("kriging_clay" <12) & ("kriging_silt" >= 80), 7, 99)

Silt Loam 1
Con (("kriging_silt" >=50) & ("kriging_clay" >=12) & ("kriging_clay" <27), 8, 99)

Silt Loam 2
Con (("kriging_silt" >=50) & ("kriging_silt" < 80) & ("kriging_clay" < 12), 8, 99)

Loam
Con (("kriging_clay" >=7) & ("kriging_clay" <27) & ("kriging_silt" >=28) & ("kriging_silt" <50) & ("kriging_sand" <= 52), 9, 99)

Sandy Loam 1
Con (("kriging_clay" >=7) & ("kriging_clay" <20) & ("kriging_sand" > 52) & ("kriging_silt" + 2 * "kriging_clay" >=30) , 10, 99)

Sandy Loam 2
Con (("kriging_clay" <7) & ("kriging_silt" <50) & ("kriging_silt" + 2 * "kriging_clay" >=30), 10, 99)

Loamy Sand
Con (("kriging_silt" +1.5*"kriging_clay" >=15) & ("kriging_silt" +2*"kriging_clay" < 30), 11, 99)

Sand
Con (("kriging_silt" +1.5*"kriging_clay" < 15), 12, 99)