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The effects of water management and climate change on catchment scale:

The case of Salinja di Vlijt catchment on Bonaire

Satellite picture Bonaire (Earth, 2022)

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The case of Salinja di Vlijt catchment on Bonaire

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Abstract

This study examines the impact of climate change and water management choices on infiltration and runoff in the case of the Salinja di Vlijt catchment on Bonaire. Climate change will affect precipitation, temperature will increase, sea level will rise (at least 0.2 meters), and tropical storms will be more intense. This will influence the catchments hydrology – runoff will decrease in base flow and increase in peak flow. The current water management measures – drain pipes, channels, reservoirs, and dams – lead to nuisance flooding and partly are in need of maintenance. Evaluating different water management scenarios, rain barrels and rooftop disconnection systems with water storage can reduce runoff and improve infiltration, while additional infiltration trenches decrease catchment discharge and increase infiltration in specific sub-catchments. Extra reservoirs have limited impact on overall runoff and infiltration. Implementing selected measures can help mitigate the effects of changing urbanization and climate change in the catchment. Further research is required to explore the combined effects of measures and assess spatial feasibility. This study contributes valuable insights for effective water management strategies in the Salinja di Vlijt catchment, and the approach presented can be applied to other catchments.

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1 Introduction

Climate change is an intensively studied and discussed topic all over the world. The effects of climate change are already visible globally and will become more severe (UN, 2022). Known global changes in climate are increases in temperature, (extreme) precipitation, and sea level rise (IPCC, 2022). Especially low lying islands have a vulnerable position, with sea level rise and heavy storms posing the biggest threats (Greenpeace, 2022; UN-Habitat, 2015). While low-lying islands in general are a self-sufficient ecosystem with the sea as a clear boundary, changes in the nature area or urban areas will affect the islands resilience (Hemmati et al., 2020). The popularity of tropical islands increases, resulting in a higher demand for houses and roads (UN-Habitat, 2015). Transforming rural areas into pavements and buildings, changes the islands landscape (Olivera & DeFee, 2007). The combination of climate change effects and urbanization influences the hydrology of low lying islands.

Climate change effects on a catchment can aggravate problems. For example, the combined effect of increased temperature and heavy precipitation leads to runoff and erosion causing flooding and sediment accumulation (Greenpeace, 2022; KNMI, 2021). Sediment transport into the ocean is a problem for the corals that are close to the shoreline (Roberts et al., 2017). The terrestrial runoff can cause bleaching of corals or even kill exposed coral tissue (Roberts et al., 2017; Weber et al., 2012). To comprehend the effects of climate change on catchment scale, understanding the key components of the water balance is needed (Shen & Chen, 2010). Terms of the water balance are: precipitation, evaporation, change in storage, and runoff. These terms are also influenced by the urbanization and climate change.

Among the islands that are affected by climate change, urbanization, and coral bleaching is Bonaire. Bonaire is a tropical island in the Caribbean sea, acclaimed for its coral reefs and impressive sea life (Beautiful-Bonaire.nl, 2010-2022). In the past, intense precipitation events on Bonaire have caused large amounts of infiltration excess runoff (Haas, 2005), influencing the health of sea life near the shore. The most recent urban flooding and sediment transport event occurred on Bonaire in November 2022, after more than 100 mm of rain had fallen in 5 hours (KNMI, 2022). The villages of Kralendijk and its marina flooded and the sediment transport was clearly visible, as seen in Figure 1 **Fout! Verwijzingsbron niet gevonden.**(NOS, 2022). As these floods heavily degrade corals and sea life, they have a big impact on the economy of Bonaire, because coastal waters are the main tourist attraction of the island (Beautiful-Bonaire.nl, 2010-2022). A critical part in these flooding events are the water management measures that are and are not taken. One flooding event was caused by the collapse, failure of a poorly maintained dam after heavy rainfall in 2022 (Pourier, 2023). This demonstrates that maintenance of water management measures is important.

Figure 1: Sediment plume in the Salinja di Vlijt outlet in November 2022 (Douma, 2022)

Research on erosion and runoff in the Salinja di Vlijt catchment has been reported by (Koster, 2013; Roos, 2018). According to these studies most surface runoff is generated in the central part of Kralendijk. Reducing paved areas would not decrease flooding, increasing vegetation cover would decrease the rate of soil loss and increasing the drainage capacity would decrease runoff and flooding (Koster, 2013).

The knowledge gap for the Salinja di Vlijt catchment, but also for the whole island, is an overview of the current water management measures and their maintenance status. Including the influence of climate change on catchment scale and what therefore is needed for the water management measures. The Salinja di Vlijt catchment is a relevant case study area, because of the microtidal salt flat (Salinja di Vlijt) which is important for the various birds that feed there (like flamingos) and the combination of urban and rural areas in the catchment. Little data are available (as yet) on Bonaire and more specifically on the catchment of Salinja di Vlijt. Given the importance of this research a tool is created that can be adjusted and improved over time. The focus of this tool will be on water management options that are currently in the study area and their operational condition. The water management measures need to decrease runoff into the sea while taking into account the changing climate. Therefore, new measures will be tested to improve the climate resilience of the catchment.

2 Research objective

The objective of this study is to understand how climate change and water management measures will affect the water balance, and especially infiltration and runoff processes in the Salinja di Vlijt catchment on Bonaire.

2.1 Research questions

To meet the objective, the following research questions will be answered:

- Which factors determine runoff in the Salinja di Vlijt catchment?
- How will climate change affect the runoff in the Salinja di Vlijt catchment?
- What are the current water management measures taken in the Salinja di Vlijt catchment?
- What is the effect of different water management scenario's on the runoff and infiltration of the Salinja di Vlijt catchment?

3 Method

The method for this study contains several elements to answer the sub questions and eventually, the main objective. The fieldwork and the ArcGIS analyses have been done to determine the different runoff factors and current water management measures in the Salinja Di Vlijt catchment. The effects of climate change on the catchment is excecuted via literature review. The information acquired during fieldwork and ArcGIS is used to formulate a representation of the Salinja di Vlijt catchment in the Storm Water Management Model (SWMM). SWMM is then used to simulate runoff patterns and assess the effect of new water management measures. Which parameter values and scenarios are used are explained in chapter 3.5. Obtaining all the information will be enough to answer the main objective of this study.

3.1 Study area

The Salinja di Vlijt catchment is located in the west of Bonaire, north of the city centre of Kralendijk. The catchment area is approximately 18.46 km^2 with an elevation between -2.3 m (in the lowest part of the salt flat) and 132.4 m above sea level. The study area contains an urban part (8.13 km^2) and a rural part (10.33 km^2). The outlet of the catchment is situated at the harbour, which connects the Caribbean Sea to the salt flat Salinja di Vlijt. The salt flat has an area of approximately 0.13 km^2 (Earth, 2022). Bonaire has a tropical Savanna climate, with temperatures between 23°C and 32 °C and precipitation of 350-450 millimetre (Klimaatinfo, n/a). The average precipitation falls in the rain season, which are the last three months of the year (October, November, December). Where over the three month 51% of the yearly rain falls, with the highest amount in November (J.A. De Freitas, 2005). The typical vegetation on Bonaire can be compared to the vegetation found in arid areas all over the Caribbean. The highest covered vegetation type is *Casearia tremula-Prosopis juliflora*, which covers 15,7% of the vegetation on the island (J.A. De Freitas, 2005).

The map of the study area has been constructed using the DEM of Bonaire and analysing it using ArcGIS (shown in Appendix 7.1; more details below). During the fieldwork, the boundaries of the catchment were examined and verified. Following rainfall events, the surface runoff was carefully observed and mapped as it flowed towards the outflow into the sea. The fieldwork data, in conjunction with ArcGIS analysis, led to the adjustment of a portion of the catchment based on the findings from the fieldwork study. This adjustment resulted in the delineation of the catchment boundaries and the depiction of overland flow, as depicted in Figure 2.

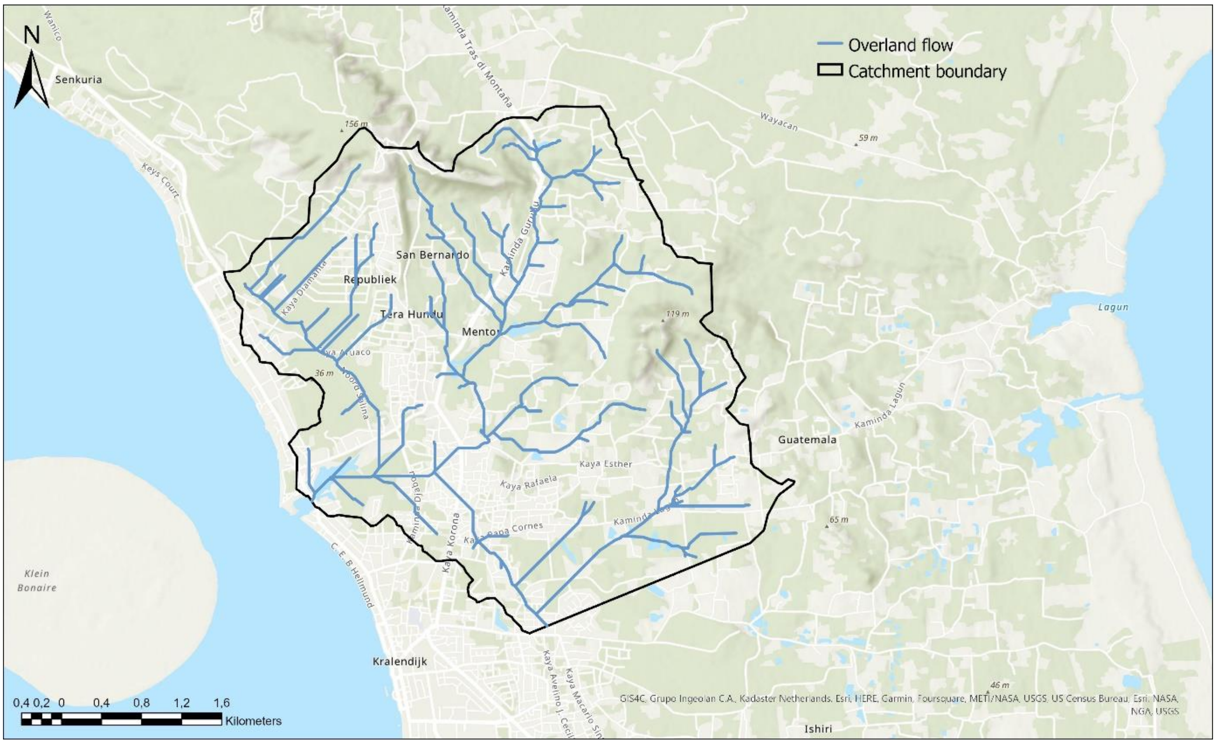

Figure 2: Catchment boundary with overland flow patterns

Apart from the catchment boundary and overland flow paths, the soil types in the catchment were identified. A map of the geology layers in the catchment was used and sample locations were taken in every layer (see Appendix 7.2 for a map and the locations). On each location a jar test is executed. For the jar test a soil sample is taken and put in a jar together with water (University, 2022). The soil type is distinguished from the different layers in the jar, for a more broad explanation read Clemson University, 2022. There was also a jar test done on locations close to reservoirs and channels, with the results shown in Appendix 7.3. The locations of the soil samples in the catchment are provided in Appendix 7.2.

The soil type is loamy sand and sand on 22 out of the 27 locations, where the jar test is executed. The soil types are used to determine the Manning roughness n of the impervious and pervious area in the study area for SWMM (explained in more detail in chapter 3.5.2).

3.2 Climate change assessment

The effect of climate change on Bonaire was limited to topics that influence the runoff of the study area, i.e.: precipitation, evapotranspiration, sea level rise, and storms. The influence of sea level rise was taken into account to analyse if the salt flat Salinja di Vijt would decrease in storage, because the base water level increased. The storm influence on the catchment is assessed to investigate a possible effect of heavy rain showers during storms. The effect of climate change on Bonaire was identified through literature review and reports done not only on Bonaire, but also the whole Caribbean. By including the whole Caribbean more information was available allowing comparison.

3.3 Fieldwork

The fieldwork was done to verify the catchment boundaries, mapping the structures in the catchment, and check the overland flow paths. Reviewing the catchment boundaries and overland flow paths was based on observations of structures and water moving towards outlets. The structures were mapped with a GPX app called: Geo Tracker (Geo-tracker, 2023). The following structures were mapped: natural channels, artificial channels, drainage pipes, bridges over a channel, culverts, reservoirs/retention basin, dams, wells, and overland flow/puddles. The information was collected regarding the height and width of the structures, vegetation cover where relevant, and status of maintenance. The pictures of all the structures with the collected information were stored in a GIS file with location.

In the GIS file height, width, vegetation cover, and maintenance status were stored. The height of the structures is measured in meters, from the top of the structure to ground level. The width of the structures is measured in meters, the width is of the structure or water body. The drains are round so the width and height are the same, the diameter. The vegetation cover and maintenance status was classified using five groups, shown in Table 1:

Table 1: Classified groups for vegetation cover and maintenance status

Number	**Vegetation cover [%]**	**Maintenance status**
1	0-20%	almost perfect conditions
2	21-40%	small maintenance should be done
3	41-60%	maintenance should be done
4	60-80%	broken down but can be fixed
5	81-100%	totally broken down

For an example what each maintenance status looked like in the field, examples for every group are provided in Appendix 7.4.

3.4 ArcGIS Pro analyse

The catchment boundaries for the Salinja di Vlijt catchment were established using the Geographic Information System ArcGIS Pro. The creation of the watershed for overland flow within the catchment and the delineation of the catchment boundary itself relied on the Digital Elevation Model (DEM) of Bonaire as input data. The DEM provided a contour map with a spatial resolution of 10 meters and a height resolution of 1 meter. (Mücher, 2017). Using the Digital Elevation Model (DEM) as a basis, the Fill and Flow direction tools were used to generate a flow direction map. This map was then utilized to establish both the catchment boundary and the streams representing overland flow. The Watershed and Raster to polygon tools were utilized to define the catchment boundary, while the following tools were employed to delineate the streams: Flow accumulation, reclassify, raster to polyline, and clip (applied twice). The first clip tool was used to exclude streams that fell outside the catchment boundaries. The second clip tool was necessary because the southern boundary of the catchment, as calculated using GIS, did not precisely match the field observations. Hence, the boundaries were refined using information obtained from fieldwork.

Another part of the GIS analyse is transforming the pictures, made of the structures during fieldwork, into point locations on a map. These photos are then combined with the information linked to the GPX location of the photo. Linking the photos to GPX is done with the tool 'Geotagged photo to point' and then the tool Delete field is utilized to delete excess information. The GPX locations with information about the height, width, maintenance status, and vegetation cover of the structures is converted to GIS with the tool GPX to feature. This tool is utilized for all the GPX files which are combined into one dataset with the tool Append. The picture data and GPX information are combined into one dataset with all the information linked in the attribute table of all the geotagged photos.

3.5 Stormwater Management Model (SWMM)

The Storm water management model (SWMM) was chosen to model runoff in an urban and rural environment. SWMM is a model used to simulate rainfall-runoff responses in a primarily urban environment and can be used for single events or long-term simulations (Gironás et al., 2010). The model can be used to test systems, test resilience of the system and/or to test Low Impact Development systems (LIDs) to prevent flooding or more general decrease runoff (Huong & Pathirana, 2013; Palla & Gnecco, 2022). The model can be used to model pollution or different land uses in a catchment as well (Qin et al., 2013). There is also a climate adjustment tool built into the SWMM5 version; this tool (currently) is only available for the US, therefore not used in this study (Jones, 2017).

SWMM was used to simulate rainfall-runoff for the Salinja di Vlijt catchment in Bonaire. The input for this model was acquired during fieldwork on Bonaire. During the fieldwork, as explained in section 3.3, the structures in the catchment were measured and mapped. The channels and reservoirs in SWMM were based on the GIS map made for this research. The reconstruction in SWMM is a simplification of the reality. Parameters utilized are briefly explained in the upcoming chapters. For this research the reconstruction of the Salinja di Vlijt catchment is used to simulate the runoff during the rainfall events of November 2022. After the present situation is simulated, the other scenarios are also tested (cf. section 3.6) with the rainfall event of November 2022. The simulation was based on the rainfall amount of 271.4 mm recorded in November 2022. This specific month was used, because there were floodings that happened in this month as shown in Figure 1. Hence, it was worth exploring the potential of simulating possible bottlenecks in real-life using the model.

3.5.1 Model Parameters

The parameters of the model are kept at their default value unless stated otherwise. The reporting time steps are 1 minute, to make sure the continuity error is acceptable. For surface runoff and flow routing this error should be lower than 10%, for the model result to be acceptable (Simon, 2022). For the flow routing continuity error this percentage can be higher (1 or 2 percent) if it can be explained at node level, by for example lengthen short conduits.

The method used in SWMM for flow routing is dynamic wave routing. This is the more complex routing method which can account for channel storage (Simon, 2022).

The evaporation rate in the model is a constant value of 7.14 mm/day (Haas, 2005). The windspeed is based on average monthly windspeeds on Bonaire, which varies between 18.0 and 25.2 km/hr (Information, 2023). The temperature and rainfall are based on the November 2022 data (KNMI, 2022).

In Figure 3, can be seen that the system responds to observed precipitation in calculated runoff. Where a minimum amount of precipitation needs to fall in the system before runoff starts. This threshold is based upon the water balance where infiltration and evaporation are influencing the start of the runoff.

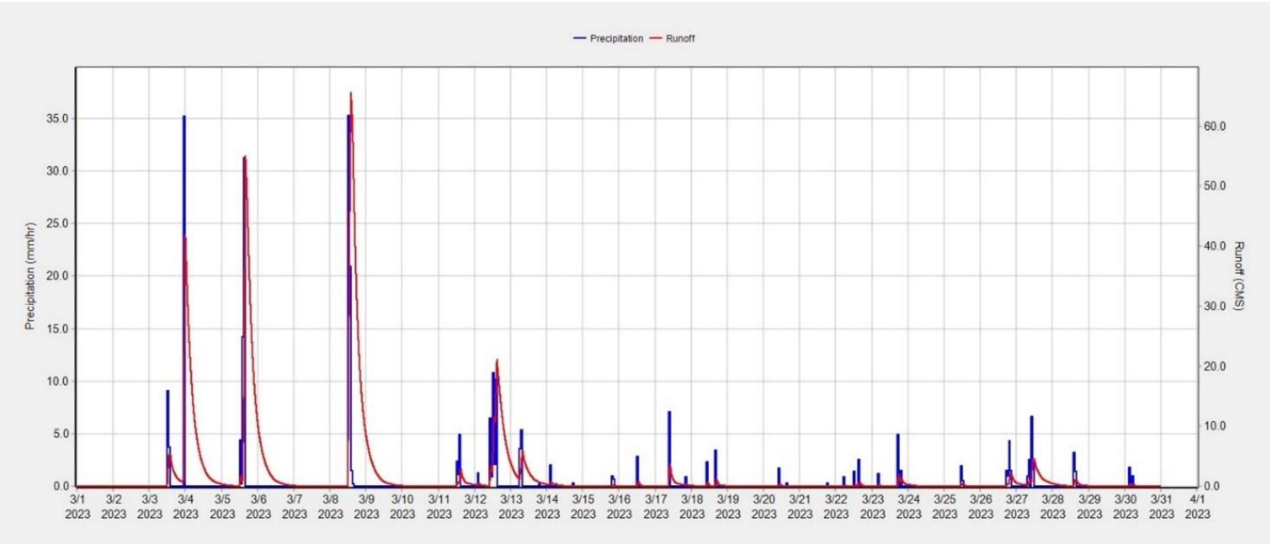

Figure 3: Graph of observed precipitation and calculated runoff of the system by SWMM

3.5.2 Sub catchments

The study area is divided in 7 different sub catchments, also shown in Figure 5 in section 4.2. Sub catchment S5 flows towards S4 and sub catchment: S2, S3, S4, S6, and S7 flow towards S1. Sub catchment S1 flows towards a reservoir, which represents Salinja di Vlijt.

In this study pollution, land use, and groundwater flow are not taken into account. Therefore, land use, initial build up, groundwater, and Curb length stays zero.

Each sub catchment has the same rain gage (Gage1) and thus the same amount of precipitation. The area of the sub catchments is based on Google earth (2023) images and measurements. The width of the overland flow is based on the furthest distance between a spot in the sub catchment to the nearest channel. The width, slope, percentage (im)pervious area, and depth depression storage (im)pervious area of the sub catchments are estimated combining the data of the map made in ArcGIS Pro and Google Earth.

The Manning roughness parameter is characterized using two groups: The rural part and the urban part of the catchment. For the urban part sand is used as soil type, based on observations of the jar test done during fieldwork. For the rural area loamy sand is the base soil type, also based upon the jar test done during fieldwork (Appendix 7.27.3). The Manning roughness (n) coefficient of sand is based on a particle size of 1 millimetre with n_b=0.026, for loamy sand the particle size 0.2 millimetre is used, which results in a n_b=0.012 (George J. Arcement, 1989). However based on observations some adjustments need to be made to the Manning roughness using average vegetation cover and channel conditions.
For the urban area the adjustments would be: degree of irregularity; n_1=0.005, variation of channel cross section; n_2=0.005, effect of obstruction; n_3=0.010, amount of vegetation; n_4=0.010, degree of meandering; m=1 (George J. Arcement, 1989). For the rural area the adjustments would be: degree of irregularity; ; n_1=0.010, variation of channel cross section; n_2=0,005, effect of obstruction; n_3=0.020, amount of vegetation; n_4=0.025, degree of meandering; m=1 (George J. Arcement, 1989). The adjustment n values are all added up to the base n value of the rural and urban areas, resulting in the following equation; $n=(n_b+n_1+n_2+n_3+n_4)m$. The Manning value n for the urban area will be; n_u=0.056. The Manning value n for the rural area will be; n_r=0.072.

3.5.3 Junctions

The junctions in this study can represent a well and bridges connecting channels. The maximum depth is based on the information in the map in ArcGIS. The ponded area of the junctions is zero, because it would indicate there is a storage area where flooded water can enter (another channel for example), this has not (yet) been observed in the study area. The initial depth is also zero, because most of the channels were empty. For simplicity all the channels initial depth are set to zero.

3.5.4 Conduits

Conduits are channels that move water from one node to another. The dimensions of the conduits are based using the data from the ArcGIS Pro map. The Manning roughness, shape and length used for the different conduits (channels) is based on observation in the field, pictures from the GIS map and sources on Manning roughness (George J. Arcement, 1989; Toolbox, 2004). Furthermore, the seepage loss per conduit is the same which is an average at the LVV bij Openbaar Lichaam Bonaire site, which is just outside the catchment. The seepage loss to groundwater is 10 mm/day, which is 0.417 mm/hr (A.J. van Kekem, 2006).

3.5.5 Streets

The streets function as conduits, channels that move water from one node to another. The difference is that the water flows on the side of the road and in this model has no gutter and different curb heights depending on the street. Within the model there a four different streets that represent the actual street flow in the study area. Each street has different dimensions of the curb and road width. The streets are impervious and seepage loss is zero.

3.5.6 Storage units & weirs

In the model the storage units represent reservoirs, a distinction is made between smaller reservoirs with a dam and the Salinja di Vlijt reservoir connecting the catchment to the sea. Each storage unit has a weir which connects the storage unit to a junction or the next storage unit. These weirs simulate a dam or outlet of the reservoir.

The evaporation factor of the storage unit is 1, which indicates it has the same evaporation loss as the whole catchment. The seepage loss is estimated using the saturated hydraulic conductivity (Ksat) based upon the soil type. The soil type of the storage units is in between loamy and sandy soils, which has a Ksat of 2 cm/d corresponding to 0.833 mm/hr (Gupta et al., 2021).

3.5.7 Weir

The length and heights of the weirs are based on the fieldwork done in the Salinja di Vlijt catchment. The discharge coefficient (D_C) of the weir needs to be represent of an overflowing dam. In the literature these values differ between 0.3 up to 4.0, depending on different variables (discharge, height etc.) (Chen et al., 2018; Salmasi, 2022; Suprapto, 2013). The discharge of the flow of the water is unknown, therefore the coefficient cannot be calculated precisely. The D_C value used for all the weirs is 2.2. To test the effect of different values for the discharge coefficient, 3.33 (default of SWMM) and 5 were used. There is a large difference in the flooding of the nodes: J8, SU2, SU3 & SU4, overflow with values D_C=3.33 and D_C=5, but do not overflow with D_C=2.2. One of the differences between D_C=3.33 and D_C=5 is the total hours the nodes are flooded and the total flood volume, which increases with an higher D_c. On the other hand, with D_C=3.33 and D_C=5 the continuity error of flow routing is above the maximally acceptable 10% (for D_C=3.33 = 28.48 % and D_C=5 = 27.34 %). The value D_c=2.2 is therefore used, because the continuity error is below 10%.

3.5.8 Outlet

For this catchment there is only one outlet which is connected to the reservoir Salinja di Vlijt. All the sub catchments, conduits and junctions flow towards reservoir Salinja di Vlijt. The outflow represents the connection between the catchment and the sea.

3.6 Scenarios and measures

The current catchment in SWMM is represents the situation established in February 2023. Certain scenarios and measures are tested using this model. The scenarios and measures are all explained in the next paragraphs.

3.6.1 Low Impact Development measures

Low Impact Development measures (LIDs) are designed to capture surface runoff and contribute to higher detention, infiltration and evapotranspiration. In this study the focus is on the capture of surface runoff and infiltration. There are multiple LIDs that were tested within SWMM in the study area. The LIDs were divided in LIDs in the urban areas: S3, S7 and partly S2, and LIDs in the rural area: S4, S5, S6 and partly S2. S1 is not used for LIDs because it represents Salinja di Vlijt and there is more use for measures upstream to slow down or store water to prevent flooding downstream (Gunnell et al., 2019). The LIDs that are tested in the urban area are rain barrels and rooftop disconnection system in the urban area. In the rural area infiltration trenches and adding an extra reservoir are tested for their effect on runoff. All the measures are tested individually using the rainfall events in November 2022. Two scenarios are compared: current surface sealing, and further urbanization with increased surface sealing. For the future surface of the study area, only the urban measures are tested. The increase in surface sealing of the study area is based on the urbanization trend seen in the past 11 years (Statistiek, 2023). This results in six different scenarios as shown in Table 2.

Table 2: Scenarios and LIDs usage tested in SWMM

LIDs	**Urban area + current sealing surface sealing**	**Rural area + current sealing surface sealing**	**Urban area + future sealing surface sealing**
Rain barrels	X		X
Rooftop disconnection	X		X
Infiltration trench		X	
Extra reservoirs		X	

3.6.2 Future surface sealing of the study area

The future surface sealing is based upon the urbanization trend of the past 11 years on Bonaire. An average of 2.27 persons per household was used to determine the increase in housing on Bonaire (Statistiek, 2017). In 2011 the population of Bonaire was 15,679 people, currently (2023) the population is 24,090 (Statistiek, 2023). This increase of 8,411 people occurred in 11 years, which is an increase of 34% of the population. With the average household of 2.27 persons per house, this results in an increase of 8,411/2.27= 3.705 houses. Assumed is that all these houses are built within the study area, and are equally divided over three sub catchments, S2, S4 and S6. In every sub catchment 1,235 houses are built with an average area of 160 m^2 (based upon the same size for the rooftop disconnection systems). The area that would transform from pervious to impervious for every sub catchment would be 160*1,235= 197,600 m^2. The changes in percentage impervious area per sub catchment are shown in Table 3.

Table 3: Changes in impervious area per sub catchment

Sub catchment	**Total area (m^2)**	**Old impervious area (%)**	**New impervious area (%)**
S2	1.680.000	15	26.8
S4	5.000.000	15	19.0
S6	3.000.000	15	21.6

This scenario takes into account that there will be more area with houses that were previously built on pervious area, ultimately decreasing pervious area and increasing impervious area. The scenario assumes an increase in urban area. The LIDs used for this scenario are only urban area measures (rain barrels and rooftop disconnection).

3.6.3 Rain barrels and rooftop disconnection system

To establish how many rain barrels and rooftop disconnection measures could be constructed in the area, the amount of houses in the different sub catchment areas are determined. To do so Google earth and the CBS database is used. The amount of households, which would indicate the number of houses in the area, per neighbourhood are shown in Table 4. That are also the amount of rain barrels or rooftop disconnection systems are installed per sub catchment. The only difference is the maximum measures per sub catchment is 1000, so for S7 it is 1000 instead of 1935. The rain barrels are evaluated with and without a drain to see the difference in effect of the drain. The rooftop disconnection system is evaluated with and without storage. The parameters used for the rain barrels and the rooftop disconnection system can be found in Appendix 7.5.

Table 4: Neighbourhoods with amount of households per sub catchment (CBS, 2017)

S2	Hato= 350		
S3	Nawati= 307	Noord Salinja= 473	Santa Barbara= 193
S7	Amboina= 295	Entrejol (Antriol) = 1643	

3.6.3.1 Future scenario

Assuming further urbanization more rain barrels can be placed in the sub catchments. The maximum number of rain barrels per sub catchment is 1000, so the sub catchments (S2, S3, S4, S6, S7) have now 1000 rain barrels with each the same specifics as the rain barrels in the present situation (chapter 3.6.3). The difference between the present and future situation is the percentage impervious area and the amount of rain barrels. For rooftop disconnection systems the same is applicable.

3.6.4 Infiltration trench and extra reservoirs

The infiltration trench (IT) measure is taken in rural areas where the pervious area is treated with the LIDs to slow down the surface runoff. The infiltration trench is a narrow ditch filled with gravel that intercept runoff from upslope impervious areas. These trenches provide storage volume and additional time for surface runoff to infiltrate. The infiltration trench is used in the rural area upstream to create a delay effect of the surface runoff going down stream. There are two options tested, one with only infiltration trenches next to the roads and one scenario with extra trenches to analyse the effect of more ITs.

The width of the infiltration trench is 1 m, to make the implementation as easy as possible. The number of infiltration trenches and the area of the IT per sub catchment depends on the length of roads in the sub catchment. The ITs would be installed next to a road, so depending on the length of the roads the area of the IT was calculated. The estimated area of an IT per sub catchment, with a width of 1 m, is shown in Table 5.

Table 5: Infiltration trenches per sub catchment, tested with SWMM

Sub catchment	**Area of one IT [m^2]**	**Number of ITs (next to roads)**	**Total area of ITs [m^2]**	**Number of ITs (extra)**	**Total area of ITs (extra) [m^2]**
S2	350	25	8750	250	87500
S4	500	20	10,000	800	400,000
S5	200	10	2000	500	100,000
S6	350	22	7700	800	280,000

For the area that is treated, it will be the pervious part of the sub catchment area. This is because the sub-catchments where the measures were tested contain impervious roads and houses, which cannot be removed to create infiltration trenches. The specific parameters for the infiltration trenches used in SWMM can be found in Appendix 7.6.

4 Results

4.1 How climate change affects Salinja di Vlijt catchment

The effects of climate change on Bonaire, the factors that are discussed are: precipitation, temperature, tropical storms, and sea level rise. The influences of these variable on the runoff and infiltration on the study area are either direct or indirect. A change of precipitation influences a water balance immediately, while a change in temperature influences a water balance through the evaporation. Sea level rise influences the hydrology through moving the outlet land inwards, more specifically for this study area this would mean a decrease in storage capacity of salt flat Salinja di Vlijt. The tropical storms would influence the catchment directly by extreme rainfall.

4.1.1 Climate of Bonaire

Besides the current climate it is also relevant to determine trends that could change the climate of Bonaire in the upcoming years. To investigate if the climate of Bonaire would change there was a report written by the KNMI (2021) to analyse the different trends in precipitation, temperature, sea level rise and tropical storms. The data that was used by the KNMI to analyse the climate trends form 1960 until 2020 on Bonaire were: precipitation data from the Global Precipitation Climatology Centre (GPCC), temperature from long term data collection on Curaçao and statistic model that predicts 'synthetic' hurricanes (KNMI, 2021). The KNMI (2021) report is going to be compared to other literature found per criteria.

4.1.2 Precipitation

There is a strong variation between the years in precipitation, and no significant trend was observed in precipitation data (Debrot & Bugter, 2010; KNMI, 2021). Globally there is a precipitation trend where the rainfall would decrease, but more in a shorter time span. This would result in higher intensity rainfall events and a higher pressure on the water management of countries (Dore, 2005). It is projected that there will be a decline in precipitation in the months June, July and August. (Dore, 2005; KNMI, 2021) The combination between less precipitation and higher temperatures in these summer months, would cause drought problems for vegetation. Another aspect influencing precipitation is an increase in Sea Surface Temperature (by 1 degree), which influences the cloud formation (Angeles et al., 2007). The change in cloud formation would therefore, cause an increase in rain production in the rain seasons of the Caribbean.

The precipitation and temperature on the Caribbean is influenced by El Niño and La Niña events, which results in less or more precipitation in the region (Cavazos et al., 2020). The effect of climate change on El Niño and La Niña is however still uncertain, because the mechanism underlying them is still not fully understood (Niranjan, 2023). The expected effects of climate change would be a stronger El Niño and La Niña, because of the increased global temperature. El Niño and La Niña are not the only phenomena that will change with climate change and alter the precipitation in the Caribbean. The Caribbean Low Level Jet, will intensify from May through November (Taylor et al., 2013). The continued presence of the strong Caribbean Low-Level Jet from July to November is associated with the ongoing maintenance of a dry weather pattern in the Caribbean region going forward (projected to happen around 2071-2100).

4.1.3 Temperature

Different analyses of the temperature change on Bonaire arrive at different conclusions. Temperature data indicate an increase of 0.15°C per year (KNMI, 2021). On the other hand Global climate models predict a 1-2 °C increase in temperature around 2050 under the lowest IPCC climate scenario (Campbell et al., 2011). Debrot et all (2010) expects a slight bigger increase of 1.4 to 3.2 °C in air temperature before 2100**.** Cavazos et al. (2020) also conclude that the Caribbean region has a warming trend, around 0.34°C/decade. This warming trend is partly correlated to the warming of the North Atlantic Ocean.

There certain different values for temperature increase on Bonaire, but they all indicate an increase in temperature. It is still uncertain what the exact number will be. This also depends on the emission scenario (IPCC, 2000).

4.1.4 Tropical storms

Hurricanes have a minimum speed of 33 m/s where a tropical storm has a minimum of 18 m/s. Hurricanes have an effect at a distance of 500 km. Since 1981 there were 14 tropical storms/hurricanes with a minimum wind speed of 18 m/s within 250 km of Bonaire. The biggest hurricane so far was Ivan in 2004, which reached windspeeds of 63 m/s, the last tropical storm that went directly over Bonaire was Cesar in 1996 with windspeeds of 20 m/s (KNMI, 2021). The effects of hurricanes can be catastrophic as they can trigger storm surges, extreme high water levels and floodings (KNMI, 2021; NPO, n/a). For Bonaire the recurrence time for a storm surge would be 100 years for a small increase (0.28 m) while for a recurrence time of 1000 years it would be 0.4 m and for 10 000 years it would be 0.5 m (KNMI, 2021). Additionally, it is possible that an increase of 0.2 m in water level could happen every year. Especially for Bonaire, where the vital infrastructure lies relatively low, this could be important (KNMI, 2021). Despite an increase in vertical wind shear, it generally remains below 8 m/s, which, coupled with sea surface temperatures (SST) exceeding 26.5 °C, creates favourable conditions for potential future upticks in the frequency of tropical storms (Angeles et al., 2007).

Tropical storms also influence precipitation, the influence of major hurricanes on rainfall may be most apparent in extreme daily events while weaker storms may be more critical for assessing trends in cumulative seasonal rainfall (Shepherd et al., 2007; Smith et al., 2001). These extreme rainfall events would trigger floodings and including urbanization within models is important for future risk assessment (Smith et al., 2001; Zhang et al., 2018).

4.1.5 Sea level rise

As mentioned in the Tropical storms chapter the most vital infrastructure of Bonaire lies relatively low in the landscape close to the sea. Which makes the island vulnerable for sea level rise. The current predictions in sea level rise for Bonaire depend per SSP scenario. With a SSP2-4,5 the expected sea level rise for the year 2040 are between the 0-0,25 meter and 0,2-1,05 meter by 2100 (Greenpeace, 2022; van Oosterhout et al., 2023). The level rise will be between 0.18 and 0.59m according to the IPCC scenario A1B by the end of this century (Debrot & Bugter, 2010; IPCC, 2022)

4.1.6 Runoff

Climate change has a broad impact on runoff, not only through modifications in hydrological inputs like precipitation and potential evaporation but also by modifying the watershed characteristics (Jiang et al., 2015). On the other hand, the effects of human activities on runoff primarily occur by altering the characteristics of the watershed. Combining all the different effects of climate change, would indicate a decrease in base flow runoff and an increase in peak flow runoff, which is also the same found in other catchments (Vormoor et al., 2017; Yan et al., 2020).

4.2 Current water management measures

Current water management measures in the study area have been assessed. The information is combined into one ArcGIS map, where each point has a picture with if possible: location, structure type, height, width, vegetation cover, and maintenance status. The ArcGIS file is an interactive map similar to the "legger kaart" of the Water boards in the Netherlands (Limburg, 2023). The result of the current measures in the ArcGIS file is shown in Figure 4. For specific information on certain points, an example table is provided in the Appendix 7.7. The ArcGIS map is used to create a simplified version of the study area in SWMM, which results in the map shown in Figure 5.

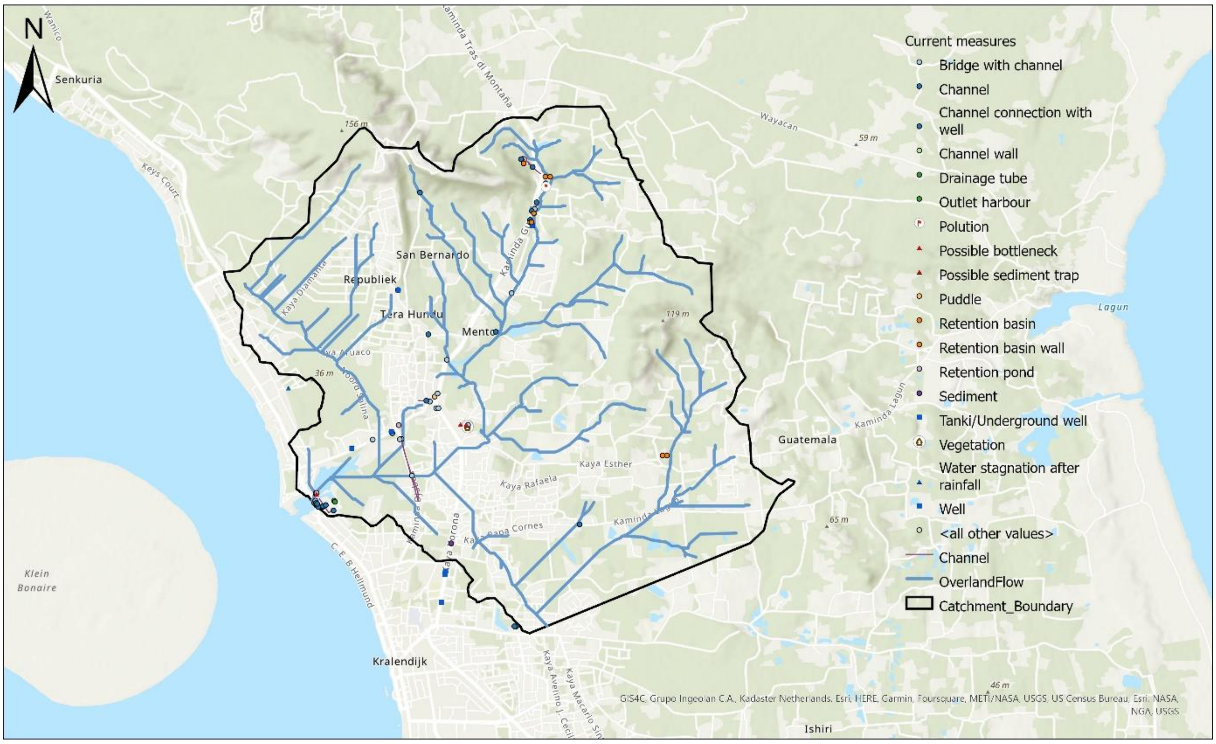

Figure 4: Current measures in the study area

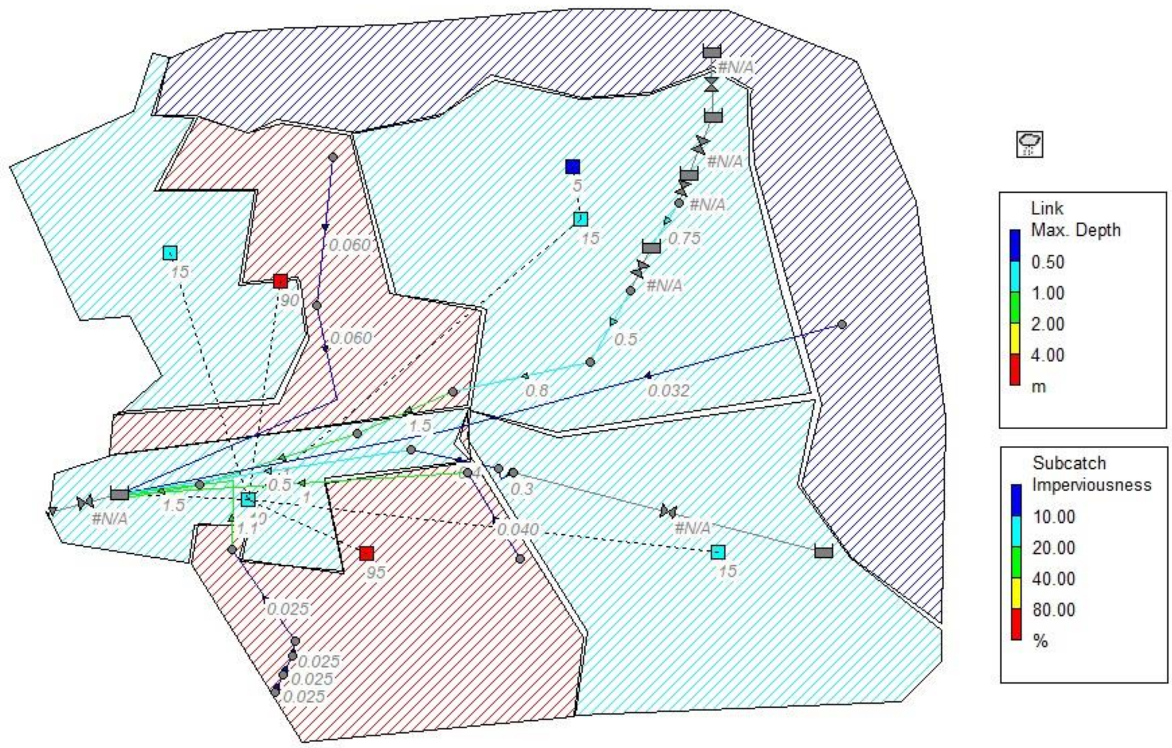

Figure 5: SWMM map of catchment representation

4.2.1 Changes with future surface sealing

With the future expectations for the urbanization and surface sealing of the catchment, changes in impervious area are made. Resulting in a change in runoff that leaves the outlet of the catchment, shown in Table 6. The difference in total volume that leaves the catchment is:
$924.490 \times 10^6 - 902.909 \times 10^6 = 21.581 \times 10^6\ L.$

This change is explained by an increase in impervious runoff and decrease in infiltration in the sub catchments S2, S4, and S6. The infiltration decreases with 21.12 mm over the whole system (Table 6)

Table 6: Flow calculations of the outflow of the catchment and change in infiltration of the whole system within SWMM

Outfall Node	Total volume [10^6 L]	Scenario	Infiltration [mm]
Out1_Current	902.909	Current	640.81
Out1_Future	924.490	Future	619.69

In addition to a difference in runoff infiltration between the present and future situation in the study area changes. This change is influenced by the decrease of pervious area (or an increase of impervious area).

4.3 Evaluating the scenarios with new measures

This chapter will evaluate the effect of different measures on the runoff and infiltration within SWMM. The measures that are evaluated are: rain barrels, rooftop disconnection system, infiltration trench, and extra reservoirs. The rain barrels an rooftop disconnection system are also evaluated for the future surface sealing scenario, because these are the urban area measures. The measures are evaluated on the effect on the outflow at the outlet of the catchment. Where the change in outflowing volume is calculated by: with measure outflow – Out1_Current. With the future scenario the original outflow of the future (Out1_Future) is used to examine the possible change. The change in infiltration is based on the whole catchment. The results of the effect of all different measures on the runoff and infiltration on the system are shown in Table 7.

Table 7: Summary of the effect of the measures on the runoff and infiltration of the catchment

Water management measure	**Scenario**	**Impact on runoff [10^6 L]**	**Impact on infiltration [mm]**
Rain barrels with drain	Present	-6.530	12.92
Rain barrels without drain	Present	-4.559	10.72
Rooftop disconnection system with storage	Present	-14.738	-10.42
Rooftop disconnection system without storage	Present	0.827	-0.97
Infiltration trench	Present	2.277	2.09
Extra infiltration trench	Present	-63.033	45.88
Extra reservoirs	Present	-0.564	0.00
Rain barrels with drain	Future	-2.619	4.48
Rain barrels without drain	Future	-0.943	-0.08
Rooftop disconnection system with storage	Future	-25.252	-28.54
Rooftop disconnection system without storage	Future	15.392	-9.12

4.3.1 Rain barrels

The findings presented in Table 7, show that the rain barrels in the current and future situation do have a decreasing effect on the outflow of the catchment. Whereas, the effect of rain barrels is higher in the current situation than in the future scenario. While in the future scenario there are more rain barrels installed in the catchment the effect of these rain barrels is not improving. This can be explained by the increase in impervious area, which decreases the infiltration capacity of the catchment. Also it can be established that the runoff reduces more ($1.971 \times 10^6\ L$ more) with rain barrels with this type of drain installed. The rain barrels increase infiltration with and without drain. The rain barrels retain water and after some time they overflow or water leaves through the drain. At this point the soil is less saturated, because of the delay, increasing infiltration.

4.3.2 Rooftop disconnection system

The rooftop disconnection system is analysed with and without a storage component on the roof. It is an urban area measure, so the measure is tested in the present and future scenario. The rooftop disconnection system with storage has a bigger effect on the outflow of the system than without storage in both the present and future scenario (Table 7). For both scenarios the rooftop disconnection without storage increases the total outflow of the system even more than the original. This increase is due to the fact that the slope of the roofs is higher than the slope of the surrounding area, decreasing the runoff time towards the outlet. However, if the measure is used with storage it decreases the outflow significantly. Comparing the effect of the measure in future and present scenario, the effect is higher in the future scenario. In this scenario there is also the possibility to implement more measures, because there are more houses. Shown in Table 7 as well is the change in infiltration in the present scenario for the two rooftop disconnection systems. What can be observed is a higher decrease with a rooftop disconnection system with storage compared to without storage. The overall change in infiltration is a decrease, which would indicate that the measure only negatively impacts the infiltration. For the future scenario, the infiltration decreases more than for the present scenario. The slope (1%, 3%, and 8%) was altered to analyse the effect of different slopes of the measure, on the runoff and infiltration. This had no significant effect on the infiltration or runoff of the catchment.

4.3.3 Infiltration trench

The infiltration trenches (ITs) are installed on pervious areas in the rural part of the catchment, only in the present day scenario. There are two different amounts of infiltration trenches examined within SWMM. As shown in Table 7, Only placing ITs next to roads, will increase runoff from the outlet of the catchment. However, when implemented additional ITs the runoff decreases quite severe. This shows that implementing infiltration trenches indeed can decrease runoff, if used enough. The implementation possibility of extra ITs is not taken into account for the calculations. Not only runoff is influenced by ITs, but as shown in Table 7, the infiltration is also influenced. Especially with the extra ITs there is a 5 to 20% increase in infiltration compared to the original situation without ITs.

4.3.4 Extra reservoirs

The extra reservoirs are implemented on the nodes that were flooded, with the original runs in SWMM (Table 8). The flooded nodes are also possible bottlenecks in the system, J17, J18, J19, and J20 is a place in the catchment with street flow over the Kaya Korona. With the original situation (no measures taken) in SWMM (Figure 5), there are certain conduits that overflow with the rainfall event of November 2022 (shown in Table 8). These overflowing conduits are overlapping with the bottlenecks established during fieldwork. Nodes J2 and J3 have a value of zero, which results in a flooding that was not visible (with three decimals), but with more precision is still flooded according to the model.

The nodes that are flooded in the current scenario are improved with extra reservoirs to prevent flooding of the currently flooded nodes. The modifications of the nodes that were flooded so reservoirs or deepened junctions are presented in Table 9. When the changes presented in Table 9 were implemented, the nodes did not overflow anymore. With the extra reservoirs and changes to the channels there is a negligible change in infiltration and runoff from the outlet (Table 7).

Table 8: Flooded nodes within SWMM with the original situation and the rainfall events of November 2022

Node	Hours flooded	Day of max flooding	Hour of max flooding	Total flood volume [10^6 L]
J12	104.06	3	01:03	207.063
J17	0.49	7	15:35	0.086
J18	0.79	12	23:31	0.264
J19	0.56	3	10:13	0.198
J2	0.01	7	14:41	0.000
J20	0.80	6	18:21	0.112
J3	0.01	13	13:14	0.000
SalinjaDiVlijt	46.07	7	15:00	1116.673

Table 9: Changes made in the catchment to prevent flooding

Flooded node/reservoir	Change/addition made to node, link or reservoir	Old value	New value
J2	J2	Max depth= 0.8 m	Max depth= 1 m
J3	J3	Max depth= 1 m	Max depth= 1 m
J17	Drain1 and ExtraStorage	-	Drain1+2+3+4: diameter drain= 0.2 m
J18	Drain2 and ExtraStorage	-	Drain1+2+3+4: length= 50 m
J19	Drain3 and ExtraStorage	-	Drain1+2+3+4: roughness= 0.02
J20	Drain4 and ExtraStorage	-	ExtraStorage: Depth= 0.5 m, area= 10 m^2

5 Discussion

The model develop in this study uses LIDs to prevent flooding in the catchment. The use of LIDs is effectively used to reduce peak flood or mitigating urban flood impacts based upon other studies (Li et al., 2021; Pour et al., 2020; Vo et al., 2020). The LIDs grass swales and permeation pavement are not used in this research, however, these changes have been investigated and found to be favourable in reducing peak flow and delaying the peak time (Li et al., 2021). The combination of green roofs, infiltration pavement, and grass swales, implemented as low-impact development (LID) techniques in urban build-up areas, yielded the most promising outcomes when different LIDs were combined. However, in Bonaire green roofs are not applicable, because of the year round Savanne climate. This climate cannot accommodate all vegetation types, therefore most vegetation cannot grow on the roofs. Another option to prevent flooding from stormwater runoff, which is similar to LIDs, could be Regenerative stormwater conveyance (RSC) (Cizek et al., 2017). The implementation of the RSC in coastal areas effectively addresses the issue of reduced surface flow by raising groundwater levels and promoting increased evaporation rates (Cizek et al., 2017). RSCs could be interesting for further research to look into the implementations on Bonaire. Bonaire was a case study for water management in a changing climate on catchment scale. Focussing on Small Island Developing States, there could be more research done into the effects of climate change and water management for these islands. These islands are vulnerable for climate stress, and water stress (Gohar et al., 2019).

The SWMM model that was used from this study was based on the information from the fieldwork. However, it was not possible to validate or calibrate the model, as there was no discharge data available. The model was tested on sensitivity on different changes, the effect of the changes was examined and thus by trial and error adjusted to the right value. When discharge data become available, this can be combined with DEM, land use, and metrological data to model river systems with GIS and SWMM (Rai et al., 2016). Rai et all, (2016) used SWMM and GIS to develop a model that effectively model floods from a river system. For urban storm water management there also other tools besides SWMM that could have modelled flooding and examine the effects of different water management solutions. Whereas, Raei, E. et all, (2019) analysed if SWMM could be replaced with a MLP-based meta-model, when simulating runoff in an urban environment. Also Low Impact Development measure could be tested in the urban area and the results were a decrease of 99% of the runoff volume with the optimal LID scenario (Raei et al., 2019).

For water management solutions the options within SWMM are called LIDs, where each LID can be adjusted with different components like drains and/or storage etc. The measures that were used in this study were chosen based upon the suggestions of the Openbaar Lichaam Bonaire and their expertise of what could work in the catchment and which measure they would like to investigate. Therefore, rain barrels, rooftop disconnection systems, infiltration trenches and extra reservoirs are examined. Each measure has its own improvements that would be possible. For the extra reservoirs the method that was used to place and change the system to prevent flooding was trial and error. Where most of the flooded nodes are adjusted and no flooding occurred within the SWMM run. A more systematically approach to place the reservoirs, as described by Environmental Agency, (2016). First investigate the sights itself and see if placement of a reservoir is possible. Followed by investigating foundation conditions, like the ground properties and local availability of the building materials. Also the impact on the environment and third parties like land owners or local residents should be low (Agency, 2016). These steps were not taken for this study, as only the SWMM map was used and no fieldwork on the impact of the placement of the reservoirs was done. The possible implementation of the additional amount of infiltration trenches was also not investigated on feasibility just as the additional reservoirs. For the measures rain barrels and rooftop disconnection systems, it would have been interesting to investigate the combination of the methods to get the best possible effect on runoff delay. However this was not possible within SWMM to combine the measures. Initially, the concept was to direct the flow from the rooftop disconnection system into the rain barrels. As replacement, it was chosen to test the effects of drains with the rain barrels and a storage component for the rooftop disconnection system. Another limitation of SWMM would be that the maximum of LIDs in a sub catchment is 1000 individual measures. While calculated in this study the amount of measure could be more for different sub catchments (S7 with the current surface sealing).

Climate change is a wide spread investigated subject, however there is more data about the effect of climate change worldwide for one implication, rather than for one country specific (Labriet et al., 2015; PARTON et al., 1995). The effects per country are investigated, however these countries are most of the times quite vulnerable for climate change or big and/or rich (Juhola & Westerhoff, 2011; Rahman et al., 2019). The existing literature on the impact of climate change on land and catchment scale in Bonaire is limited. It would have been beneficial to explore these effects through climate models, which could have enhanced the research. However, due to time constraints, a comprehensive study on the effects of climate change on Bonaire could not be included in this research. Additionally, it is important to note that the combined influences of climate change and land use change have an even greater impact on runoff than when analysed individually. (Marhaento et al., 2018). Therefore, for further research it would be interesting to include both drivers in the same model study.

In this study topographical data (DEM) is used to calculate the catchment boundaries and overland water flow. The precision of this data set influences on catchment scale, the overland flow in a significant way. Comparing the catchment boundaries from Koster (2013) are therefore, different than the boundaries in this study. Another report made by the consultancy firm CEC has another DEM resulting in different catchment boundaries. This shows that the precision of the DEM is quite important in determining the catchment boundaries and overland water flow. Improving the quality of the DEM can improve research the Salinja di Vlijt catchment, but also other catchments all over the world.

6 Conclusion

This research aimed how climate change and water management measures will affect the water balance, and especially infiltration and runoff processes in the Salinja di Vlijt catchment on Bonaire. This has been done via the following sub questions:

- Which factors determine runoff in the Salinja di Vlijt catchment?
- How will climate change affect the runoff in the Salinja di Vlijt catchment?
- What are the current water management measures taken in the Salinja di Vlijt catchment?
- What is the effect of different water management scenario's on the runoff and infiltration of the Salinja di Vlijt catchment?

The factors that determine runoff in the Salinja di Vlijt catchment are identified through fieldwork and ArcGIS analyses, and subsequently incorporated into the SWMM model simulations. These factors encompass infiltration, precipitation, evaporation, storage, and water management structures. Each factor is influenced by various other aspects, such as temperature and soil type, which are characterized for the specific catchment.

The investigation focused on the influence of climate change, as supported by a literature review. The key findings highlight the uncertain nature of precipitation trends, with no discernible trend. Furthermore, the presence of La Niña and El Niño events introduces the possibility of both drier and wetter years. The temperature on Bonaire is expected to rise, contingent upon fossil fuel scenarios, warranting further investigation for precise quantification. Sea level rise is projected to impact the catchment by displacing its outlet further inland, with a minimum rise of 0.2 meters. Additionally, tropical storms are anticipated to intensify, leading to more frequent occurrences of extreme winds and extreme rainfall events in Bonaire. Leading to overall decrease in baseflow runoff, but increase in peak flow runoff.

The current water management measures in the Salinja di Vlijt catchment consist of drainage pipes, channels, reservoirs, and dams all varying in maintenance status and covered by vegetation. Future scenarios considered the urbanization trend over the past decade, resulting in increased impervious area, increasing outlet runoff by 2% and decreasing system infiltration by 21.12 mm, as simulated by the Storm Water Management Model (SWMM) from the whole simulation of the month November 2022 (with 271.4 mm rain)

The evaluated measures in Bonaire were assessed based on their impact on runoff and infiltration dynamics. Implementation of rain barrels, both with and without drain, exhibited a modest reduction in outlet runoff. However, the effectiveness of rain barrels was found to be reduced in the future scenario compared to the original scenario. The effect rain barrels on the infiltration in the original scenario is positive, meaning an increase in infiltration with and without drain. In the future scenario, the infiltration is not significantly impacted. The rooftop disconnection system was effective in reducing runoff in both scenarios, if the roof has a storage component. Nevertheless, when the roof storage component was absent, the rooftop disconnection system contributed to increased runoff in the future scenario. Regardless of storage, the rooftop disconnection system deprived infiltration in the catchment. Infiltration trenches, when positioned alongside roads in the rural sub catchments, displayed minimal influence on runoff and infiltration in the catchment. However, implementing an excessive number of infiltration trenches resulted in noticeable effects, significantly decreasing outlet runoff and increasing infiltration by 5% to 20% per executed sub-catchment. Lastly, the introduction of additional reservoirs proved effective in alleviating bottlenecks and addressing flooded nodes, on the other hand it did not result in significant changes to the catchment runoff or infiltration.

The hydrology of the Salinja di Vlijt catchment will be affected by the combined forces of urbanization and climate change. Consequently, the implementation of measures such as rain barrels and rooftop disconnection systems in urban areas may prove beneficial, reducing runoff while enabling water storage. However, further research is needed to explore the effects of combining the measures together. Additionally, the introduction of extra reservoirs and an optimal quantity of infiltration trenches for reducing runoff, while increasing infiltration and mitigating bottlenecks. However, a consideration should be made of space availability when implementing such measures. This study contributes valuable insights into effective water management strategies in the Salinja di Vlijt catchment and offers a foundation for future investigations in the catchment.

7 Appendix

7.1 DEM Bonaire

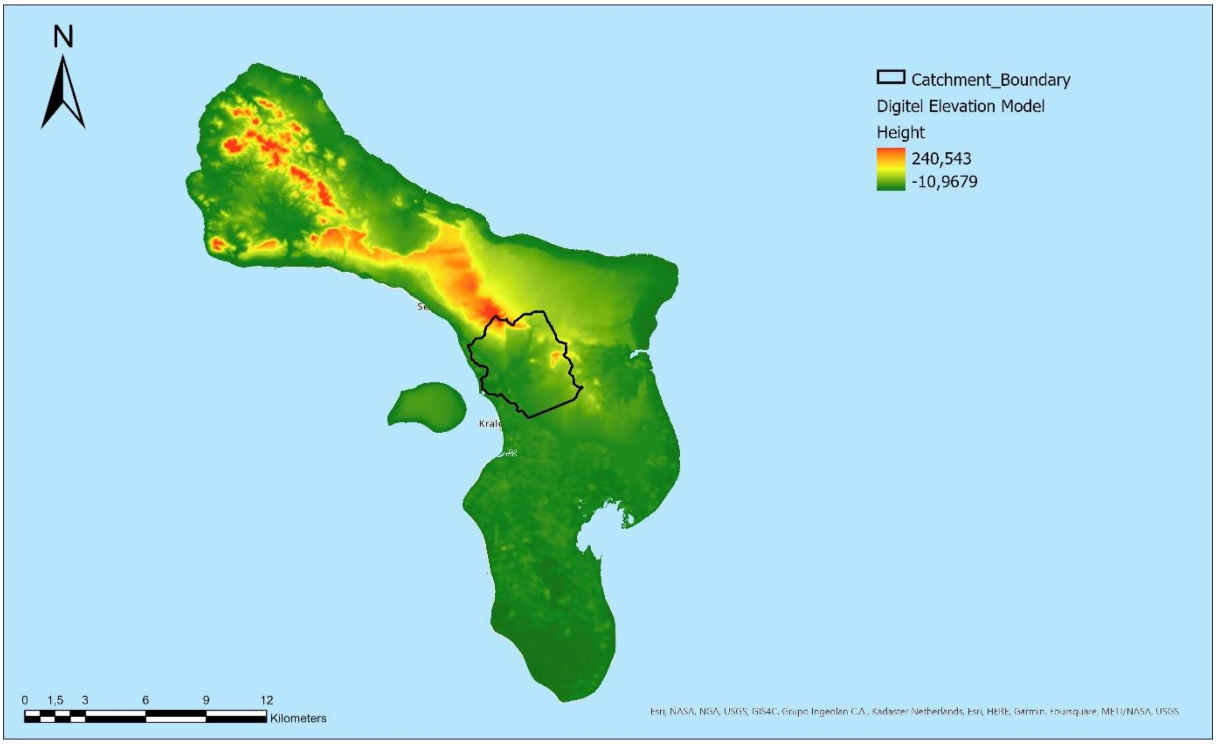

Figure 6: DEM Bonaire with catchment boundary

7.2 Jar test locations and geology layers

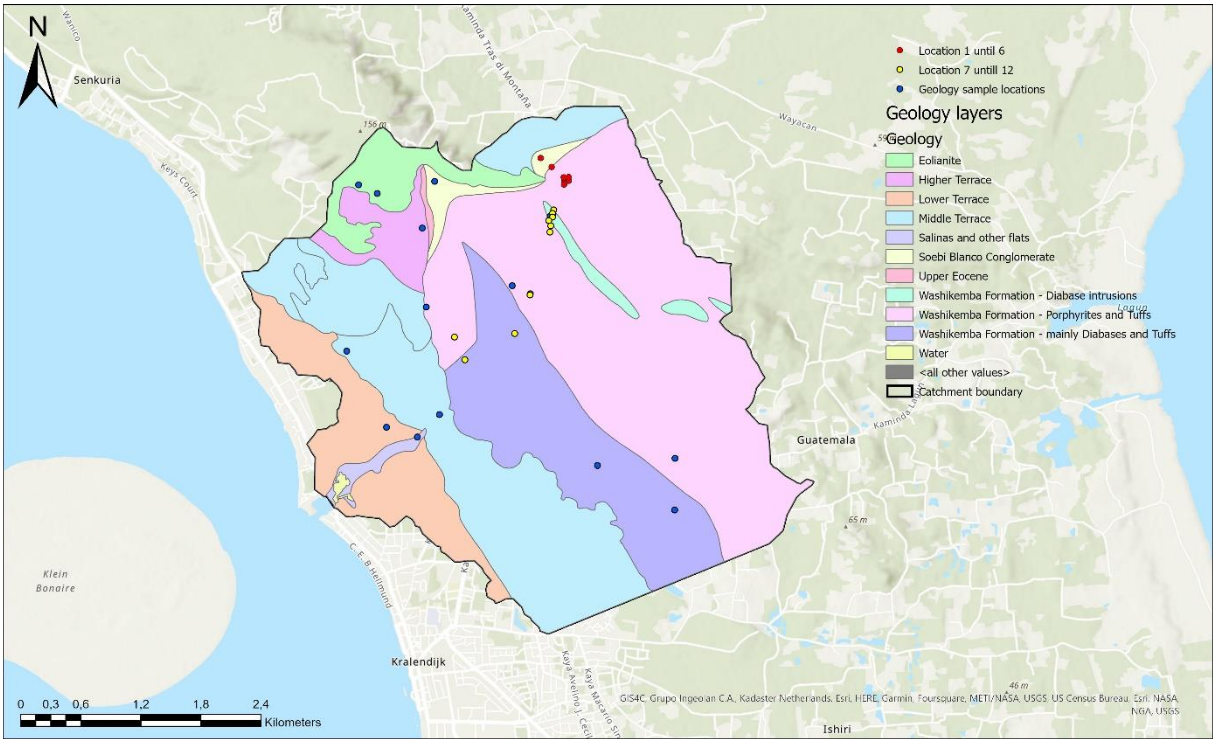

Figure 7: Jar test locations and geology layers in the catchment

7.3 Soil types in the catchment

Table 10: Soil types on different locations in the study area acquired via jar test

Location	Soil type	Location Geology	Soil type
1	Sandy Loam	1a	Sand
2	Sand	1b	Loamy sand
3	Loamy sand	2a	Loamy sand
4	Sandy loam	3a	Loamy sand
5	Loamy sand	4a	Loamy sand
6	Clay	4b	Loamy sand
7	Sand	5a	Sandy loam
8	Loamy sand	6a	Sand
9	Sand	7a	Loamy sand
10	Loamy sand	7b	Loamy sand
11	Sandy loam	8a	Sand
12	Sand	8b	Sand
		8c	Sand
		9a	Sand
		9b	Sand

7.4 Maintenance status examples in the catchment

1=almost perfect conditions

2=small maintenance should be done

3=big maintenance should be done

4=broken down but can be fixed

5=totally broken down

7.5 Parameter explanation of rain barrels and rooftop disconnection system

Parameters that are used in SWMM for rain barrels:

- Height of the rain barrels is 889 mm, width of the rain barrels is 0.6096 m (Strickler, 2015)
- No drain, to maintain as much water as possible.
- With drain, then the drain has the following measurements;
  - Flow coefficient → 10 mm/hr
  - Flow exponent → 0.5
  - Drain delay → 3 hr

The maximum amount of rain barrels is used per sub catchment to investigate the maximum influence of rain barrels. Which results in the following number of rain barrels per sub catchment:

- S2, 350 rain barrels
- S3, 973 rain barrels
- S7, 1938 rain barrels.

The maximum rain barrels per sub catchment is 1000, so for S7 the amount will be 1000.

Area: 0.38 m^2
Surface width: 0.6096 m
% impervious area percentage impervious area of the sub catchment

The measurements used for the rooftop disconnection system in SWMM are:

- Storage depth → 10 mm or 0 mm, because the rooftops are made of material that does not store water, but to test the effects of storage, if it would be possible
- Surface roughness of Manning → 0.012 (George J. Arcement, 1989; Toolbox, 2004)
- Surface slope → which is the slope of the roof is 8.3% (Archtoolbox, 2023)
- Area → 160 m^2
- Surface width → 12 m
- Outflow → return all outflow to pervious area (gardens)
- The roof drain has a flow capacity of 0 mm/hr, meaning it can handle every flow capacity and it does not overflow. All the water entering the drain leaves it via the drain pipe.

For the rooftop disconnection system the same percentage impervious area is used as for the rain barrels. Also the same amount of systems are installed per sub catchment.

7.6 Parameter explanation of the infiltration trenches

The parameters used to define the various factors of the infiltration trench in SWMM are as follows:
Surface;

- Berm height → 150 mm
- Vegetation Volume Fraction → 0, because no vegetation is used for this LID
- Surface roughness → the manning n from gravel, which is 0.023 (George J. Arcement, 1989; Toolbox, 2004)
- The surface slope → 1 percent to slow down the surface runoff and still be in line with the surroundings.

Storage;

- Thickness → 150 mm, based upon the lowest amount as indication of the SWMM manual (Simon, 2022)
- Void ratio → 0.5 (Dallo, 2022; Tao et al., 2021)
- Seepage rate → 0.5 mm/hr based upon the saturated hydraulic conductivity of the model
- Clogging factor → 0.

To keep the measure simple for implementation there is no drain installed with the infiltration trench.

7.7 Table with ArcGIS measures table

Table 11: First nine of the whole GIS table of the geotagged photos

ID	Name	DateTime	X	Y	Description	Maintenance status	Vegetation cover	Height	Width	Extra
1	A4.jpg	16-1-2023 09:27	0	0	Bridge with channel	1	1	1,9	3,7	Depth was difficult to establish, more than 1 m.
2	B2Upstream.jpg	16-1-2023 14:28	-68,275,955	12,170,052	Channel	<Null>	3	<Null>	<Null>	<Null>
3	B3..jpg	16-1-2023 15:13	-68,273,361	12,173,416	Bridge with channel	2	3	1,1	5	Almost no water in the channel
4	B3.jpg	16-1-2023 15:14	-68,273,361	12,173,416	Bridge with channel	2	3	1,1	5	Almost no water in the channel
5	B4Downstream.jpg	16-1-2023 15:20	-68,272,774	12,172,831	Bridge with channel	2	3	1	11,8	Mostly grass vegetation and some water that flows towards Salinja di Vlijt
6	B4Upstream.jpg	16-1-2023 15:23	-68,272,567	12,172,837	Bridge with channel	2	3	1	11,8	Mostly grass vegetation

										and some water that flows towards Salinja di Vlijt
7	B5.jpg	16-1-2023 15:32	-68,276,794	12,170,574	Bridge with channel	2	1	0,2	0,2	No water visible
8	B6.jpg	18-1-2023 12:57	-68,272,888	12,173,867	Puddle	<Null>	2	<Null>	12	No channel visible just flat surface and old tire tracks
9	B7.jpg	18-1-2023 13:07	-68,272,636	1,217,416	Bridge with channel	1	4	0,6	11,7	

7.8 Detailed explanation of the sub catchment infiltration changes

7.8.1 Future sealing

Table 12 shows the change in infiltration comparing the current and future surface sealing of the catchment. The infiltration results are shown in Table 12. What can be seen is that the infiltration capacity of S1 is higher than the other sub catchments. This can be explained by the larger area that is also occupied by the storage unit (SalinjaDiVlijt). The storage unit itself also has an infiltration rate, low slope of the sub catchment, and combining with the high pervious area makes the infiltration capacity of the sub catchment bigger than the others. The change in infiltration between the future and present situation is increasing only in S1. The explanation for this can be derived from the decrease in infiltration in S2, S4, and S6 which have an increase in impervious area. Therefore, more runoff flows toward S1, so more possibility for S1 and storage unit SalinjaDiVlijt to evaporate or infiltrate water. The sub catchments that have zero change, do not have a change in impervious area, so the situation stays the same.

Table 12: Infiltration results per sub catchment of the present and future scenario

Sub catchment	Original infiltration [mm]	Future infiltration [mm]	Change in infiltration [mm] (Future-OG)
S1	223.05	227.97	4.92
S2	79.68	67.38	-12.3
S3	10.07	10.07	0.00
S4	105.29	100.12	-5.17
S5	120.33	120.33	0.00
S6	97.91	89.34	-8.57
S7	4.48	4.48	0.00

7.8.2 Rain barrels

In Table 13, the infiltration in mm per sub catchment with implementation of rain barrels (with and without drain) are shown, including the change in infiltration compared to the original situation. Another result can be observed in the future scenario, which is shown in Table 14. The change in infiltration has almost no increase or decrease with the implementation of the rooftop disconnection system.

Table 13: Infiltration differences per sub catchment in present scenario with rain barrels

Sub catchment	Present infiltration, no drain [mm]	Change in infiltration [mm] (no drain-OG)	Present infiltration with drain [mm]	Change in infiltration [mm] (with drain-OG)
S1	217.57	-5.48	217.32	-5.73
S2	80.97	1.29	81.76	2.08
S3	19.3	9.23	20.28	10.21
S4	105.29	0.00	105.29	0.00
S5	120.33	0.00	120.33	0.00
S6	97.91	0.00	97.91	0.00
S7	10.16	5.68	10.84	6.36

Table 14: Infiltration differences per sub catchment in future scenario with rain barrels

Sub catchment	Future infiltration, no drain [mm]	Change in infiltration [mm] (no drain-future)	Future infiltration with drain [mm]	Change in infiltration [mm] (with drain-future)
S1	227.95	-0.02	232.51	4.54
S2	67.36	-0.02	67.36	-0.02
S3	10.07	0	10.07	0
S4	100.11	-0.01	100.11	-0.01
S5	120.33	0	120.33	0
S6	89.32	-0.02	89.32	-0.02
S7	4.47	-0.01	4.47	-0.01

7.8.3 Rooftop disconnection system

Shown in Table 15, is the change in infiltration in the present scenario for the two rooftop disconnection systems per sub catchment. For the future scenario, shown in Table 16, the infiltration decreases more than for the future scenario by installing the rooftop disconnection systems.

Table 15: Infiltration differences per sub catchment with rooftop disconnection system in present scenario

Sub catchment	Present infiltration, no storage [mm]	Change in infiltration [mm] (no storage-OG)	Present infiltration with storage [mm]	Change in infiltration [mm] (with storage-OG)
S1	226.58	3.53	217.13	-5.92
S2	76.67	-3.01	76.67	-3.01
S3	9.01	-1.06	9.01	-1.06
S4	105.29	0	105.29	0
S5	120.33	0	120.33	0
S6	97.91	0	97.91	0
S7	4.05	-0.43	4.05	-0.43

Table 16: Infiltration differences per sub catchment with rooftop disconnection system in future scenario

Sub catchment	Future infiltration, no storage [mm]	Change in infiltration [mm] (no storage-future)	Future infiltration with storage [mm]	Change in infiltration [mm] (with storage-future)
S1	237.27	9.3	217.85	-10.12
S2	59.79	-7.59	59.79	-7.59
S3	8.98	-1.09	8.98	-1.09
S4	96.67	-3.45	96.67	-3.45
S5	120.33	0	120.33	0
S6	83.48	-5.86	83.48	-5.86
S7	4.05	-0.43	4.05	-0.43

7.8.4 Infiltration trench

The effect of infiltration trenches per sub catchment is show in Table 17, with ITs only next to roads and the effect of additional ITs.

Table 17: Infiltration differences per sub catchment with infiltration trenches

Sub catchment	Infiltration, only road ITs [mm]	Change in infiltration [mm] (road ITs-OG)	Infiltration with extra ITs [mm]	Change in infiltration [mm] (extra ITs-OG)
S1	221.79	-1.26	213.98	-9.07
S2	80.92	1.24	92.3	12.62
S3	10.07	0	10.07	0
S4	106.73	1.44	120.96	15.67
S5	120.46	0.13	126.54	6.21
S6	98.45	0.54	118.36	20.45
S7	4.48	0	4.48	0

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