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Understanding Saba's (ground)water system and nutrient pathways

An integrated hydrogeological and nutrient flux study of Saba, Caribbean Netherlands

Understanding Saba's (ground)water system and nutrient pathways

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Project reference	
Keywords	Groundwater, nutrients, nitrate, phosphate, islands, Saba, Caribbean

Document control	
Version	1.0
Date	10-07-2025
Project nr.	11210862-002
Document ID	11210862-002-BGS-0001
Pages	89
Classification	
Status	Final

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Summary

This report presents a quick scan assessment of groundwater flow and nutrient dynamics on the island of Saba, commissioned by the Public Entity Saba. The study aims to understand how nutrients, particularly nitrogen (N) and phosphorus (P), are transported from land-based sources to the surrounding marine environment, with a focus on the role of groundwater. This knowledge is essential for protecting coral reef ecosystems and guiding sustainable environmental management.

Key Objectives
- First understanding of the hydrogeological system of Saba.
- Identify and quantify nutrient sources and transport pathways.
- Quick scan assessment of the impact of groundwater on coastal water quality.

Methodology
To achieve this, the quick scan research combined a literature review, field surveys, stakeholder interviews, water quality sampling, laboratory analysis, and the development of a conceptual groundwater model. Nutrient and water balances were calculated for individual catchments to estimate the contributions of various sources, including domestic wastewater, livestock, tourism, agriculture, and atmospheric deposition.

Main Findings
- Groundwater is a major pathway for nutrient transport to the sea, with elevated nitrate levels detected in wells and springs.
- At present, cesspits are the dominant nutrient source, followed by livestock and atmospheric deposition.
- Two potential subsurface flow routes were hypothesized:
    - A slow, permanent groundwater flow discharging year-round into the sea.
    - A quick interflow route during heavy rainfall, contributing to erosion and nutrient pulses.
- Nutrient concentrations in coastal waters are elevated and approach ecological thresholds for coral reef health.
- Historical goat overpopulation (5,000 goats in 2020) significantly contributed to nutrient loads; current levels (~150 goats) have reduced this impact.

Conclusions
- It is hypothesized that Saba's geology and steep terrain create a dual water flow system: slow groundwater discharge and fast interflow during storms.
- Groundwater is the primary year-round carrier of nutrients to the sea, especially nitrate from cesspits.
- Nutrient levels in groundwater are high enough to pose a risk to coral reef ecosystems, even though total nutrient inputs are modest compared to larger islands.
- The reduction in goat population has significantly decreased nutrient pressure, but human wastewater remains a key concern.

Recommendations:
- Improve monitoring of rainfall, groundwater, and runoff to reduce uncertainty.
- Enhance rainwater infiltration and reduce surface runoff through better land and road design.
- Continue goat control programme and improve wastewater management in new developments when possible and economically viable.

Contents

1 Introduction

1.1 Problem definition

The coastal waters and coral reefs of Bonaire, Saba and St. Eustatius form marine protected areas that are internationally recognized for their high biodiversity. The coastal strip around each island form protected marine parks and the Saba Bank has been designated as a Particularly Sensitive Sea Area by the International Maritime Organization because of its great ecological, socio-economical, and scientific value. The Nature and Environment Policy Plan for the Dutch Caribbean (2020-2030) describes the need and strategy for sustainable use of natural resources in the Caribbean Netherlands.

One of the four strategic goals of this plan is to reverse the trend of coral degradation in order to create healthy and resilient coral reefs in the Dutch Caribbean. Figure 1.1 shows a schematic overview of the key components of the coral reef ecosystems and the local stressors. For Saba, the nutrient inputs into the environment such as those from domestic sources, livestock and tourism, and the role of the groundwater system in transporting these nutrients are not yet well understood. The island lacks a centralised sewage system, and most households rely on cesspits. Additionally, there were historically more than 5,000 free roaming goats contributing to nutrient loads. To effectively reduce nutrient discharge into the marine environment, it is essential to quantify the island's nutrient emissions, identify their sources, and understand the transport mechanisms to the sea, including the role of groundwater.

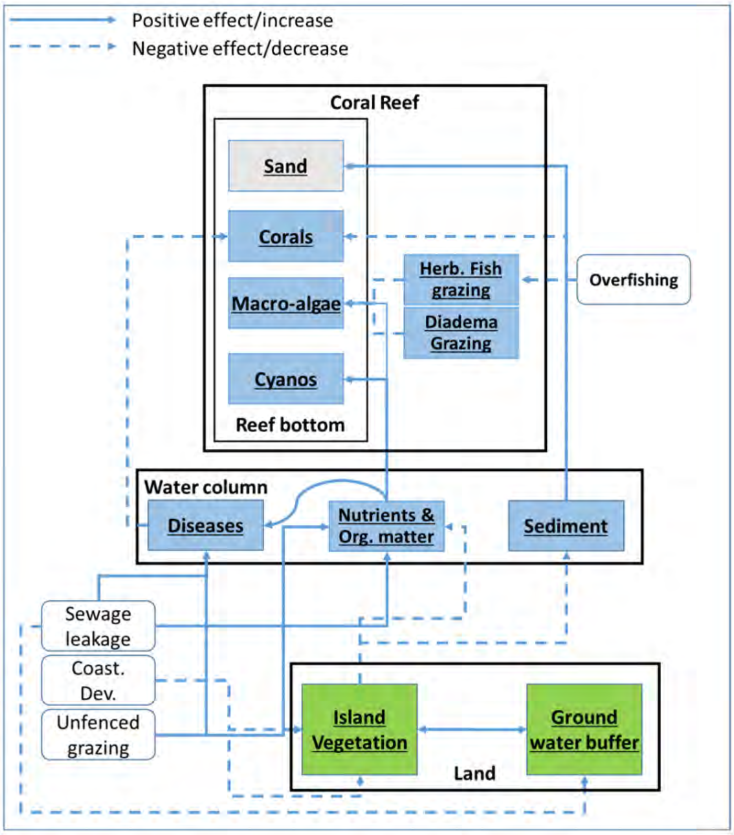

Figure 1.1 A schematic overview of the key components of coral reef ecosystems and the local stressors (Ministerie van LNV, IenW & BZK, 2020).

To achieve the goal of reversing coral degradation on Saba, it is essential to gain a better understanding of the nutrient fluxes in order to identify which components require improved management, such as enhanced wastewater treatment. Additionally, a thorough understanding of the groundwater system is crucial to determine how nutrients are transported to the sea.

1.2 Objective of the study

The overarching objective of this project is to get a better understanding of the hydro(geo)logical system of Saba and to estimate the contribution of different nutrient sources (specifically nitrogen (N) and phosphorous (P)) to the marine environment. Since nutrients may reach the sea via the groundwater, improving insight into the groundwater system is essential. This knowledge is crucial for better understanding the role of groundwater in the nutrient pollution of coastal waters and for supporting more effective management of nutrient emissions on the island.

This understanding will be developed by analysing the existing data, collecting additional data and information during field visits, via quick-scan field measurements, observations, interviews, lab analyses, and developing a conceptual groundwater model. Based on the collected existing and new data, preliminary explorative water and substance (nutrients) balance calculations for Saba will be done, for a first indicative estimation of the contribution of different contaminant sources.

1.3 Research setup

In order to develop a better understanding of the hydrogeological (groundwater) system of Saba, with a focus on identifying potential sources of contamination, particularly septic tanks, cesspools, and their contribution to wastewater fluxes toward the ocean. Existing data, reports, and literature will be reviewed to identify knowledge gaps and guide the design of additional data collection. During a field survey, field observations, stakeholder interviews, and water quality measurements have been collected. These water quality measurements include both quick-scan field tests and the collection of groundwater and surface water samples for laboratory analysis. The lab analyses have been carried out by St. Maarten Laboratory Services (SLS). The information gathered is used to develop a conceptual description of the (ground)water system and the most related contaminant sources that integrates both existing knowledge and new field data. Finally, an assessment is then made regarding the contribution of various contaminant sources to ocean pollution. This includes indicative calculations of nutrient loads and fluxes from different sources, such as groundwater and surface runoff, to estimate their relative impact on coastal water quality.
It should be emphasized that this study involves a quick scan analysis with limited resources and time and a first attempt to understand the subsurface flows on Saba and their contributions to the nutrient loads to the marine environment. Additional monitoring and field data are essential to validate the hypothesized mechanisms of the subsurface water system and to achieve more precise quantifications.

Chapter 2 provides a physical and geographical description of Saba. Chapter 3 outlines the research approach and methodology. Chapter 4 presents the findings from the field survey and lab results. Chapter 5 delves into the hydrogeological context through a literature review and introduces a conceptual model of the groundwater system. Chapter 6 examines the nutrient balance, including estimated sources, loads, and transport pathways. Finally, Chapter 7 summarises the key insights and offers recommendations for future management and research.

2 Physical and geographical description of Saba

2.1 Introduction

Saba is a small Caribbean Island located in the northeastern part of the Caribbean Sea. It forms part of the Caribbean Netherlands and is one of the Windward Islands (Bovenwindse Eilanden) of the Dutch Caribbean, together with Sint Eustatius and Sint Maarten. Since 2010, Saba has held the status of a special municipality (public body) within the Kingdom of the Netherlands.

This chapter provides a general overview of the physical and geographical characteristics of Saba. Understanding these characteristics is essential to assess how nutrient fluxes occur from terrestrial sources to the marine ecosystem. The island's topography, geology, size, population, and climatic conditions form the basis for interpreting land use, runoff patterns, and potential impacts on coastal and marine waters.

2.2 Physical and Geographical setting

Saba covers a total land area of approximately 13 square kilometres, making it one of the smallest inhabited islands in the Caribbean, and is roughly circular in shape (Figure 2.1). According to the Census Bureau (2025), the island has a population of 2,154 residents. The population is primarily concentrated in four small villages: The Bottom (the administrative centre), Windwardside, St. John's, and Zions Hill (Hell's Gate). Human settlement is generally limited to the more accessible lower slopes and valley areas.

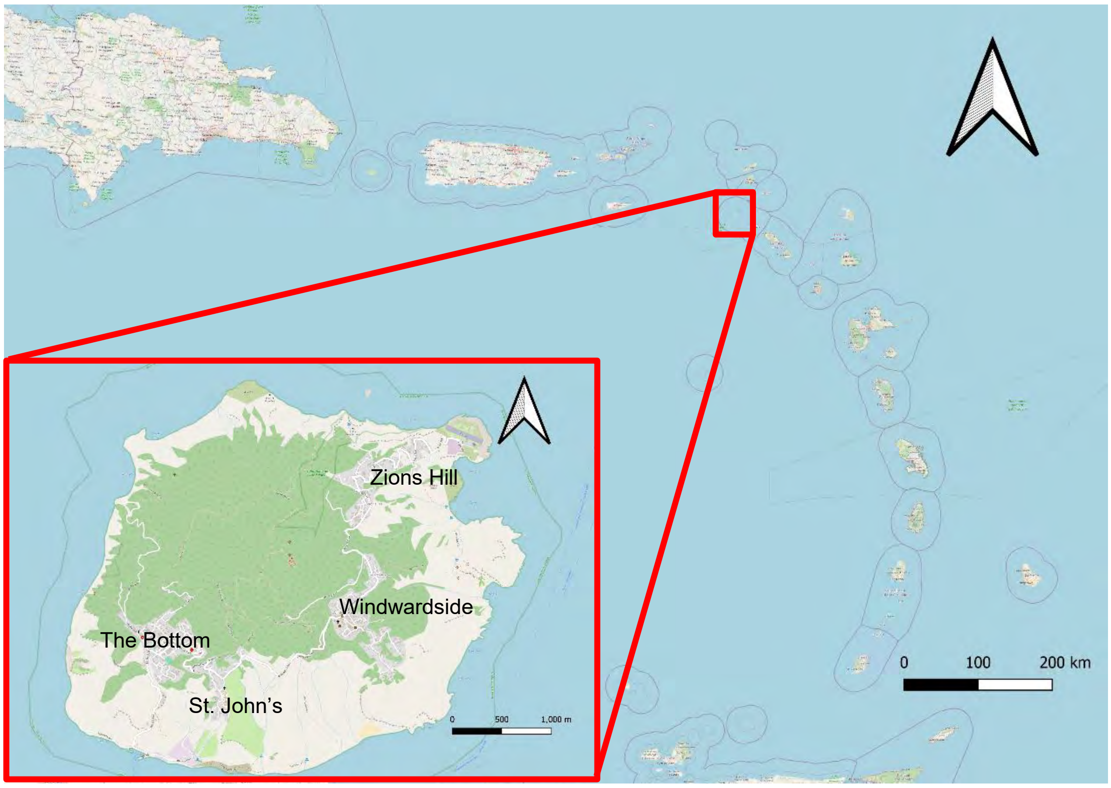

Figure 2.1 Geographical overview of Saba (OpenStreetMap (OSM)).

The topography of the island is dominated by Mount Scenery, a stratovolcano that reaches an elevation of 870 metres, which is also the highest point in the Kingdom of the Netherlands. The landscape is steep and rugged, with limited flat areas. From the summit, the slopes descend quickly to sea level, resulting in short water pathways and a high potential for surface runoff. This steep terrain plays an important role in the transport of nutrients from land to sea, especially during heavy rainfall.

Saba has a tropical oceanic climate, with temperatures generally ranging between 26 and 29°C throughout the year. The island receives an average annual rainfall of approximately 1034 mm (KNMI, 2023), with a clear wet season between August and November. The dry season typically occurs from February to April. Rainfall can be intense during tropical storms and hurricanes, which increases the risk of erosion and rapid nutrient transport. Spatial variation in elevation has a significant impact on the amount of rainfall and the rainfall distribution. At higher elevation there is a higher amount of rainfall. An extensive water flux analysis can be found in *6.3 Water fluxes*.

2.3 Human activity and land use

Human presence on Saba began more than 3,000 years ago. The earliest known site, Plum Piece, dates to around 1300 BC. Archaeological evidence suggests that the island was inhabited by pre-Columbian communities who cultivated root crops and relied on the marine environment for food. More than 20 pre-Columbian sites have been identified across the island. Pottery fragments found at The Bottom and Windwardside (Hartog, 1975) indicate that Saba supported a significant Indigenous population. By the time Europeans arrived, this population had either disappeared or was reduced to a small group living near freshwater sources such as the springs at Spring Bay (Hofman & Hoogland, 2003).

European colonisation began in the seventeenth century. Initially, agriculture played a dominant role in the local economy, with sugar and indigo plantations operated using enslaved labour. Over time, these activities declined and fishing, particularly lobster fishing, became more important (Public Entity Saba, n.d.).

In the twentieth century, infrastructure development changed the island's economy and land use. The construction of the island road in 1943, the Juancho E. Yrausquin airport in 1963, and the Fort Bay harbour in 1972 improved accessibility and supported the gradual development of tourism. Since then, tourism has become a key part of Saba’s economy, alongside government services and education. Approximately 10.000 tourists visit Saba each year.

Saba’s sulphur mine, located near Zions Hill (Hell’s Gate), was briefly active in the late 19th and early 20th centuries during a period of global demand for sulphur from volcanic sources. Ownership of the land and mining rights passed through various hands, including American and British investors, but the site proved too remote and logistically challenging for sustained operations. Despite renewed interest and several attempts at exploitation, the mine was eventually abandoned. Today, the ruins remain a historical landmark, though access is restricted due to safety concerns.

There are no centralized wastewater management systems in place. Most households rely on the use of cesspits (cesspools) to manage their waste. In cesspits the untreated wastewater is able to infiltrate directly into the subsurface. There are a couple of septic tanks present on the islands, but no options for treatment of the sludge from the septic tanks. For a more detailed explanation on the wastewater management on Saba see *6.2.2.1 Wastewater management.*

Rainwater harvesting is done throughout Saba and is an important freshwater source. The rainwater is collected in cisterns, an often underground concrete structure used to store water. Most households have their own cistern. Another source of freshwater is Reverse Osmosis (RO) water, which is desalinated seawater. The desalination plant is owned by the company AquaSab. The RO water is then converted into drinking water by the local drinking water company Saba Splash, which is regulated by The Public Entity Saba. This can be used directly as drinking water, during times of droughts, cisterns are also filled with the desalinated water. At present, no groundwater is used.

Land use on Saba is shaped by its steep terrain and small size. Only a small part of the island is urban, with most buildings located in the four villages: The Bottom, Windwardside, St. John’s, and Hell’s Gate. The rest of the island is largely covered by natural vegetation (Figure 2.2). At the highest elevations, Mount Scenery is covered by tropical rainforest and cloud forest, with dense, humid vegetation such as tree ferns and mosses. These forests help retain water and prevent erosion. On the middle slopes, the vegetation consists mainly of secondary forest and shrubland. Towards the coast, the land becomes drier with grasses, scattered trees, and exposed bedrock.

Agriculture on Saba has declined substantially compared to earlier periods, when it formed an integral part of daily subsistence. Historically, cultivation was concentrated in the island’s mid and high elevation zones. Mount Scenery, for example, was extensively terraced for agricultural production. These areas have since been largely abandoned for such purposes. Goat herding was once an important food source, but as imported food became more accessible, the practice was largely abandoned, and goats were left to roam freely. In 2020, the goat population was estimated at around 5,000, but this has been reduced to approximately 150 through the goat control programme. Chickens remain widespread across the island, while cattle are nearly absent, with only five cows currently present, see *6.2.3 Livestock*. Some small-scale agriculture still exists, in Hell’s Gate and Windwardside, as well as a hydroponics farm. More information about agriculture can be found at *6.2.4 Agriculture*.

Although land use is low in intensity, small-scale gardens, trails, and unpaved roads are present. The natural vegetation plays an important role in reducing erosion and limiting the transport of nutrients to the sea.

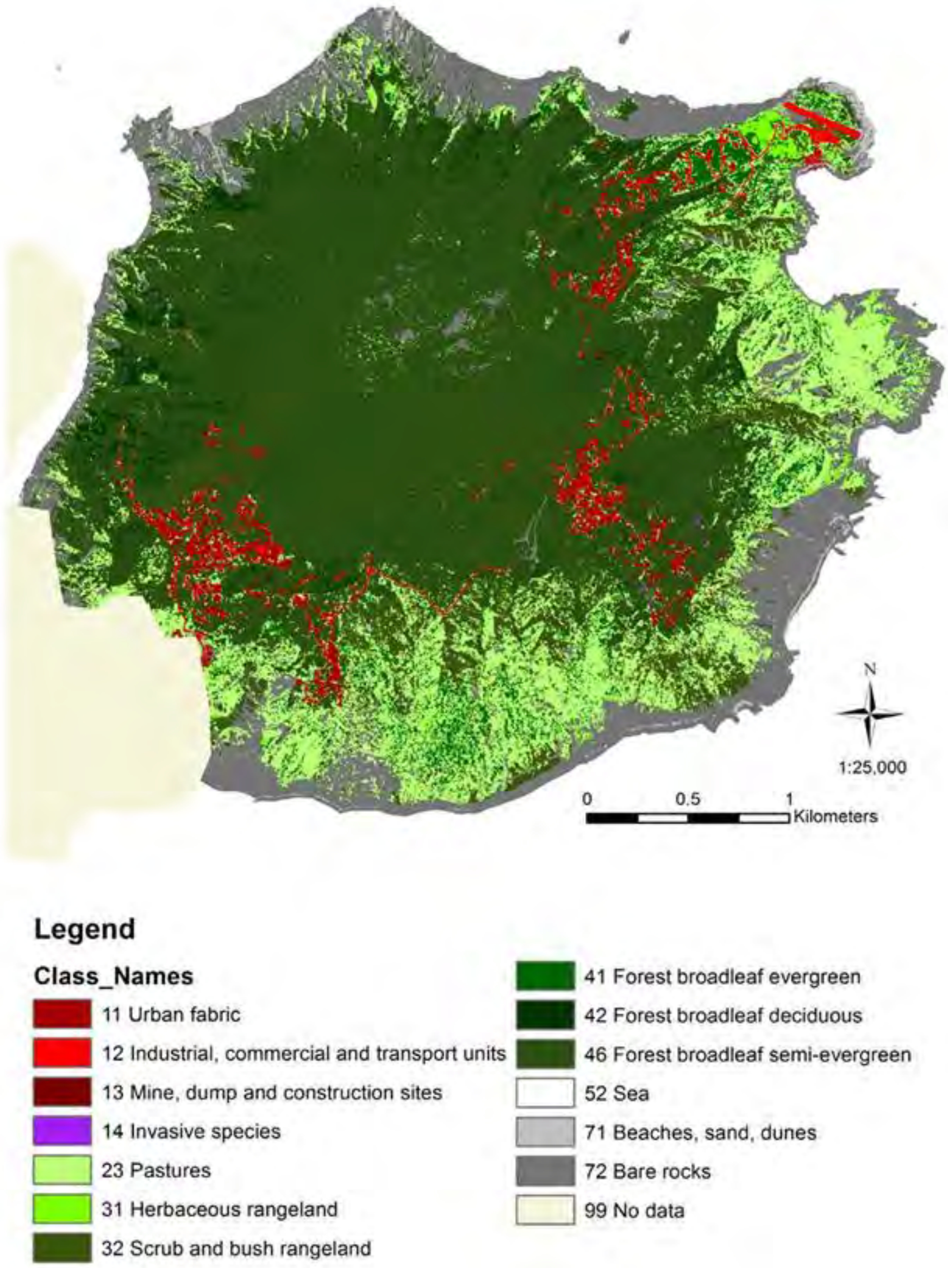

Figure 2.2 Land use patterns derived from satellite data (Smith et al., 2013).

2.4 Geology and geomorphology

Saba belongs to the Lesser Antilles Arc, an island arc located north of South America and consists of a row of ten volcanic islands that extend over a length of 740 km (from Grenada in the south to Saba in the north). The island arc is formed by westward subduction (at a rate of 2.2 cm per year) of the Atlantic Plate beneath the Caribbean Plate. The subduction trench is located approximately 150 km east of the active young arc and is completely filled with sediments that were brought in from South America (among others by the Orinoco River) (Vroon, 2012).

The island of Saba is probably less than 1 million years old. The oldest known dated rocks exposed at the surface on Saba island are thought to be around 400,000 years (Roobol and Smith, 2004). The island is a complex stratovolcano composed of over 20 andesitic domes of Pelean-style eruptions (explosive) with pyroclastic flows and ashes. The last identified eruption was a small eruption from Great Hill that has been dated at 280 years BP (Smith and Roobol, 2005). The Mount Scenery volcano is still an active volcano, indicated by two active hot springs, one in the southwest (900 m south of Ladder bay, Figure 2.8) and one northeast (below sulphur mine, in front of Green Island, Figure 2.8), with temperatures of respectively 50-60 °C and 70-80 °C. The Ladder bay hot spring was recently covered by a landslide and is not reachable anymore.

Figure 2.3 show a geological map of Saba and the old and younger andesite domes spread around the island are clearly visible, surrounded by lithified to unlithified andesite, ash and pyroclastic flows, and fluviatile reworked material. Figure 2.4 shows a more simplified geological map with andesite hard rock around Mount Scenery and on the lower slopes agglomerates (mainly pyroclastic flow deposits) and tuffs which are poorly sorted, and contain small to big blocks, volcanic bombs in a matrix of fine ash, sand or tuff. An agglomerate is geological name for volcanic deposits containing small to big blocks, volcanic bombs embedded in a matrix of fine ash, sand or tuff, resulting from eruptions and associated pyroclastic flows. The agglomerates are in general very permeable for water. At Well's Bay these agglomerates deposits are at least 50 to 100 m thick (see Figure 2.5). Due to its mostly unlithified character, the slopes are unstable and subject to slope debris flows and landslides. The volcanic domes and more lithified andesite hard rock are less permeable for water but contains fractures and cracks through which flow of water is possible.

Due to the rapid infiltration through volcanic deposits and preferential flow through fractures within the hard rocks, limited geochemical attenuation of dissolved nutrients is expected. For denitrification for example, the required electron donor (organic matter or pyrite) is largely absent in these deposits. However, relict organic matter in buried soils or woody debris in the subsurface can locally fuel denitrification in a volcanic subsurface (Stenger et al., 2018).

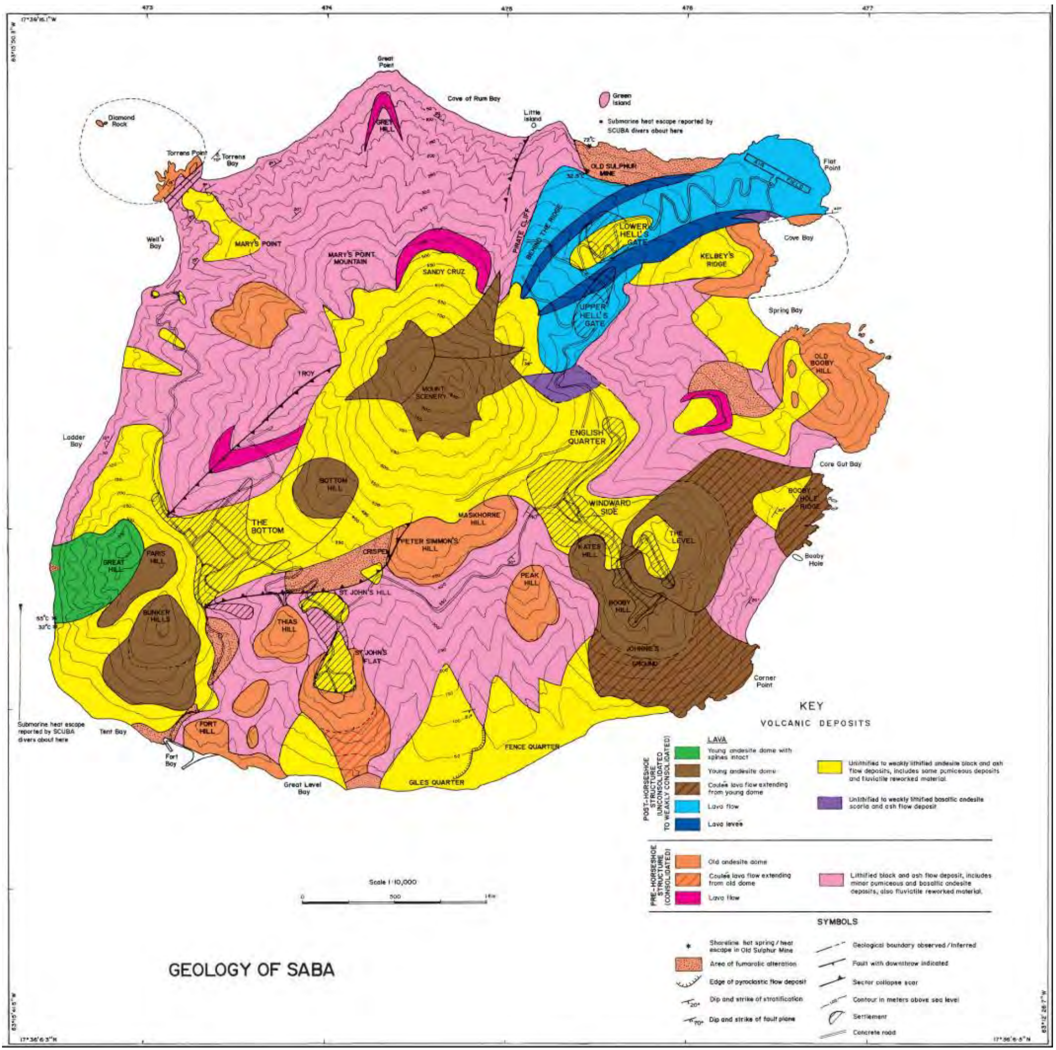

Figure 2.3 Geological map of Saba (Roobol and Smith, 2004)

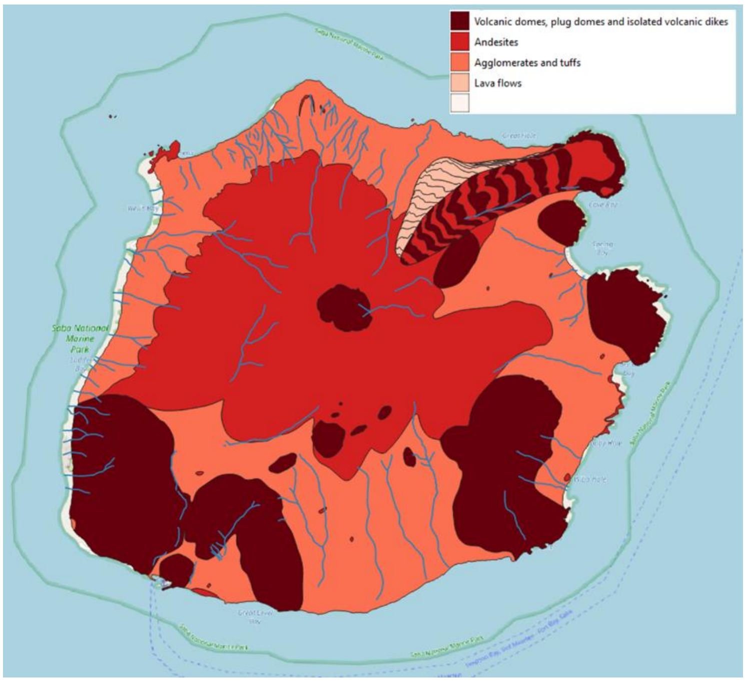

Figure 2.4 Simplified geological map showings domes, andesite hard rock, and agglomerates on the lower slopes (Geological Survey of the Netherlands).

Figure 2.5 Agglomerates deposits as cliffs at Well's Bay (Photograph by author).

It is expected that below the domes only andesite hard rock is found. However, in the rest of the area between the domes a (heterogeneous) sequence of agglomerates, tuffs and lava flows is found, which result from different volcanic stages and eruptions during the development of the island. This sequence can be clearly seen in the schematic representation of the different stages of volcanic activity and the corresponding sequence of sediments in Figure 2.6, made by Roobol and Smith (2004). Stage IV shows the current situation, with old and young Pelean domes of andesite reaching large depths, pumice and lava flows surrounding it and the largest volumes of volcanic deposits consists of block and ash deposits from pyroclastic flows, either reworked by hill slopes or not. From this it can be derived that the subsurface of Saba is very heterogeneous with a sequence of permeable (pumice, block and ash deposits, agglomerates) and less permeable layers (domes and lava flows). Groundwater flow occurs primarily through these permeable layers, while the andesitic (Pelean) domes and lava flows hinder groundwater flow or act as completely impermeable barriers.

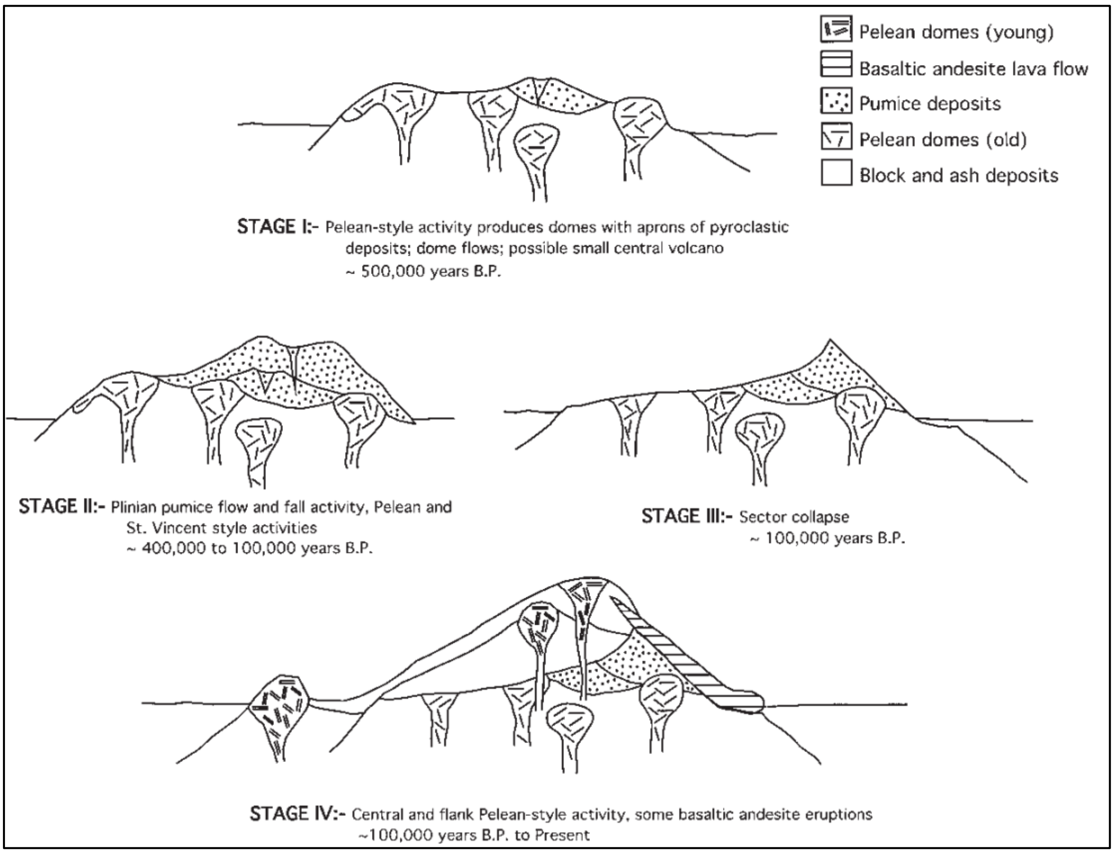

Figure 2.6 Four stages in the structural evolution of Saba volcano. Stage II is characterized by three different types of activity, which were repeated several times (taken from Roobol and Smith, 2004)

The geomorphology map of Saba (Figure 2.7) further distinguishes key landscape features associated with geological composition, volcanic activity, and hillslope-forming processes. The upper and lower domes (summits and slopes) consisting of hard rock (andesite) are dominant features in the landscapes. Between the domes, most of the slopes are gullied and different steep valleys parallel to each other can be distinguished (in Figure 2.7 indicated by the blue lines).

Most of the top soils can be classified as loamy sand to sandy loam and are very permeable for water, as also shown by the infiltration tests (see paragraph *4.2.2 Infiltration tests*). Around the top of Mount Scenery, the soil is locally more clayey hindering the infiltration of rainwater. However, the abundance of roots, organic matter and soil organisms of the tropical vegetation and trees provide an open soil structure through which water may flow relatively easily even in clayey soils. Small gullies and valleys are largely absent in the higher elevations of the island.

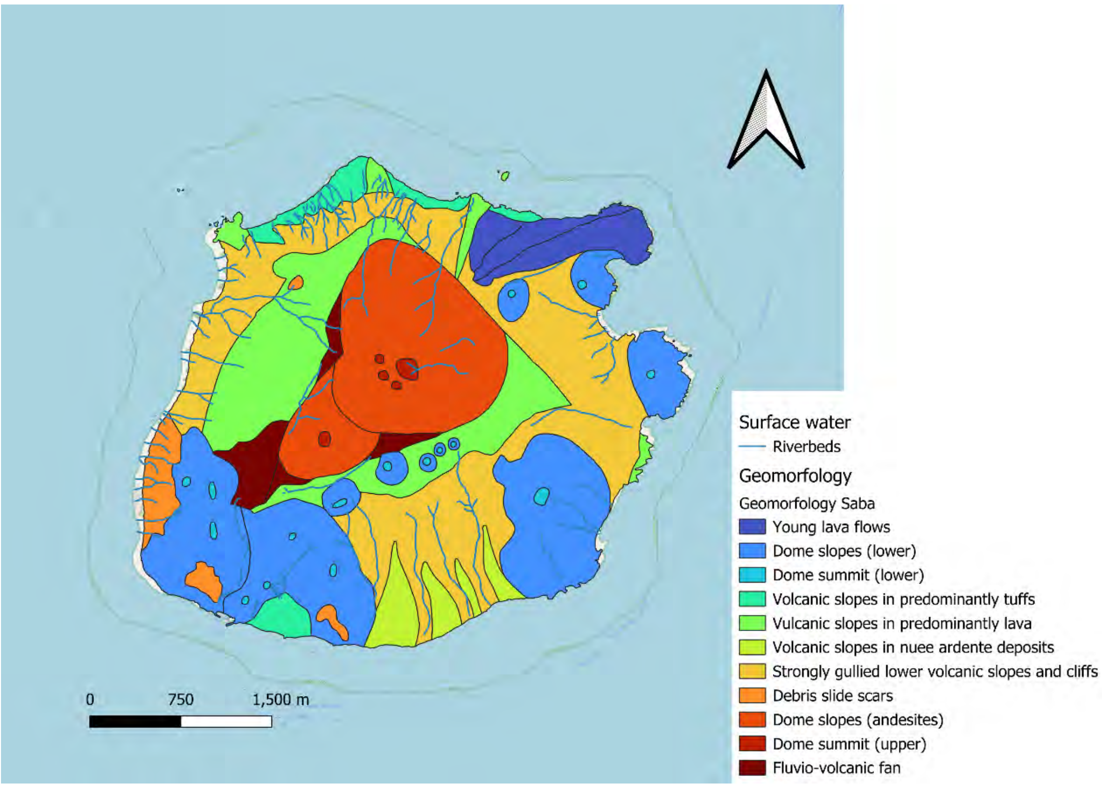

Figure 2.7 Geomorphology map of Saba

2.5 Groundwater wells and (hot) springs

On Saba several groundwater wells are or were present and they all occur at the coast, close to the sea. The shallow groundwater levels below surface are the obvious reason why these wells are located close to the sea. In ancient times, these locations were the only possibilities to collect freshwater on the island as surface water bodies are lacking and groundwater levels are too deep elsewhere on the island. The groundwater wells are all found in bays where groundwater flow converges and discharges beneath sea level as submarine groundwater discharge (SGD).

Based on literature and interviews, six locations where groundwater wells are still present or disappeared have been identified (see Figure 2.8 and Figure 2.9) which are summed up below.

- **Cove Bay well:** this groundwater well was removed a couple of years ago and was located at the present playground at Cove Bay. No remains of this well are visible today.
- **Spring Bay well:** this well remains functional, with water still present. It is located about 50 meters from the sea side, close to an ancient small settlement. The top of the well is made of concrete and the water can be reach via a hatch at the top. A bucket is required to sample the groundwater since the water level is about 8 m below the surface.
- **Core Gut Bay well:** this old historical groundwater well is part of an old settlement of which some remains are still visible. The well is still present but is filled with sand and doesn’t contain water. Based on the position of the well relative to the sea level, it is assumed that groundwater can be found within 2 meter below the current surface in the well. Attempts to remove the sand and drill a small hole to the groundwater level failed during the field survey.

- **Hole in the corner well:** this well is also located very close to the seaside and is still in operation. The groundwater level in the well is at about sea level, and the water can be reached via a ladder.
- **Well's bay:** this historical well is not present anymore, because it was covered during the construction of a road. During hurricane Irma (2017), the road was washed away and the location of the well appeared again. At this location, a well-like construction was built to indicate the historical position of the well and the new road was constructed next to it.
- **Groundwater spring Tent bay:** a groundwater spring was present at Tent bay but was covered by a landslide a couple of years ago. During the field survey, a very small spring was discovered after a rainy day, and this could be the remains of the covered old Tent bay spring.

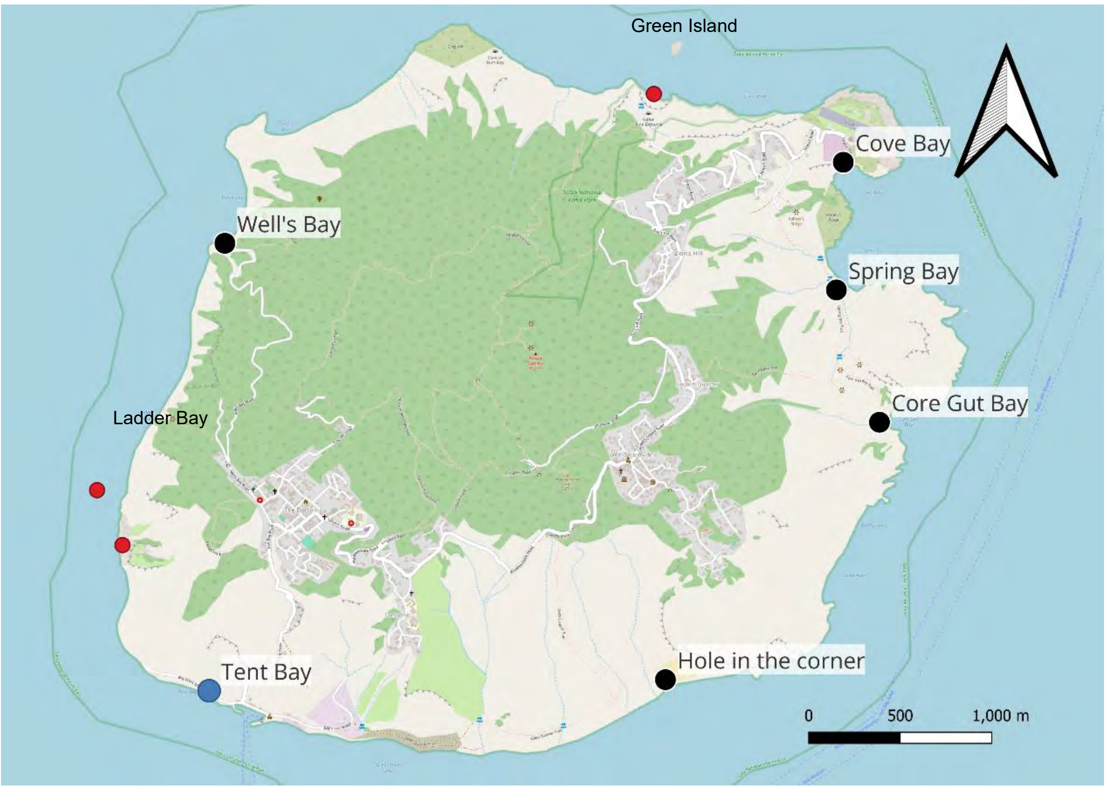

Figure 2.8 The location of the five groundwater wells (black), one freshwater spring (blue) and the three hot springs (red).

Hot springs have long been known on the island of Saba and were first described by Sapper (1903). Today three hot springs are known at sea level around the coast of the island (from Roobol and Smith, 2004).

A hot spring opposite Green Island

This hot spring is situated on the northern shoreline immediately below the abandoned sulphur mine and opposite Green Island. Access both from the sea due to the high surf, and from land, down a vertical cliff below Lower Hell's Gate is difficult. The spring occurs at sea level and is often flooded by seawater and covered by surf, boulders and gravel and standing water is absent. At present, this hot spring is visited by volcanologists of KNMI twice a year to collect data from their temperature sensor. Attempts to sample surface water for a chemical analysis failed but recently during their visit in May 2025 they were able to take a water sample. The analyses of this sample were not yet available while finishing this report.

Gunnlaugsson (1981) was able to take some water samples from this spring and analysed the chemistry (chemistry data in 8A.1). The analysis show a salinity equal to that of seawater (high sodium concentrations). Since the hot spring is flooded regularly by sea water, the samples are highly contaminated by sea water as also concluded by Gunnlaugsson.

Figure 2.9 Photos of groundwater wells at the coast of Saba, A) Hole in the corner, B) Well's Bay, C) Spring Bay, D) Core Gut Bay (Photographs by author).

Hot springs between Ladder Bay and Tent Bay

These were the most accessible of the hot springs on Saba but are covered by a landslide nowadays. They were located 900 m south of the Ladder below the steep, high cliffs that truncate the Great Hill dome. Two closely-spaced springs occur at sea level and are just covered by seawater at high tide. Temperature of this hot spring is around 55 ºC. Gunnlaugsson (1981) determined a flow rate of less than 0.1 Liter per second (from Roobol and Smith, 2004), indicating that this hot spring was discharging groundwater. Gunnlaugsson (1981) also took samples from these hot springs and the results are presented in Annex A. The sodium concentrations are also very high but a bit lower than the other hot spring opposite Green Island. The sodium indicate a mixture of about 80% sea water and 20% freshwater.

Interestingly, Roobol and Smith (2004) report freshwater discharging at this hot spring: *"In previous literature the hot springs near the Ladder on Saba have been described as saline, however on March 10, 1994, we were fortunate to visit the Ladder Bay spring at low tide. The hot spring water was emerging from a fissure in the Great Hill andesite at a point normally covered by the sea. At the same time the sea was calm, and the spring water was found to be fresh and potable. It seems likely that the records in the literature that the springs are saline are in fact records of emerging fresh water springs that are being contaminated by seawater at high tide."*

An interesting historical observation of a submarine freshwater spring was also mentioned by Roobol and Smith (2004). *"Westermann and Kiel (1961) report an account by Benest in 1899 of a submarine upwelling of fresh water off the coast of Saba. About 0.5 km to the southwest of the island, fresh water was reported bubbling up on the surface of the sea and there were reports of boats filling their water barrels from this submarine stream of fresh water. Today, in spite the increased boating and SCUBA activity in the Saba Marine Park no trace of this spring is evident."*

Submarine hot springs
Between Tent Bay and Ladder Bay, hot springs occur at the sea bed at a depth of about 10 meter, about 150 meter offshore, indicated as Hot Springs Diver site number 14 (red dot in sea in Figure 2.8). It is regularly visited by SCUBA divers and increased temperature of the sandy sediments can be felt. There are no reports of water emerging from the sea bed.

3 Method

3.1 Introduction

This chapter outlines the methodology used to investigate the hydrogeological system of Saba and to assess the contribution of potential nutrient pollution sources, particularly via groundwater and surface water systems, to coastal water resources. The research approach consists of a literature review, field surveys carried out between March 24th and April 5th, 2025, and laboratory analysis of collected water samples. Data gathered during these phases support a preliminary nutrient balance and understanding of the subsurface flow systems and help identify key pollution sources across the island.

3.2 Literature study

A literature study was conducted to gather existing knowledge on Saba's geology, hydrogeology, climate, land use, and known contamination sources. Relevant reports, hydrological data, maps, and academic publications were analysed to identify knowledge gaps and inform the design of the field activities. The literature review also provided baseline information used in the conceptual model and nutrient balance estimations. The literature study is mainly described in chapter 2, 5, and 6, but used throughout the report.

3.3 Field survey

Field activities were carried out over a two-week period, from March 24th to April 5th, 2025. Field site visits were documented using a tablet, where forms were completed directly on-site. This method allowed for the immediate recording of coordinates, streamlining data interpretation and ensuring accuracy. Activities included geological and hydrogeological observations, infiltration testing, on-site water quality screening, and sample collection for laboratory analysis. These efforts aimed to enhance the understanding of local flow systems and identify key pathways and sources of nutrient transport across the island.

3.3.1 Geological and hydro(geo)logical observations

Geological and hydrogeological observations were conducted to characterize the subsurface and surface conditions that influence water movement and nutrient transport. Attention was given on identifying variations in soil surface permeability across different locations. Infiltration tests were performed using a simple method in which a PVC pipe was pushed vertically into the soil, filled with water, and the infiltration rate was estimated by measuring the change in water level over time. Figure 3.1 shows the PVC pipe in the field. The applied method is simple but effective, providing a rough estimate of infiltration rates. More accurate methods (e.g. double ring infiltration test or SATURO meter) were not used due to additional logistics and effort, which were not necessary for the purpose of this study. The results provided insight into the infiltration capacity of the soil and supported interpretations of groundwater recharge potential. All this information was used in the development of the conceptual (ground)water model.

Figure 3.1 PVC infiltration ring used in the field (Photograph by author).

3.3.2 Quick-scan field tests

To obtain preliminary insights into the quality of groundwater, surface water, and coastal seawater, quick-scan field tests were performed on-site during the field visit. Measurements included electrical conductivity and temperature, as well as a range of parameters tested using test strips. The following parameters were assessed:

- Electrical conductivity (EC) and temperature using a handheld EC meter (WTW - Cond 3310)
- Nitrate (mg/L) (Hach Aquachek)
- Nitrite (mg/L) (Hach Aquachek)
- Ammonium (mg/L) (Dosatest)
- pH (Dosatest)
- Hardness (°d) (Dosatest)
- Chloride (mg/L) (Dosatest)
- Sulphate (mg/L) (Quantofix)
- Phosphate (mg/L) (Dosatest)
- Total Iron (mg/L) (Dosatest)

These rapid measurements supported the identification of locations for further sampling and helped detecting areas of potential concern.

3.3.3 Laboratory testing

In addition to field measurements, groundwater and surface water samples were collected and sent to St. Maarten Laboratory Services (SLS) for detailed laboratory analysis. Quick-scan field tests were performed at all sites where laboratory samples were collected; however, laboratory sampling was not conducted at all sites where field tests were carried out. The sample numbering is as follows: SABA000, with an increase with 1 with every sample. An overview of where the samples were collected can be found here: *4.3.2 Lab analyses.*

The samples were collected using the glass sample jars provided by SLS. After returning from the field the samples were stored in the refrigerator and were kept cool using cool packs when they were shipped to the lab. The samples were not filtered or acidified.

To assess the concentration of soluble components in the soil under conditions of limited moisture, soil samples were collected and treated with demineralized water. The samples were shaken to facilitate the dissolution of soil-bound minerals into solution. Subsequently, field kit analyses were performed, and samples were sent to the laboratory for further chemical analysis.

Figure 3.2 Glass sample jars stored in the fridge before being send to the lab (Photograph by author).

SLS operates under ISO/IEC 17025 standards. The laboratory testing included a broad set of parameters to allow for a more complete understanding of nutrient concentrations and general water chemistry. The following components were analysed:

- Wastewater package (including pH, conductivity, total coliform, total nitrogen, total phosphorus, biochemical oxygen demand (BOD), and chemical oxygen demand (COD))
- Total hardness
- Alkalinity
- Fluoride (F)
- Nitrite (NO_2)
- Nitrate (NO_3)
- Sulphate (SO_4)
- Ammonium (NH_4)
- Potassium (K)
- Calcium (Ca)
- Magnesium (Mg)

The following parameters were requested for analysis, but were not done because the equipment needed for the testing was unavailable at SLS:

- Chloride (Cl)
- Bromide (Br)
- Phosphate (PO_4)
- Sodium (Na)

The laboratory results served to validate and complement the quick-scan field data and played an important role in the subsequent nutrient balance calculations.

3.4 Conceptual (ground)water model

A conceptual (ground)water model was developed to describe the key characteristics, processes, and interactions within Saba's (ground)water system. Such a conceptual model provides a simplified, visual representation of how groundwater moves through the subsurface and how it interacts with other hydrological components, such as surface water and sources of contamination. Unlike numerical models, a conceptual model is descriptive and integrative, serving as a foundation for understanding, interpretation, communication, and potential future numerical modelling.

The development of the conceptual model relied on all available data from the literature review, field observations, infiltration tests, water quality screening, and laboratory analysis. Information such as geological structure, permeability, recharge potential, water quality, and spatial patterns of contamination were synthesized to understand the behaviour of the groundwater system across the island.

The (ground)water analysis helps to support the spatial interpretation of contaminant transport, to identify possible flow paths, and to locate areas of particular concern with regard to nutrient leaching or discharge to the ocean. It also helped visualize connections between pollution sources and vulnerable zones and provided a framework for integrating data collected from different sources in a coherent way. This information is required to setup nutrient balance and link sources to flows.

It is important to note that the development of the conceptual (ground)water model is based on a quick scan field survey and very limited available data. It is a first attempt to understand the subsurface flows on Saba and additional monitoring and field data are essential to validate the hypothesized mechanisms.

3.5 Integrated Nutrient and Water Balance Analysis

A nutrient balance was calculated using Microsoft Excel, based on a rapid assessment, to estimate the contribution of various pollution sources to nutrient loading across the island. Emission factors for nutrient release were derived from literature, while population statistics, livestock numbers, tourism data, and other relevant inputs were provided by local stakeholders and institutions.
In addition to the nutrient balance, a water balance analysis was conducted for each catchment, based on the limited data available, to quantify inflows and the partitioning of water into deep groundwater recharge and interflow. This analysis combined existing hydrological data with newly collected field data and insights from the conceptual (ground)water model.

The results of the water balance were then integrated with the nutrient balance to estimate the nutrient fluxes, allowing for a more comprehensive understanding of nutrient transport dynamics within the catchments. This combined approach helps quantify the scale and movement of nutrient emissions from human waste, domestic animals, and other sources to the coastal waters. By linking these estimates with spatial patterns observed in the field and the results of lab analyses, the study was able to identify key nutrient contributors and pollution hotspots. This integration of hydrological and nutrient data supports the investigation of how different pollutant sources affect marine contamination, which is essential for protecting the coral reef ecosystems surrounding Saba.

4 Field results

4.1 Introduction

During the field surveys, a total of 93 observation locations (of which 7 locations were at sea) were documented across the island (Figure 4.1). At each of these sites, a variety of geological, hydrogeological, and water quality observations were recorded, providing a comprehensive dataset for analysis. The field activities were designed to gather essential data on the groundwater and surface water systems, as well as potential sources of nutrient contamination. This chapter presents an overview of the results, including the quick-scan field measurements, laboratory analysis of water samples, and insights gained from interviews with local residents and stakeholders. Together, these results form the foundation for understanding the island's hydrological dynamics and identifying key pollution sources that contribute to nutrient loading in the environment. A complete overview of all the observations can be found in appendix 8A.2.

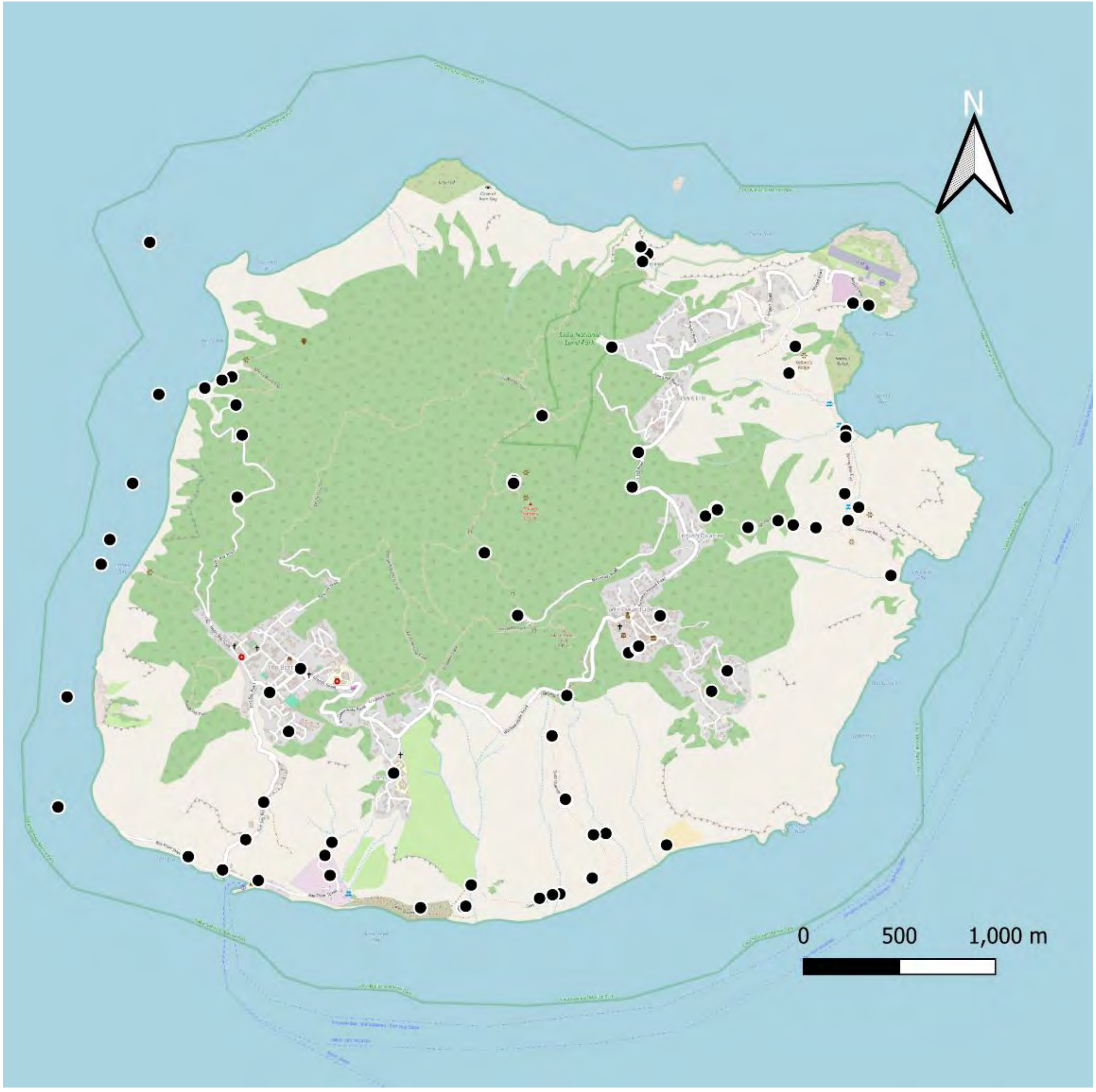

Figure 4.1 Overview of all the field observation sites.

4.2 Field observations and interviews

4.2.1 Geology and geomorphology

Geological observations were made at 50 locations across the island (Figure 4.2). Note that the locations indicate the position from where the observations were made (e.g. observations Geo40 until Geo46 were made from a boat).

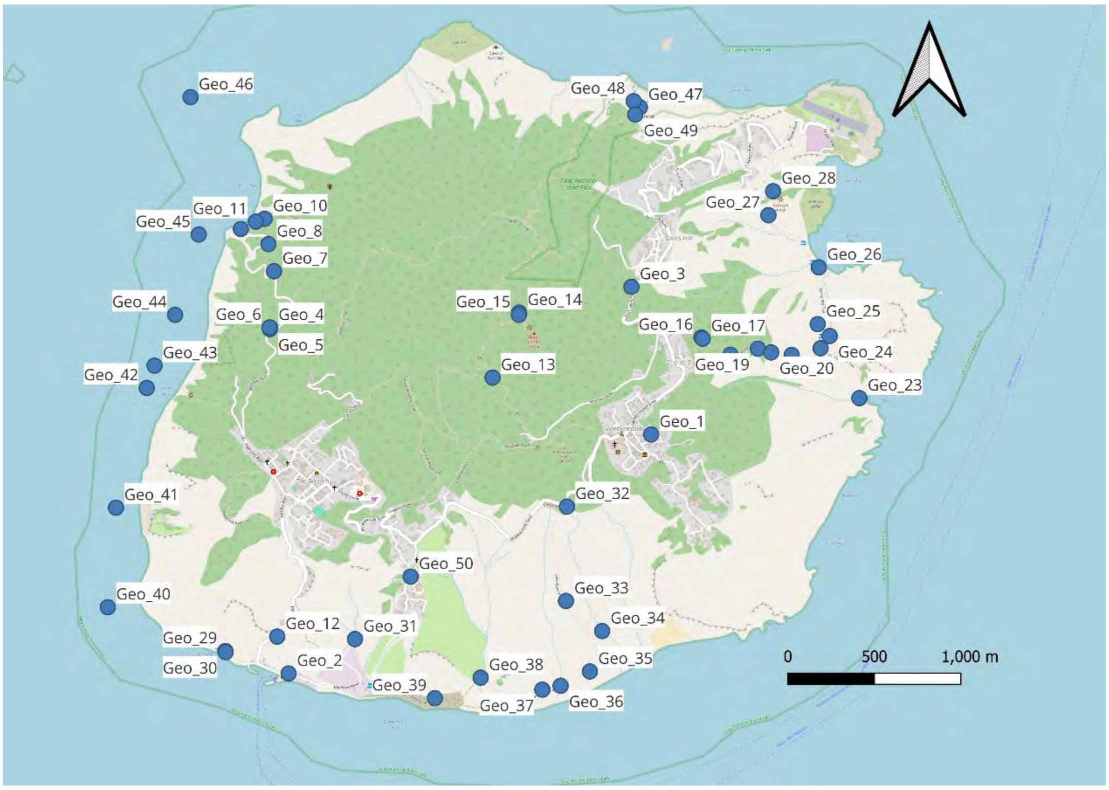

Figure 4.2 Geological observation location.

At several locations thick layers of agglomerates could be observed. The occurrence of this geological formation is widespread and important for groundwater flow and nutrient transport due to the high permeability. An agglomerate is the mixture of volcanic deposits containing small to big blocks, volcanic bombs embedded in a matrix of fine ash, sand or tuff. Figure 4.3 and Figure 4.4 illustrate outcrops at locations Geo_11 and Geo_8, respectively, showcasing the agglomerate deposits. These agglomerates are widespread surrounding the different domes observed throughout Saba, with its thickness increasing at lower elevations, particularly toward the coastline.

Below the agglomerates, the andesite bedrock, often called “blue/black rock” by locals, is found (Figure 4.5). This hard volcanic rock is part of a layered subsurface, built up from different volcanic eruptions over time. The result is a sequence of layers with varying permeability. The andesite itself is mostly impermeable, but where fractures occur, some groundwater flow is still possible. In contrast, the overlying agglomerates and pyroclastic deposits are much more permeable and allow easier infiltration. This interbedded system of more and less permeable layers controls how groundwater moves through the subsurface. The groundwater flow is therefore strongly influenced by the location and connectivity of these layers.

Figure 4.3 Outcrop at Well's Bay (Geo_11 in Figure 4.2). Human (1.70cm) for scale. Layered agglomerates consisting of fine and big boulders and volcanic bombs in a loose sandy matrix of tuff and ashes (Photograph by author).

Figure 4.4 Outcrop at Geo_8, on the road to Well's Bay. Agglomerates with ranging boulder sizes (Photograph by author).

Figure 4.5 Outcrop at Geo_12, on road towards harbour. Andesite rock of one the domes exposed at the surface (Photograph by author).

4.2.2 Infiltration tests

Based on the infiltration test results (Table 4.1, Figure 4.6), it was observed that the infiltration rates are generally very high and vary across the island, largely depending on the underlying geological formations and moisture levels in the soil.

In areas dominated by agglomerate rock, such as locations Infil_1, Infil_2, Infil_5, Infil_6, Infil_7, Infil_8, Infil_9, Infil_10, Infil_13, Infil_14 and Infil_15, water infiltrates very rapidly, often at rates exceeding 1 cm per second (blue dots in Figure 4.6). These results suggest that the agglomerate rocks, with its loose gravel and boulders embedded in a sandy matrix, provides excellent conditions for water infiltration, especially where the rock is exposed or covered by only a thin layer of soil. Additionally, the presence of soil, soil life and vegetation further enhances infiltration, as root systems improve soil structure and promote preferential flow pathways.

However, at the top of Mount Scenery, where the cloud forest is present, infiltration rates were notably slower, as seen in tests Infil_11 and Infil_12 (orange dots in Figure 4.6), where the water infiltrated at rates of 2 cm in 5 minute and 1 cm in 6 minutes, respectively. The soil here is characterized by a loamy texture resulting from tropical weathering processes resulting in lower permeability compared to the other locations. Although the cloud forest maintains consistently high moisture levels, the dense root network and organic-rich soil create a permeable structure that still allows water to infiltrate into the subsurface. Rather than producing surface runoff or visible flow paths, rainfall continues to percolate through the soil.

These findings indicate that groundwater recharge potential is generally high across the island. In many areas, particularly where agglomerate rock is present, such as lower elevations and steeper slopes, rainwater infiltrates efficiently due to the porous and loosely packed structure of the material. While soils around Mount Scenery are somewhat less permeable, infiltration remains effective in most locations. Only the steep andesite outcrops significantly limit infiltration.

Vegetation plays a key role in supporting infiltration. Root systems improve soil structure, allowing water to enter the subsurface more easily. In the past, heavy grazing pressure from an estimated 5,000 goats reduced ground cover, leading to increased surface runoff and soil erosion. With goat numbers now reduced to around 150 vegetation has recovered, resulting in improved infiltration capacity and a decrease in erosion at the steep slopes and gullies. This shift has enhanced the island’s overall potential for groundwater recharge.

Table 4.1 Overview of the sites where an infiltration test has been conducted, including the ID, the results from the infiltration test and remarks.

Infiltration test ID	Infiltration test	Remarks
Infil_1	1.5 cm in 10 s	Water infiltrates fast
Infil_2	2 cm in 20 s	Infiltration ring could not be installed properly, lateral flow. Infiltration is fast. Matrix loamy sand, soil is dry, grass is yellow.
Infil_3	-	Infiltration observation during rain event. Water infiltrates fast on slope but part is surface runoff.
Infil_4	-	Infiltration observation during rain event. Very fast infiltration, matrix rocky sandy loamy
Infil_5	1 cm in 30s	Down along the ridge, water infiltrates very quickly. Steep grassy slope towards Gulle. Conglomerate, scree slope. Uppermost meters, likely not very thick.
Infil_6	2cm in 1s	Very fast infiltration
Infil_7	2cm in 15s	Geology, loose material with coarse stones in a sandy matrix.
Infil_8	1 cm in 40s, 1.6cm in 1 minute, 2cm in 1.5 minute	On top of cliff Well’s Bay, geology same as before
Infil_9	1cm in 1 s	Conglomerate with a very thin soil on top of it with dry grasses
Infil_10	1.5 cm in 30s	-
Infil_11	2cm in 5 minutes	On top of Mt Scenery, andesite dome, soil very loamy many roots, low permeability
Infil_12	0.5 cm in 1 minute, 0.8 cm in 2 minutes, 1 cm in 6 minutes	On top, 2nd infiltration test

Infil_13	2cm in 2s	Small part up the trail. Soil super permeable, no traces of run off
Infil_14	0.5 cm in 10s, 1cm in 28s, 1.2cm in 56s, 1.5cm in 1.5 minute, 2.5cm in 2 minutes	Conglomerate with a sandy matrix. Also wet around it. Still wet quite deep, it's wetter deeper than it is wide. At least 10 cm wet. Loamy, a bit malleable, but still sandy.
Infil_15	2cm in 2s	Tropical soil. Subsoil is loamy sand but heterogeneous.

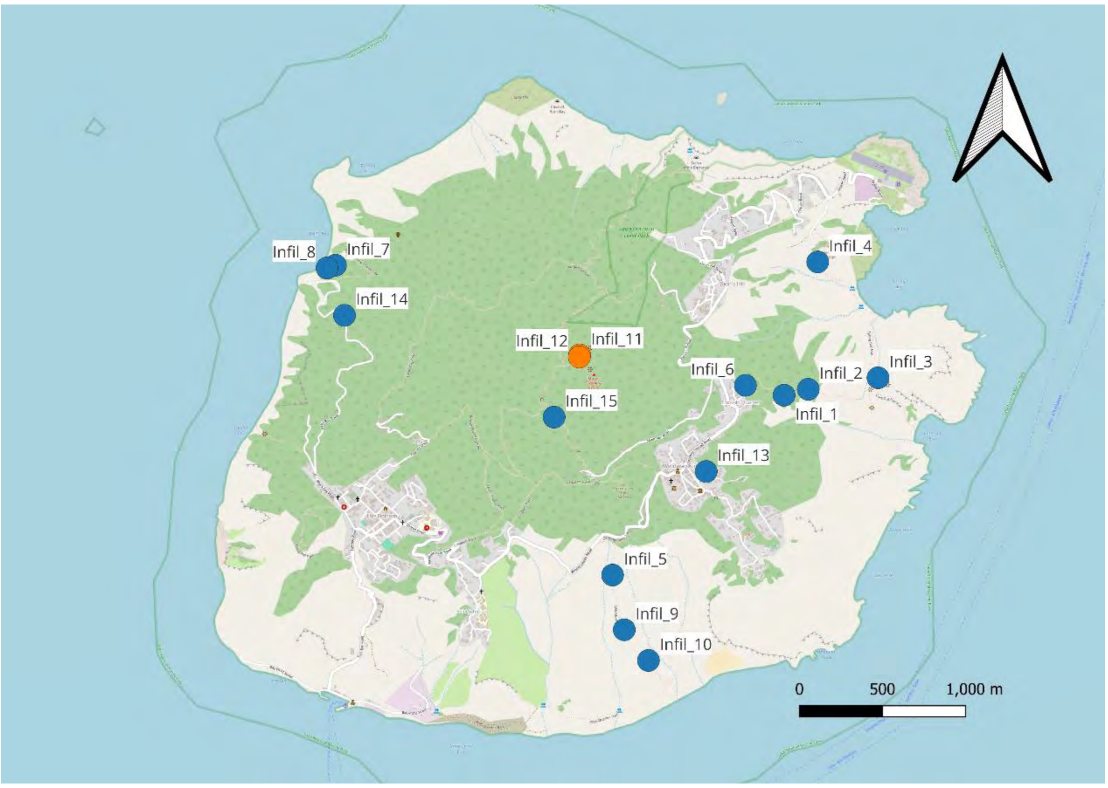

Figure 4.6 Infiltration test location with as a label their test location ID. In blue very fast infiltration and in orange relatively slower infiltration.

4.2.3 Interviews

During the field visit 13 people were interviewed with different background and affiliations (Table 4.2). Their responses have been anonymised for privacy reasons.

Table 4.2 Overview of the people that were interviewed during the field visit.

Name	Affiliation	Relation to this study
Niké Dekkers	Public Entity Saba	Project leader, wastewater specialist
Sarah Van der Horn	Public Entity Saba	Former wastewater specialist. Current lead for goat population control program
Jordan Every	Public Entity Saba	Drinking water, Saba Splash
Oscar Vander Kaap	Public Entity Saba	Drinking water, Saba Splash
Randall Johnson	Public Entity Saba	Head of Agriculture, Hygiene and Vector Control
Zelda Meeuwsen	Public Entity Saba	Spatial planning expert, works on Black Rock Harbour

Zoubier El Atmani	Public Entity Saba	Work focusses on the road, knowledge about rainwater flows during heavy downpours
Roxanne Simmons	Public Entity Saba	Waste Facility Manager
Javier Dinten Fernandez	Rijkstrainee at Public Entity Saba	Performed a rainwater analysis.
Peter Johnson	Saba Electric	Electrical Grid Manager. Personal observation on land and in water
Sanne Mooij	SCF	Fisheries Research Officer
Otto de Vries	Sea Saba Dive centre and board member of SCF	Dive guide and boat captain. Personal observations on land and in water
Alwin Hylkema	Van Hall Larenstein	Associate Lector Coastal Ecosystem Restoration

The interviews conducted yielded a wealth of valuable information regarding water infrastructure, environmental conditions, and hydrogeological features on the island.

A recurring topic across several interviews was the potential use of septic tanks for wastewater management. At present, the majority of household use cesspits (or cesspools) with the exception of the Public Administration building, the “Under the Hill” system, the dorms at the Medical University and the Saba Cares Hospital, which use septic tanks. While considered a feasible option, concerns were raised regarding the lack of a clear solution for the disposal or treatment of sludge after the septic tanks are emptied.

Interviewees also identified additional groundwater wells that were not previously documented. While Well’s Bay and Spring Bay were known locations, new information emerged about the well location at Core Gut Bay and Hole in the Corner. The road was built on top of the Well’s Bay well. In 2017, during hurricane Irma, the road was destroyed and the well was uncovered. After that the old well location has been restored, filled with concrete, and turned into a fire pit that marks the old well location. Tents Bay also previously had a (natural) spring , which was destroyed by a landslide. Similarly, a former well at Cove Bay Beach is no longer accessible due to the construction of a playground on the site.

The submarine hot springs were mentioned by multiple interviewees. It is uncertain if only warmth is emitted here or if there is submarine groundwater discharge. These vents exhibit temperatures ranging from 30 to 39°C.

Runoff and flooding were also frequently discussed. Many residents noted that water regularly flows along roads during rainfall events. Approximately three to five times a year, rainfall is heavy enough to cause significant flooding and landslides (sediments and rocks on the road), rendering the road to the harbour impassable during those times (Figure 4.7). During periods of intense rainfall, visible sediment plumes are observed in Fort Bay and Spring Bay, indicating surface runoff and erosion into the marine environment.

Figure 4.7 Rainwater runoff on the road towards the harbour (Dinten Fernandez, 2025).

In relation to land use and ecological changes, it was noted that goats were once commonly seen across the island, particularly in the lower, grassy areas. Historically, goats were imported as a food source. They used to be herded for their meat. Once the importing of food became more common, this practice was largely abandoned and most goats were left to roam freely. Because of a lack of natural predators the goat population grew out of control until there were approximately 5000 goats in 2020. However, their numbers have significantly declined in recent years, to approximately 150 goats, due to the goat population control program. Over the last couple of years (since the start of the goat control program) the island is visibly greener, in the lower areas the grasses are significantly higher and less erosion is visible.

Regarding the construction of the new harbour, various geological and hydrogeological investigations have been conducted. Coring activities revealed a hard black/blue andesitic rock, identified as the hydrogeological basement, which was described as extremely difficult to penetrate.

Concerns were also raised about potential contamination of domestic cisterns. Cisterns are typically installed uphill from the corresponding household's own cesspit. But, they are often situated downhill from their neighbours' cesspits, raising the risk of contamination. Cesspits are typically installed at a depth of 2.5 to 3 meters below the ground surface.

4.3 Field measurements

In the field a combination of quick scan field kits are applied as well as sampling for the lab. Below the results of both the field kits and lab results are presented together to form one coherent story. The spatial patterns and key findings for nitrate, sulphate, phosphate, and electrical conductivity (EC) are discussed in detail. The remaining results can be found in Appendix 8A.2 for the in-field observations and Appendix 8A.3

4.3.1 Quick-scan field tests

The quick scan field measurements (as described in *3.3.2 Quick-scan field tests*) were conducted at 24 locations across the island, covering a mix of surface water and groundwater sites (Figure 4.8). These rapid on-site tests provided an initial indication of water quality conditions in the field. A complete overview of all measurements is included in Appendix 8A.2.

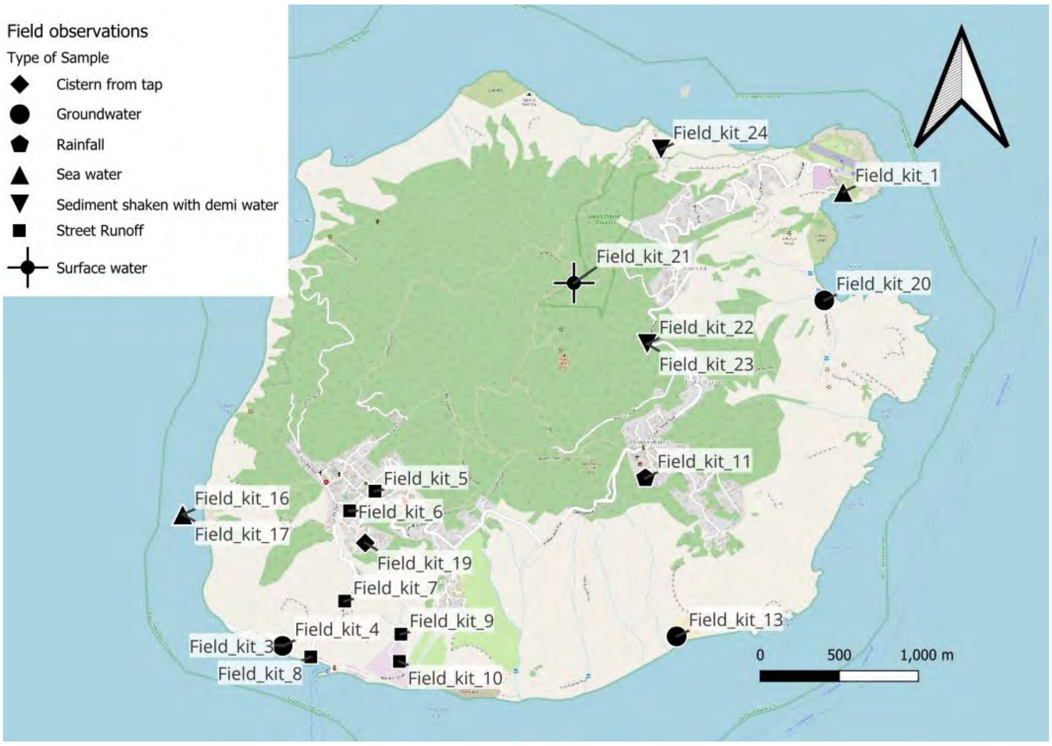

Figure 4.8 Overview of the observation locations where quick scan field kits were applied.

4.3.2 Lab analyses

A total of 14 water and sediment samples were collected on Saba in late March and early April 2025 (Figure 4.11, Table 4.3). These included 3 surface runoff samples collected during heavy rainfall events, and 4 groundwater samples, of which 3 were taken from two different wells and 1 from a spring. Additionally, 2 seawater samples were collected near the hot springs, 1 lake water sample, and 1 cistern water sample from a household tap. The dataset also includes 3 sediment samples from areas with organic waste and mining activity, processed with demineralized water to extract nutrients, as described in *3.3.3 Laboratory testing*.

As mentioned, 4 groundwater samples in total were taken. In the end two wells were sampled. Two samples were collected from Spring Bay (SABA008 and SABA009, Figure 2.9 C) and one sample was collected from Hole in the corner well (Figure 2.9 A). These samples were all clear water. One spring was sampled in Tent Bay (SABA004). Here, groundwater is seeping from the side of the hill after heavy rainfall (Figure 4.9). The seepage was slow and in the end 100 ml water was captured. In order to test it in the lab 300ml demineralized water was added. This is why the lab results of SABA004 have been multiplied by 4 in order to achieve the original concentrations. The sample SABA004 was turbid due to suspended sediment in the water.

The seawater samples (SABA006 and SABA007) were collected during a diving trip by Sea Saba as close to the submarine geothermal vents as possible.

At the time of writing, SABA014, the sediment shaken with demineralized water from the sulphur mine, has not been analysed in the lab and is therefore excluded from the result description and interpretation described below.

The laboratory results (as shown in Appendix 8A.3) are presented in ppm. Because ppm and mg/L are the same, it was decided to present all values in mg/L for consistency.

Figure 4.9 Groundwater spring at Tent Bay (SABA004). Situation overview on the right and seeping groundwater and collection cup on the left (Photographs by author).

The street runoff was collected on the road during rainfall, such as depicted in Figure 4.10. SABA001, SABA002, and SABA003 were collected in this manner. This runoff was collected from the built environment and has not percolated through the subsurface.

Figure 4.10 Collecting street runoff in The Bottom during rainfall (SABA002) (Photograph by author).

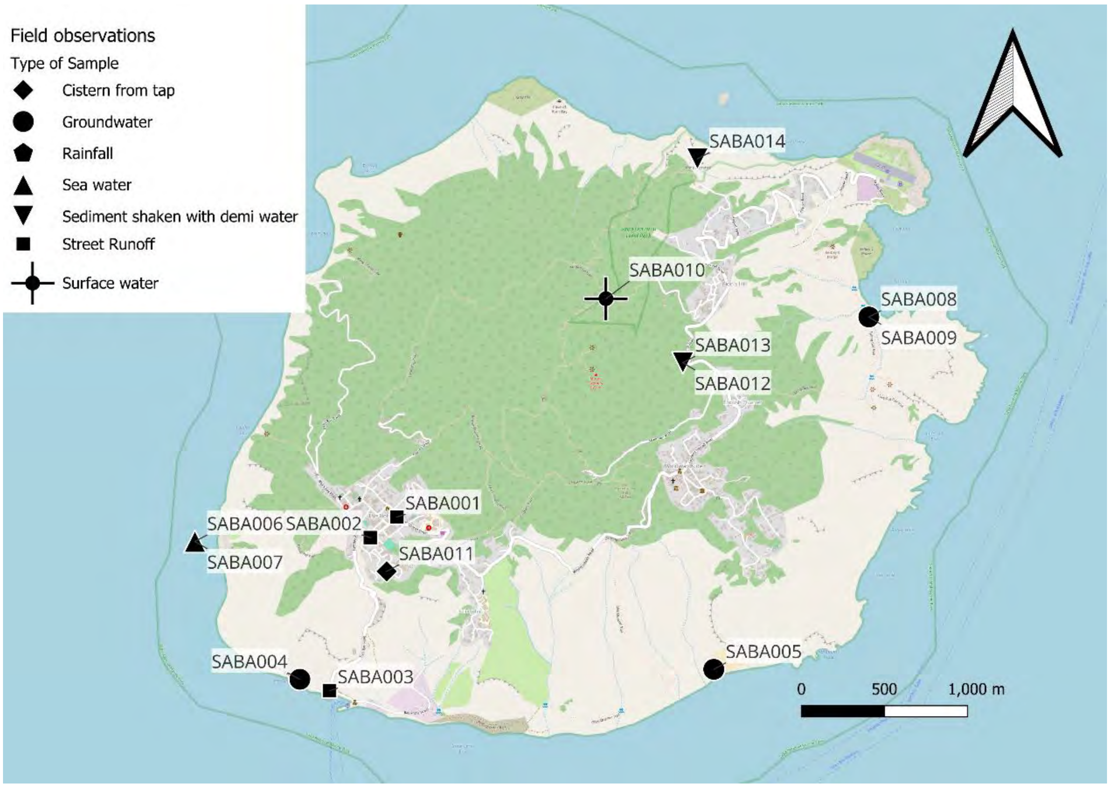

Figure 4.11 Overview of the lab sample locations together with their lab ID. Location marker indicates sample type.

Table 4.3 Overview of the lab samples with the sample number, date collected, the type of data and a description of the sample.

Sample number	Date collected	What type of water	Description
SABA001	31-3-2025	Surface runoff after rain	Collected on parking lot in The Bottom during heavy rainfall
SABA002	31-3-2025	Surface runoff after rain	Collected in The Bottom at the goat sign during heavy rainfall
SABA003	31-3-2025	Surface runoff after rain	Collected in the harbour during heavy rainfall
SABA004	31-3-2025	Groundwater from soil	Groundwater seeping from the soil at Tent's bay. Filled with 300ml demineralized water to fill up to the level needed
SABA005	31-3-2025	Groundwater from well	Collected from the well located along the Giles Quarter Trail. Hole In The Corner Well
SABA006	31-3-2025	Seawater	Collected by Sea Saba at the location of the hot springs
SABA007	31-3-2025	Seawater	Collected by Sea Saba at the location of the hot springs
SABA008	2-4-2025	Groundwater from well	Collected at well at Spring Bay
SABA009	2-4-2025	Groundwater from well	Collected at well at Spring Bay
SABA010	2-4-2025	Surface water (lake)	Collected from Lake Saba along the Elfin trail
SABA011	2-4-2025	Cistern water	Collected from a house at the bottom of The Bottom. From tap.
SABA012	2-4-2025	Organic waste dump, building material	Soil/sediment sample. With demineralized water shaken to extract nutrient.
SABA013	2-4-2025	Organic waste dump, sediment	Soil/sediment sample. With demineralized water shaken to extract nutrient.
SABA014	4-4-2025	Sulphur mine sediment/rock	Soil/sediment sample. With demineralized water shaken to extract nutrient.

4.3.3 Nitrogen (Nitrate, nitrite, ammonium, and total nitrogen)

In the field, nitrate concentrations were tested using test strips. These test strips measure the amount of NO_3-N. When comparing measurements of NO_3-N obtained from test strips with laboratory results for total nitrogen (mg/L), it is important to account for the differences in what these values represent. NO_3-N quantifies only the nitrogen (N) atom of nitrate ions (NO_3^-), whereas the full nitrate concentration includes oxygen; the conversion factor is NO_3 = NO_3-N × 4.43.

The quick-scan field measurements showed slightly elevated values of nitrite (NO_2) for SABA004 (groundwater spring), 0.15 mg/L. The presence of nitrite indicates active nitrification (ammonium is oxidized to nitrate) or denitrification (nitrate is reduced to nitrogen gas). No nitrite was detected in the other samples. No ammonium (NH_4) was detected in any of the samples. This is also in line with the lab results, where the concentrations of nitrite and ammonium were below the detection limits of the laboratory methods used.

Laboratory-reported total nitrogen (TN) includes all nitrogen species present in the sample, such as nitrate (NO_3), ammonium (NH_4), and particulate organic nitrogen (N-org). In systems, such as Saba, where most ammonium has already been oxidized to nitrate (nitrification), nitrate typically constitutes the majority of the measured TN. For example, SABA005 (Hole in the corner well), and SABA008 and SABA009 (Spring Bay well) were clear water samples without organic material, therefore it can be assumed that the total nitrogen must primarily be representing nitrate. This means that the total nitrogen lab results can be compared to the nitrate quick-scan test strips. However, total nitrogen values may exceed the corresponding NO_3-N-derived values due to the presence of residual organic nitrogen compounds and other minor nitrogen species within the sample matrix. Thus, the values in Table 4.4 can be compared directly, but it is likely that the total nitrogen concentrations exceed the nitrate levels. For the lab results the nitrate concentrations were all below the (relatively high) detection limit of 3 mg/L

The results for nitrate concentrations, tested using the field kits, are presented in Table 4.4 and Figure 4.12. Nitrate was detected in all groundwater sample locations, including Field_kit_12, Field_kit_13, and Field_kit_20. The highest concentration was measured at Field_kit_13, the Hole in the Corner well, where levels between 8 and 10 mg/L NO_3-N. The second highest nitrate level was observed in Field_kit_20, the Spring Bay well, with concentrations between 6 and 8 mg/L. At Field_kit_4, where water was seeping from an outcrop, likely the remainder of the former Tent's Bay spring (Figure 4.9), nitrate levels ranged from 2 to 4 mg/L. The EU drinking water limit for nitrate is 50 mg/L NO_3^- (European Environment Agency, 2024), which corresponds to approximately 11 mg/L NO_3-N (50 ÷ 4.43). The measured nitrate concentrations (as well as total nitrogen values) are therefore below the EU drinking water standard as well.

Slightly elevated values in the same range (2–4 mg/L) were also found at Field_kit_22 and Field_kit_23, where soil samples from the organic waste dump were shaken with demineralized water. No nitrate was measured in street runoff samples using the quick scan field kits. Note that we were not able to sample surface runoff on the land surface since the rain event was too mild for generating that. The measured nitrate levels indicate that groundwater discharge from Saba is a potential threat for the surrounding coastal ecosystem.

A similar pattern is observed in the total nitrogen values from the laboratory results. Total nitrogen concentrations are highest in the groundwater samples (SABA004: Tent Bay, 44.8 mg/L; SABA005: Hole in the Corner well, 5.3 mg/L; SABA008 and SABA009: Spring Bay, 4.5 mg/L and 4.1 mg/L respectively). Total nitrogen is detected in all samples, including surface water, as the measurement encompasses not only nitrate but also other nitrogen-species. The total nitrogen concentration at SABA004 (Tent Bay) is exceptionally high (44.8 mg/L), likely due to the presence of suspended organic material in the sample, which contributed to the total nitrogen measurement. As mentioned before, this sample from this spring was turbid and contained suspended sediment. The two other groundwater samples were clear without any visible suspended sediment; therefore it is assumed that NO_3 is the dominant nitrogen species.

On 20 October 2022 WMR (Wageningen Marine Research) collected two samples from the Spring Bay well (Table 4.5). The sample S221 and S222 show that NH_4-concentrations are very low, and NO_3-concentration are slightly elevated (~0.8 mg/L NO_3-N). The low NH_4-concentrations were confirmed by our field kit measurements.

The measured nitrate concentrations exceed the dissolved inorganic nitrogen (DIN threshold of 0.014 mg/L associated with negative impacts on coral reefs (Bell, 1992). However, since the available data represent NO_3-N rather than directly measured DIN, the comparison is approximate. Additionally, it should be emphasized that nitrate levels are expected to be strongly diluted upon entering coastal seawater. Therefore, the concentration in the sea will be much lower than the measured levels in the groundwater. Still, it should be considered that the elevated nitrate levels in the groundwater will have a negative impact on the coral reefs.

The street runoff samples (SABA001, SABA002, and SABA003) contain a relatively low concentration of total nitrogen, ranging from 1.0 to 1.1 mg/L and no nitrate was detected in any of these samples.

Both the quick field scan results as well as the lab results indicate that the nitrogen (total nitrogen and nitrate) pollution is primarily sourced from groundwater, likely related to a combination of livestock activity and cesspits. This conclusion can be derived from the fact that there is no significant nitrate measured in the street runoff measurements sampled in this study, but there are elevated nitrate levels in the groundwater samples.

*Table 4.4 Overview of the lab sample results and field kit results for the same location. Shown is total nitrogen (mg/L) from the lab and nitrate (mg/L) from the field kit. *Sample SABA004 increased by 4x from the tested lab value since the sample was diluted.*

Lab sample number	Field kit test ID	What type of water	Total Nitrogen (mg/L), Lab	Nitrate (mg/L), Field kit (NO_3-N)
SABA001	Field_kit_5	Street Runoff	1	
SABA002	Field_kit_6	Street Runoff	1.1	0
SABA003	Field_kit_8	Street Runoff	1	0
SABA004	Field_kit_12	Groundwater	44.8*	2
SABA005	Field_kit_13	Groundwater	5.3	10
SABA006	Field_kit_14	Sea water	2.2	0
SABA007	Field_kit_15	Sea water	2.4	0
SABA008	Field_kit_20	Groundwater	4.5	5-10
SABA009	Field_kit_20	Groundwater	4.1	5-10
SABA010	Field_kit_21	Surface water	2.9	0
SABA011	Field_kit_19	Cistern from tap	0.7	0
SABA012	Field_kit_23	Sediment shaken with demineralized water	0.9	2
SABA013	Field_kit_22	Sediment shaken with demineralized water	2.5	2

Table 4.5 Samples collected from the Spring Bay well on 20 October 2022 by Wageningen Marine Research.

Sample Number	NH_4–N (mg/L)	NO_3–N (mg/L)
S221	0.085	0.792
S222	0.127	0.833

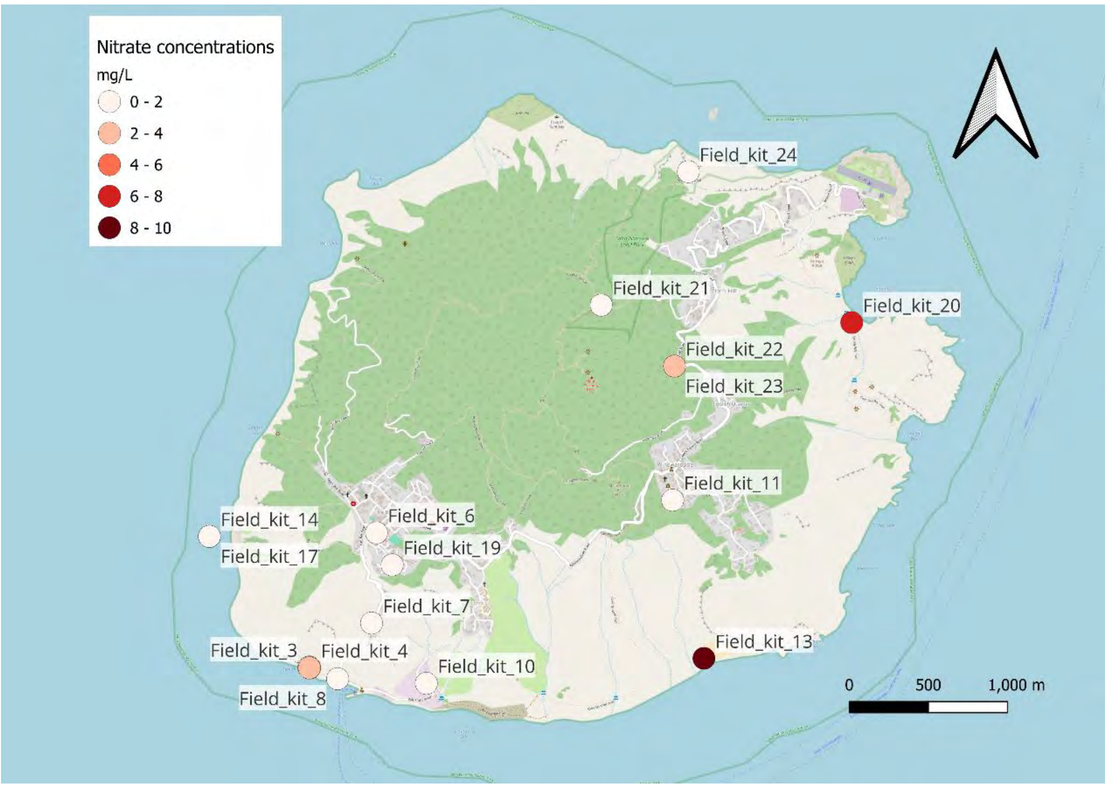

Figure 4.12 Nitrate concentrations NO_3-N, (mg/L) concentration measured with the quick scan field kits.

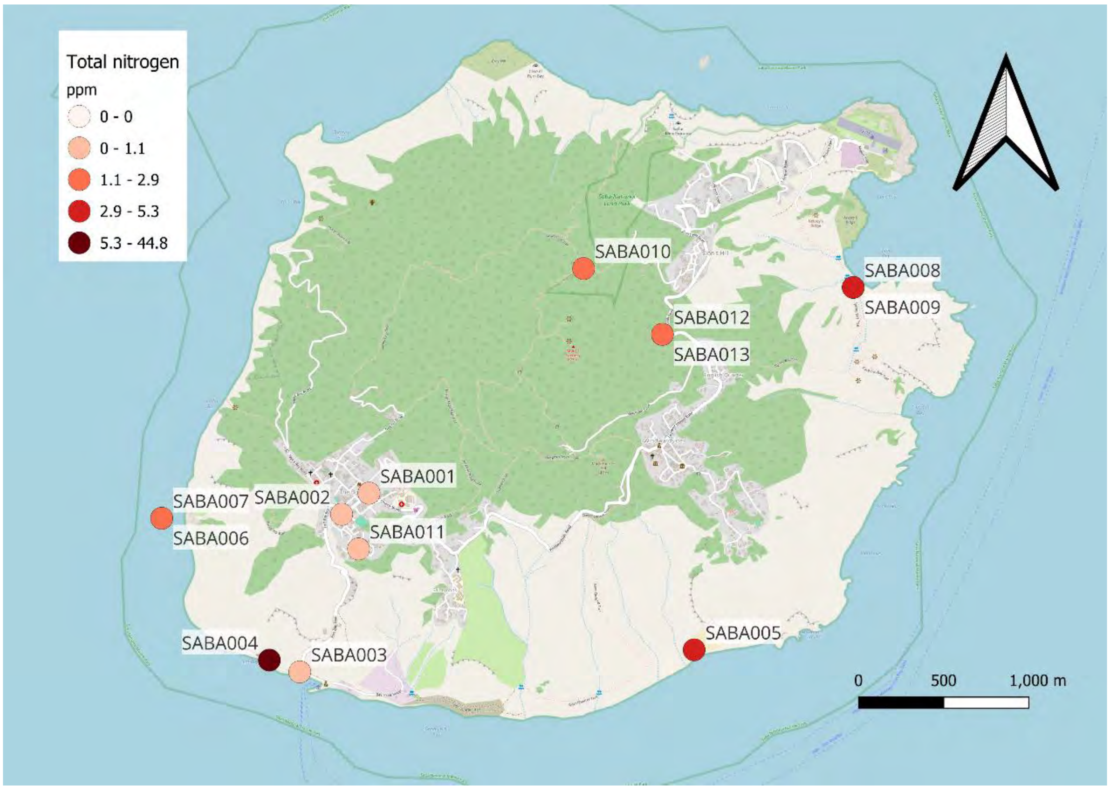

*Figure 4.13 Lab results for the total nitrogen (mg/L) found in water around Saba. Both surface runoff and groundwater displayed in one figure. *Sample SABA004 increased by 4x from the tested lab value since the sample was diluted, this sample contained suspended organic matter.*

4.3.4 Sulphate

Elevated sulphate (SO_4) concentrations were observed in both the lab and field kit tests (Table 4.6). The highest levels were measured in seawater at Field_kit_14 (2470 mg/L lab, >1200 mg/L field kit), Field_kit_15 (3690 mg/L lab, >1200 mg/L field kit). The measurement limit of the field kits is 1200 mg/L; therefore the lab results far exceed the field kits results. Moderately high sulphate levels were also found in groundwater sample SABA004 / Field_kit_12 (636 mg/L lab, 401 mg/L field kit) and SABA005 / Field_kit_13 (703 mg/L lab, 0 mg/L field kit). The elevated concentrations in seawater are consistent with the influence of geothermal activity, which is known to enrich surrounding waters with sulphate (Wang et al., 2021). In contrast, elevated groundwater sulphate likely results from geological weathering processes; volcanic activity typically releases significant amounts of sulphur, which becomes embedded in volcanic rocks and can transform into sulphate (SO_4) as the rocks weather and oxidize over time. Surface water, wells, street runoff, and cistern samples generally exhibited low or undetectable sulphate levels (< 25 mg/L lab; 0 mg/L field kit). While the field kit provided useful qualitative confirmation of elevated sulphate in seawater, it tended to underestimate or fail to detect moderate concentrations in groundwater samples, expect for SABA004 where 400 mg/L sulphate was measured. Therefore, lab results provide a more reliable quantification.

In environmental terms, the high sulphate levels in seawater are expected and not anthropogenic . The sulphate concentrations in the freshwater samples generally remain below drinking water limits (< 500 mg/L according to WHO guidelines (WHO, 2004)), with some exceptions linked to natural geology.

Table 4.6 Overview of the lab sample results and field kit results for the same location. Shown is sulphate (mg/L) from the lab and sulphate (mg/L) from the field kit.

Lab sample number	Field kit test ID	What type of water	Sulphate (mg/L), Lab	Sulphate (mg/L), Field kit
SABA001	Field_kit_5	Street Runoff	6	0
SABA002	Field_kit_6	Street Runoff	8	0
SABA003	Field_kit_8	Street Runoff	13	0
SABA004	Field_kit_12	Groundwater	636	400
SABA005	Field_kit_13	Groundwater	703	0
SABA006	Field_kit_14	Sea water	2470	1200
SABA007	Field_kit_15	Sea water	3690	1200
SABA008	Field_kit_20	Groundwater	104	0
SABA009	Field_kit_20	Groundwater	75	0
SABA010	Field_kit_21	Surface water	21	0
SABA011	Field_kit_19	Cistern from tap	9	0
SABA012	Field_kit_23	Sediment shaken with demineralized water	24	0
SABA013	Field_kit_22	Sediment shaken with demineralized water	87	0

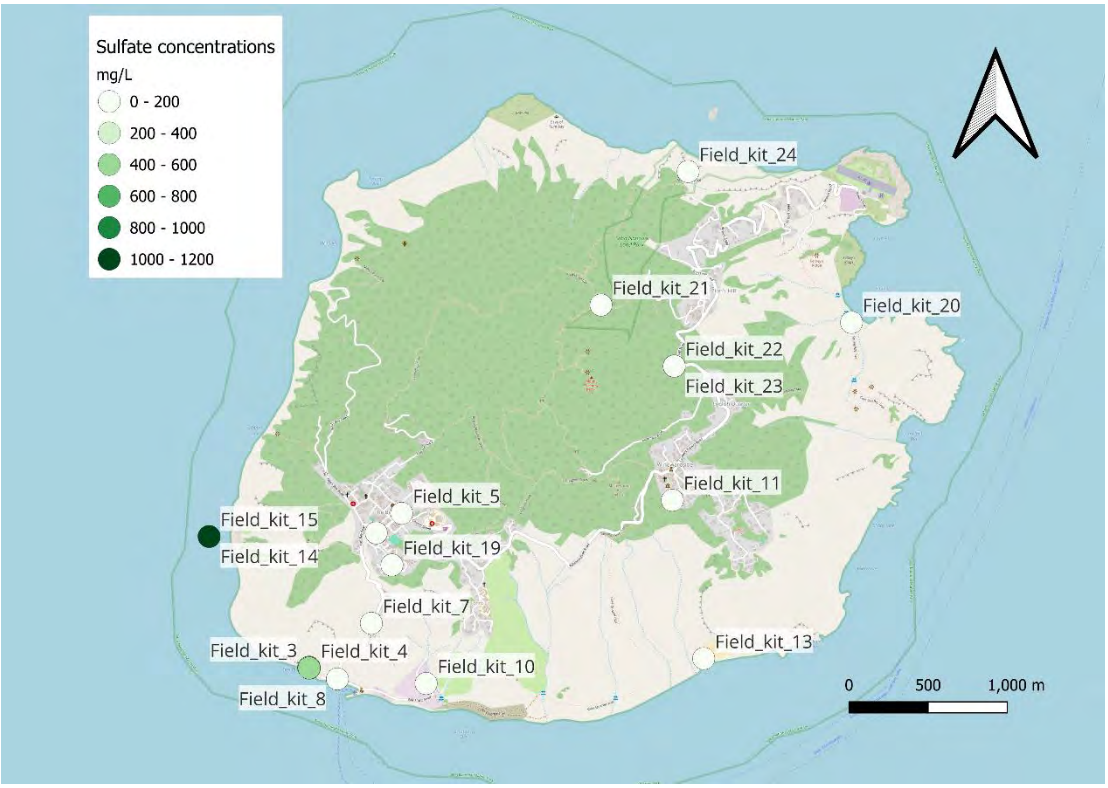

Figure 4.14 Sulphate (mg/L) concentration measured with the quick scan field kits.

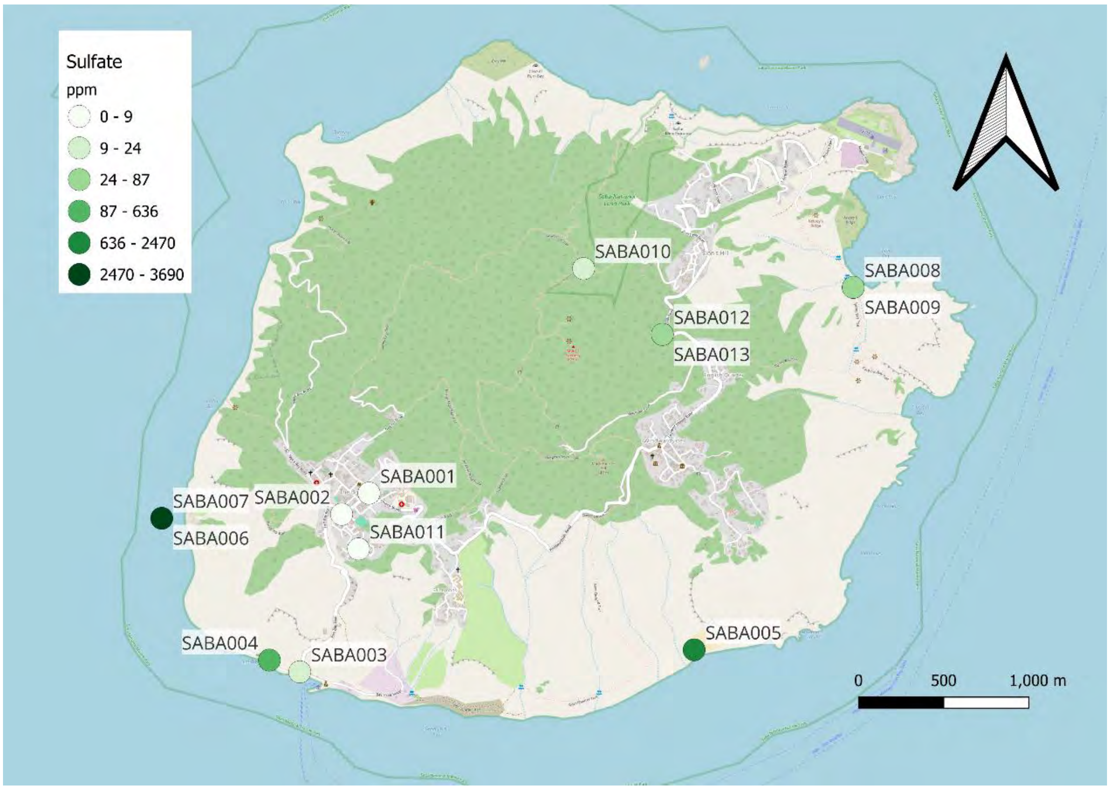

Figure 4.15 Sulphate (mg/L) concentration lab results.

4.3.5 Phosphate

Phosphate measurements can be expressed either as PO_4^{3-} (phosphate) or as PO_4-P (elemental phosphorus, P). The field kit used in this study reports phosphate as mg/L PO_4^{3-}, while the laboratory analysis reports total phosphorus (mg/L P). To enable comparison, phosphate values from the field kit were converted to PO_4-P using the factor PO_4-P = PO_4^{3-} ÷ 3.066 (Table 4.7).

Elevated phosphate concentrations are detected in both the lab and the field kits (Table 4.7). Figure 4.16 and Figure 4.17 show the spatial distribution of the results. The highest value, 8.15 mg/L PO_4-P, was measured at Field_kit_22, a sample taken from the organic waste dump. This value is not representative of the concentration in the groundwater because this is sediment shaken with demineralized water. This sample was mainly taken to confirm that the sediment can release PO_4 when it gets wet. Groundwater samples from Field_kit_12, Field_kit_13, and Field_kit_20 each showed field kit concentrations of 3.26 mg/L PO_4-P. In comparison, the laboratory results for these groundwater samples showed a wider range of total phosphorus: 0.4 mg/L P (SABA004, Tents Bay), 0 mg/L P (SABA005, Hole in the corner Well), 7.1 – 7.8 mg/L P (SABA008 and SABA009, Spring Bay well). This discrepancy is likely due to differences in what is measured: the field kit captures dissolved reactive phosphate, while the laboratory measures total phosphorus, including particulate phosphorus.

Saba Lake (Field_kit_21) showed a lower but still elevated phosphate concentration of 0.98 mg/L PO_4-P), with the corresponding lab value being 0.1 mg/L P.

The Dutch standards for surface water (Water Framework Directive) for TP are around 0,1 mg/L in most water bodies. Several groundwater and waste-related samples exceeded this limit, particularly those influenced by anthropogenic sources or geological background.

The elevated concentrations can be partly attributed to the island's geology. The bedrock in Saba consists primarily of (basaltic) andesite, which is relatively rich in phosphorus (Porder & Ramachandran, 2013). Through natural weathering processes, this phosphorus is released and converted into phosphate, which subsequently infiltrates into the groundwater (Bi et al., 2024).

Table 4.7 Overview of the lab sample results and field kit results for the same location. Shown is phosphorus (mg/L) from the lab and phosphate (mg/L) from the field kit.

Lab sample number	Field kit test ID	What type of water	Total Phosphorus (mg/L), Lab	Phosphate – P (mg/L), Field kit
SABA001	Field_kit_5	Street Runoff	0.6	
SABA002	Field_kit_6	Street Runoff	0.7	
SABA003	Field_kit_8	Street Runoff	0.6	
SABA004	Field_kit_12	Groundwater	0.4	3.26
SABA005	Field_kit_13	Groundwater	0	3.26
SABA006	Field_kit_14	Sea water	0	
SABA007	Field_kit_15	Sea water	0	
SABA008	Field_kit_20	Groundwater	7.6	3.26
SABA009	Field_kit_20	Groundwater	7.1	3.26

SABA010	Field_kit_21	Surface water	0.1	0.98
SABA011	Field_kit_19	Cistern from tap	0	
SABA012	Field_kit_23	Sediment shaken with demineralized water	0.2	
SABA013	Field_kit_22	Sediment shaken with demineralized water	4	8.15

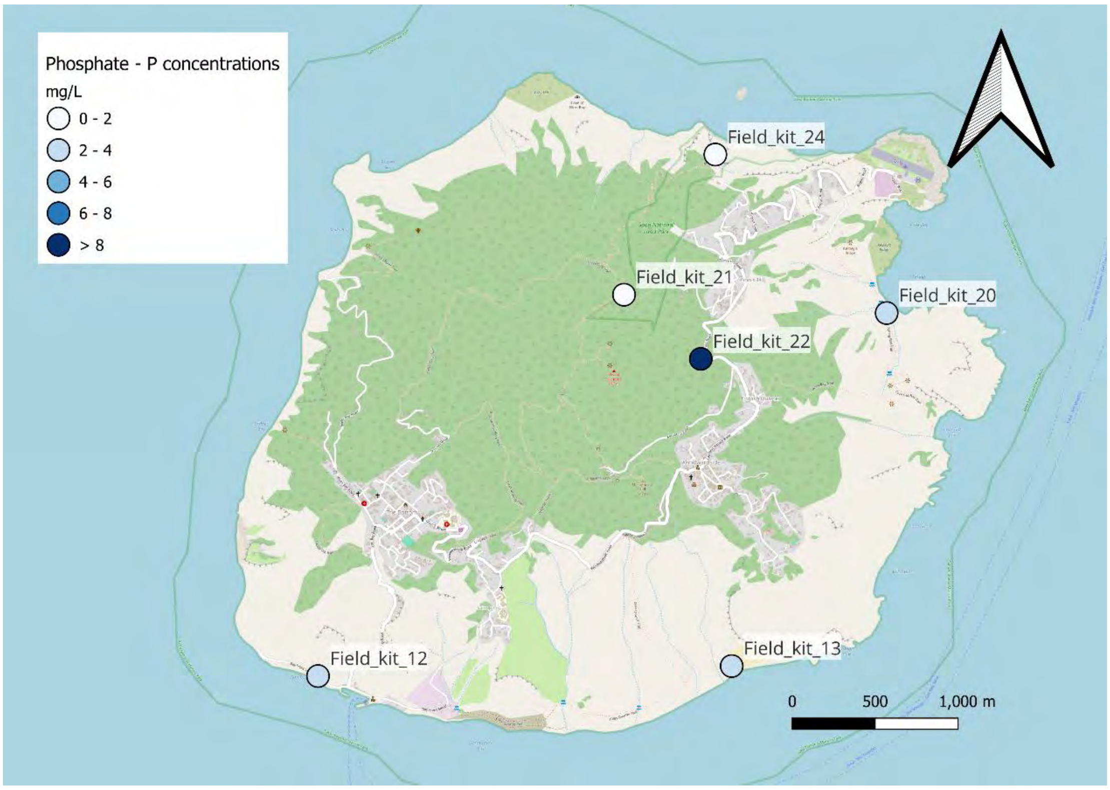

Figure 4.16 Phosphate - P (mg/L) concentration measured with quick scan field kits.

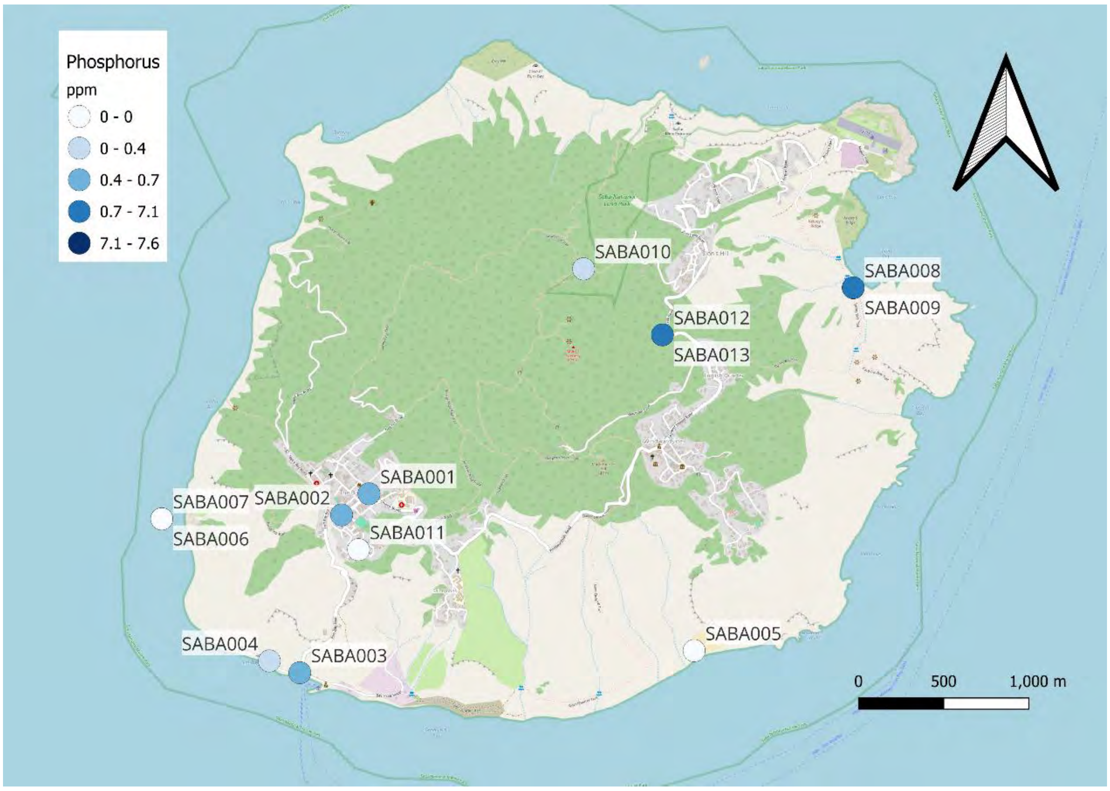

Figure 4.17 Phosphorus - P (mg/L) concentration lab results.

4.3.6 Electrical conductivity (EC)

Electrical conductivity (EC) is a measure of water's ability to conduct an electric current, which depends on the concentration of dissolved ions. These ions originate from dissolved salts and minerals, including substances like sodium, calcium, chloride, and sulphate. Because pure water conducts electricity very poorly, EC increases as more ions are present in the solution.

EC is typically reported in micro-Siemens per centimetre (µS/cm). It is also temperature-dependent, as temperature rises, so does conductivity. The EC is automatically corrected for the standard temperature 25 ^{o}C.

The electrical conductivity of natural waters can be used to estimate their salinity level, and based on EC values, water is generally categorized as fresh, brackish, or saline (saltwater). Table 4.8 shows typical EC ranges for these classifications.

Table 4.8 Typical EC ranges for freshwater, brackish water, and seawater (Hayashi, M., 2004).

Water Type	EC Range (µS/cm)	Salinity Context
Freshwater	< 1,500 µS/cm	Low salinity; typical of rivers/lakes
Brackish water	1,500 – 15,000 µS/cm	Intermediate salinity; estuaries, deltas
Seawater	> 15,000 µS/cm	High salinity; typical of oceans/seas

Table 4.9 shows the measured EC from the lab measurements and using the handheld EC meter. Figure 4.18 displays the EC measurements across the various test locations using the handheld EC meter and Figure 4.19 shows the EC lab results. A complete list of these values can be found in Appendix 8A.2. For clarity, the results have been categorized into fresh (blue), brackish (green), and saline (red) waters.

The lab and field measurements are similar. Field_kit_14 through Field_kit_18 (SABA006 and SABA007) were all collected from seawater, as reflected in their high EC values. Slightly brackish conditions were found at Field_kit_12 (SABA004), where groundwater was seeping from the soil with an EC of ~2000 µS/cm, and at the Hole in the Corner well (Field_kit_13), which showed an EC of 6070 µS/cm, suggesting a mix of approximately 15% seawater and 85% fresh groundwater. In contrast, the Spring Bay well (Field_kit_20, SABA008 and SABA009) was classified as fresh, with an EC of ~1400 µS/cm, and Saba Lake (Field_kit_21) showed very fresh conditions with an EC of ~330 µS/cm.

All remaining samples, which were either from street runoff or collected rainwater, were also classified as fresh, with EC values below 1500 µS/cm.

*Table 4.9 Overview of the lab sample results and field kit results for the same location. Shown is Electrical Conductivity (µS/cm). *Sediment shaken with demineralized water; EC measurements not representative.*

Lab sample number	Field kit test ID	What type of water	Electrical Conductivity (µS/cm), Lab	Electrical Conductivity (µS/cm), Field kit
SABA001	Field_kit_5	Street Runoff	121	128
SABA002	Field_kit_6	Street Runoff	139	119
SABA003	Field_kit_8	Street Runoff	167	164
SABA004	Field_kit_12	Groundwater	2372	2000
SABA005	Field_kit_13	Groundwater	6070	6070
SABA006	Field_kit_14	Sea water	56500	54000
SABA007	Field_kit_15	Sea water	57000	54600
SABA008	Field_kit_20	Groundwater	1320	1400
SABA009	Field_kit_20	Groundwater	1301	1400
SABA010	Field_kit_21	Surface water	333	328
SABA011	Field_kit_19	Cistern from tap	193	180
SABA012	Field_kit_23	Sediment shaken with demineralized water	*	*
SABA013	Field_kit_22	Sediment shaken with demineralized water	*	*

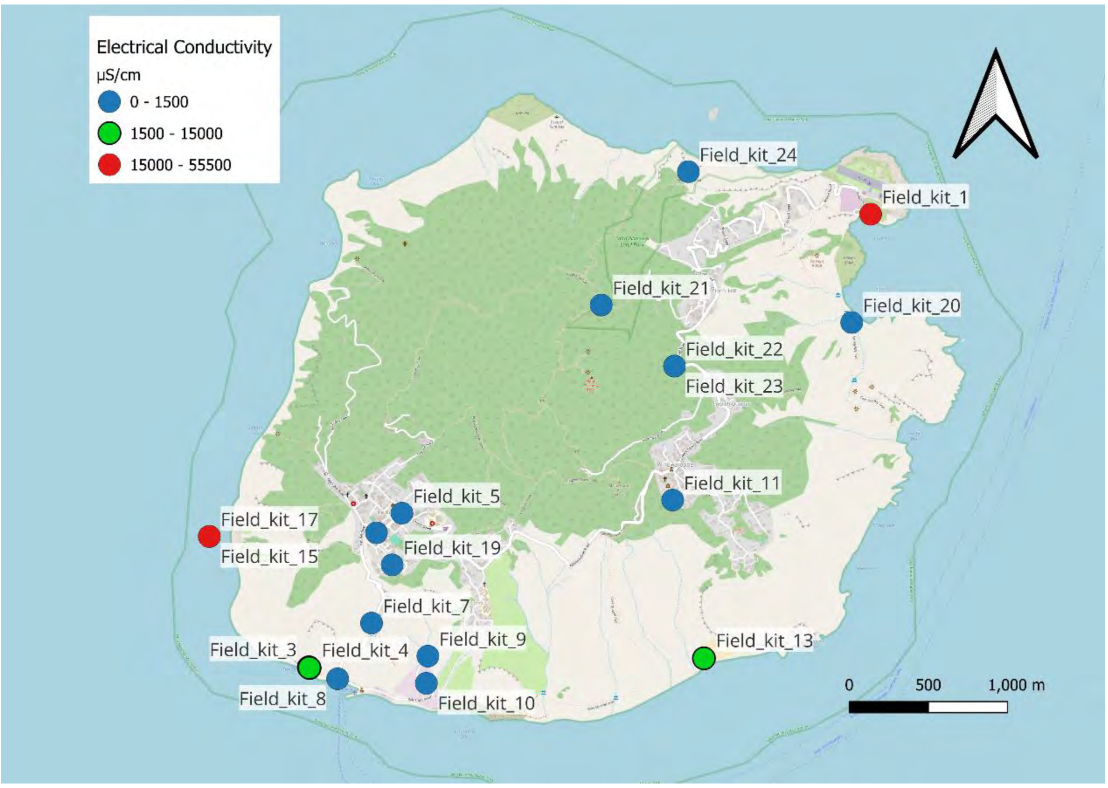

Figure 4.18 Electrical Conductivity (EC) measurements around Saba. Measured using handheld EC meter. Red is saline water, green is brackish and blue fresh. A combination of surface water and groundwater samples are displayed at the same time.

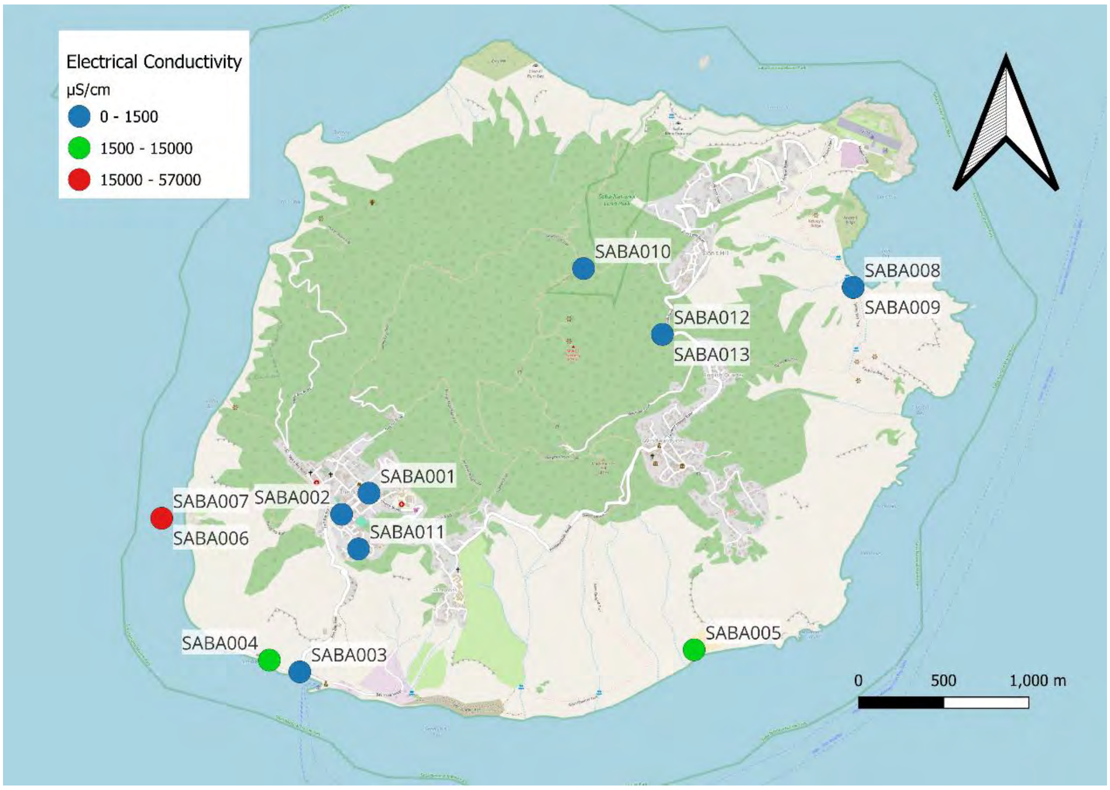

Figure 4.19 Electrical Conductivity (EC) measurements around Saba. Results from the lab. Red is saline water, green is brackish and blue fresh. A combination of surface water and groundwater samples are displayed at the same time.

5 Conceptual description of (ground)water systems

To get more insight into the nutrient loads from the island into the coastal waters, it is important to better understand the groundwater and surface water flows on the island. These flows are driven by precipitation falling on the island and it can be assumed that the entire precipitation surplus, which is rainfall minus evapotranspiration, will eventually flow into the sea, either via slow or quick routes.
Therefore, based on the geology, geomorphology, (ground)water samples and field observations (see also photos in Figure 5.3), a conceptual description of the (ground)water flow systems is made, also referred to as a conceptual (ground)water model.

The lithological composition of the subsurface plays an important role in the flow paths of infiltrated rainwater towards the coastal waters. The domes consist of fractured andesite hard rock and flow of water is limited to cracks and factures. In the rest of the area surrounding the domes, a heterogeneous sequence of permeable agglomerates, tuffs and ashes and less permeable lava flows are found (Figure 5.1). Groundwater flows much easier and faster through the very permeable sediments between the lava flows.

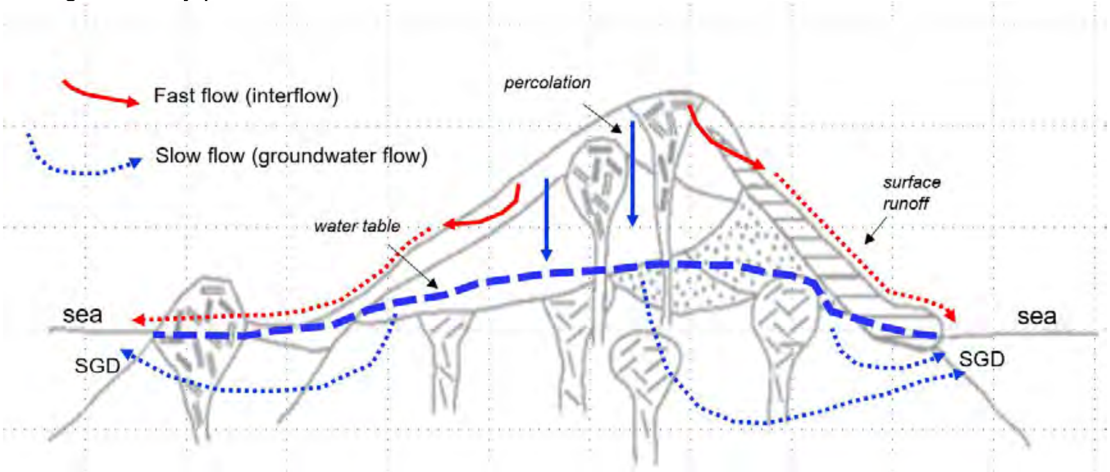

Figure 5.1 Conceptual visualisation of quick and fast subsurface flow on the island of Saba (geology background taken from Roobol and Smith, 2004). SGD stands for Submarine Groundwater Discharge.

The conceptual functioning of the (ground)water flow systems from rain drop to discharge into the sea is described below and schematic visualisations are given in Figure 5.1 and Figure 5.2.

Interception, infiltration and evapotranspiration of rainwater
During rain events, part of rainwater falling on vegetation and the soil surface will directly evaporate. Dense tropical rainforest like on the slopes of Mount Scenery will intercept much more rainwater compared to grassland (see Figure 5.3). The rainfall passing through the vegetation cover will infiltrate into the soil due to the permeable character of the soil. Observations during rain events and the infiltration test (see Infiltration tests) demonstrated that the surface is highly permeable for water and the plausible assumption can be made that almost all rainwater on the island (not intercepted and evaporated) is infiltrating into the soil. Only at the steep eroded slopes with outcrops of hard rock and lacking vegetation, water may not be able to infiltrate and flows down over the surface, mostly in shaped valleys and gullies (see Figure 5.3). While flowing down, this water can still infiltrate when passing a more gentle sloped permeable zone.

Obviously, in the build-up area large amounts of rainwater is intercepted by streets and roofs. Rainwater falling on roofs is harvested and collected in cisterns for domestic use. Rainwater falling on streets and parking places is flowing downhill on the paved surface until it reaches unpaved soil where it can infiltrate. It is observed that the main road on Saba (from the airport via the towns to the harbour) serves as a preferential flow path for surface runoff. Due to the low walls along the road the water can only leave the road in places where there are holes in the wall (see Figure 5.3).

The infiltrated rainwater will reach the rootzone and part of this soil moisture is transpired by the vegetation via their roots. The tropical rainforest at the slopes of Mount Scenery (see Figure 5.3) are able to transpire 2.5-4.5 mm per day (Waring et al., 1976) while grass land uses much less water (~1.5 to 3 mm per day) (Downes, 1969). All the remaining water which is not used by vegetation will pass through the rootzone and will percolate downward towards the groundwater.

Quick and slow subsurface flows
Based on the hydrogeology, geomorphology, observations and measurements we think there is a slow and a quick route of subsurface flow (see Figure 5.1).

The slow route is related to a permanent groundwater flow system recharged during rainfall events and mainly discharging into the sea as submarine groundwater discharge (SGD). After passing the rootzone, water is percolating slowly by gravitational forces to greater depth. As water continues to move downward, it eventually reaches the saturated zone (the groundwater table), where all the soil pores are filled with groundwater. Water in this saturated zone is also able to flow laterally. This is influenced by the hydraulic gradient (the slope of the water table), the permeability of the soil or rock, and any barriers to flow.

The historical wells along the coast providing freshwater in earlier days are fed by this slow groundwater system. Water samples from the two remaining functional wells on the island were fresh (Spring Bay, EC ~1400 μS/cm) and slightly brackish (Hole in the Corner well, EC 6070 μS/cm; 85% freshwater, 15% seawater). When there is a significant permanent groundwater flow into the sea, groundwater levels will never drop below sea level, which is the case at the two sampled wells. One small spring at Tent Bay, about 5 meters above sea level (probably remains of a larger spring covered by a landslide), was discharging fresh water after a rain event.

The fact that the wells are fresh or slightly brackish at such a short distance from the sea is another indication of the existence of a permanent groundwater flow, otherwise salt water intrusion would have taken place. Besides, the three groundwater samples all contained elevated concentrations of nitrate indicating anthropogenic influence from further up the hill.

Due to a lack of groundwater wells on the island it is unknown at which depth this permanent water table can be found. There are different options depending on the sequence of different lithological layers. Given the fact that most of the groundwater is discharged submarine and terrestrial springs are almost entirely lacking, it is expected that the gradient of the water table is much more gentle than the slope of surface, as indicated in the cross-section in Figure 5.2. Therefore, on the entire island groundwater will be found at large depth, except along the coast. Another possibility is that the occurrence of andesitic hard rock or lava flows in the subsurface prevent that groundwater reaches these great depths, resulting in an elevated water table (perched on hard rock), closer to the surface. This latter option is thought to be less plausible but could locally play a role.
The travel time of a rain drop infiltrating, then percolating through the unsaturated zone recharging the groundwater, and subsequently flowing as saturated groundwater flow

towards the sea where it is finally discharged in the sea as SGD is estimated to be at least years to several decades.

There is also a quick route of subsurface flow (also called interflow or subsurface runoff) which occurs only a few times a year during heavy rainfall events. These are the rain events when surface runoff through steep gullies and valleys is observed. Again, almost all the rainwater normally infiltrates into the soil but due to a larger amount of water, more pores are filled with water (saturated) resulting in a higher flow capacity. Probably, low permeable layers are responsible for these locally saturated conditions resulting in sort of perched water tables. With these locally saturated conditions, the flow isn't solely vertically by gravitational forces but starts to flow more laterally influenced by a hydraulic gradient of the partially saturated part of the soil. Thereby, water will flow laterally towards lower elevated valleys and gullies where this subsurface water is discharged and returned to the surface. These concentrated fast surface water flows also cause erosion (see Figure 5.3), taking large amounts of sediments. The road from The Bottom to the harbour is an important corridor for these quick flow routes collecting water of the subsurface flows from surrounding hills mixed with precipitation falling on roofs and streets it-selves (see Figure 5.3).
Street runoff is generated during almost every rain events and in general only consists of water falling on roofs and streets. Surface runoff generated by the process of interflow and discharging in nearby valleys and gullies is only generated a couple of times a years (3 to 5 according to the residents). This water may partly also end up on the streets taking sediments and boulders from the slopes and flowing further on the streets downward towards the sea to the harbour and airport.

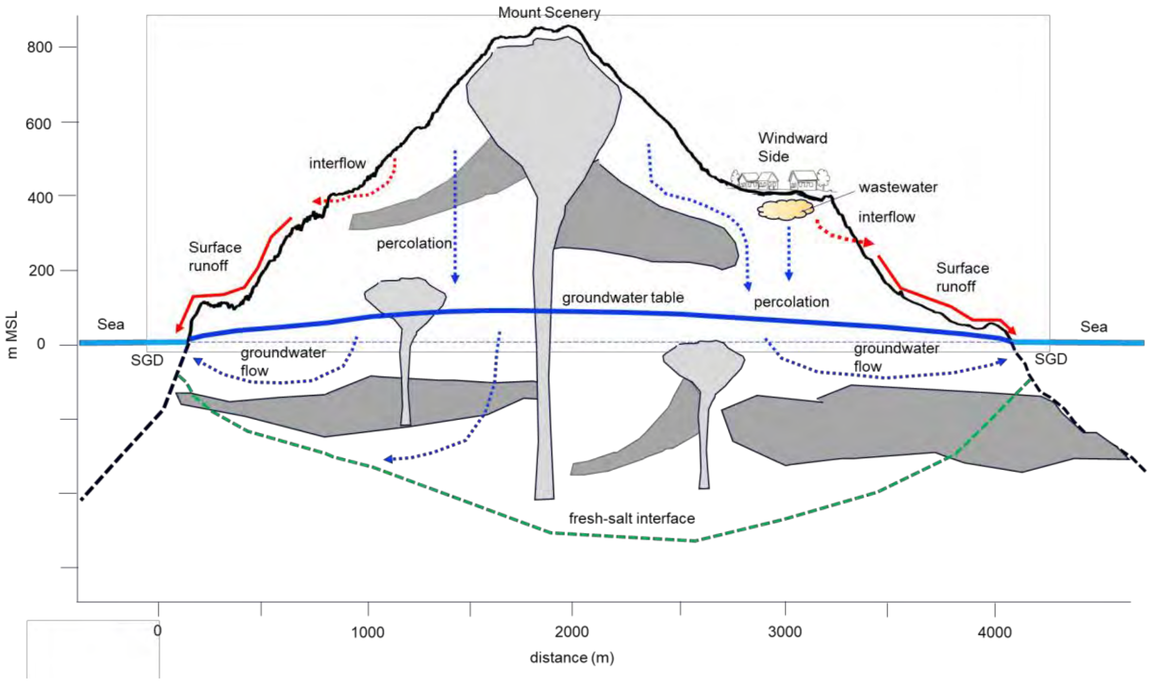

Figure 5.2 Conceptual representation of groundwater flow, interflow and surface runoff for a west-east cross-section of Saba based on the DTM.

Subsurface flow and nutrients
The produced domestic wastewater on Saba is mostly directed into the ground, either through bottomless cesspits (most households) or, in the case of full septic tanks, through overflow (Vei, 2022). The human waste is usually accompanied with water from the flushing of toilets making the infiltration into soil much easier. This nutrient rich water is percolating slowly downwards and will eventually reach the groundwater where it flows laterally toward

the sea (see Figure 5.2). This leads to a permanent nutrient rich groundwater flow towards the sea. Most of the nitrogen transport will be in the form of dissolved nitrate formed by the mineralisation of organic N and the oxidation of ammonium during the percolation of the waste water (see chapter 6).
During heavy rain events when the quick subsurface flows occur, a part of the subsoil containing nutrients (from the downward percolation of waste matter) is flushed and nutrients are taken downward (see Figure 5.2). This could lead to peak nutrient loads into the sea. The dissolved nitrogen will be a mix of ammonium and nitrate depending on which part of the subsoil is flushed by the subsurface flow.

Grassy V-shaped valleys and gullies (eastside of the island)

Erosion on exposed steep slopes and gullies without any vegetation

Pyroclastic flow sediments with volcanic bombs at Wells Bay (left) and outcrop of andesitic hard rock (right)

Street runoff after a moderate rainfall event *Waste dump*

Spring Bay with in the distance a andesitc dome (Old Booby Hill) and Cove Gut Bay (right)

Tropical vegetation at the Mount Scenery national park

Figure 5.3 Photos of the geology, geomorphology and hydrogeology made during the field survey (Photograph by author).

6 Nutrient balance / loads / fluxes

6.1 Introduction

In order to quantify the role of (ground)water in the transport of nutrients, it is essential to have a clear overview of the nutrient inputs into the system. In this chapter, for each nutrient source a description and rough estimation of the total input in the system is given. This data is used for a nutrient balance of the island and an estimation of the nutrient loads to the coastal waters. The (ground)water flows driven by rainfall are the transporters of these nutrients and a first attempt is made to quantify the fast and quick routes by making a water balance. Subsequently, the nutrient input and (ground)water flows are combined for the different delineated catchments to get an idea of the spatial variation of the nutrient loads. After that, two years of nutrient measurements in the surrounding ocean waters are being discussed with respect to the estimated nutrient loads from the island. Finally the calculated nutrient loads are compared to Bonaire to put it into regional perspective.

This study focuses on nitrogen and phosphorus. Nitrogen and phosphorus are vital nutrients that can become significant environmental contaminants. Their excessive presence can lead to harmful algal blooms in aquatic systems, disrupting ecosystems and depleting oxygen. Nitrate also brings health risks when they contaminate drinking water. In coral reef ecosystems specifically, elevated levels of these nutrients can disrupt the natural balance by fuelling algal blooms, which competes with corals for light and space. This reduces coral growth and reproduction, weakens reef resilience, and can lead to long-term reef degradation and biodiversity loss.

6.2 Nutrient sources

6.2.1 General overview

Figure 6.1 shows the total amount of N and P (kg/d) put into the system from various sources. This overview assumes the current state of 150 goats. Figure 6.2 shows the total amount of N and P (kg/d) assuming 5000 goats, which was the situation in 2020. The overview in Figure 6.1 and Figure 6.2 does not consider the attenuation of the nutrients by adsorption or denitrification. These processes are considered in the nutrient fluxes calculation and is discussed in paragraph *6.4 Nutrient fluxes.* In the paragraphs below a detailed explanation is given about nutrient sources and processes and how the values in the figures are derived.

The most striking factor on Saba is the impact of the goat population. In 2020, about 80% of the total nitrogen (N) and phosphorus (P) input came from livestock, mainly goats. With the current numbers, this share has dropped to around 25% for nitrogen and 45% for phosphorus. Today, the human population is the largest contributor of nutrients to the system.

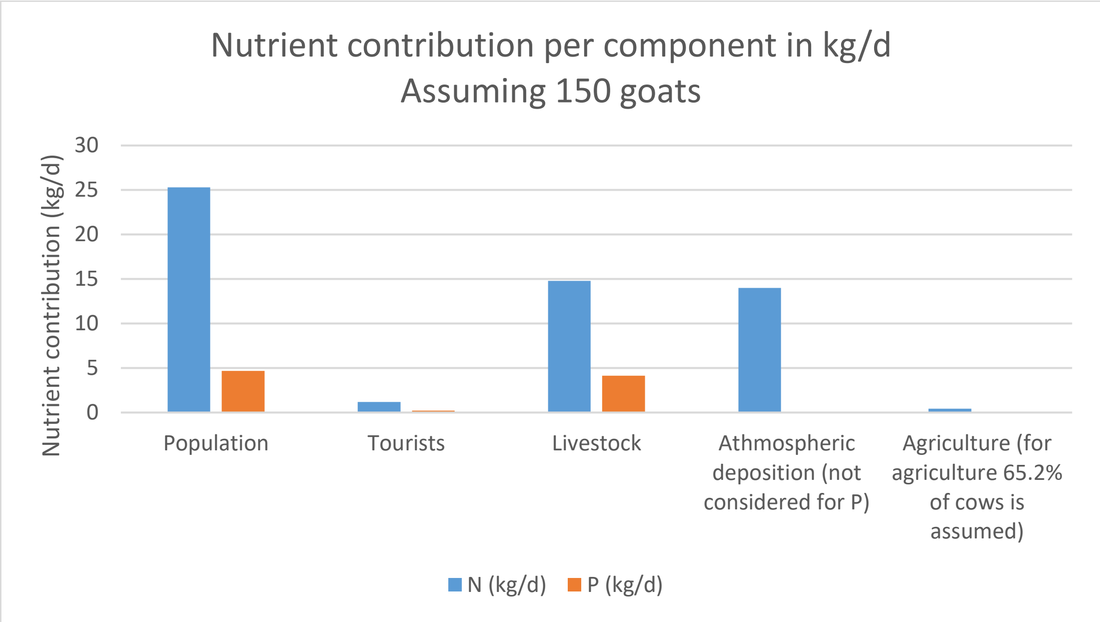

Figure 6.1 Total amount of nutrient input (N and P) in kg/d. Assuming the current situation of 150 goats.

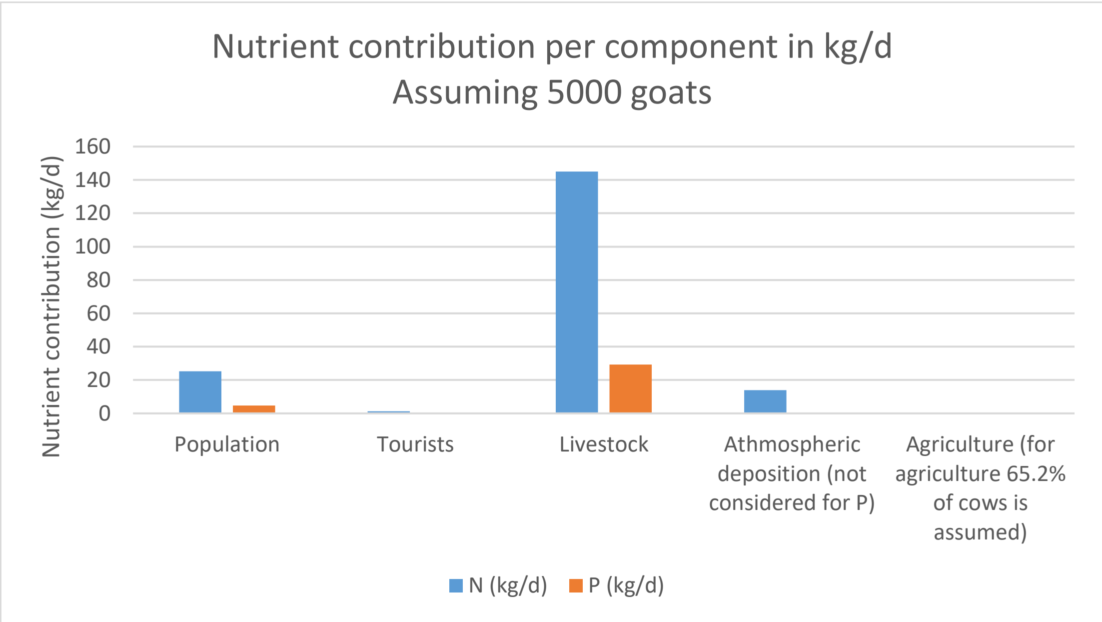

Figure 6.2 Total amount of nutrient input (N and P) in kg/d. Assuming the 2020 situation of 5000 goats.

6.2.2 Humans

Human excrements contain nutrients. The amount of nutrients that potentially end up in the environment depends on the waste water management systems in place and the amount of humans (local population and tourists). For the amount of nitrogen and phosphorus the values in
Table 6.1 are used. These values are in kg/d/capita. The same amount per day is used for local population and tourists.

Table 6.1 Nitrogen and phosphorus loading (kg/d/capita) for humans (Deltares & TNO, 2020).

Source	N loading (kg/d/capita)	P loading (kg/d/capita)
Humans	0.0117	0.0022

6.2.2.1 Wastewater management

In 2023 VEI performed a wastewater study for Public Entity Saba. In this study they explored the current wastewater management system and explored possible wastewater management systems for the future. On Saba most houses have their own cesspit (or cesspool). A cesspit is a shallow, underground structure used for the disposal of sanitary waste. On Saba, cesspits typically consist of a pit with brick-lined walls, closed top, and an open bottom, allowing wastewater to percolate directly into the surrounding soil (see Figure 6.3 and Figure 6.4). Wastewater from toilets flows into the cesspit, where liquid effluent infiltrates the soil, while solid sludge accumulates at the base. Although cesspits are intended to contain and discharge sanitary waste, they do not provide any form of treatment (EPA, 2023). Additionally, greywater, such as discharge from sinks, showers, and washing machines, is often released untreated via sink holes or on the ground surface, for example, in residential yards.

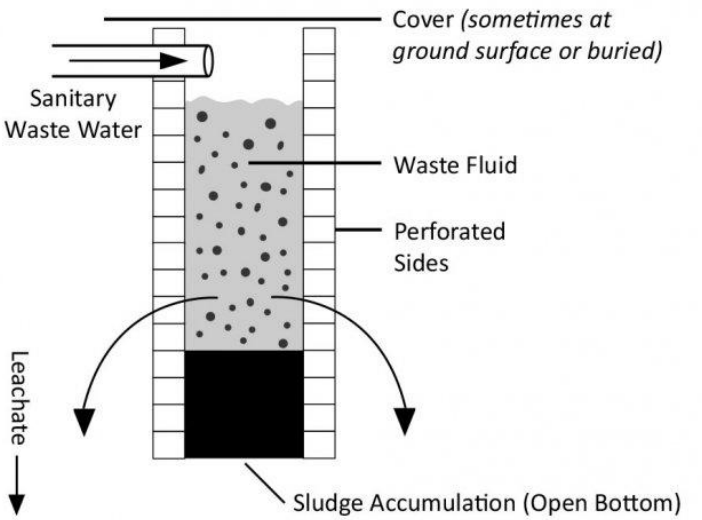

Figure 6.3 Schematic representation of a cesspit (EPA, 2025).

Figure 6.4 Cesspit in construction (VEI, 2023)

There is a limited amount of septic tanks in use on Saba, among which the Public Administration building, the “Under the Hill” system, the dorms at the Medical University and the Saba Cares Hospital. In these septic tank systems, normally solids are removed and dissolved and suspended nutrients remain in the effluent that flows out (Figure 6.5). On Saba, septic tanks and occasionally full cesspits are emptied, but there is currently no proper system for disposing of the wastewater.

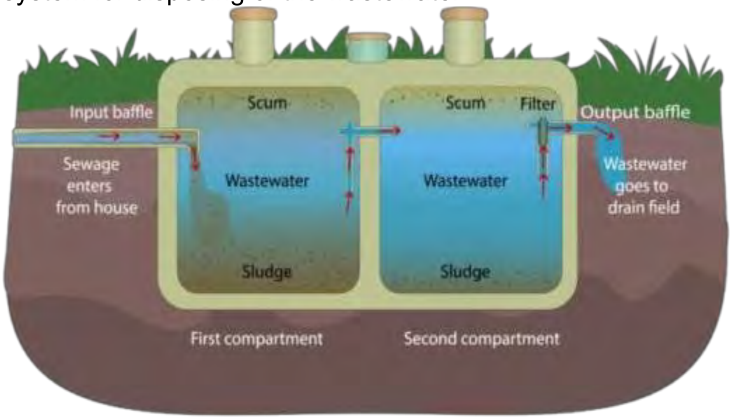

Figure 6.5 Schematic representation of a septic tank (DKK Consulting, 2023).

Within the cesspits the compounds within the human waste can undergo a series of microbiological transformations. These processes are influenced by the availability of oxygen and environmental conditions such as temperature, pH, and moisture. First an overview of these processes is given of nitrogen, followed by phosphorus.

Nitrogen
The dominant forms of nitrogen present in human excreta are ammonia and organic nitrogen, both of which derive from the breakdown during digestion.

The transformation processes typically follow this sequence:

- *Ammonification*
  In the largely anaerobic conditions of cesspits, ammonification is the primary process. Microorganisms decompose organic nitrogen from faeces and urine into ammonia (NH_3) and ammonium (NH_4^+). The detection of ammonia or ammonium in groundwater typically indicates close proximity to the contamination source, as these compounds are usually rapidly oxidised to nitrate through nitrification under aerobic conditions.

- *Nitrification*
  If oxygen becomes available, aerobic bacteria begin the nitrification process. This is a two-step oxidation of ammonia to nitrate, mediated by specific groups of autotrophic bacteria:
  Step 1: Ammonia and ammonium to Nitrite
  $NH_3 + O_2 \longrightarrow NO_2^- + 3H^+ + 2e^-$
  $NH4^+ + 1.5O_2 \longrightarrow NO_2^- + 2H^+ + H_2O$

  Step 2: Nitrite to Nitrate
  $NO_2^- + H_2O \longrightarrow NO_3^- + 2H^+ + 2e^-$
  These bacteria use ammonia, ammonium or nitrite as an energy source and require aerobic conditions to function effectively.

- *Denitrification*
  In subsequent anoxic zones (low oxygen but not completely anaerobic) and in the presence of an electron donor (organic matter or pyrite), denitrifying bacteria can reduce nitrate (NO_3^-) to nitrogen gas (N_2), which escapes into the atmosphere. The

general reaction is:
$NO_3^- \longrightarrow NO_2^- \longrightarrow NO \longrightarrow N_2O \longrightarrow N_2$ (gas)

Although denitrification can play an essential role in reducing nitrate concentrations, the process is often incomplete or constrained in real environmental settings. Limited oxygen-free zones, a lack of available organic carbon or pyrite, low microbial activity in deeper soils, and rapid water percolation all reduce the extent of nitrate removal. As a result, nitrate frequently persists in the subsurface, especially in the low-reactive volcanic deposits and fractured rocks of Saba.

Phosphorus
Phosphorus from human excrement enters the subsurface primarily in the form of dissolved phosphate (PO_4^{3-}). This form is biologically available and can leach into surrounding soils and groundwater, particularly under conditions of poor containment (the cesspits) and the high permeability of the soil.

Phosphorus in human waste originates from dietary intake and is released in two main forms: inorganic phosphate and organic phosphorus compounds. The organic forms are mineralized by microbes into phosphate. Upon release into the environment, phosphate quickly binds to soil particles, particularly Fe- and Al-(hydr)oxides. Because of its strong affinity for these minerals and low solubility, phosphate moves very little vertically and tends to accumulate in the upper layers of the subsurface.

Nutrient removal
Because of the above described processes, it is unlikely that there is significant biochemical nutrient removal of human waste water on Saba. Because of the depth of the cesspits (~3 m below surface) it is unlikely for there to be significant uptake of the nutrients by plants. Since no significant nutrient removal processes take place, it is assumed that all nutrients that enter the system via the cesspits and septic tanks will eventually end up in the ocean.

6.2.2.2 Local population

Table 6.2 shows the total amount of N and P input in kg/d for each neighbourhood and the total population of Saba. For the total population the N input is 25 kg/d and P input is 5 kg/d.

Table 6.2 Total amount of N and P input in kg/d. Amounts based on the population multiplied by the N and P input from

Table 6.1.

Neighbourhood	Population	Total N (kg/d)	Total P (kg/d)
Unclassified	15	0.2	0.0
Zions Hill	463	5.4	1.0
St. John's	200	2.3	0.4
The Bottom	785	9.2	1.7
Windwardside	691	8.1	1.5
Total	**2154**	**25.2**	**4.6**

6.2.2.3 Tourism

Table 6.3 shows an overview of the total amount of tourists on the island. The input via tourists is highly depend on their length of stay. For the day tripper (arrive by ferry) it is

assumed they stay 1 day. It is assumed that plane visitors stay 7 days and cruise and yacht visitors stay 1 day. Multiplying the length of stay by the amount of tourists divided by 365 results in an average amount of tourist on the island per day. This amount is multiplied by the N and P inputs per capita (
Table 6.1) and result in the total nutrient load per day for tourists in Table 6.4. The nutrient inputs from tourist sum up to about 5% of the inputs from the permanent residents.

Table 6.3 Total amount of tourists and their average length of stay in days.

Type of tourist	Annual amount of tourists	Average length of stay (days)
Day tripper (Ferry)	1200	1.0
Plane visitors	8800	4.0
Cruise and yacht	400	1.0

Table 6.4 Average total amount of tourists on island per day and their total N and P output in kg/d.

Total amount of tourists on island per day	Total N (kg/d)	Total P (kg/d)
101	1.2	0.2

6.2.3 Livestock

Another source of N and P is livestock. Table 6.5 shows the amount of N and P input in the system per animal in kg/d (Schreiber, 2003). To put it into perspective of humans, a cow emits approximately 10 times as much as a human, goats and pigs twice as much as a human, and a chicken ten times less.

Table 6.5 N and P loading in kg/d/animal for goat, cow, pig and chicken (Schreiber, 2003).

Animal	N loading (kg/d/animal)	N loading (kg/d/animal)
Goat	0.0268	0.0052
Cow	0.1370	0.0274
Pig	0.0255	0.0060
Chicken	0.0016	0.0005

The number of animals is crucial in understanding the total N and P input into the system through livestock. The numbers in Table 6.6 are based on data provided by the Public Entity Saba and through interviews with locals.

In 2020 there were approximately 5000 goats on the island (roughly 380 goats per km^2). The goats were recognized as a problem for overgrazing. The overgrazing resulted in an increase in erosion. Because of this, it was decided to launch a goat control program to bring down the goat population. At present there are about 150 goats left on the island. For the future there are plans to reduce the number of chickens as well.

In Table 6.6 is the original number of goats assumed (5000) as opposed to the current number of goats (150). This is because of the delay in the groundwater system. Groundwater responds slowly to surface changes, as it often has long travel times through the subsurface, meaning that current water quality still reflects nutrient inputs from the period when goat numbers were much higher. Therefore, the measured amounts of N and P will be represented by the original number of goats. Considering 150 goats the total N emitted by the goats is 1.6 kg/d and total P is 0.3 kg/d.

Table 6.6 Total amount of N and P emitted by the livestock on Saba in kg/d.

Livestock	Amount on the Island	Total N (kg/d)	Total P (kg/d)
Goats	5000	134.2	26.0
Cows	5	0.7	0.1
Pigs	100	2.5	0.6
Chicken	5000	8.2	2.7
Total		**146.6**	**29.4**

In the final overview presented in Figure 6.1 and Figure 6.2 in "Livestock" the cows are not considered. This is because the cow manure is used as fertilizer for the agriculture. The N and P input by the cow manure is therefore considered as a source for the agriculture, see *6.2.4 Agriculture*.

Nutrient input from livestock differs significantly from that of human waste. Unlike human excrement, which is typically discharged into localised cesspits, livestock waste is spread more diffusely across the landscape where the animals graze. This waste is deposited directly onto the soil surface, where it is immediately exposed to environmental processes such as rainfall, evaporation, and plant uptake.

Although the same biological processes apply (ammonification, nitrification, and denitrification) the extent to which these processes occur varies due to the exposure and distribution of the waste. Because goat droppings remain on the surface, there is a greater opportunity for the resulting nitrate to be denitrified. The remaining nitrate may be leached into the groundwater, especially during heavy rainfall events.

On Saba, the extent of nitrate leaching is largely influenced by soil type and climatic conditions. Given the island's highly permeable volcanic soils, as demonstrated in the infiltration tests described in *4.2.2 Infiltration tests*, its low-reactive subsurface, and its frequent intense rainfall, it is likely that a considerable proportion of nitrates enter the groundwater. Under these conditions, it is estimated, based on expert knowledge, that approximately 50% of the nitrogen and phosphorus produced by livestock waste reaches the groundwater system, more details can be found in *6.4 Nutrient fluxes*.

6.2.4 Agriculture

Agriculture is very limited on Saba. There are only three small agriculture sites located on Saba:

- Zion's Hill
- Hydroponics farm at the end of Mountain Road
- Saba Reach farm on The Level (Windwardside)

Based on interviews and site visit it was decided to not consider the hydroponics farm and the Saba Reach farm in the nutrient balance. The hydroponics farm is an essentially closed system which limits the input of nutrients in the environment (Sharma et al., 2018). The Saba Reach farm is a completely organic farm which does not use artificial fertilizers.

The Zion's Hill farm is taken into account for the nutrient balance. In interviews it was told that the local cow manure is used as fertilizer on the farm as well as some artificial fertilizer. It is assumed that all manure from the above described 5 cows is used as fertilizer. From this amount it is assumed that 50% of the nutrients is attenuated (crop uptake, absorption and denitrification) and 50% of the nutrients leach to groundwater. For the artificial fertilizers it is assumed that the nutrient amount is 25% of the cow manure, from which also half is absorbed and half is leached. In total an input of 62.5% of nutrients produced by the cows end up in the water system. Table 6.7 shows the total N and P input (kg/d) from agriculture.

Table 6.7 Total N and P input (kg/d) from agriculture.

	Total N (kg/d)	Total P (kg/d)
Agriculture (for agriculture 62.5% of cows is assumed)	0.43	0.09

6.2.5 Organic Waste Dump

Figure 6.6 Location of the organic waste dump (black arched) along The Road.shows the organic waste dump located along The Road between Zions Hill and Windwardside. The organic waste dump consists of both organic waste (e.g. garden clippings), as well as excavated rock and building materials. On a volcanic island like Saba, such a dump is likely to release only limited amounts of nitrogen and phosphorus. While garden waste does contain organic matter with some nitrogen and phosphorus, decomposition tends to be slow, especially under dry or unmanaged conditions.

In volcanic soils, particularly those formed from andesite rock, the ability of the soil to retain phosphorus can be high. This is because these soils often contain reactive minerals, which strongly bind phosphorus. As a result, when organic material breaks down and releases phosphate, the soil readily adsorbs it, limiting its mobility and reducing the risk of leaching into the environment.

As described in *4 Field results*, two soil samples were taken from the organic waste dump. These were shaken with demineralized water and analysed using both a quick scan field test and laboratory testing. The samples did show that significant amounts of NO_3 and PO_4 were released.

While some phosphate on Saba may originate from the natural weathering of volcanic rock (the excavated rock), particularly from phosphate-bearing minerals such as apatite, this process is generally slow. As rainwater and slightly acidic soil water interact with the rock, apatite can break down and release phosphate. However, the amount released through this geological pathway is typically low compared to input from human sources.

Overall, the nutrient load from garden clippings remains modest compared to human or livestock waste. Excavated rock contributes negligibly, as it is chemically stable, does not decompose, and is similar to the rocks found elsewhere on the island.

Due to the likely small amounts of nitrogen and phosphorus released from the organic waste dump, combined with the challenges of accurately quantifying these emissions, they have been excluded from the overall nutrient input assessment.

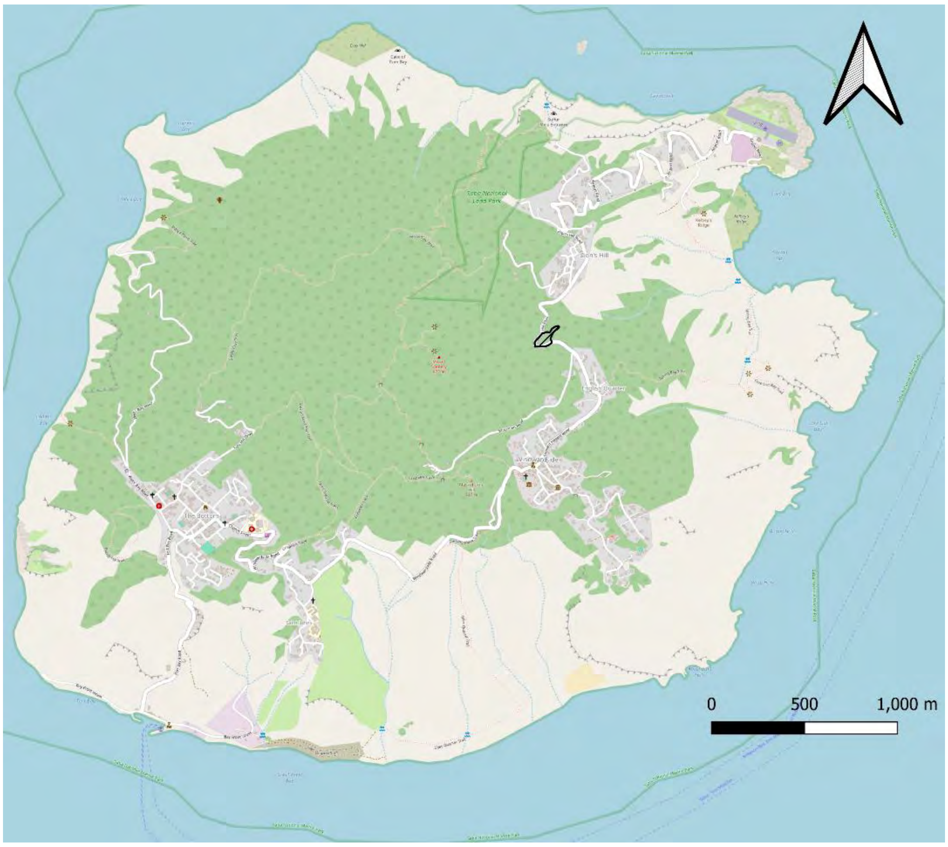

Figure 6.6 Location of the organic waste dump (black arched) along The Road.

6.2.6 Atmospheric deposition

According to Vishwakarma et al. (2023), atmospheric nitrogen deposition in the region is between 3 and 5 kg per hectare per year. For Saba, which has an area of 13.1 square kilometres, we assume an average of 4 kg per hectare per year. This means about 5,240 kg of nitrogen per year, or roughly 14 kg per day (Table 6.8). Presently, this is the second largest source of nitrogen, after humans. Phosphorus deposition via atmospheric pathways is negligible and not included as a source.

Table 6.8 Total amount of atmospheric deposition in kg/d on the entire island of Saba.

	Total N (kg/d)
Atmospheric deposition	14

6.3 Water fluxes

The entire water balance can be found in Appendix 8A.4, the most important components are discussed in this paragraph. The catchment delineation used in this study is based on the catchments defined in *Rainwater management and erosion control plan* (Dinten Fernandez, 2025). The catchment delineation is based on the topography of the island. The Digital Terrain Model (DTM) used is the 2024 version based on LiDAR data. Figure 6.7 shows the delineated catchments and their assigned catchment number. In the background the DTM is visible. The catchment number relates to the surface area: catchment 1 is the largest, catchment 16 the smallest. For each catchment, a water balance is estimated using rainfall measurements and literature data.

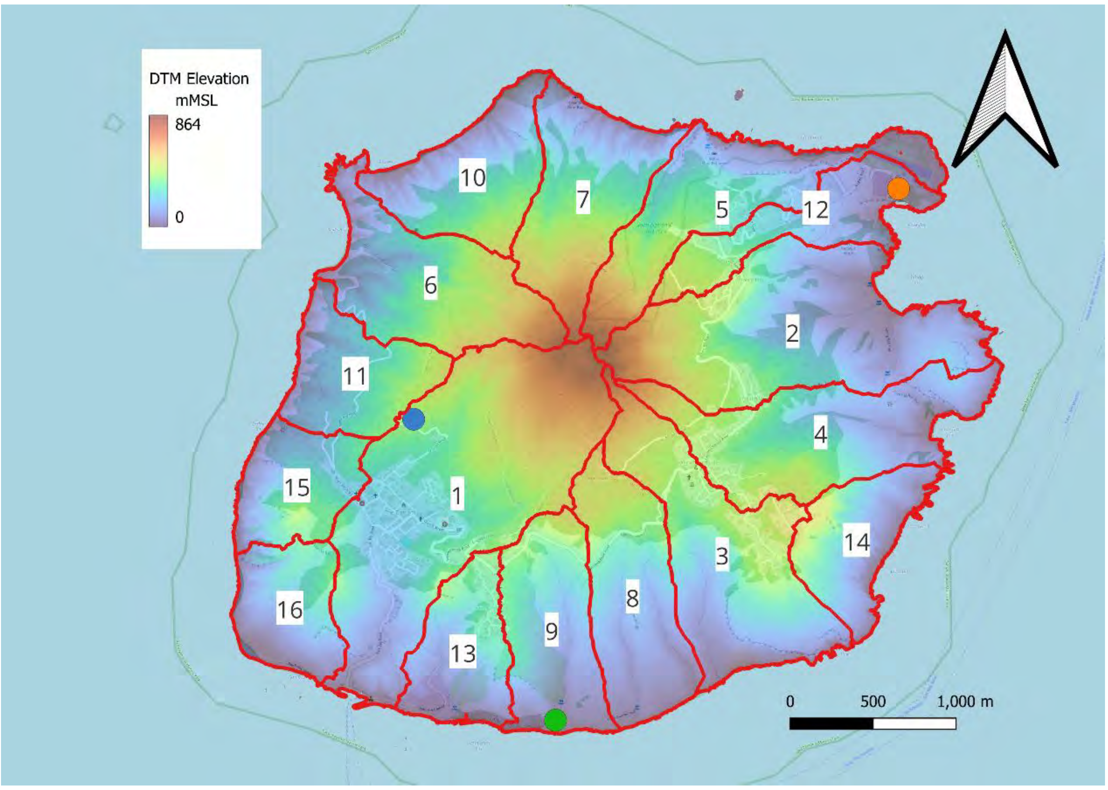

Figure 6.7 Delineated catchment area (red) together with their catchment number, in the background the digital elevation map. The Troy Hill measurement location (blue) and the KNMI harbour (green) and KNMI airport (orange) locations.

Three sources of rainfall data are used: the KNMI stations at the airport and the harbour, and measurements at Troy Hill by Tom van het Hoff (locations are shown in Figure 6.7). At KNMI station at the airport hourly data is collected, at the harbour every 5 minutes and the data at Troy Hill was only available on a monthly base while probably daily measurements should be available. Figure 6.8 presents the monthly total rainfall (mm) at these three locations. Elevation and measurement location clearly affect the rainfall amount. Comparing data from July 2021 to September 2024, Troy Hill measurements are on average approximately 1.24 times higher than harbour measurements (although some peaks are lower), and harbour measurements are about 1.02 times higher than airport measurements.

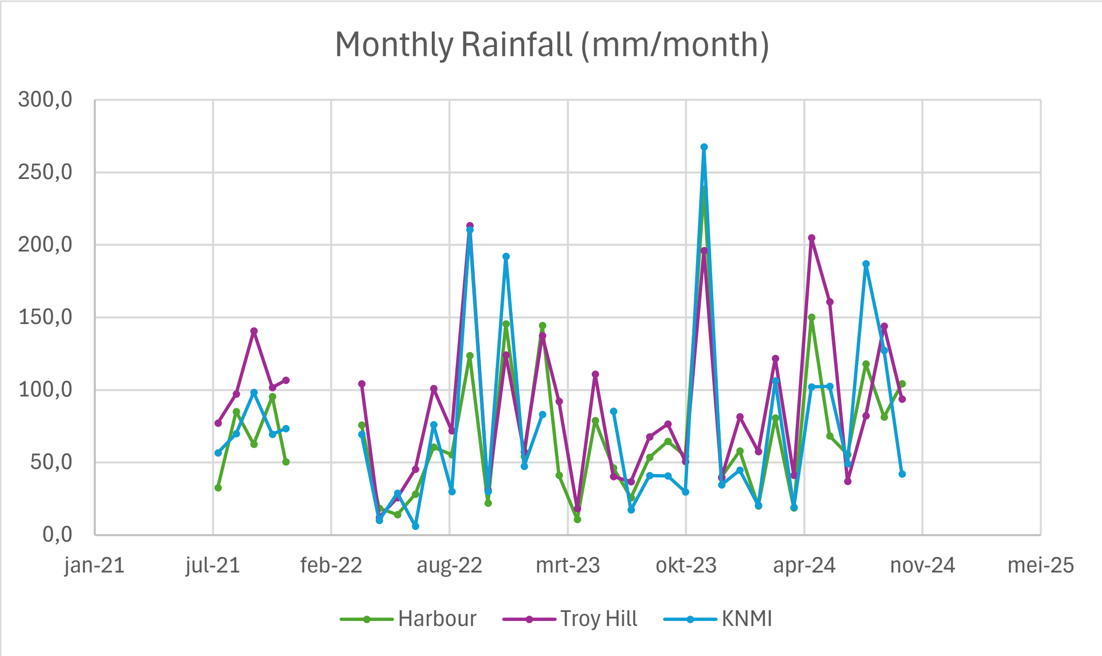

Figure 6.8 Total monthly rainfall (mm) for the three rainfall observation locations.

To make water balance analyses comparable for all catchments, the long-term average rainfall from the harbour station (900 mm) is used as the baseline. This station was chosen because it provides the most complete dataset, whereas the meteorological station at the airport contains significantly more missing data. An elevation-dependent factor is applied per catchment to account for spatial variation: factor 1.0 for elevations below 250 meters, 1.25 for elevations between 250 and 500 meters, and 1.5 for elevations above 500 meters. This factor is based on the difference between the Troy Hill, Airport and Harbour measurements mentioned before. Figure 6.9 shows the spatial distribution of these factors. The average factor per catchment is used, and these values are listed in Table 6.10. Applying these factors results in an average rainfall of 1039 mm across all catchments, which is comparable to the KNMI climate average for 1991–2020 of 1034 mm (KNMI, 2023). It is clear that the spatial variation of precipitation on Saba is large due to huge differences in elevation and the position on the island (leeward and windward sites). This variation cannot be captured by the available rainfall stations and the assumptions made may therefore contain significant uncertainties.

Due to limited data availability for Saba, several assumptions were made to calculate the water balance, summarized in Table 6.9.

In order to distinguish between the amount of rainfall responsible for the quick flow routes (interflow and subsequently runoff in gullies) and the slow flow route (groundwater recharge and flow), a distinction is made between regular rainfall resulting in groundwater recharge and intense rainfall events leading to runoff events on the hill slopes in the gullies. Based on stakeholder interviews, 3 to 5 of such runoff events occur per year; this study assumes four events annually. The available rainfall data was analysed and the four highest daily rainfall sums were selected. These peak events have rainfall sums exceeding 30 mm up to 90 mm per day and in general also show high rainfall intensities like hourly totals of 15 to 20 mm. The total rainfall from these four events represents about 25% of the annual precipitation. Interflow only occurs during these peak rainfall events and not during regular rainfall. Therefore the entire precipitation surplus during regular rainfall is assumed to be deep groundwater recharge.

To distinguish between fluxes of quick flow (interflow and runoff) and groundwater flow, separate balances were made for regular rainfall and peak events. For regular rainfall events, it is assumed that approximately 80% of the rainfall is lost through evapotranspiration, while about 20% is considered the precipitation surplus. This is an evapotranspiration of approximately 1.5 mm per day. These values are based on average evapotranspiration rates observed across the Caribbean region and are subject to considerable uncertainty due to local variability and data limitations.

During peak events, the rainfall amount is very high in a short time, resulting in a lower percentage of evapotranspiration compared to the rainfall. Part of the peak rainfall is stored in the rootzone and evapotranspirated in the days after the rainfall event. For these peak events we assume that about ~16% is evapotranspirated resulting in a ~84% precipitation surplus. It is assumed that 50% of this precipitation surplus from peak events contributes to deep groundwater recharge, and the other 50% flows to interflow and surface runoff. These assumptions are also shown in Table 6.9.

By combining the water balances for regular and peak rainfall, the total annual amounts of water discharged to interflow and deep groundwater recharge are estimated. From the total annual precipitation surplus (rainfall minus evapotranspiration) approximately 71% is deep groundwater recharge and 29% is groundwater interflow.

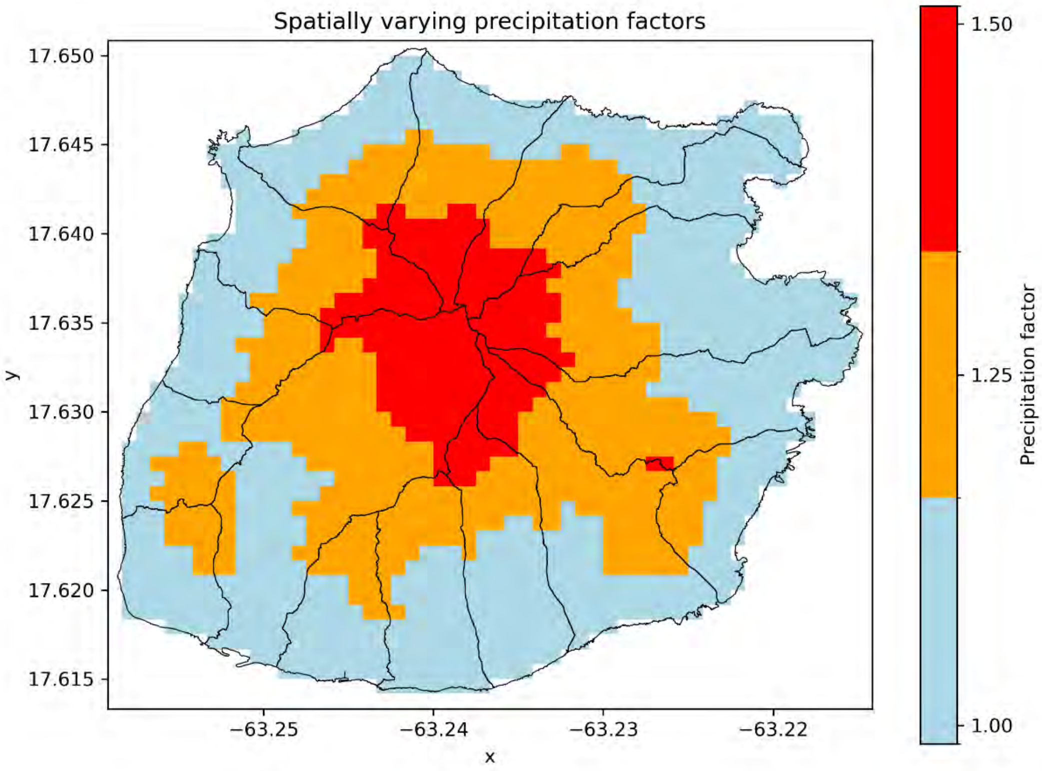

Figure 6.9 Spatially varying precipitation factors. These factors are averaged within each catchment and multiplied with the long term average from the Harbour station. Factors are based on elevation. Below 250 m 1.0, between 250 m and 500 m 1.25 and above 500 m 1.5.

Table 6.9 Overview of assumptions for the water balance. The absolute values mentioned are representative for the harbour.

Type of rainfall	Description	Value
Total rainfall	Mean annual precipitation	900 mm
Regular rainfall events	Share of annual rainfall during regular events	75%
	Annual rainfall volume (non-peak)	675 mm
	Assumed percentage evapotranspiration	80%
	Assumed percentage annual precipitation surplus (precipitation minus evapotranspiration)	20%
	Evapotranspiration (non-peak)	540 mm
	Deep groundwater recharge (non-peak)	135 mm
Peak rainfall events *(4 events/year; 25% of annual rainfall)*	Share of annual rainfall during peak events	25%
	Annual rainfall volume (peak events)	225 mm
	Evapotranspiration during peak events	35 mm
	Evapotranspiration as percentage	16%
	Assumed percentage from precipitation surplus percolating to deep groundwater during peak events	50%
	Assumed percentage from precipitation surplus interflow during peak events	50%

Table 6.10 Water balance per catchment.

Catchment number	Elevation precipitation factor	Precipitation per catchment (mm annually)	Evapotranspiration (mm annually)	Total groundwater recharge (mm)	Deep groundwater recharge (mm annually)	Groundwater interflow (mm annually)
1	1.24	1118	714	404	286	118
2	1.14	1028	657	371	263	109
3	1.19	1072	685	387	274	113
4	1.14	1029	657	372	263	109
5	1.17	1052	672	380	269	111
6	1.22	1094	699	395	280	115
7	1.22	1097	701	396	280	116
8	1.13	1013	647	366	259	107
9	1.09	984	628	355	251	104
10	1.10	986	630	356	252	104
11	1.10	986	630	356	252	104
12	1.10	994	635	359	254	105

13	1.08	973	621	351	249	103
14	1.08	974	622	352	249	103
15	1.09	985	630	356	252	104
16	1.06	956	611	345	244	101
Area weighted average (mm annually)		**1039**	**664**	**375**	**265**	**110**

6.4 Nutrient fluxes

The next step involves combining the defined nutrient sources with the water fluxes in order to estimate the resulting nutrient fluxes.

Nutrient fluxes are not spatially uniform; they depend on both the distribution of the nutrient sources (such as farms and settlements) and the size and location of the catchments. Therefore, the nutrient input per catchment is first calculated. Not all nutrients reach the water system directly; a certain proportion is assumed to be the attenuated by adsorption or denitrification before entering the hydrological pathways. For nutrient inputs originating from the population and tourism (e.g. cesspits), no attenuation of ammonium is assumed, due to the anaerobic conditions typically present in cesspits. Once the ammonium is flushed towards the water system it is converted to nitrate and because of the absence of organic material and non-reactive nature of the volcanic subsurface it is assumed that all ammonium from the cesspits enter the water system. Because of the ability of the soil to retain the phosphate it is assumed that 50% of the phosphate emitted by humans enter the water system

For livestock, an attenuation rate of 50% is assumed for both nitrogen and phosphor. This assumption is based on the exposure of livestock waste to environmental processes when deposited on the surface. In the case of atmospheric deposition, it is assumed that 90% of the nitrogen is attenuated through denitrification. These nutrients, primarily in the form of nitrate and ammonium, are water-soluble and can be directly absorbed by plant roots. As a result, they are quickly incorporated into biomass, leaving only a small fraction to be lost through leaching or runoff.

For livestock the situation of 2020 with 5000 goats is assumed. Current nitrate concentrations in groundwater are the reflection of historical input due to the slow percolation and flow velocities of the groundwater system. Over time the concentration is expected to decrease if the other inputs remain the same.

Following these assumptions, the nutrient inputs are spatially distributed across the catchments. Using the land use map shown in Figure 2.2, the percentage of urban area per catchment is determined. Based on this, the human nutrient inputs are allocated accordingly. The total area and percentage of urban area per catchment is provided in Table 6.11. Inputs from livestock and atmospheric deposition are distributed evenly across all catchments, while nutrient inputs from agriculture are assigned entirely to catchment 5, due to the location of the agricultural area in Zion's Hill. The total nutrient input into the system, after accounting for breakdown and conversion, is presented in Table 6.11.

Table 6.11 Total N and P input (kg/d) per catchment. Also shown the area of the catchment (m²) and the percentage of urban area of Saba within that catchment.

Catchment number	area (m²)	Percentage urban of Saba total (%)	Total N input per catchment (kg/d)	Total P input per catchment (kg/d)
1	1964048	27.7	18.4	2.9
2	1458898	8.1	10.4	1.8
3	1115840	11.1	9.2	1.5
4	1001151	9.7	8.2	1.4
5	858619	9.9	7.9	1.3
6	854253	0.2	4.9	1.0
7	785916	0.0	4.4	0.9
8	783037	1.2	4.7	0.9
9	688194	3.4	4.8	0.9
10	635180	0.0	3.6	0.7
11	544661	0.5	3.2	0.6
12	517747	19.4	8.1	1.1
13	499084	5.7	4.3	0.7
14	491987.0	0.7	3.0	0.6
15	462235.9	2.5	3.3	0.6
16	455251.7	0.0	2.6	0.5
		Total	**100.8**	**17.2**

These nutrient inputs are then combined with the results of the water balance to calculate nutrient concentrations, shown in Table 6.12. It is assumed that 80% of the total nutrient input enters deep groundwater recharge, while 20% is transported via interflow.

Table 6.12 N and P concentrations (mg/L) per catchment are for both the deep groundwater and the interflow.

Catchment number	N concentration in deep groundwater (mg/L)	P concentration in deep groundwater (mg/L)	N concentration in groundwater interflow (mg/L)	P concentration in groundwater interflow (mg/L)
1	9.6	1.5	5.8	0.9
2	7.9	1.4	4.8	0.8
3	8.8	1.5	5.3	0.9
4	9.1	1.5	5.5	0.9
5	10.0	1.6	6.0	1.0
6	6.0	1.2	3.6	0.7

7	5.9	1.2	3.6	0.7
8	6.8	1.3	4.1	0.8
9	8.0	1.4	4.9	0.9
10	6.5	1.3	4.0	0.8
11	6.8	1.3	4.1	0.8
12	17.9	2.3	10.8	1.4
13	10.2	1.6	6.2	1.0
14	7.1	1.4	4.3	0.8
15	8.2	1.5	5.0	0.9
16	6.7	1.3	4.1	0.8
Average	**8.5**	**1.5**	**5.1**	**0.9**

Figure 6.10 and Figure 6.11 show the spatial distribution of the calculated nitrogen concentrations per catchment for the deep groundwater flow and interflow respectively. The same is shown for phosphorus in Figure 6.12 and Figure 6.13.

Focusing first on deep groundwater concentrations, the calculated values show a reasonable agreement with available measurements. In catchment 1, the calculated nitrogen (which is assumed to be mainly nitrate) concentration is 9.6 mg/L, compared with the observed nitrate concentration of 2 mg/L at Tent Bay, measured with the quick scan field kit. In catchment 2 (Spring Bay), the calculated concentration is 7.9 mg/L, while observed values range between 4.1 and 4.5 mg/L Total Nitrogen and 5-10 mg/L nitrate. For catchment 3 (Hole in the Corner Well), the calculated concentration is 8.8 mg/L, compared with the observed value of 5.3 mg/L Total Nitrogen. Although the exact values differ, the order of magnitude and general trend are consistent, with Hole in the Corner Well showing higher concentrations than Spring Bay.

For the remaining catchments, where no measurements are available, several observations can still be made based on the calculated values. Catchment 12 shows a particularly high concentration of 17.8 mg/L (Figure 6.10) in the deep groundwater. This can be explained by the fact that much of Zion's Hill and the airport fall within this catchment, while the catchment area itself is relatively small. As a result, high nutrient input is combined with limited water availability, leading to elevated concentrations.

Nutrient concentrations in interflow are significantly lower (e.g. the difference in nitrogen concentrations between Figure 6.10 and Figure 6.11). This is due to the assumption that only a small portion of the total nutrient input is associated with interflow. Given that large rainfall events, responsible for interflow, occur only three to five times per year, it is unlikely that a significant share of nutrients is transported through this pathway. In comparison, groundwater recharge occurs throughout the remainder of the year, allowing more time for nutrients to infiltrate and accumulate.

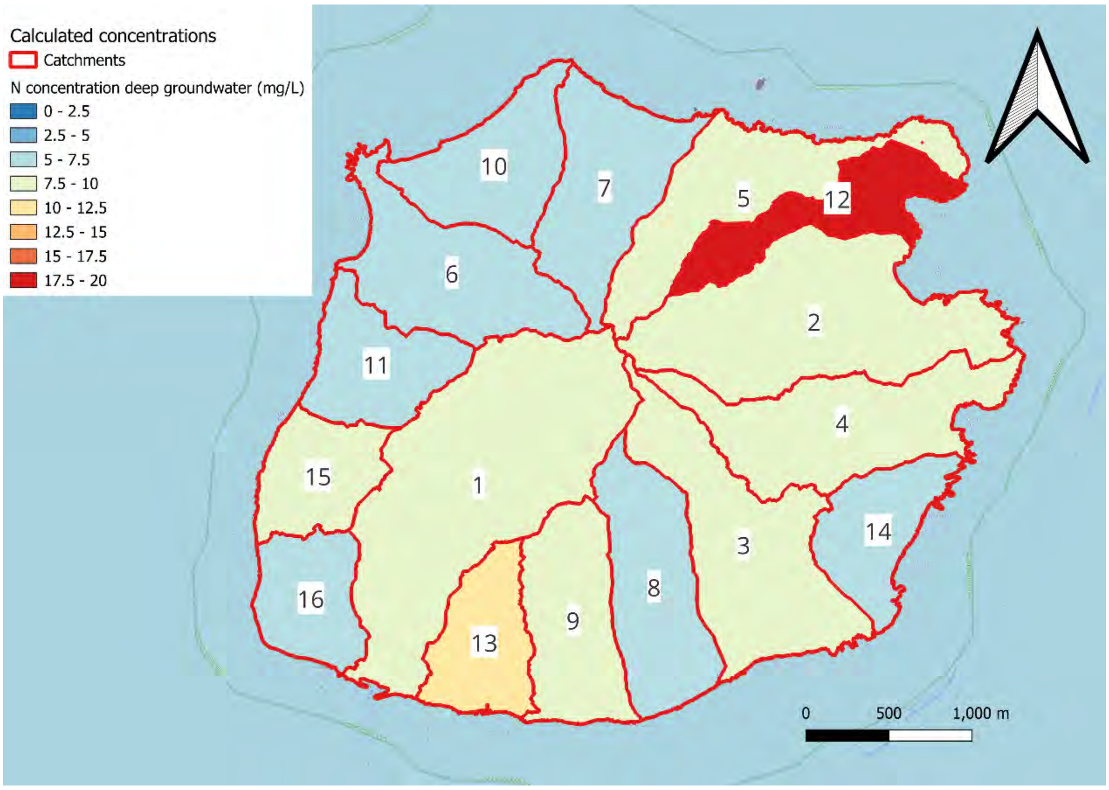

Figure 6.10 Calculated nitrogen concentrations in the deep groundwater (mg/L) per catchment.

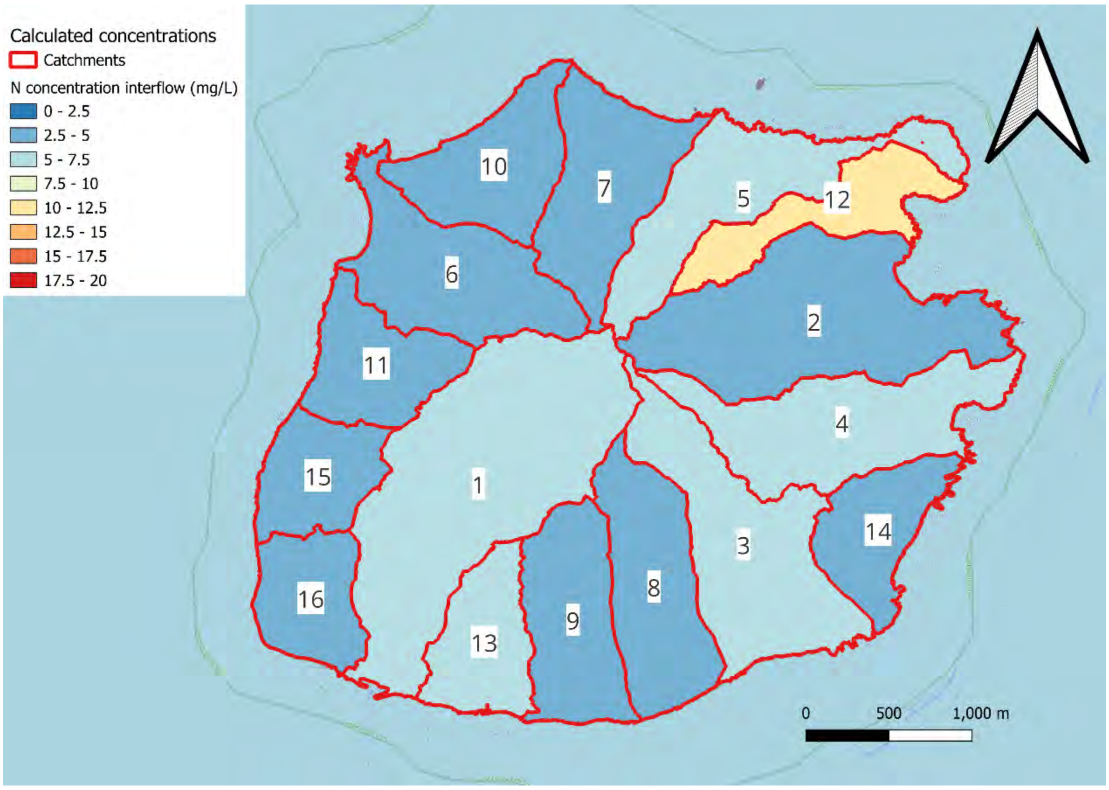

Figure 6.11 Calculated nitrogen concentrations in the groundwater interflow (mg/L) per catchment.

For phosphorus, the calculated concentrations are substantially lower than the observed values. This discrepancy is likely due to the exclusion of phosphorus input from geological weathering in the nutrient balance calculations, resulting in an underestimation of total phosphorus concentrations.

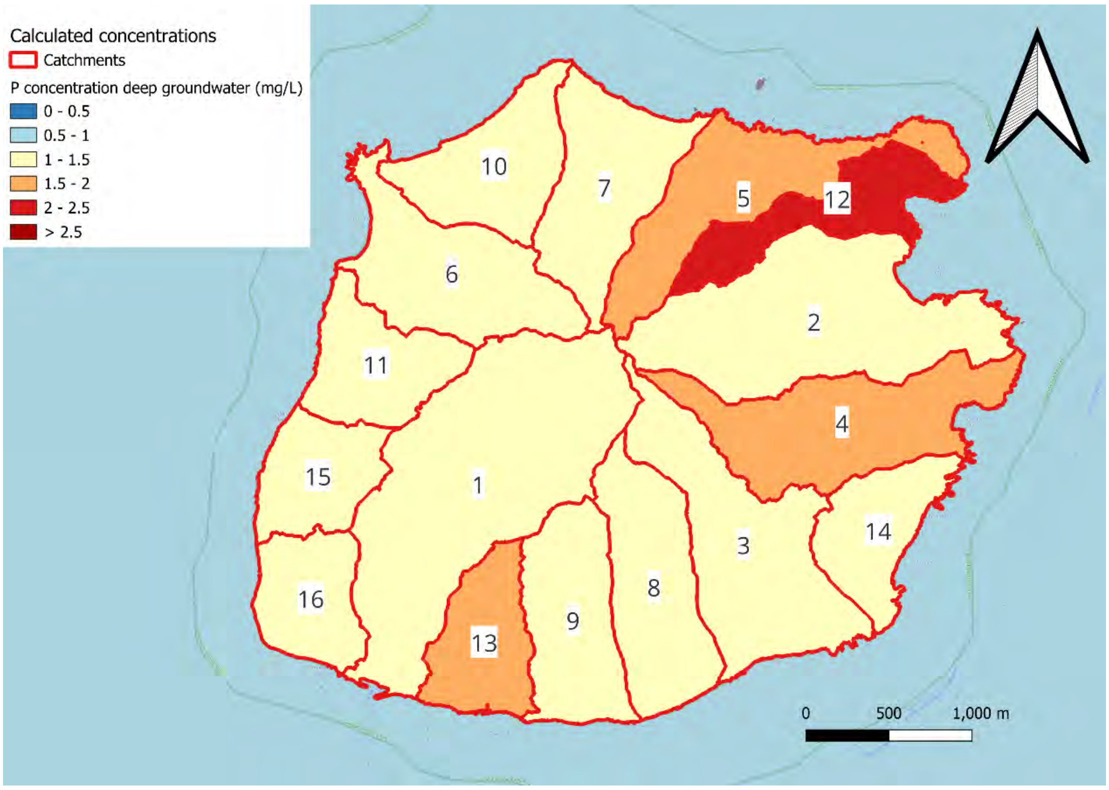

Figure 6.12 Calculated phosphorus concentrations in the deep groundwater (mg/L) per catchment.

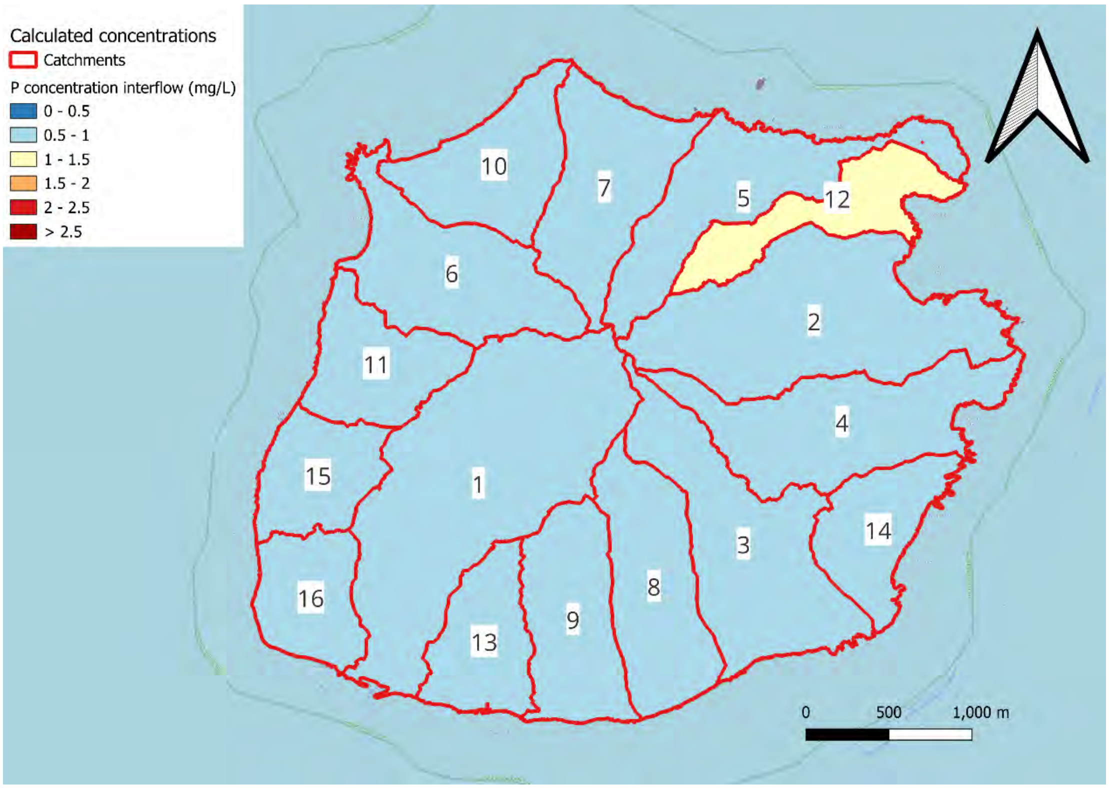

Figure 6.13 Calculated phosphorus concentrations in the groundwater interflow (mg/L) per catchment.

It is important to note that nutrient *loads*, rather than nutrient *concentrations*, are the critical factor influencing nutrient input into coastal waters, and consequently, the health of coral reefs. Upon discharge into the ocean, nutrients are rapidly diluted by the vast volume of seawater relative to the comparatively small freshwater flows from the island. As a result, seawater nutrient concentrations are primarily determined by the total nutrient loads entering the system (see Table 6.11).

Figure 6.14 and Figure 6.15 illustrate the spatial distribution of nitrogen (N) and phosphorus (P) loads (in kg/day) per catchment, as presented in Table 6.11. These spatial load maps reveal a slightly different pattern compared to the previously discussed nutrient concentration maps. The highest nutrient loads correspond closely with the most densely populated areas. Specifically, the catchment containing The Bottom exhibits the highest inputs of both nitrogen and phosphorus, followed by the catchment that includes Windwardside.
Given the elevated nutrient loads in these catchments, it is expected that the adjacent coastal areas at the catchment outlets will exhibit increased nutrient concentrations.

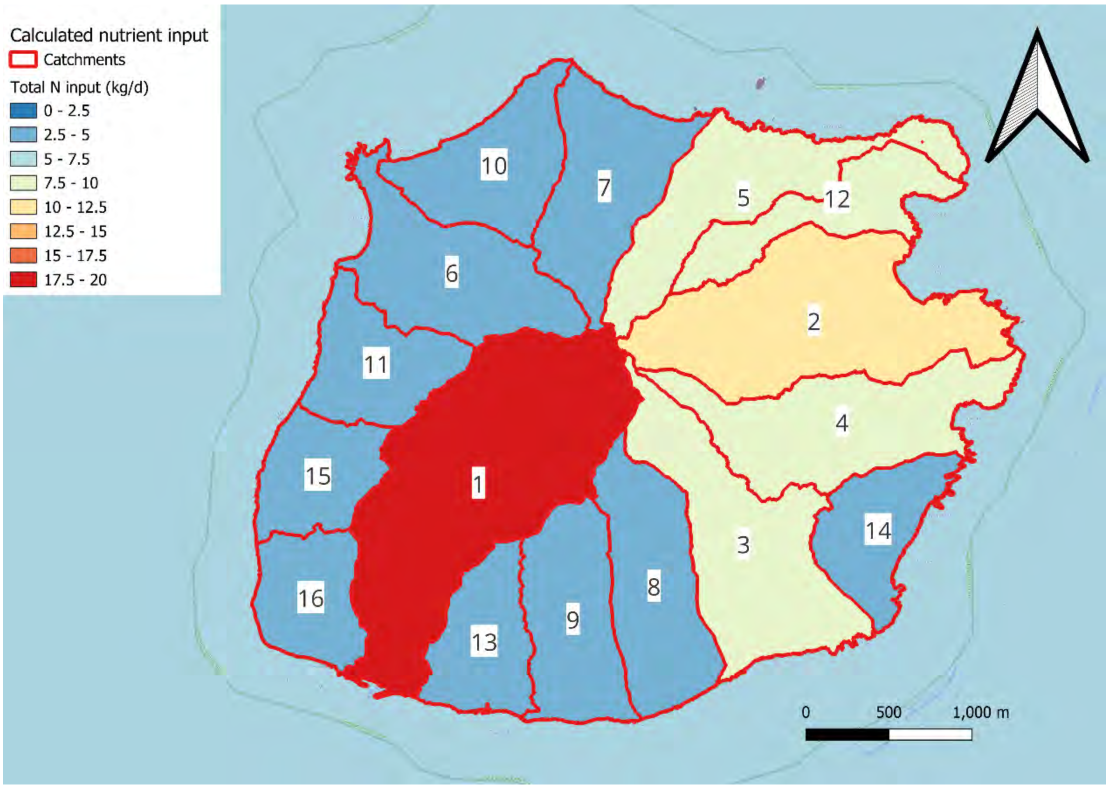

Figure 6.14 Spatial distribution of the calculated N loads (kg/d) per catchment.

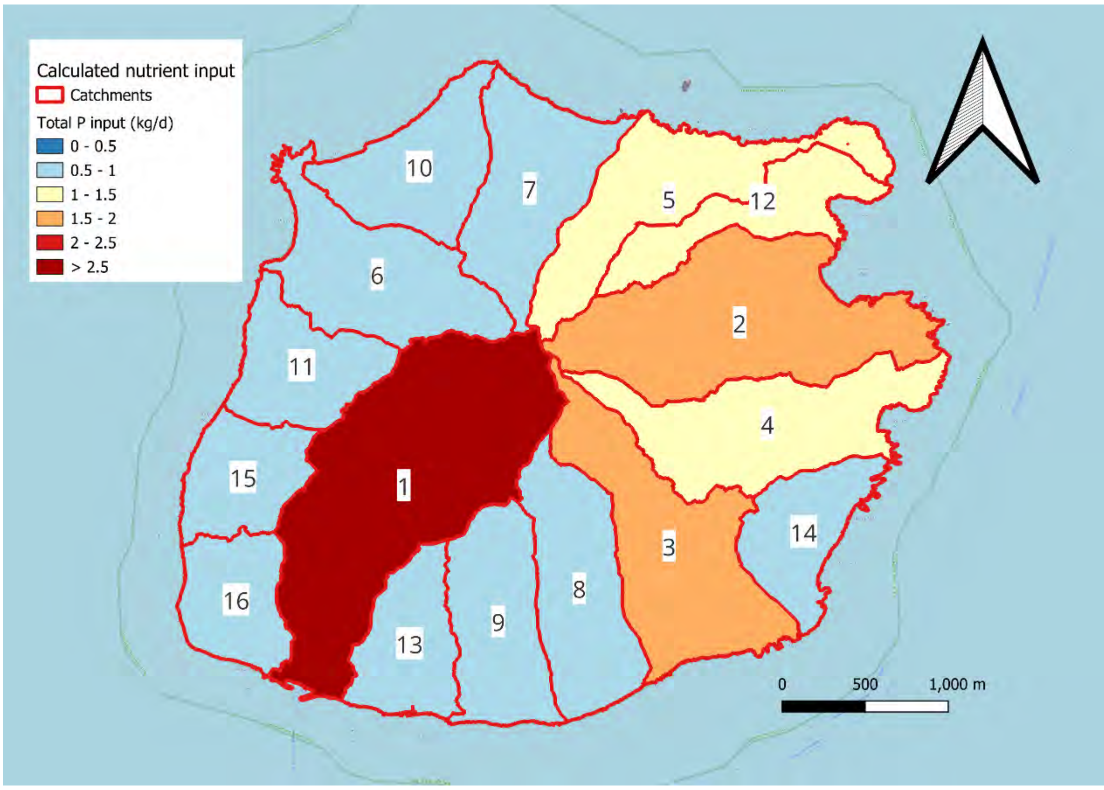

Figure 6.15 Spatial distribution of the calculated P loads (kg/d) per catchment.

6.5 Nutrient concentrations coastal waters

Wageningen Marine Research (WMR) is conducting research in collaboration with Saba Conservation Foundation (SCF) into the sea water quality around Saba in relation to the condition of the coral reefs. Since May 2022 every month samples are taken at 11 locations around Saba and at 3 reference point (see Figure 6.16). The samples are analysed for Dissolved Inorganic Nitrogen (NO_2^-, NO_3^- and NH_4^+) and Dissolved Inorganic P (PO_4^{3-}). They also analysed groundwater from the well at Spring Bay and a couple of surface runoff samples.

The spatial and temporal variations of these nutrients could provide valuable insights into nutrient loads originating from the island and they have made their data available to Deltares for further analysis. At the time of writing this report, WMR is finalising their own report, which includes their initial analysis results.

Figure 6.16 The (water quality) sample locations of the coastal waters around Saba (from WMR and SCF, 2025)

Boxplots of NH_4 and NO_3 concentrations for the sample locations are given in Figure 6.17. They show that NH_4-concentrations are 5 to 10 times higher than NO_3-concentrations. The 3 reference locations (further away from the island) show significant lower NO_3 concentrations than the sample points around the island but for NH_4 this not the case. The elevated NO_3-concentration around the island compared to reference points is a strong indication that the island is an important source of NO_3. Another important observation is that this is valid for the entire period of 2 years which indicates that NO_3-loads from the island should be a more or less constant input. Both observations are strong indications that a rather permanent groundwater flow is responsible for these elevated NO_3-concentration, supporting the conceptual groundwater model described in chapter 5. The elevated nitrate concentration of the Spring Bay well and the 3 fresh groundwater samples described in chapter 3 are in line with this hypothesis as well. Note that NO_3-concentrations of groundwater (Spring Bay well: 56.6 and 59.5 µmol/l, equal to 3.5 and 3.7 mg/L) are up to 500 times higher than sea water concentration due to dilution of the groundwater discharged into the sea. NH_4-concentration in groundwater are much lower (Spring Bay well: 0.60 and 0.91 µmol/l, equal to 0.05 and 0.07 mg/L) and in the same range as the sea water concentrations. This indicates that the NH_4-concentration in seawater is not determined by the inflow of groundwater. Phosphate concentrations of groundwater of the Spring Bay well (32.4 and 36.2 µmol/l, equal to 3.1 and 3.4 mg/L) are more than 1000 times higher than the reference seawater concentrations, and therefore an input source for the coastal waters.

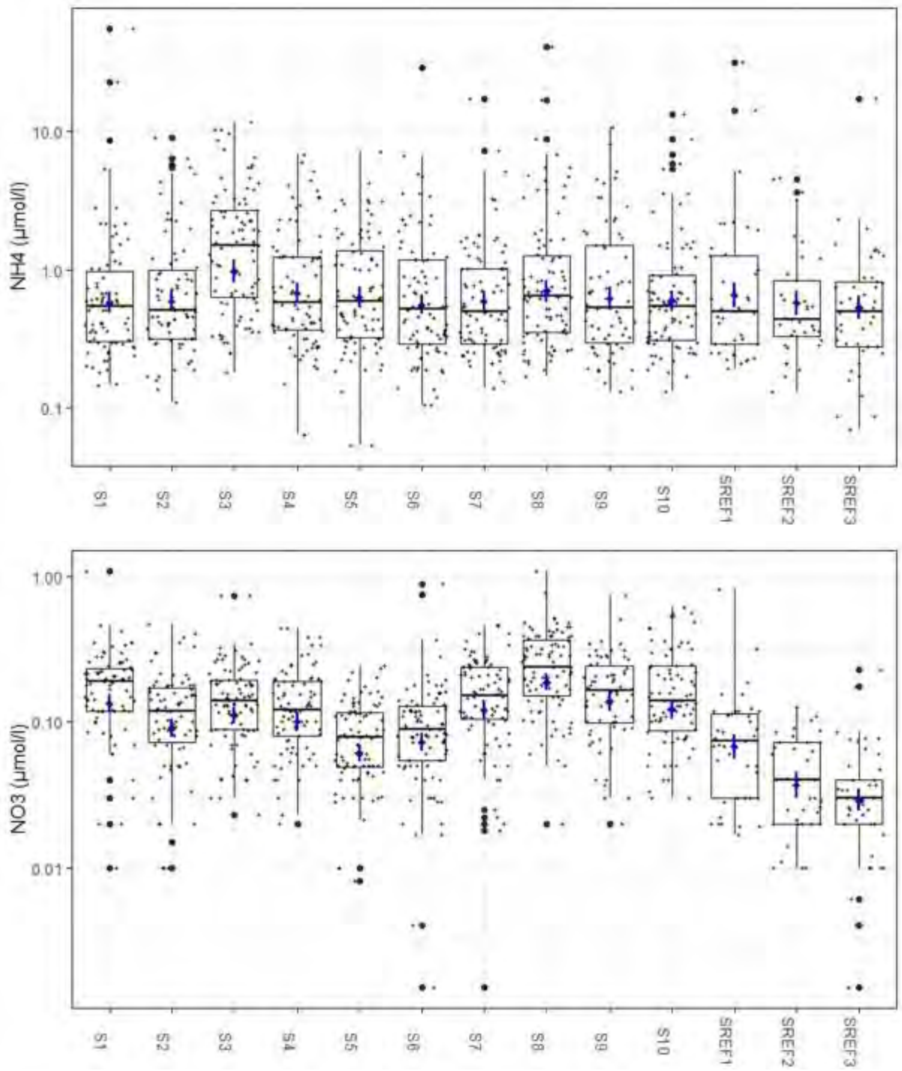

Figure 6.17 Boxplots with NH_4 and NO_3 concentrations for all 14 sample locations (data from WMR and SCF, 2025)

The boxplots also show significant variations in NO_3-concentrations between the sample locations. S8 (Cove Bay) shows the highest concentrations and S5 and S6 at the west side of the island (Wells Bay and Ladder Bay) are significantly lower than all other point situated at east and south coast of Saba. The lower concentrations on the west side are attributed to the absence of residential areas, and consequently the lack of cesspits and associated nutrient inputs within their groundwater catchment zones. This is also in line with the calculated nutrient inputs in this study (see *6.4 Nutrient fluxes*): high calculated concentrations and loads in catchment 12, which has its outlet in Cove Bay (S8) and low calculated concentrations around Wells Bay and Ladder Bay (S5 and S6) (see Figure 6.10 and Figure 6.11 and Table 6.11).

For NH_4 the spatial variation is much less with no clear differences between the locations except for S3 at the harbour shows, This location clearly shows the highest ammonium concentrations, 2 to 3 times higher than all other locations. The anomalous higher concentration cannot be related to groundwater input because of the relatively low NH_4-concentration in groundwater. It can also not be related to surface water runoff input because the NH_4-concentrations are consistently high and surface runoff only occurs a couple of times per year. A possible source could be the discharge of the brine of desalinated seawater at the harbour but this possibility is not clear at the moment. The fact that no elevated NH_4-

concentrations around the island are observed (except S3) compared to the reference locations is also a strong indication that the source of NH_4 concentration is not from the island.

The temporal variations of NH_4 and NO_3 could also give some information of the nutrient contribution of the island, either via quick interflow or slow groundwater flow towards the sea. An important question is, do we see elevated nutrient concentrations after rainfall events or in more general, is there a relation between the rainfall on the island and the nutrient concentration in the coastal waters. Therefore, the measured nutrient concentrations in the sea are combined with measured rainfall data. For every sample date, the sum of rainfall for the previous 1, 3, 7, 14, 28 and 56 days were determined. This was done for both weather stations on the island (at the airport and at the location east of the harbour) to include the spatial variations of rainfall on the island. It should be noted that these stations do have missing data and still do not cover the spatial variations so that significant rain events can be missed.

Figure 6.18 and Figure 6.19 show the correlation scatter diagrams between the measured nutrient concentrations of S3 and S8 and the summed rainfall (weather station near harbour) for the week before sampling. The graphs show that there is no direct relation between nutrient concentrations (NO_3, NH_4 and PO_4) and the amount of rainfall. Both low and high concentrations are measured during periods with high and low rainfall amounts.

However, for S8, the two highest NO_3 and PO_4-concentrations are linked to the highest weekly rainfall amounts; 105 mm for sampling date 11-11-2022 and 90 mm for 17-1-2023 with 90 mm. Most likely, these NO_3 and PO_4-peaks might be correlated with heavy rainfall on the island. On sampling date 17 January 2023 also for NH_4 the highest concentration was measured. This indicates a probably important role of peak flow events for incidental peak nutrient loads into the coastal waters.

Besides these two nutrient peaks, the concentration levels could not be linked to rainfall amounts. And this is valid for all periods (from 1 to 56 days) for which the summed rainfall amounts were derived (but not shown here). Besides the summed rainfall, also correlation diagrams were derived for the maximum daily rainfall and the number of heavy rainfall events (> 20mm /day) and also no relation was found with the measured concentration. The general conclusion from this analysis is that the temporal variations of nutrient concentrations in the coastal water cannot be explained by the current available data of rainfall on the island, except for some (1 or 2) nutrient peaks. This indicates that the more delayed and constant groundwater flux from Saba probably is a more important pressure for the surrounding coastal waters compared to the quick, more surficial flow routes.

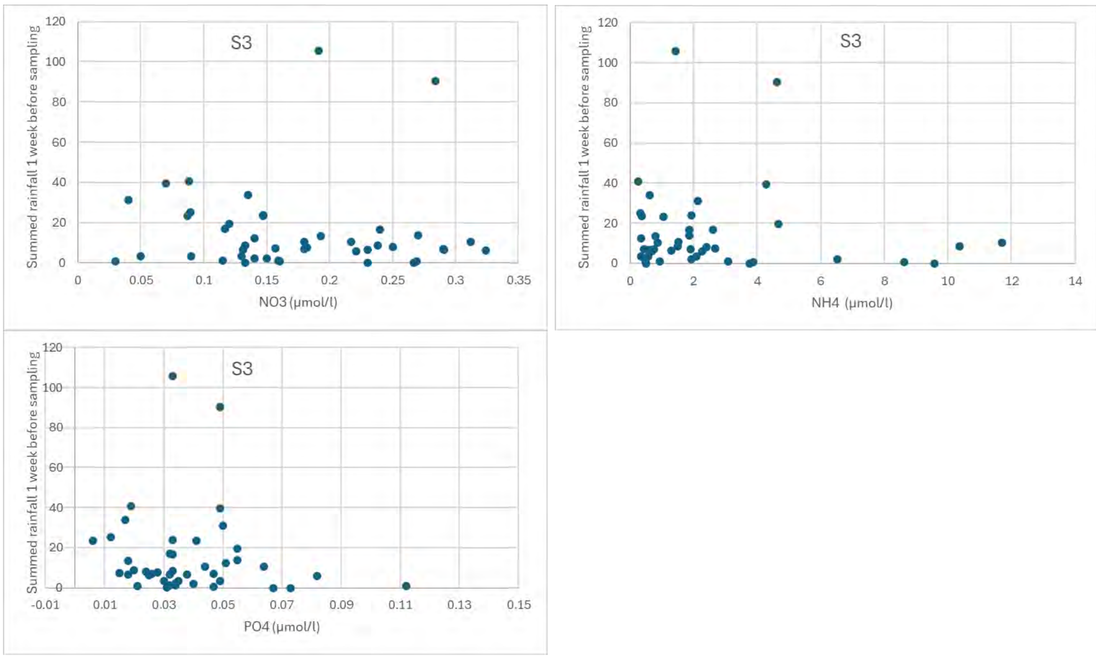

Figure 6.18 Scatter diagram between nutrient concentration (NO_3, NH_4 and PO_4) at 5 m depth for sample location S3 and the summed rainfall (in mm) in the week before sampling.

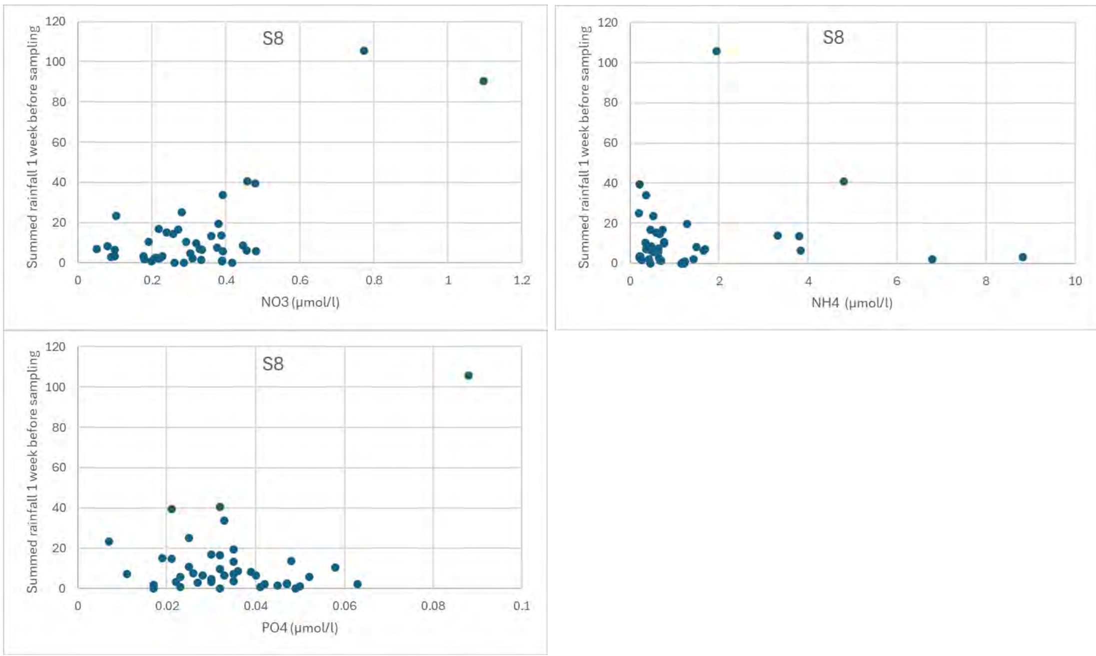

Figure 6.19 Scatter diagram between nutrient concentration (NO_3, NH_4 and PO_4) at 5 m depth for sample location S8 and the summed rainfall (in mm) in the week before sampling. One outlier with high NH_4 (44.1 µmol/l) and PO_4 concentration (0.52 µmol/l) both on sampling date 17-1-2023 corresponding with summed amount of 90.4 mm rainfall is not shown due to the scale of the x-axis.

During four runoff events samples were taken and analysed for nutrients by WMR and SCF. The median concentration of NH_4 was 2.8 µmol/l (0.22 mg/L), 1.0 µmol/l (0.06 mg/L) for NO_3 and 0.2 µmol/l (0.02 mg/L) for PO_4. The NO_3 and PO_4 concentrations in the groundwater samples are much higher, respectively 58.0 (3.6 mg/L) and 34.3 µmol/l (3.2 mg/L). NH_4 concentrations in groundwater (0.8 µmol/l, 0.06 mg/L) are a bit lower than for the runoff samples. These runoff concentrations are relatively low compared to the seawater concentration with median concentrations of 0.63 for NH_4 (0.05 mg/L), 0.24 µmol/l (0.01 mg/L) for NO_3 and 0.03 µmol/l (0.03 mg/L) for PO_4 (sample site S8). With these low concentrations, it's difficult to explain the nutrient peaks in the sea indicating that surface runoff play a less prominent role than groundwater input. However, only a few samples of surface runoff are available, and it is recommended to collect more samples during much more events and at different locations to better understand the contribution of runoff to the nutrient loads. Also, more groundwater analyses at different locations are needed to get a better understanding of the contributions via groundwater.

From the quick scan analysis of the sea water samples from WMR and SCF the most important observations are:

- NO_3-concentration are elevated around the island compared to the reference points showing that the island is an important source.
- These elevated NO_3 concentrations are year-round, indicating a constant contribution from the island.
- These two observations combined with the fact of elevated NO_3 concentrations in the groundwater, makes it very plausible to assign submarine groundwater discharge as the most important flow pathway of NO_3.
- NH_4-concentration doesn't show elevated concentrations around the island compared to the reference points, except at the harbour (S3). These elevated NH_4 concentrations at the harbour are consistently through time and therefore cannot be attributed to the incidentally runoff events. Considering the low concentrations in groundwater, also groundwater cannot be a major source. A possible source could be the permanent brine discharge as a rest-product of the desalinisation plant.
- At least two measured peak concentrations of NO_3 and PO_4 (and in 1 case also NH_4) could be related to heavy rain events in the 3-7 days before sampling which could be explained by the occurrence of surface runoff via interflow. However, more data during these kinds of events are required to get more insight in these processes.
- It should be noted that the two rainfall stations cannot cover the large spatial variation of rainfall and that important rainfall events could be missed in the analysis. It is therefore recommended to increase the number of rainfall stations (spread over the island at different elevations) and also introducing rain event-based sampling and increasing the number of groundwater and surface runoff samples to further improve the understanding of the nutrient loads into the coastal water and related island processes,

6.6 Regional perspective

To put these nutrient inputs into perspective, Saba has been compared to Bonaire using data from the *Model Development BES Coastal Waters (2024)* study. Bonaire has about 25,000 residents and 32,200 goats, spread over an area of 288 km². As a consequence, the nutrient input of both nitrogen and phosphorus on Bonaire is significantly higher than on Saba.

For nitrogen, livestock contributes approximately 870 kg per day on Bonaire, while locals add around 163 kg per day, and tourists about 54 kg per day. For phosphorus, the numbers are roughly 167 kg, 31 kg, and 10 kg per day, respectively. While on Saba the livestock contributes 15 kg nitrogen per day (used to be 145 kg nitrogen per day with 5000 goats), locals input 25 kg nitrogen per day, and tourists 1.2 kg per day. For phosphorus, the numbers are roughly 4 kg (29 kg with 5000 goats), 5 kg, and 0.2 kg per day, respectively.

Assuming the current situation with approximately 150 goats, the total nitrogen input on Bonaire is about 26 times higher than on Saba, and the phosphorus input is about 22 times higher. This difference is mainly explained by the larger human population and livestock numbers on Bonaire.

When looking at nitrogen and phosphorus emissions per km², the values are closer, but Bonaire is still higher. Bonaire emits approximately 3.8 kg/day of nitrogen and 0.7 kg/day of phosphorus per km². Saba emits around 3.1 kg/day of nitrogen and 0.7 kg/day of phosphorus per km².

For coral reefs, nutrient load per km of coastline is more relevant, as it shows how much actually reaches the water. Based on a coastline of ±100 km, Bonaire emits about 10.9 kg/day of nitrogen and 2.1 kg/day of phosphorus per km of coastline and Saba, with ±15 km of coastline, about 2.6 kg/day of nitrogen and 0.6 kg/day of phosphorus. This comparison doesn’t include localised point sources but shows that per km coastline, emissions are 3 to 4 times higher on Bonaire than on Saba.

7 Conclusions and recommendations

This chapter presents the main conclusions on nutrient pollution and the role of groundwater around Saba. Nutrients have been identified as an important local stressor for coral reef ecosystems, with concentrations near Saba already approaching ecological thresholds. The study aimed to clarify the contribution of groundwater and cesspits to nutrient loading in coastal waters. To do so, the following research questions were addressed:

- To what extent does groundwater contribute to nutrient discharge into the marine environment?
- What are the different nutrient sources on Saba and how much do the cesspits contribute specifically?
- How are nutrients transported through the subsurface system?

A quick scan approach was used, based on field observations, water quality measurements, laboratory analyses, and the development of a conceptual groundwater model. The approach includes indicative load estimations and substance balances. Despite uncertainties due to limited data, methodological assumptions, and the exploratory nature of the work, the outcomes provide valuable first insights into the main nutrient sources and transport mechanisms affecting coastal water quality near Saba.

First the overarching conclusions of the study are presented, followed by the recommendations.

7.1 Conclusions

7.1.1 Conceptual model

The geology of Saba, characterised by fractured andesitic domes and heterogeneous layers of tuff, agglomerates, and lava flows, plays a major role in directing groundwater flow. Water mainly infiltrates into permeable zones between lava layers, while hard rock outcrops and steep slopes lead to surface runoff.

Two main groundwater flow components are identified:

- **A slow flow route** forms a permanent groundwater system, recharged by infiltration and discharging into the sea as submarine groundwater discharge (SGD). This flow occurs through deeper layers and is responsible for sustained transport of dissolved substances to the sea.
- **A quick flow route** occurs only during heavy rainfall events. Water percolates to a shallow depth, encounters less permeable layers, and moves laterally (interflow) towards nearby gullies and valleys where it subsequently discharges rapidly as surface runoff to the coastal waters. This flow contributes to erosion and occasional peak discharges of nutrients and sediments.

Groundwater is a key pathway for transporting contaminants from cesspits toward the coastal waters. Wastewater infiltrates into the soil, reaches the groundwater and eventually the sea. Interflow and the following surface runoff processes are less likely to transport large amounts of contaminants from waste water towards the sea.

The lack of surface water and limited presence of springs supports the conclusion that most of the water leaves the island via subsurface routes, either as deep slow groundwater or as quick shallow interflow.

Field data, infiltration tests, and the presence of fresh and slightly brackish coastal wells indicate an active and significant permanent groundwater system. Elevated nitrate concentrations in groundwater samples confirm anthropogenic influence from uphill sources.

While exact groundwater depths and flow paths remain uncertain due to data limitations (e.g. lack of wells and subsurface mapping), the conceptual model provides a clear framework for understanding how water, and with it the nutrients, moves through the island's system.

Despite the assumptions and uncertainties in subsurface structure and flow dynamics, the conceptual model offers valuable insight into the hydrological functioning of Saba and helps identify groundwater as a critical pathway for nutrient pollution toward the marine environment.

7.1.2 Nutrient Sources

Historically, goats were the largest source of nutrients on the island, with goat waste accounting for about 80% of total nitrogen and phosphorus inputs in 2020. However, due to a successful goat control program that reduced the population from around 5,000 to just 150 animals, their nutrient contribution has dropped significantly.

Currently, humans are the primary nutrient source. The local population of 2,154 people contributes approximately 25 kg of nitrogen and 5 kg of phosphorus per day, with tourists adding about 10% more to these amounts. Other sources such as livestock, agriculture, and atmospheric deposition play smaller, but still measurable, roles. Organic waste dumps and natural sources are considered negligible in the nutrient budget.

Overall, total nutrient inputs on Saba remain low compared to islands like Bonaire. Still, localized nutrient inputs on Saba could impact sensitive coral reef systems.
Despite the relatively low absolute nutrient levels, coral reefs are near ecological thresholds and very sensitive to even small nutrient increases. This underscores the importance of reducing all avoidable nutrient sources to support reef resilience.

7.1.3 Water Balance

The water balance on Saba is based on limited and often incomplete data, requiring several assumptions. Catchment delineation based on the DTM were used, and rainfall was corrected for elevation and location effects. Precipitation varies strongly across the island due to steep topography and windward–leeward differences which is not captured with the two current rainfall stations.

Rainfall is divided into two types:

- **Regular rainfall** accounts for 75% of annual precipitation. About 80% of this water is lost through evapotranspiration, and the remaining 20% infiltrates as deep groundwater recharge. Interflow does not occur during regular events.
- **Peak rainfall events** (3–5 times per year) contribute 25% of annual rainfall. These short, intense storms result in high runoff and interflow. Roughly half of the surplus water from these events recharges groundwater, while the other half contributes to interflow and surface runoff.

Combining both rainfall types, approximately 71% of the annual water surplus contributes to deep groundwater recharge, and 29% flows via interflow. These values highlight that most water leaves the island through subsurface pathways, with deep infiltration being the dominant component.

Uncertainty remains high due to sparse data, but the conceptual model offers a first understanding of how water is partitioned between evapotranspiration, deep infiltration, and quick flow processes. More data and monitoring is required to get a better understanding of these subsurface flow processes towards the coastal waters.

7.1.4 Nutrient Fluxes

Nutrient inputs correlate strongly with catchment land use and population density. Catchments with higher urban percentages, such as catchment 1 (27.7% urban), exhibit elevated nutrient loads. Notably, catchment 12, which includes the airport area and Zion's Hill, shows the highest calculated nitrogen concentration at 18.1 mg/L, driven by its relatively small size combined with large nutrient inputs.

The calculated nitrogen concentrations in deep groundwater align reasonably well with measured values, giving confidence in the method despite data limitations. However, phosphorus concentrations are consistently underestimated and natural inputs from rock weathering which were not included, could be responsible for that.

Nutrient transport occurs via two main flow components: a fast pathway (interflow followed by surface runoff) during intense rainfall events (3-5 times per year), and a slow pathway (deep groundwater recharge) during regular rainfall periods. The fast component contributes a smaller nutrient load due to its short duration and limited nutrient uptake, whereas the slow component allows nutrients to accumulate over time, resulting in higher concentrations in groundwater.

For example, nitrogen concentrations in deep groundwater average around 8.4 mg/L but can reach nearly twice that in catchments with high nutrient input and limited water volume. In contrast, nitrogen levels in interflow are lower, averaging about 5.1 mg/L. This difference highlights the temporal and spatial variability of nutrient transport mechanisms on the island. Overall, nutrient flux patterns reflect the influence of human activity and catchment characteristics. The model offers a solid basis for guiding management strategies and highlights the need for ongoing monitoring to capture both immediate and long-term impacts on water quality.

7.1.5 Measured nutrient concentrations coastal waters

The quick scan analysis of the sea water samples from WMR confirm the postulated conceptual (ground)water model and calculated water and nutrient fluxes. The main conclusions from this analysis are:

- Elevated NO_3 concentrations around the island compared to the reference locations, indicating the island as a significant source.
- Year-round NO_3 concentrations indicate a constant contribution from the island.
- Submarine groundwater discharge is likely the main flow pathway for NO_3, as also evidenced by the elevated NO_3 concentrations in groundwater samples at the coast.
- Year-round NH_4 concentrations are only elevated at the harbour (S3), probably due to permanent brine discharge from the desalination plant.
- Peak concentrations of NO_3 (and NH_4) and PO_4 Levels are likely related to heavy rain events generating surface runoff via interflow.

7.2 Recommendations:

7.2.1 Monitoring and data collection

For Saba there is not much quantitative information available about the water system in general and the water and nutrient flows on the island in particular. The assessment described in this report was based on the limited data available and extra data and information collected during a quick scan field survey during 24th of March until 4th of April 2025. This assessment gives a first insight about the (ground)water system of the island and the most important nutrient sources, and first attempt to quantify these water and nutrient flows.

The hypotheses and assumptions about the working of the island's water system need to be confirmed (or adjusted) based on more data. More data via a monitoring program on the island's processes helps to better understand and quantify processes like groundwater flow and submarine groundwater discharge in relation to nutrient loads to the coastal waters, surface runoff processes related to nutrient and sediment loads, erosion and flood events, urban water management, effective waste water management, coastal groundwater extraction in relation to the production of drinking water, and hydrological triggered landslide processes. Regarding such a monitoring program, the following recommendations can be made with the focus to better answer the questions posted in this research but also beyond this to address other issues like erosion, sediment loads, drinking water production, urban (rain) water management and flood control.

- Spatial variation of rainfall is large (altitude, leeward-windward). Extra rain gauges are required to tackle this, placed on different altitudes and in the most important catchment concerning nutrient and sediment flows. Manual rainwater gauges by volunteers spread over the island may also help a lot.
- Installation of permanent groundwater observation wells (piezometers) at the coast in the main bays like Spring Bay, Core Gut Bay, Cove Bay, Hole in the Corner, Harbour, Tent Bay, Wells Bay.
  - Manual monitoring of water levels every 2 weeks or equipped with automatic water pressure sensors.
  - Groundwater sampling and analysis on macro-chemistry, nutrients, metals, coliform, BOD, COD, isotopes
- Radon-222 surveys in the coastal waters to map submarine groundwater discharge (SGD) and estimate these nutrient-containing SGD-flows.
- Monitoring of runoff events in the (5 to 10) main gullies of the island related to nutrient and sediment fluxes.
  - Discharge measurements would be too difficult but detecting when and the duration of runoff events would be very valuable.
  - Water pressure sensors could be an option for this and installed (on-line) cameras and visual observations would additionally be very valuable.
  - More data about the nutrient concentrations for different runoff events is required to better estimate nutrient loads via these quick routes and understand the role of these different nutrient sources. Sampling during these events for the main 5 to 10 gullies is therefore needed.
  - Additionally, determination of the sediment loads of these samples during runoff events will help to quantify sediments to the coastal waters.
- The spatial and dynamic variations of the nutrient concentrations are currently monitored every month by WMR and SCF which also give information about the processes on the island. We think by adding the following additional monitoring

activities, the contribution of the island to nutrient loads of the coastal waters can be better quantified.

- Add three extra reference locations further away from the island (~5 to 10 km) than the current ones, but the same position relative to the island. This will help to better quantify the contribution of the island since the current ref-point are probably too close to the island.
- Apply event-based sampling, preferably directly after heavy rain events or periods with prolonged and large rainfall amounts.
- Besides the continuous chlorophyll, pH and EC surveys during sampling, add a Radon-222 survey to detect the locations of SGD and for estimations of SGD-fluxes.

7.2.2 Rainwater management

Better rainwater management can significantly improve the groundwater system. More opportunities should be created for water to infiltrate into the soil instead of running off over roads. This can be achieved by using infiltration fields, wadis, or other techniques that allow water to soak into the ground. When the new road is built, water management must be an integral part of the design to avoid excessive runoff.

This not only helps recharge groundwater but also improves road accessibility by reducing water accumulation and erosion. Less erosion means lower sediment loads entering the ocean, which is important since sediment is a threat to coral reefs. It also reduces the amount of nitrogen and phosphorus bound to soil particles that ends up in the sea.

By integrating smart water management into construction, both the environment and infrastructure benefit.

7.2.3 Nutrient input reduction

Although the overall nutrient loads on Saba are not extremely high, they are still significant, especially for sensitive ecosystems like coral reefs. Currently, ocean concentrations are close to ecological thresholds. With the decline in goat populations due to the goat control programme, nutrient input from that source is expected to drop. If the number of residents and tourists remains stable, future nutrient levels could improve slightly. It is therefore recommended to keep monitoring the water quality, as described above, and maintain the goat control programme in the future.

The main source of nutrient input is now Human waste. While this is less than on many other Caribbean islands, it still plays a major role. Tackling this issue is difficult, mainly because of existing cesspits and the high cost of changing the system. Retrofitting is both expensive and complex because of the island's infrastructure and geography.

While the reduction in goats is not yet visible in the nutrient concentration measurements, if one would like to reduce the input by humans, future construction and renovation projects could offer a good opportunity. By integrating decentralized wastewater treatment systems in new developments, it is possible to reduce the nutrient input by humans. These systems are flexible and suitable for small, spread-out communities like Saba’s.

However, one major gap remains: there is no centralized wastewater or sludge treatment. Sludge treatment options are essential when installing septic tanks. Installing such a facility would help, but it would require a large investment. Given Saba’s relatively small contribution compared to larger islands, it is important to carefully weigh the costs and benefits. Even small improvements might make a difference, but only if they are economically and practically viable.

If Saba wants to grow in terms of population or tourism, investment in better wastewater infrastructure becomes more urgent and more justifiable. Planning ahead, by including wastewater solutions in new developments, can help protect groundwater and nearshore waters, and supports long-term ecological health and resilience.

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A Appendix

A.1 Composition of geothermal waters (in ppm) from the Lesser Antilles

Tabel from Gunnlaugsson (1981).

TABLE 41. Composition of geothermal waters (in ppm) from the Lesser Antilles

	SABA[1]			ST. EUSTATIUS[2]		MONTSERRAT[3]		GUADELOUPE[4]		ST. LUCIA[5]	
Location	Spring opposite Green Island	Ladder Bay (spring)	Spring Bay (spring)	Cherry Tree (well D)	Concordia (well E)	Galways (soufriere)	Plymouth (spring)	d'Entrecast -eaux dome (sea floor emission)	Shoe Rock scarp (sea floor emission)	Sulfur Springs	Diamond Spring
Temp °C	66	40	25	36.0	33.7	98	89.8	25.9	25.6	72	43.1
Li	N.D.	N.D.	N.D.	0.0276	0.0246	0.030	8.90	N.D.	N.D.	0.09	0.22
Na	11665.	9500.	761.	362.96	369.66	114.	7880.	12000.	11000.	54.	129
K	486.1	347.2	44.8	14.283	13.680	12.0	1,030.	392.	337.	13.7	11.0
Mg	800.0	1255.0	65.5	64.62	47.92	42.8	302	1410	1370	9.3	42.3
Ca	1111.0	405.0	107.8	129.97	104.77	207	2,510	395.0	359.0	72.3	69.2
Sr	N.D.	N.D.	N.D.	14.27	12.11	N.D.	N.D.	N.D.	N.D.	0.66	0.47
Mn	N.D.	N.D.	N.D.	0.0002	0.0002	N.D.	N.D.	N.D.	N.D.	0.81	0.29
Fe	N.D.	N.D.	N.D.	0.0119	0.0162	N.D.	N.D.	N.D.	N.D.	16.4	0.20
HCO_3	N.D.	N.D.	N.D.	N.D.	N.D.	55	128	159	159	0	6.86
SO_4	1802.3	2172.3	50.4	N.D.	N.D.	1018.	161.	3260.	3020.	1,085.	21.8
Cl	19290.	14548.	1118.	768.21	760.00	21.2	18220	20500	21400	32.9	40.0
F	1.0	0.7	0.2	N.D.	N.D.	0.148	0.22	N.D.	N.D.	0.05	0.15
I	N.D.	N.D.	N.D.	0.1202	0.2065	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
SiO_2	130.8	78.3	56.6	47.05	45.32	216.	315.	N.D.	N.D.	186.	171.
B	11.50	5.10	0.65	N.D.	N.D.	0.30	22.9	N.D.	N.D.	15.1	11.1
Al	N.D.	N.D.	N.D.	0.0014	0.0017	N.D.	N.D.	N.D.	N.D.	22	<0.05
Ba	N.D.	N.D.	N.D.	0.0837	0.0909	N.D.	N.D.	N.D.	N.D.	0.13	0.09
Br	N.D.	N.D.	N.D.	2.624	3.045	N.D.	N.D.	N.D.	N.D.	<0.1	<0.1
Co	N.D.	N.D.	N.D.	0.0002	0.0002	N.D.	N.D.	N.D.	N.D.	0.004	<0.001
Cr	N.D.	N.D.	N.D.	0.0274	0.0278	N.D.	N.D.	N.D.	N.D.	0.026	<0.001
Rb	N.D.	N.D.	N.D.	0.0113	0.0075	N.D.	N.D.	N.D.	N.D.	0.11	<0.01
Zn	N.D.	N.D.	N.D.	0.0009	<d	N.D.	N.D.	0.044	0.053	0.09	<0.02
CO_2	320.0	424.0	503.0	N.D.	N.D.	N.D.	N.D.	0.0	0.0	N.D.	N.D.

N.D. Not Determined
<d Less than detection limit of 0.00002 ppm
1. Data from Gunnlaugsson, (1981)
2. Data this paper (analyses by Activation Laboratories).
3. Data from Chiodini et al. (1997)
4. Data from Polyak et al. (1992)
5. Data from Ander et al. (1984)

A.2 Complete overview of all field observations

Latitude	Longitude	Type of observation	Type of observation/Groundwater (well / piezometer / ...)	Type of observation/River	Type of observation/Drain / ditch	Type of observation/Lake / pool	Type of observation/Geology	Type of observation/Interview	Type of observation/Sea water	Type of observation/other	general_obs_other	Remarks	Type of sample	measure_sample_other	Sample for lab?	Water level (m)	Discharge (L/s)	EC (uS/cm)	Temperature	Nitrate	Nitrite	Ammonium	pH	Hardness (mol/m3)	Chloride	Sulfate	Phosphate	Total iron	Measurement remark
17.6287947	-63.2305782	Groundwater (well / piezometer / ...) Geology	1	0	0	0	1	0	0	0		Small part up the trail	Groundwater																Ilfiltration test, 2cm in 2 sec. Soil super permeable, no traces of run off
17.6163046	-63.2503085	Geology	0	0	0	0	1	0		0		Blue rock. Keihard vulkanisch gesteente, geohydrologische basis.																	
17.6364959	-63.2316582	Geology Groundwater (well / piezometer / ...)	1	0	0	0	1	0		0		Donkere vlekken op rotswand. Kan een teken zijn dar hier het gw uitkomt na regen. Is nu droog.																	
17.634344	-63.2513331	Geology	0	0	0	0	1	0		0		Pyroklastische flow. Grovere stenen met een fijnere matrix																	
17.6342675	-63.251354	Geology Groundwater (well / piezometer / ...)	1	0	0	0	1	0		0		Zelfde plek als hiervoor. Witte afzettingen op de zijkant, waarschijnlijk kalk. Hier komt als het nat is waarschijnlijk het water uit.																	
17.6343546	-63.2513671	Geology	0	0	0	0	1	0		0		Slopen downward tge road, very steep gullied slopen. Groundwater seeping out up slope and water from road collectes at spot flowing down the hill, lot of erosion. No infiltration possible																	
17.6372867	-63.2511287	Geology	0	0	0	0	1	0		0		Zelfde geologische eenheid als net, conglomeraat met zand	Groundwater																Infiltratie proef, zie foto
17.6387014	-63.2514339	Geology	0	0	0	0	1	0		0		Slope debris, heterogeneous, bolders from 5 to 40 cm, matrix sand, lagering.																	
17.6394861	-63.2529377	Geology	0	0	0	0	1	0		0		At the coaster, cliffs of agglomeratie, bolders of all sizes sedimenten slope processen, clearly layered																	
17.6394964	-63.2529688	Groundwater (well / piezometer / ...)	1	0	0	0	0	0		0		Well is dismantled, concrete, no water visible																	
17.6400219	-63.2516453	Groundwater (well / piezometer / ...) Geology other	1	0	0	0	1	0		1	Infiltration test	Geology, los materiaal met grove stenen in zandige matrix	Groundwater																Infiltration test 13 begin 10 sec 15.
17.6398703	-63.2521259	Groundwater (well / piezometer / ...) Geology other	1	0	0	0	1	0		1	Infiltration test	On top of cliff wells bay, geology same as before	Groundwater																Infiltration test, 12 begin,13 na 40s, 13,4 na 1m, 14 na 1,5m
17.6182272	-63.25093	Geology	0	0	0	0	1	0		0		Bedrock visible, blue rock lavaflow																	
17.6317511	-63.2392179	Geology Groundwater (well / piezometer / ...)	1	0	0	0	1	0	0	0		Tropische bodem. Ondergrond lemig zand maar wel hetrogeen	Groundwater																Infiltration test, 2cm in 2 seconden
17.6351435	-63.2377713	Geology other	0	0	0	0	1	0	0	1	On top of mt scenery, andescite dome, soil loamy many roots, low permeability		other	Infiltration test															0 12 cm, 30 s, 12 cm, 3.50 13,5 cm, 5 min, 14 cm. Very loamy
17.6350283	-63.2377897	Geology other	0	0	0	0	1	0	0	1		On top, 2nd infiltration test	other	Infiltration test															0s 9cm, 1 min 9,5 cm, 2 min 9.8 cm, 6 min 10 cm
17.6174879	-63.2470384	Interview	0	0	0	0	0	1	0	0		Waste management, metals, plastic, cans, carboard, wood, shipped to miami. 20.000 dollar eery 3 week. Cleanup every year. many cars are imported.	Surface water																With heavy rain, surface runoff is happening, in smaller gullies more frequently tham in the bigger ones.
17.6334941	-63.2283551	other	0	0	0	0	0	0	0	1	Infiltration		other	Infil															0s, 1 s 2 cm, 2cm per sec, fast
17.6338621	-63.2278444	Geology	0	0	0	0	1	0	0	0		Big boulders, old eroded, mixture of																	
17.6337941	-63.2277732	Geology	0	0	0	0	1	0	0	0		Debris slope, big ans small boulders, steep but ver permeable, agglo																	
17.6329605	-63.2261618	other	0	0	0	0	0	0	0	1	Infil test		other	Infi															1.5 cm in 10 s, fast
17.6329584	-63.2262664	Geology	0	0	0	0	1	0	0	0		Gentle slope with smaller boulders, infiltration area																	
17.6332762	-63.2247701	Geology	0	0	0	0	1	0	0	0		Very flat area with grass and trees. Infiltration area, no signs of surface runoff, no gullies or streams																	
17.6332852	-63.2247889	other	0	0	0	0	0	0	0	1	Infil test		other																2 cm in 20 s but infiltration ring couldnt installed properly, lateral flo. But infiltration is fast. Matrix loamy sand, soil is dry, grass is yellow
17.6330826	-63.2240456	Geology	0	0	0	0	1	0	0	0		From this steep again, and gullie to the right (walking down), thick sedimentation layer																	
17.6329531	-63.2229279	Geology	0	0	0	0	1	0	0	0		Ge view point. Hill of previous odk has andescite core and is eroded, domes surrounding spring bay and small bay. More description see pictures																	
17.6333036	-63.2213527	Geology	0	0	0	0	1	0	0	0		Ereoded slope looking at mnt snenery, vast gesteente, no infiltration possible																	
17.6306379	-63.2192175	Groundwater (well / piezometer / ...)	1	0	0	0	0	0	0	0			Groundwater																Put is droog. 1.45 vanaf maai eld
17.6307061	-63.2192375	Geology	0	0	0	0	1	0	0	0		Cove gut bay, surrounded by hard rock, well present but dry																	
17.6339447	-63.2208549	Geology	0	0	0	0	1	0	0	0		Geo view point																	
17.6339155	-63.2208268	other	0	0	0	0	0	0	0	1	Infil test		other																Water infiltrates fasr on slope but part is surface runoff
17.6345601	-63.2215126	Geology	0	0	0	0	1	0	0	0		Outcrop, 10 m thick c Agglo with small big boulders in matrix of sand. Water infiltrates on terras and exfiltrates nearby gullie																	
17.6372475	-63.2214761	Groundwater (well / piezometer / ...)	1	0	0	0	0	0	0	0			Groundwater																Water in well about 7 to 8m below surface.
17.6375222	-63.2214582	Geology	0	0	0	0	1	0	0	0		Outcrop of allavial fan of spring bay. 10 m thick, big ans small boulders in matrix of sand. White precipitation of calcereous																	
17.6402394	-63.2242028	Geology	0	0	0	0	1	0	0	0		Steep slope towards spring bay, with grass yellow and shrubs, agglomorate thin I assume but permeable.																	
17.6402311	-63.2242607	other	0	0	0	0	0	0	0	1	Infil test		other																Very fast infi.tration, matrix roc,y sandy loamy
17.6414928	-63.2239496	Geology	0	0	0	0	1	0	0	0		Outcrop, first meter very sandy with boulders, very permeable. Agglo?																	
17.6414476	-63.2329712	Interview	0	0	0	0	0	1	0	0		At agricultural farm. 5000 goats, now 800. Pilot project. To regenerate agriculture. Water is collected for irrigation. By gravity. The biggest farm but small. For wednesday market. 5 cows manure.																	
17.6288026	-63.2375798	other	0	0	0	0	0	0	0	1	Hydroponics . Agriculture. Tomatos,																		
17.6262085	-63.2272769	Interview	0	0	0	0	0	1	0	0		Agricultural farm. Social project.																	
17.6435303	-63.2211166	Groundwater (well / piezometer / ...)	1	0	0	0	0	0	0	0		Playground build over fresh water well, at tidal pool																	
17.6434327	-63.2203493	Sea water	0	0	0	0	0	0	1	0		At tidal pools	Sea water					54500											
17.625244	-63.2280456	other	0	0	0	0	0	0	0	1	Cess pits	Three cess pits at momo cottages, open connection with soil, steep slope.																	
17.6174736	-63.2537502	Groundwater (well / piezometer / ...) Geology	1	0	0	0	1	0		0		At tents bay, water seems to be seeping from the side of the road. Heavy rainfall yesterday.	Groundwater		No			250		0	0		8	4	500	400		5	Ijzeroxide te zien rond de uitrede plek. Komt echt uit de wand niet vanaf het oppervlak. Bodem zandig lemige conglomeraat. Lijken wat kalkafzetting in te zitten. Potje met ondergrond meegenomen. EC uit potje, maar hij zat niet helemaal onder water. Klein plasje wat eruit komt heeft EC 3mS. Wss beetje zout door seaspray
17.6174547	-63.2537824	Lake / pool	0	0	0	1	0	0		0		Klein plasje op de weg naast andere punt, ter referentie gemeten. Waarschijnlijk vrij zout omdat het direct naar de zee ligt, seaspray	Surface water		No			6.33		0	0		7.5	4	5001000	400		5	
17.6174149	-63.2537387	Groundwater (well / piezometer / ...) Geology	1	0	0	0	1	0		0		Zelfde punt, net een beetje in de heuvel met begroeiing eroverheen. Water opgevangen en bij het hotel gemeten	Groundwater		No			2190		0	0		8	4	500	400800		0	Heel mooi zoet, 2.19 mS/cm
17.6262851	-63.2482485	Drain / ditch	0	0	1	0	0	0	0	0		Drainage of parking place	Surface water		Yes			128	23				6.5	0	0	0		0	Sample code. Saba001. Rainwater collected at parkingplace Bottom.
17.6251618	-63.2497626	Drain / ditch	0	0	1	0	0	0	0	0		Street Runoff	Surface water		Yes			119	24.4	0	0		6.5	0	0	0		0	Street runoff, low ec, no nutrients
17.6199897	-63.2500494	Drain / ditch	0	0	1	0	0	0	0	0		Street runoff, halw way bottom harbour, low ec, almost contamination,	Surface water					138		0	0		6.5	0.307	0	0		0	
17.6167989	-63.252065	Drain / ditch	0	0	1	0	0	0	0	0		Street runoff down at the harbour	Surface water		Yes		2	164	24.4	0	0		7	0.7	0	0		0	Saba003, street runoff, all solutes on road are taken. Slighly elevated hardness.
17.6181044	-63.2466918	Geology other	0	0	0	0	1	0	0	1	Runoff missing	At waste dump, no surface runoff in surrounding slopes, street runoff yes. All water infiltrated	Surface water		No			140											Street runoff
17.6165473	-63.2467811	River Drain / ditch	0	1	1	0	0	0	0	0		Surface runoff on road, downstream from wastedump	Surface water		No			218		0	0		7	0.712	0	0		0	

17.6250301	-63.2351575	Geology	0	0	0	0	1	0	0	0		Slope downward, steep intp gullie, green bottom. No much wasteward above, probaly leftside of gullie recieves from windsward																
17.620107	-63.2352051	Geology	0	0	0	0	1	0	0	0		Steep de ris slope, grassy, some land slides. Water infiltration very high.																
17.6185383	-63.2332321	Geology	0	0	0	0	1	0	0	0		In gullie, any shrubs, green, no sign of water																
17.6164316	-63.2338976	Geology	0	0	0	0	1	0	0	0		Below gentle slope, wgere water infiltrates																
17.6156849	-63.2354889	Geology	0	0	0	0	1	0	0	0		In gullie with shrubs,																
17.6154791	-63.2364873	Geology	0	0	0	0	1	0	0	0		VAlleyno gullie																
17.616101	-63.2398451	Geology	0	0	0	0	1	0	0	0		Big gullie, no erosion. Grass and shrubs everywhere																
17.6150562	-63.2402308	other	0	0	0	0	0	0	0	1	Meteo station																	
17.6150284	-63.2423357	Geology	0	0	0	0	1	0	0	0		Hard ro k dome andeschit, steep, fractured																
17.6270517	-63.2321231	other	0	0	0	0	0	0		1	Rainfall	Quote heavy rainfall, runoff starts appearing on the street, a lot in windwardside. Mainl, water that infiltrates some water captured with a bucket and testen.	other	Rainfall	No		24		0	0		7	0	0	0		0	Alles 0, zeer lage EC
17.6174219	-63.2537511	Groundwater (well / piezometer / …)	1	0	0	0	0	0		0		Same gw point as yesterday, close to tent bay and the harbor. Steady gw flow. Water troebel	Groundwater		Yes		2000		2	0.15	0	7.5	4	500	400	10	0	Sample for lab 100 ml, added 300 ml demi water. SABA004
17.6231326	-63.2358857	Groundwater (well / piezometer / …) other	1	0	0	0	0	0		1	Infiltratietest.	Op kam naar beneden, water infiltreert zeer snel. Stijle grashelling richting gulle. Conglomeraat, puinhelling. Iig bovenste meters, zal niet heel dik zijn			No													14.5, 15,5 na 30sec. 1cm in halve minuut
17.620149	-63.2352215	other	0	0	0	0	0	0		1	Infiltration test	Conglomerate with a very thin soil on top of it with dry grasses			No													1cm in 1 s
17.6184763	-63.2338425	other	0	0	0	0	0	0		1	Infiltration test, 1.5 cm in 30s																	
17.6179965	-63.230247	Groundwater (well / piezometer / …)	1	0	0	0	0	0		0		Mooie gw put aan de kust. Helder water. 15% zeewater 85% gw	Groundwater		Yes	0	6070	29	10	0	0	8	4	1000	0	10	0	Nitraat houdend grondwater. SABA005. Put 40m van de zee. Water op zeeniveau
17.6156487	-63.2358486	Geology other	0	0	0	0	1	0		1	Oude nederzetting	Restanten van een oude nederzetting. Oude muren van een huisje en vlakker gemaakt land. Waarschijnlijk is hier ook iets van landbouw geweest, ook een input van nitraat			No													
17.6151007	-63.2401116											Meteostation																
		other	0	0	0	0	0	0		1	Sea water. Sampled by sea saba on hotspring location. Hotspring 1		Sea water		Yes		54		0	0		7.5	4	2000	1200		0	SABA006
		other	0	0	0	0	0	0		1	Sea water	Sea water. Sampled by sea saba on hotspring location. Hotspring 2	Sea water		Yes		54.6		0	0		7.5	4	2000	1200		0	SABA007
		other	0	0	0	0	0	0		1	Sea water	Sea water. Sampled by sea saba on hotspring location. Hotsprings 3	Sea water				54.5		0	0		7.5	4	2000	1200			
		other	0	0	0	0	0	0		1	Sea water	Sea water. Sampled by sea saba on hotspring location Hotsprings 4	Sea water				55.5		0	0		7.5	4	2000			0	
17.6197498	-63.2601562	Geology	0	0	0	0	1	0	0	0		Steel slope hard rock, big landslides																
17.6249383	-63.2597182	Geology	0	0	0	0	1	0	0	0		Hot springs, no indication in t ec or geology	Sea water				55.5	27.4										
17.6311885	-63.2580517	Geology	0	0	0	0	1	0	0	0		Agglomorates bottom, on top of it hard rock																
17.6323504	-63.2576288	Geology	0	0	0	0	1	0	0	0		From this point only agglomorates.																
17.6350036	-63.2565106	Geology	0	0	0	0	1	0	0	0		Agglomorates, with ash layers																
17.6391933	-63.2552287	Geology	0	0	0	0	1	0	0	0		Wells bay, agglo orates																
17.6463569	-63.2556873	Geology	0	0	0	0	1	0	0	0		Andescite outcrop																
17.6233237	-63.2488271	other	0	0	0	0	0	0	0	1	Cistern from tap	Water from tap downstream of the bottom	other	Cistern from tap	Yes		180		0	0		6.5	0	0	0		0	SABA011
17.6372317	-63.2214653	Groundwater (well / piezometer / …)	1	0	0	0	0	0	0	0		Gw well at spring bat. 2 water samples taken for lab using a bucket	Groundwater		Yes		1400	31	510	0	0	7.5	1.425	500	0	10	0	Nitraat tussen 5 en 10. 2 samples for lab. Saba008 en saba009
17.6382139	-63.2363908	Lake / pool	0	0	0	1	0	0	0	0		Lake saba	Surface water		Yes		328	20.5										
17.6348605	-63.2319617	other	0	0	0	0	0	0	0	1	Organic waste dump, vooral veel stenen, bouwafval. Niet veel plantenmateriaal				Yes													Na schudden met demiwater
17.6273378	-63.2316606											Fieldkit samples saba lake. Not the richting location.	Surface water		Yes		334	20.2	0	0		6	0.5	0	0	3	0	Saba lake code saba010
17.6273206	-63.231677	other	0	0	0	0	0	0	0	1	Sample van org waste dump, from slope. Sandy material. Not real location.		other	Shaked with demi water	Yes		115		2	0	0	7.5	0.5	0	0	25	5	Code saba013, sediment shaking. 50 so.ld 50 water, 4x verdund. Ander sample bouwmateriaal, 70 ml sample, 330 ml demiwater.
17.6272973	-63.2316954	other	0	0	0	0	0	0	0	1	Shake sample from org waste dump. Building material		other	Shake sample waste dump building material	Yes		671		2	0		8.5	2.5	0	0	3	20	50 perceel material 50 water. Sample Diluted by. Sample saba 012
17.6458541	-63.2312101	Geology	0	0	0	0	1	0	0	0		Sulphur mine. Yellow sediments. Warm in the mine																
17.6461787	-63.2315558	Geology	0	0	0	0	1	0	0	0		Grassy flat part below steep hark rock hill, sandy sediments																
17.6454801	-63.2314637	Geology	0	0	0	0	1	0	0	0		Steep rocky hill. Thin layer of agglomorates with big boulders																
17.6273624	-63.2316299	other	0	0	0	0	0	0	0	1	Shake sample at sulpher mine		other	Shake sample sulpher m8ne. SABA014	Yes		360		0	0	0	5	1.3	0	0	0	0	Shake sample sulphur mine
17.6213666	-63.2436646	Geology	0	0	0	0	1	0	0	0		St johnson on hill, flat area																

A.3 Laboratory results

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Water Analysis Report

ACCREDITED CERT #5343.02

Waste Water Results

Customer: Public Entity Saba
Address: Power Street 1, The Bottom
Phone: 5994167743
Email: nike.dekkers@sabagov.nl

Collection Date:	4/1/2025
Received Date:	4/1/2025
Date of Analysis:	4/1/2025
Date of Release:	4/5/2025

DESCRIPTION	Acccession	BOD	COD	Total Nitrogen	Total Phosphorus	Total Coliform	E. coli	pH	Conductivity
Method >		EPA BOD-5	EPA 410.4	EPA 351.1	USEPA 365.3	Iso:9308 2000	Iso:9308 2000	epa 8156	epa 8160
Reference Value >		<30	<150	<5	<1	<200	<200		
Unit of Measure >		ppm	ppm	ppm	ppm	CFU/100ml	CFU/100ml		µs/cm
SABA001	250401191	0	30	1.0	0.6	TNTC	TNTC	8.1	121
SABA002	250401192	0	27	1.1	0.7	TNTC	TNTC	7.9	139
SABA003	250401193	0	35	1.0	0.6	TNTC	TNTC	8.3	167
SABA004	250401194	0	9	11.2	0.1	TNTC	6	7.9	593
SABA005	250401197	23	**	5.3	0.0	TNTC	2	8.3	6070
SABA006	250401198	0	**	2.2	0.0	90	6	8.0	56500
SABA007	250401199	1	**	2.4	0.0	280	280	8.1	57000

CODs for SABA005,006 & 007 results are inconclusive. There were too many interferences. To be able to resolve the interferences to determine the exact measurement of COD in those samples, more sample was needed to run further testing.

Conclusion: Samples were taken on March 31st.
BODs for samples 001, 006 & 007 were ran on April 3rd.
CODs** >70 mg/L

Amanda Bryan | Environmental Department

SLS Qualified, Certified and here to Provide!

These results relate only to the items tested and apply only to the sample as received.

Print Date: 5/5/2025

ST. MAARTEN LABORATORY SERVICES

Water Analysis Report

Airport Rd #39
Simpson Bay
+1721-542-2518 ext. 1030
Email: info@sls.sx

Extra Chemistry Results

Customer: Public Entity Saba
Address: Power Street 1, The Bottom
Phone: 5994167743

Collection Date:	4/1/2025
Received Date:	4/1/2025
Date of Analysis:	4/1/2025
Date of Release:	4/5/2025

DESCRIPTION	Acccession	Lithium*	Sodium*	Ammonium*	Potassium*	Manganese*	Calcium*	Magnesium*	Aluminum	Zinc	Ammonia	Boron*	Cadmium*	Alkalinity	Hardness*
Method >		iso 14911	iso 14911	iso 14911	iso 14911	iso 14911	iso 14911	iso 14911	epa						
Reference Value >		<0.2	<120	<0.5	<150	<0.05			<0.2	<3	<0.5	<0.3	<0.003		
Unit of Measure >		ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
SABA001	250401191			<0.3	3		13	1						14	18
SABA002	250401192			<0.3	3		15	2						55	44
SABA003	250401193			<0.3	4		28	2						85	69
SABA004	250401194			<0.3	6		75	10						65	227
SABA005	250401197			<0.3	<1		72	188						588	105
SABA006	250401198			<0.3	<1		0	1260						164	7080
SABA007	250401199			<0.3	<1		0	1430						164	6380

Conclusion: Samples were taken on the 31st of March.

Disclaimer: ***All quantitative (analytical) chemistry results carry a measurement uncertainty which is primarily*** **caused by the analytical variability of any test. This uncertainty may be up to plus/minus 5% of the stated results. Therefore, results close to upper/lower limits as stated by the law should be confirmed by repeating a sample from the same location**

These results relate only to the items tested and apply only to the sample as received.

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***:Not included in the accredited scope**

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ACCREDITED CERT #5343.02

DESCRIPTION	Acccession	Fluoride*	Chlorite*	Bromate*	Chloride*	Nitrite	Bromide*	Chlorate*	Nitrate*	Phosphate	Sulfate*	Iron	Cupper*	Lead*	Nickel*
Method >		iso 10304	iso 10304	iso 10304	iso 10304	iso 10304	iso 10304	iso 10304	iso 10304	iso 10304	iso 10304	epa 3500Fe-B		<0.01	<0.02
Reference Value >		<1.5		<0.001	<150	<0.1			<50		<150	<0.2	<2		
Unit of Measure >		ppm	ppm	ppm	ppm	ppm	ppm	ppb	ppm	ppm	ppm	ppm	ppm	ppm	ppm
SABA001	250401191	<1.5				<0.1			<3		6				
SABA002	250401192	<1.5				<0.1			<3		8				
SABA003	250401193	<1.5				<0.1			<3		13				
SABA004	250401194	<1.5				<0.1			<3		**159**				
SABA005	250401197	<1.5				<0.1			<3		**703**				
SABA006	250401198	1.5				<0.1			<3		2470				
SABA007	250401199	1.5				<0.1			<3		3690				

Conclusion: Samples were taken on the 31st of March.

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Environmental Laboratory
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Waste Water Results

Customer: Public Entity Saba
Address: Power Street 1, The Bottom
Phone: 5994167743
Email: nike.dekkers@sabagov.nl

Collection Date:	4/3/2025
Received Date:	4/1/2025
Date of Analysis:	4/1/2025
Date of Release:	4/8/2025

DESCRIPTION	Acccession	BOD	COD	Total Nitrogen	Total Phosphorus	Total Coliform	E. coli	pH	Conductivity
Method >		EPA BOD-5	EPA 410.4	EPA 351.1	USEPA 365.3	Iso:9308 2000	Iso:9308 2000	epa 8156	epa 8160
Reference Value >		<30	<150	<5	<1	<200	<200		
Unit of Measure >		ppm	ppm	ppm	ppm	CFU/100ml	CFU/100ml		µs/cm
SABA008	250403174	6	27	4.5	7.6	TNTC	5	8.0	1320
SABA009	250403175	34	36	4.1	7.1	TNTC	10	8.0	1301
SABA010	250403176	33	90	2.9	0.1	TNTC	26	6.4	333
SABA011	250403178	0	1	0.7	0.0	TNTC	77	7.2	193
SABA012	250403179	0	16	0.9	0.2	69	0	9.8	127
SABA013	250403180	25	32	2.5	4.0	TNTC	TNTC	8.5	125

Conclusion: Samples were taken on April 2nd.
BODs were ran on April 7th. BOD 013 ran on 11-April
Sample 013 too turbid to analyse immediately. Analysis started 14-April

Amanda Bryan | Environmental Department

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Extra Chemistry Results

Customer: Public Entity Saba
Address: Power Street 1, The Bottom
Phone: 5994167743

Collection Date:	4/3/2025
Received Date:	4/3/2025
Date of Analysis:	4/3/2025
Date of Release:	4/5/2025

DESCRIPTION	Acccession	Lithium*	Sodium*	Ammonium*	Potassium*	Manganese*	Calcium*	Magnesium*	Aluminum	Zinc	Ammonia	Boron*	Cadmium*	Alkalinity	Hardness*
Method >		iso 14911	iso 14911	iso 14911	iso 14911	iso 14911	iso 14911	iso 14911	epa						
Reference Value >		<0.2	<120	<0.5	<150	<0.05			<0.2	<3	<0.5	<0.3	<0.003		
Unit of Measure >		ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
SABA008	250403174			<0.1	22		60	17						189	216
SABA009	250403175			<0.1	18		61	17						171	221
SABA010	250403176			<0.1	8		13	7						19	49
SABA011	250403178			<0.1	7		9	1						23	14
SABA012	250403179			<0.1	5		27	1						73	63
SABA013	250403180			<0.1	2		18	4						39	51

Conclusion: Samples were taken on the 2nd of April.

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DESCRIPTION	Acccession	Fluoride*	Chlorite*	Bromate*	Chloride*	Nitrite	Bromide*	Chlorate*	Nitrate*	Phosphate	Sulfate*	Iron	Cupper*	Lead*	Nickel*
Method >		iso 10304	iso 10304	iso 10304	iso 10304	iso 10304	iso 10304	iso 10304	iso 10304	iso 10304	iso 10304	epa 3500Fe-B		<0.01	<0.02
Reference Value >		<1.5		<0.001	<150	<0.1			<50		<150	<0.2	<2		
Unit of Measure >		ppm	ppm	ppm	ppm	ppm	ppm	ppb	ppm	ppm	ppm	ppm	ppm	ppm	ppm
SABA008	250403174	<0.3				<0.1			<3		104				
SABA009	250403175	<0.3				<0.1			<3		75				
SABA010	250403176	<0.3				<0.1			<3		21				
SABA011	250403178	<0.3				<0.1			<3		9				
SABA012	250403179	<0.3				<0.1			<3		24				
SABA013	250403180	<0.3				<0.1			<3		87				

Conclusion: Samples were taken on the 2nd of April.

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A.4 Water and Nutrient Balance

Catchment number	Elevation precipitation factor	area (m^2)	Area percentage of total area	percentage urban within catchment	percentage urban of total	Precipitation per catchment (mm annually)	Evapotranspiration (mm annually)	Total groundwater recharge (mm)	Deep groundwater recharge (mm annually)	Groundwater interflow (mm annually)	Total N input per catchment(kg/d)	Total P input per catchment (kg/d)	N concentration in deep groundwater (mg/L)	P concentration in deep groundwater (mg/L)	N concentration in groundwater interflow (mg/L)	p concentration in groundwater interflow (mg/L)
1	1.24	1964048.1	15%	8.0	27.7	1117.5	714.0	403.6	285.6	118.0	18.4	3.6	9.6	1.8	5.8	1.1
2	1.14	1458897.6	11%	3.2	8.1	1028.2	656.9	371.3	262.8	108.5	10.4	2.0	7.9	1.5	4.8	0.9
3	1.19	1115840.0	9%	5.7	11.1	1072.1	684.9	387.1	274.0	113.2	9.2	1.8	8.8	1.7	5.3	1.0
4	1.14	1001151.3	8%	5.5	9.7	1029.1	657.5	371.6	263.0	108.6	8.2	1.6	9.1	1.8	5.5	1.1
5	1.17	858618.6	7%	6.5	9.9	1052.1	672.2	379.9	268.9	111.1	7.9	1.5	10.0	1.9	6.0	1.2
6	1.22	854252.9	7%	0.1	0.2	1094.1	699.0	395.1	279.6	115.5	4.9	1.0	6.0	1.2	3.6	0.7
7	1.22	785916.1	6%	0.0	0.0	1097.4	701.1	396.3	280.5	115.8	4.4	0.9	5.9	1.2	3.6	0.7
8	1.13	783036.9	6%	0.9	1.2	1012.5	646.9	365.6	258.8	106.9	4.7	0.9	6.8	1.3	4.1	0.8
9	1.09	688193.6	5%	2.8	3.4	983.7	628.5	355.2	251.4	103.8	4.8	0.9	8.0	1.6	4.9	1.0
10	1.10	635179.9	5%	0.0	0.0	985.9	629.9	356.0	251.9	104.1	3.6	0.7	6.5	1.3	4.0	0.8
11	1.10	544660.9	4%	0.5	0.5	986.0	630.0	356.1	252.0	104.1	3.2	0.6	6.8	1.3	4.1	0.8
12	1.10	517747.4	4%	21.4	19.4	994.4	635.3	359.1	254.1	105.0	8.1	1.5	17.9	3.4	10.8	2.1
13	1.08	499084.4	4%	6.5	5.7	972.6	621.4	351.2	248.5	102.7	4.3	0.8	10.2	2.0	6.2	1.2
14	1.08	491987.0	4%	0.8	0.7	973.8	622.1	351.6	248.9	102.8	3.0	0.6	7.1	1.4	4.3	0.8
15	1.09	462235.9	4%	3.1	2.5	985.3	629.5	355.8	251.8	104.0	3.3	0.6	8.2	1.6	5.0	1.0
16	1.06	455251.7	3%	0.0	0.0	956.3	610.9	345.3	244.4	100.9	2.6	0.5	6.7	1.3	4.1	0.8
Total	1.00					900.0	575.0	325.0	230.0	95.0	100.8	19.7	8.5	1.7	5.1	1.0

2021-2024 mean precipitation	900.00
Assumed percentages not during peak events, but the rest of the year	
Assumed percentage evapotranspiration	**80%**
Assumed percentage recharge	20%
Assumed percentage deep gw recharge	**100%**
Left over recharge (apart from peak events)	675.00
Piek buien, uitgaande van 4 per jaar. 25% van de neerslag in piekbuien	
Percentage totale neerslag in piekbuien	**25%**
Neerslag in piekbuien	225
Verdamping tijdens piekbuien	**35**
Verdamping in percentage	16%
Assumed percentage deep gw recharge tijdens piekbui	**50%**
Assumed percentage interflow tijdens piekbui	50%
Assumed percentage nutrients to deep and interflow gw recharge	
Assumed percentage nutrients deep gw recharge	**80%**
Assumed percentage nutrients interflow	20%

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