

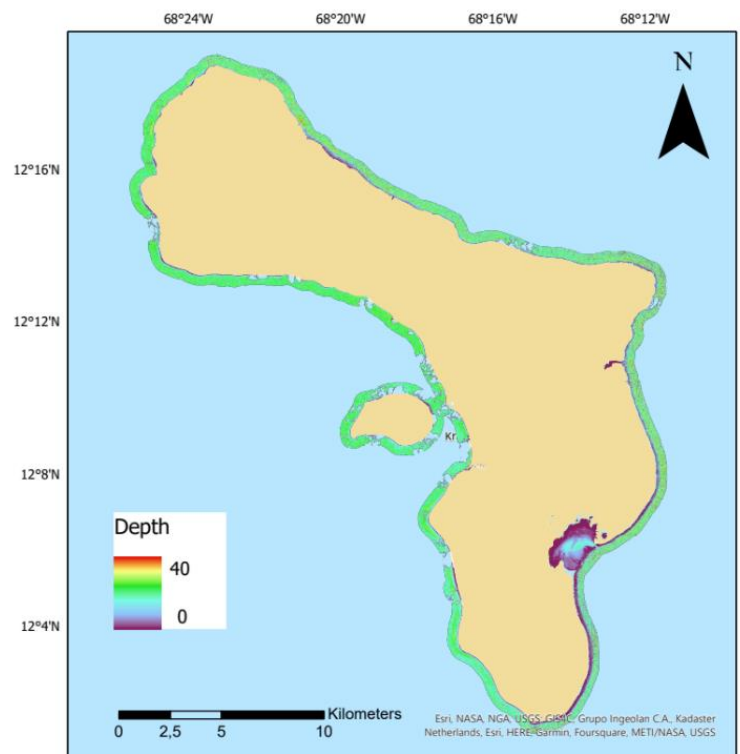
Geo-information Science and Remote Sensing  
Thesis Report GIRS-2023-29

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**Mapping the bathymetry of Bonaire through the use of  
satellite data**

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18-05-2023



**WAGENINGEN**  
UNIVERSITY & RESEARCH

# **Mapping the bathymetry of Bonaire through the use of satellite data**

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## Foreword

Since I was a child I have always been interested in the ocean and the animals that live there. I am especially fascinated by corals due to their many colours and importance. Therefore, when I got the chance to combine my two interests in geo-information sciences and coral reefs, I was immediately motivated to start this research. However, I could not have done this research without the help of some people.

Firstly, I would like to thank both my supervisors, Jan Clevers and Sander Mùcher. Thanks to their feedback, availability for meetings and questions, and their insights and suggestions, I was able to complete this research. I would like to give a special thanks for their fast feedback on my report, which made it possible for me to submit the report on time. Furthermore, I would like to thank Erik Meesters for providing the in-situ measurements which made it possible to do this research. Lastly, I would like to thank my friends and parents who checked up on me or offered help. This also helped to keep me motivated.

## Abstract

Bonaire is home to a wide range of biodiversity, and especially in the shallow coastal waters where coral reefs occur. Coral reefs provide many important ecosystem services and should therefore be protected. However, they are threatened due to many causes like global warming and diseases. Therefore, knowledge about their habitat, the shallow coastal waters, is crucial in order to ensure the conservation of this organism. This knowledge is attainable through the use of satellite data, which is called satellite-derived bathymetry (SDB). The basic principle behind SDB is the relationship between the attenuation of radiance, on one hand, and the depth and wavelength in the water column on the other. This research aims to investigate the possibilities of satellite-derived bathymetry for the island of Bonaire. Furthermore, it explores which method achieves the most accurate bathymetric models and to what extent accurate estimation of bathymetry is possible.

For this research, the bathymetry was calculated with an empirical approach that makes use of in-situ measurements and a ratio between the green and blue band. However, in order to be able to apply this formula, the data first had to be preprocessed. These preprocessing steps included the masking of land/clouds and a sun glint correction. The masking was done through thresholds of reflectance values in the visible bands. The masked images were then deglinted. After deglinting, the data was ready for the calculation of the bathymetry. This was done using two formulas:  $SDB_A$  and  $SDB_B$ . The formula of  $SDB_A$  was calibrated using all in-situ depths less than 30 metres whereas  $SDB_B$  was calibrated using all depths less than 20 metres.

The results were validated by determining the Root Mean Square Error (RMSE) for the different depth classes: 1-10m, 10-20m, and 20-30m. However, since this research mainly focuses on shallow coastal waters, especially the 1-10m depth class was interesting. The results showed that the models created with  $SDB_B$  were more accurate for depth class 1-10m, compared to the results with  $SDB_A$ . The average RMSE of depth class 1-10m for the most accurate method was 4.11m. The most accurate bathymetric model had an RMSE of 3.58m for depth class 1-10m. However, the RMSEs for the other depth classes showed that this method is not applicable for accurate results in deeper depth classes. This research showed that there are possibilities for the island of Bonaire regarding satellite-derived bathymetry. However, more research needs to be done in order to create more accurate results and be able to circumvent limitations.

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# 1. Introduction

## 1.1 Context

There is approximately 260.000 – 600.000 km<sup>2</sup> surface of coral reefs in the world (Knowlton et al., 2010). Coral reefs provide crucial functions when it comes to livelihood for humans and animals. It is estimated that there are approximately 830.000 multi-cellular species on coral reefs in the world (Fisher et al., 2015). Moreover, corals attract tourism, feed humans, protect shorelines, and ensure habitat for other organisms (Dietzel et al., 2021). However, coral abundances are declining in reefs around the world (Holstein et al., 2022). Coral reefs, especially tropical corals, are threatened worldwide by various causes, the most significant being global climate change (Wilkinson, 1999). It is estimated that, if temperatures rise by 4 degrees due to climate change, the area of suitable habitats for corals will decrease by 46% (Descombes et al., 2015). Corals function through the use of a symbiotic relationship between the coral host and an algal symbiont. The thermal stress caused by climate change interferes with this symbiotic relationship which can result in coral mortality (Holstein et al., 2022).

This negative impact of climate change on reef health is also visible in Bonaire (Schep et al., 2022). Bonaire is a Dutch Caribbean island located near Venezuela. The island is home to a wide range of terrestrial and marine biodiversity, making it a focus point for tourism and nature conservation. Bonaire is surrounded by a narrow fringe of coral reefs with an estimated area of 27 km<sup>2</sup> (Cooper, 2011). The coral reefs of Bonaire consist of various species of coral which provide habitat to more than 340 fish species (Cooper, 2011). Furthermore, the reefs function as one of the biggest attractions for tourists in Bonaire, thereby contributing to the economy of the island (Schep et al., 2013; Schep et al., 2022).

Besides the effects of climate change, coral reefs in Bonaire are also threatened by hurricanes and diseases. The most significant damage was done in the year 1999 when Hurricane Lenny passed Bonaire and caused the coral reefs to be fragmented and bleached (Bries, Debrot & Meyer, 2004). Furthermore, the reefs of Bonaire decline due to various diseases, most notably the White Band Disease (Alós LLuesma, 2022). Nature conservation is needed if we want to prevent coral from decreasing even more. Monitoring is an essential tool for nature conservation. Through monitoring, it is possible to obtain knowledge of species and conditions. This knowledge is crucial for the effective management of marine ecosystems like coral reefs and lagoons (Hoeksema, 2022). In order to conserve the Bonaire marine ecosystems with their associated marine life and their services, a large marine park is established and managed by STINAPA Bonaire (Hoeksema, 2022).

A major monitoring method applied in marine research is bathymetry. Marine bathymetry or seafloor mapping can be defined as the quantification of water depths in the ocean (Jawak, Vadlamani & Luis, 2015). A bathymetry model can be used as a monitoring tool for underwater topography and to track the movements of deposited sediments (Jawak, Vadlamani & Luis, 2015). Furthermore, bathymetry models can be combined with Digital Terrain Models to create a complete topographic model, which could be applied in various conservation studies. According to Wölfl et al. (2019), bathymetry data can be crucial to ensure sustainable usage and management of the world's oceans. Bathymetric data is also crucial for water column correction of satellite imagery for benthic mapping. Moreover, bathymetry can play a pivotal role in our understanding of patterns in coastal waters since the water depth has an exponential relationship with light attenuation (Li et al., 2019). Lastly, it is found that bathymetry is one of the main drivers for benthic species distribution (Wölfl et al., 2019).

The first attempts at mapping the seafloor go back to ancient Egypt 3000 years ago (Wölfl et al., 2019). In the centuries after, humankind has improved techniques for bathymetry, ranging from at first Single Beam Echo-Sounders (SBES) to later Multibeam Echo-Sounders (MBES). The principle of both these techniques was the determination of the seafloor depth by calculating the time it takes a sound wave to be sent to and received from the seafloor. SBES calculates the seafloor in a line whereas MBES computes a whole area (Dierssen, Theberge & Wang, 2014). A disadvantage is that these echo-sounders are often placed on a ship that cannot always reach shallow waters, such as coral reefs, causing data gaps to occur.

More recently, the bathymetry of shallow coastal waters can be determined using satellites. This practice is called Satellite-Derived Bathymetry (SDB). SDB is more advantageous compared to previous techniques due to fewer costs and a larger possible scale (ARGANS, 2019). SDB relies on the relationship between the attenuation of radiance, on one hand, and the depth and wavelength in the water column on the other (Chybicki, 2017; Wölfl et al., 2019) (shown in Figure 1). However, this relationship can only be seen till a maximum depth of 20-30 metres in ideal circumstances (Stumpf et al., 2003). Furthermore, it is important to take into account the type of substrate on the seafloor, since certain substrates reflect more than others (Stumpf et al., 2003; ARGANS, 2019).

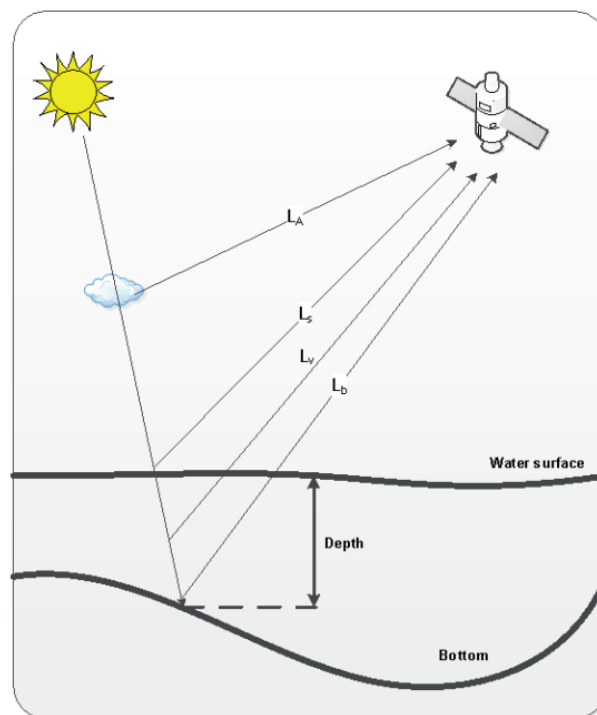


Figure 1: Physical principle of satellite-derived bathymetry (Figure adopted from Chybicki, 2017). The signal received by the sensor consists of atmospheric radiance caused by scattering ( $L_A$ ), the reflection of optical energy from the water surface ( $L_S$ ), subsurface volumetric radiance ( $L_V$ ) and finally reflection of energy from the seabed ( $L_b$ ).

A bathymetry model describing the water depths around Bonaire has been created by the Hydrografische Dienst with solar beams on research vessels. However, there are gaps present in this bathymetric model; especially along the shallow coastal waters, no data is available regarding the bathymetry. This is probably because the water in these gaps is too shallow for research vessels, or the areas are protected. The data gap in the bathymetry model could be filled in manually by doing in-situ measurements of the water depths in the gaps. However, this would be both costly and time-consuming. An alternative would be to apply airborne lidar bathymetry (ALB), but the costs of ALB are extremely high (Sagawa et al., 2019).

Another way to fill in the gaps in the bathymetry model is by utilizing SDB. Instead of measuring the depths in situ, SDB makes it possible to estimate the bathymetry through the use of satellite data. There are different approaches to SDB, but this thesis will focus on the empirical approach using a Linear Ratio equation by Stumpf et al. (2003). This approach was chosen since sufficient in-situ data was available, necessary for the empirical approach. Furthermore, the Linear Ratio equation of Stumpf et al. (2003) was selected since this method provides more accurate results over broad geographic areas, compared to other methods (Jawak et al., 2015). This will be further discussed in the Methods section.

Many studies have used satellite data to derive bathymetry in coastal waters (Jagalingam et al., 2015; Hedley et al., 2018; Li et al., 2019; Al Najar et al., 2021). However, there are only a few studies that applied the Linear Ratio equation on Sentinel-2 data for the calculation of the bathymetry (Chybicki, 2017; Yunus et al., 2019). The studies came across some challenges and problems that could limit the possibilities of satellite-derived bathymetry. Turbidity was a big limiting factor for the study of Chybicki (2017). The study calculated the bathymetry of the Baltic Sea, but due to high turbidity, the bathymetry was only accurate for depths of 12-18 metres (Chybicki, 2017). Yunus et al. (2019) calculated the bathymetry for three areas in the United States. Using the empirical approach, the bathymetric model had a Root Mean Square Error (RMSE) between 1.99 and 4.74 m for the three areas. The main problem here was also caused by water turbidity due to wave action and suspended sediment (Yunus et al., 2019). Nonetheless, both studies concluded that the Linear Ratio equation and Sentinel-2 data can effectively and accurately calculate the bathymetry (Chybicki, 2017; Yunus et al., 2019).

## 1.2 Description of experiment or design

This research will focus on the calculation of the bathymetry of Bonaire using Sentinel-2 satellite imagery for the leeward site of the island. In order to do this, preprocessing steps are needed. These preprocessing steps include atmospheric correction, masking, and deglinting. There are some uncertainties about the accuracy of or the need for the deglinting process. Therefore, this research will compare deglinted with glinted images.

After the preprocessing steps, the bathymetry can be calculated using the formula introduced by Stumpf et al. (2003). This formula is constructed using in-situ data. However, there are uncertainties about which depths to use for the construction of the formula. For this reason, a comparison between bathymetric models will be made. On the one hand, a model will be created using a formula that will be based on all available in-situ depths, and on the other hand, a model is created using a formula based on only in-situ depths up to 20 metres. These bathymetric models will then be validated in terms of overall accuracy, and accuracy per depth class. The accuracy will be measured by looking at the RMSE.

### 1.3 Knowledge gap

It is known that Sentinel-2 data can be used for the accurate estimation of the bathymetry in coastal waters (Hedley et al., 2018; Li et al., 2019). However, much less is known about the use of the Linear Ratio equation and the use of Sentinel-2 data. Moreover, no satellite-derived bathymetry studies have been done on Bonaire, whilst there is a high need for this knowledge in order to protect the valuable biodiversity in coastal waters. At this moment we do not know if satellite-derived bathymetry can be applied on Bonaire and with what accuracy this method can be applied. Furthermore, it is not known if Bonaire poses certain limitations for satellite-derived bathymetry.

### 1.4 Research Aim

The research aim of this thesis is to use Sentinel-2 satellite imagery to create a bathymetric model for Bonaire using satellite-derived bathymetry. This model can then be overlapped with an already existing bathymetric model to fill in the gaps. Moreover, this research aims to gain an understanding of the possibilities and limitations regarding SDB in Bonaire. This will be done by applying the different steps of the calculation of the bathymetry. Each step comes with certain challenges and this research will find out if these challenges can be overcome using the satellite data of Bonaire.

### 1.5 Research questions

*Research question 1: Which method yields the most accurate bathymetric model for Bonaire, using Sentinel-2 data and in-situ measurements?*

The estimation of the bathymetry using satellite data can be done in multiple ways, using various approaches. For this thesis, the empirical approach is applied using the Linear Ratio equation of Stumpf et al. (2003). For this research question, comparisons are made between deglinted and glinted images. Furthermore, a comparison is made between a bathymetric Linear Ratio equation based on all available in-situ depths and one that is only based on in-situ depths less than 20 metres. Assessing the accuracy will be done both statistically and visually. The accuracy will be determined by looking at the RMSE of different depths and distinguishing the seafloor's visual patterns.

*Research question 2: To what extent can Sentinel-2 data be used to determine the bathymetry of shallow-water areas in Bonaire?*

The extent to which Sentinel-2 data can be applied for the derivation of bathymetry will mostly be measured by looking at the maximum possible depths for which accurate bathymetry is possible. Also for this research question, the RMSE of different depths will be used to assess the accuracy.

## 2. Materials and methodology

### 2.1 Study area

The primary study area for this research consists of the complete areas of water that are located on or around Bonaire (shown in Figure 2), but the focus lies on the leeward coastal waters since this is where the gaps in the bathymetry model of the Hydrografische Dienst are located (visible in Figure 3a and b). Derivation of bathymetry along the North-East coast is not possible due to highly turbulent water as a result of trade winds.

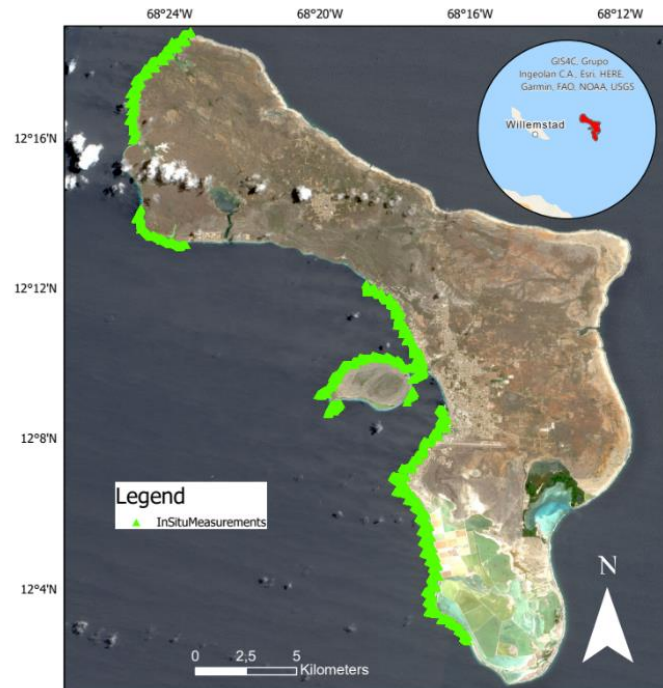


Figure 2: Map of the study area of this thesis: coastal waters surrounding the island of Bonaire. The in-situ measurements used for the calculation of the bathymetry are displayed in green.

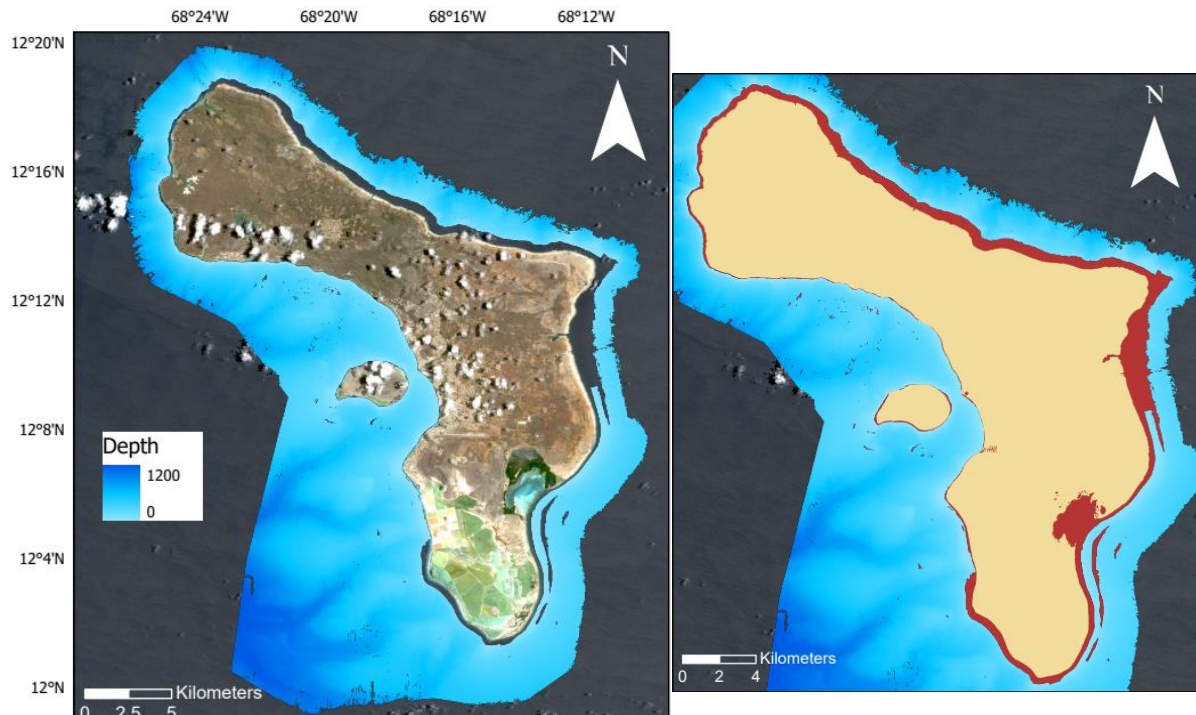


Figure 3a and b: 3a shows a map of the bathymetric model created by the Hydrografische Dienst using large research vessels. 3b shows in red the gaps in the bathymetric model along the coast of Bonaire.

## 2.2 Satellite data

This research makes use of Sentinel-2 products for the derivation of bathymetry since these are publicly available and contain the bands needed for the calculation of empirical bathymetry. Furthermore, Sentinel-2 data offers in comparison to Landsat 8 more advantages concerning spatial resolution, cost-effectiveness, and large-scale coverage (Hedley et al., 2018). In the case of Sentinel-2, the wavelengths that were primarily used were Band 2, 3, 4, and 8 (Table 1). The Blue and Green bands (Band 2 and Band 3 respectively) were used for the calculation of the bathymetry (SNAP, z.dc.; Setiawan et al., 2021). The Red band (Band 4) was used to create RGB images. Lastly, the Near - Infrared (NIR) band (Band 8) was used for the deglinting process and the creation of the land/cloud mask. This is described further on.

*Table 1: Sentinel 2 bands with corresponding resolution and wavelength. Retrieved from GISgeography (2022).*

Band	Resolution	Central Wavelength	Description
B1	60 m	443 nm	Ultra Blue (Coastal and Aerosol)
B2	10 m	490 nm	Blue
B3	10 m	560 nm	Green
B4	10 m	665 nm	Red
B5	20 m	704 nm	Visible and Near Infrared (VNIR)
B6	20 m	740 nm	Visible and Near Infrared (VNIR)
B7	20 m	783 nm	Visible and Near Infrared (VNIR)
B8	10 m	842 nm	Visible and Near Infrared (VNIR)
B8a	20 m	865 nm	Visible and Near Infrared (VNIR)
B9	60 m	940 nm	Short Wave Infrared (SWIR)
B10	60 m	1375 nm	Short Wave Infrared (SWIR)
B11	20 m	1610 nm	Short Wave Infrared (SWIR)
B12	20 m	2190 nm	Short Wave Infrared (SWIR)

Sentinel-2 satellite data was achieved through the Copernicus Open Access Hub. Users can attain two types of Sentinel-2 data: Level 1C and Level 2A. Level 1C products contain Top-of-atmosphere reflectance (TOA). By applying atmospheric correction on the Level 1C products, a Level 2A product can be achieved containing Bottom-of-atmosphere reflectance (BOA). However, the Copernicus Open Access Hub provides Level 2A satellite images. By using these products, it is no longer necessary to apply any atmospheric correction any more, making the process more efficient. Therefore, this research makes use of level 2A Sentinel-2 data from Bonaire.

Furthermore, cloud cover is one of the main limiting factors for satellite data in general, and even more important for the bathymetric calculation. For this reason, the satellite data was selected by filtering out any images with a cloud cover of more than 5%. Lastly, since the bathymetry does not differ significantly between multiple years, there is no specific time period for which the satellite data needed to be filtered (Molinari et al., 2009). In total, three Level 2A Sentinel-2 images were found that complied with the abovementioned conditions, and these three were used for this research (Table 2).

*Table 2: Information about the Sentinel-2 satellite images used for this research*

Number	Date	Time	Cloud cover %	Cloud Shadow %	Satellite
Image 1	2019-08-01	15:07:29	1.29	0.02	B
Image 2	2019-08-21	15:07:29	0.97	0.02	B
Image 3	2019-01-08	15:07:21	2.30	0.16	A

### 2.3 In-situ data

The in-situ measurements (locations shown in Figure 2) were done using a small sonar and were made available by Erik Meesters. The sonar was aboard a small boat and took measurements in the shallower waters surrounding the west coast of Bonaire and also lagoons or lakes. The data consists of point data with information about the latitude, longitude, and depth in metres.

### 2.4 Substrate data

Hyperspectral coral reef classification data (Mücher et al., 2017) was used to filter substrates. Substrates can be described as the type/composition of the seafloor e.g. sand or coral. Hyperspectral classification data contains information about the occurrence of substrates around the coastline of Bonaire. The classification was done by Mücher et al. (2017) using airborne hyperspectral data in the blue and green range of the visible light. As mentioned earlier, various types of substrates can have different reflectance values. Therefore, this research only used in-situ measurements found on one substrate type for the calculation of the bathymetry. By combining hyperspectral classification data with in-situ measurements, it was possible to determine on which substrates each in-situ measurement was found. In-situ measurements found on sand will be used for the calculation since sand has the most homogenous reflectance compared to e.g. coral. Furthermore, sand cover can increase the benthic albedo, thereby increasing the satellite image signal (Werdell & Roesler, 2003).

### 2.5 SNAP and ArcGIS

In order to pre-process the data and calculate the bathymetry of Bonaire, this research made use of two GIS programs. The Sentinel Application Platform (SNAP) toolbox is a program with tools specialised for analysing and processing remote-sensing data (Eoportal, 2022). There are different plugins created which can be used in SNAP for specific purposes, one of these plugins being the Sen2Coral toolbox plugin. This toolbox contains multiple new algorithms relevant to marine studies, such as algorithms for benthic mapping and bathymetry (ESA, 2021). These algorithms have been used for the foundation of this research. The underlying literature and formula for the algorithms in the Sen2Coral toolbox have been applied in this thesis. Furthermore, the toolbox has an algorithm for masking land, clouds, and white caps, which has been used for one of the preprocessing steps. The calculation of the bathymetry and all preprocessing steps, except for masking, was done in ArcGIS. Visualisation of the results was achieved using ArcGIS.

### 2.6 Steps of experiment

The general workflow to derive bathymetry using the empirical Linear Ratio approach was created using the workflow suggested by ARGANS (z.d.) as a baseline and altered using Stumpf et al. (2003) and Chybicki (2017);

- Atmospheric correction
- Subset & resampling
- Land mask/surface & cloud masking
- Sun-glint correction
- Empirical bathymetry
- Validation

It is important to note that this workflow slightly differs from the one used in this research due to a difference in preprocessing steps. As mentioned earlier, Level 2A Sentinel-2 data was used so there was no further need for any atmospheric correction.

The next step consists of subset & resampling. Resampling is necessary to make sure all bands have the same spatial resolution, which is not always the case for Sentinel 2 images (ARGANS, z.d.).

However, for this research, Bands 2, 3, 4, and 8 were used, all with the same spatial resolution of 10 metres for Sentinel-2. Therefore, resampling was not necessary. On the other hand, a subset was created for this research. A subset can be used to generate a dataset that only contains the Area of Interest (AOI). A subset is beneficial to decrease processing times.

#### Land mask/surface & cloud masking

Land masking is done to exclude pixels of land that are not necessary for the calculation. Cloud and white cap masking can be applied to remove pixels containing clouds or breaking waves (ARGANS, z.d.). This preprocessing step is necessary in order to be able to deglint the satellite data and calculate the bathymetry (Stumpf et al., 2003; Hedley et al., 2005). This masking process was done through an algorithm in the Sen2Coral toolbox called the “LandCloudWhiteCapMask Algorithm”. The algorithm masks pixels using a user-set threshold for the NIR band. However, this did not mask the cloud shadows. In order to also filter out the cloud shadows, another threshold was manually applied. This threshold was based on the reflectance values of Band 2 in the cloud shadows. The created mask was exported to ArcGIS, where the image was masked for land, clouds, and cloud shadows using a conditional statement.

#### Sun-glint correction

The fourth preprocessing step covers sun glint. Glint is a phenomenon that occurs in remote sensing of aquatic areas and needs to be corrected for. Glint is defined as the specular reflection of sunlight from the aquatic area into the sensor field of view (Doxani et al., 2013). This phenomenon can occur when the water surface is not flat, e.g. with waves. The consequence of glint is that the benthic data of the satellite data is unusable as it is covered by white bright areas; in other words, the amount of sun glint prevents the visibility of the sea bottom (Hedley et al., 2005; ARGANS, z.d.). Sun-glint correction is therefore crucial for accurate bathymetric calculations. This correction makes use of the method introduced by Hedley et al. (2005) in which sun glint is removed from visible wavelength spectral bands with the use of information from a spectral band in the NIR (Figure 4).

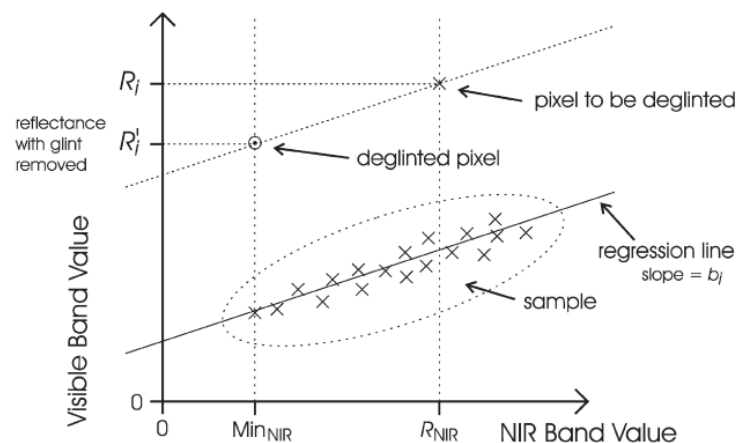


Figure 4: Graphical representation of the deglinting method of Hedley et al. (2005).  
The figure is also created by Hedley et al. (2005)

More specifically, each spectral band in visible wavelengths is corrected one at a time by referring to a band in the NIR or shortwave infrared (SNAP, z.db). In order to do this, it is necessary to select a sample area that shows sun glint, but where the image should be homogenous if there would be no sun glint (so for example deep water). This sample will be used to determine the minimum NIR value and to perform a linear regression between each visible band and the NIR band. The regression slope and minimum NIR value are then used in the formula created by Hedley et al. (2005):

$$R'_i = R_i - b_i (R_{NIR} - Min_{NIR}) \quad (1)$$

where  $R_i$  is the reflectance of band  $i$ ,  $b_i$  is the regression slope,  $R_{NIR}$  is the reflectance of the NIR band and  $Min_{NIR}$  is the minimum NIR value in the sample (Hedley et al., 2005).

The assumption behind this method is that because water is opaque in NIR, the NIR reference band only consists of the glint, and through a simple linear relationship, it is possible to determine the contribution of the glint in the visible band (Hedley et al., 2005; SNAP, z.db). In other words, by choosing a sample that is over deep water, all variance in NIR is caused by glint. This variance can then be used to calculate the amount of glint that is present, and this can then be applied to the visible bands of the whole image. The method of Hedley et al. (2005) was chosen for this research because it is less sensitive to outliers compared to the method by Hochberg et al. (2003) (Hedley et al., 2005).

The sun glint correction was done in ArcGIS by creating a point dataset of 146 points in a deeper part of the sea in the South-West of Bonaire. The reflectance values were exported to Excel. Using the reflectance values of the points, a scatterplot and regression line were created for the reflectances of each visible band on the Y-axis and the NIR values on the X-axis. The slope and minimum NIR value were then applied in the abovementioned formula of Hedley et al. (2005) for each visible band, to create the newly deglinted image in ArcGIS.

#### Empirical bathymetry using the Linear Ratio model

After these preprocessing steps, the data was ready for the derivation of the bathymetry. The bathymetry was calculated empirically, making use of both satellite data and in-situ measurements. This was done through the use of a mathematical relationship between the reflectance recorded from a water body and the known depth of a few points through in-situ measurements, called ground truth (Stumpf et al., 2003; Jawak et al., 2015). According to Jawak et al. (2015), there is a strong correlation between the water depth and the single-band reflectance for waters of uniform optical properties and bottom reflectance. In other words, there is an exponential attenuation of light with depth (SNAP, z.dc). However, each spectral band has a different absorption level over water. This difference can be used to determine the ratio between bands (Stumpf et al., 2003). Stumpf et al. (2003) introduced the so-called Linear Ratio model in which a comparison is made between the attenuation of two spectral bands (Jawak et al., 2015). The model by Stumpf et al. (2003) is summarized by the equation:

$$Z = m_1 \frac{\ln(nR_w(\lambda_i))}{\ln(nR_w(\lambda_j))} - m_0 \quad (2)$$

$Z$  is depth,  $m_1$  is a constant to scale the ratio to depth,  $n$  is a user-set constant to ensure the ratio remains positive under all values,  $R_w$  is observed reflectance, and  $m_0$  is the offset for a depth of  $m_0$ .

The two bands used for this research were the Blue and Green bands (490 nm and 560 nm respectively), where blue was the  $i^{th}$  band and green was the  $j^{th}$  band. These two bands were chosen because they have the lowest attenuation and absorption (Stumpf et al., 2003; Chybicki., 2017). According to Chybicki, the blue band has the smallest attenuation and can penetrate water up to 30 metres. The green band has a larger attenuation and absorption than the blue band, but these are smaller than the attenuation and absorption of the red band (Stumpf et al., 2003). The maximal depth for which accurate bathymetry derivation is possible depends on water turbidity and wavelength registered by the sensor (Chybicki., 2017). Therefore, by using the blue and green bands for the calculation, the derivation depth is the largest possible.

As mentioned earlier, substrate types have different reflectance values which could interfere with the calculation of the bathymetry (Stumpf et al., 2003). For this research, it was decided to use exclusively in-situ measurements located on the sand for the derivation of the bathymetry.

Therefore, before calculating the bathymetry, it was first necessary to make sure other substrate types were filtered out. This was done in ArcGIS by selecting sand in the hyperspectral classification. After this, the reflectance values were exported to Excel where the values of bands 2 and 3 were transformed with a natural logarithm.

The values for  $m_1$  and  $m_0$  were determined by applying a linear regression between the ratio of  $\ln(R_w \text{ Blue})$  and  $\ln(R_w \text{ Green})$  and the depth of the in-situ measurements. A scatterplot was created with on the Y-axis depths of in-situ measurements, and on the X-axis the ratio between the natural logarithms of the green and blue band. A linear regression of this scatterplot gave a formula, for which the slope of the formula corresponded to  $m_1$  and the intersect provided the  $m_0$  (this formula is called  $SDB_A$ ). However, this formula was based on all depths of the in-situ measurements, but according to Stumpf et al. (2003), the relationship between the blue and green Band can only be seen until depths of 20-30 metres. Therefore, another formula was created, by creating another scatterplot, but now with in-situ depths of no more than 20 metres (this formula is called  $SDB_B$ ).

After the calculation in Excel, there were two formulas to calculate the bathymetry;  $SDB_A$  and  $SDB_B$ . These formulas were then applied to both the deglinted and glinted images. So in total, there were 4 bathymetric models per satellite image.

### Validation

The last step was to validate the calculated bathymetric models. In order to do this, it was first necessary to create a dataset of all the in-situ measurements that were not on the sand substrate, the validation data. However, the validation data consisted of all in-situ depths, whereas it is known that the bathymetry is only accurate until depths of 30 metres. Therefore, the in-situ measurements were filtered to only contain depths less than 30 metres. After this, the in-situ measurements in the validation data were compared to the predicted depth by the bathymetric model. The residual was then used to calculate the RMSE. However, since one bathymetric model was created using all in-situ depths and the other using in-situ depths less than 20 metres, the validation was split up into four depth classes: total RMSE, 20-30m RMSE, 10-20m RMSE, and 1-10m RMSE. Lastly, after it was determined which satellite image was the most accurate, this image was also visually assessed. The methods can be summarized by the conceptual figure in Figure 5.

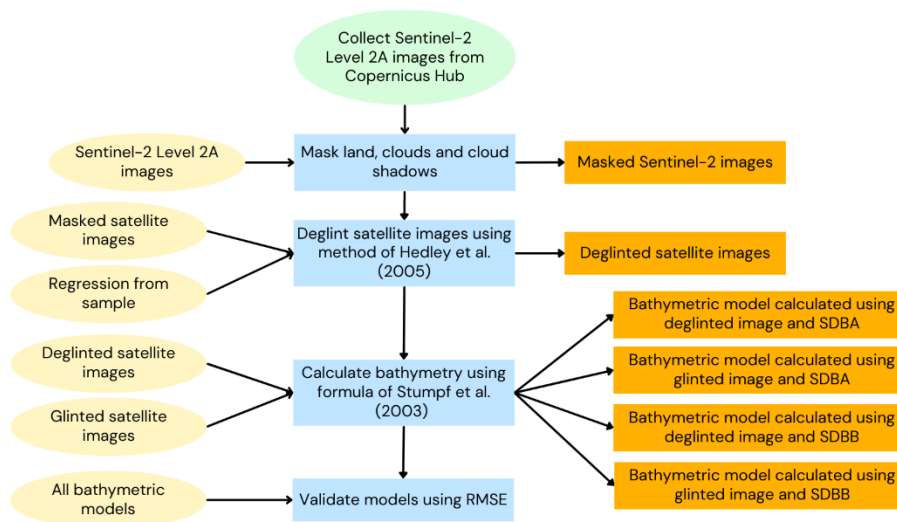


Figure 5: Conceptual figure of the thesis.

### 3. Results

#### 3.1 Accuracy of in-situ data

Before the calculation of the bathymetry, it was first important to validate the accuracy of the in-situ point measurements of Erik. This was done by comparing the points with the depth measurements of the Hydrografische Dienst. It is assumed that due to the high-quality equipment of the Hydrografische Dienst, the bathymetric model and depth measurements of the Hydrografische Dienst are accurate. This validation was done by determining the RMSE of all point measurements with a depth of less than 30 metres (since this is the range for the calculation of the bathymetry). The RMSE of all point measurements was 0.33 metres, so the in-situ measurements were considered accurate enough for this study.

#### 3.2 Cloud Masking

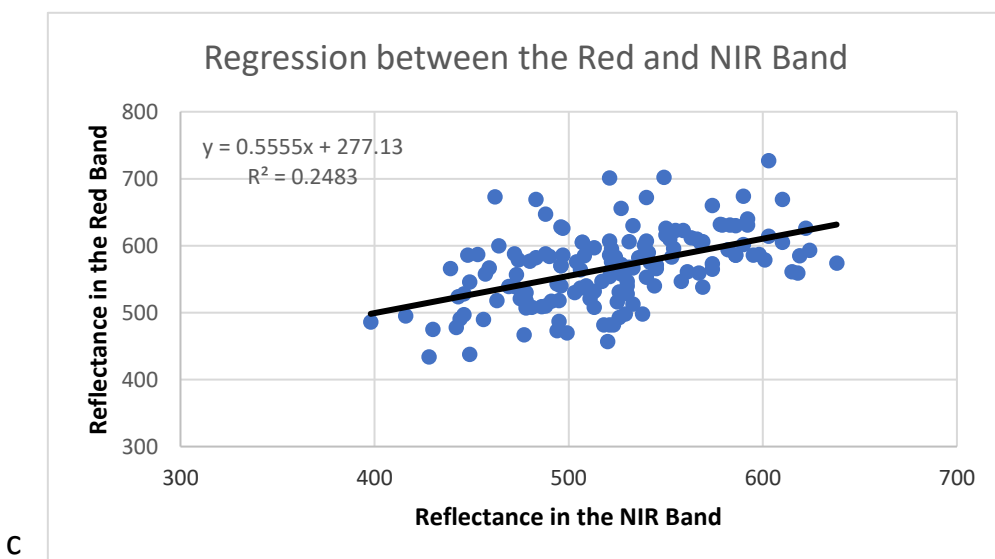
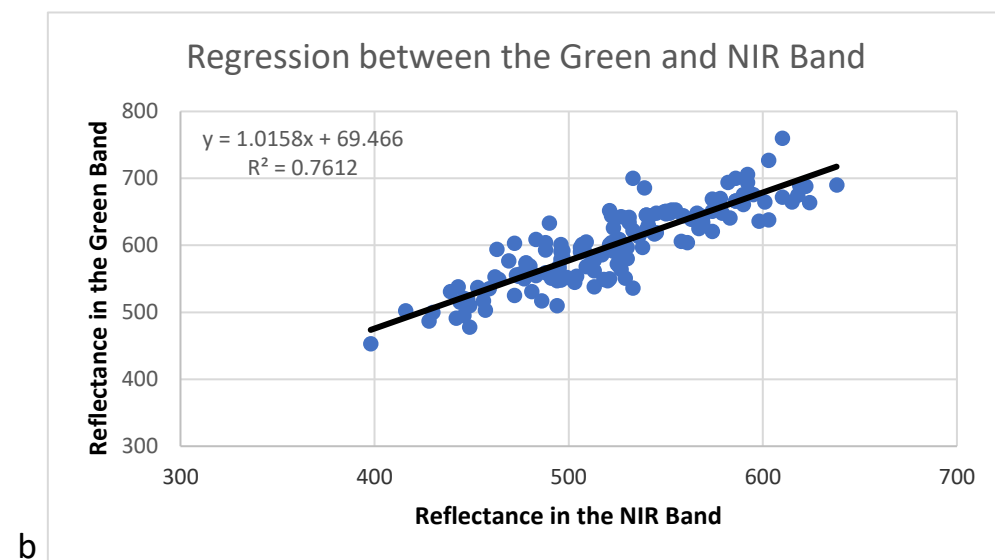
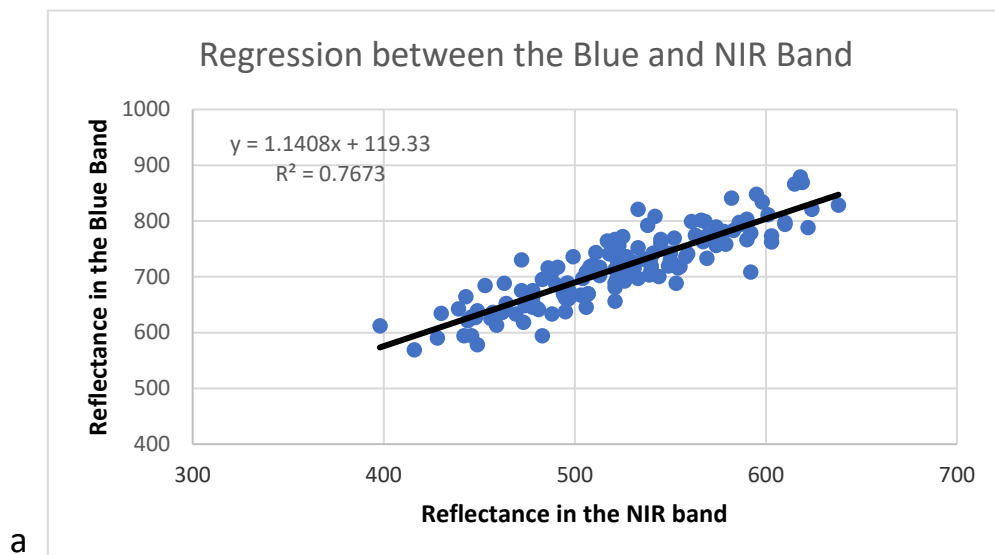
The first results of this research were available during the third processing step. As mentioned in the previous chapter, the third step was the masking of the land and clouds. In Figure 6a, the RGB image of a satellite image of Bonaire is shown. The masking was done in SNAP through the “LandCloudWhiteCapMask algorithm” and provided the mask in Figure 6b. However, the algorithm did not take cloud shadows into account, so the mask was altered with another conditional statement, eventually resulting in the mask shown in Figure 6c.



Figure 6a, b, and, c: Figure 6a shows a RGB image of the island of Bonaire. Figure 6b shows the LandCloudWhiteCap Mask created by SNAP, the parts in black are masked. Figure 6c displays the masked cloud shadows in white. The satellite image was acquired on 2019-01-08.

#### 3.3 Deglinting

After the mask was complete, the data was ready for deglinting. First, the deep sea sample was created south-west of Bonaire. Scatterplots were created using the reflectance values of the sample, with reflectance values for the three visible bands on the Y-axis and the NIR values on the X-axis (shown in Figures 7a, b, and c). The regression line was created and the formula for the line and  $R^2$  were calculated. Remarkably, the  $R^2$  for the Red Band scatterplot was significantly lower than for the other two bands. The regression slope was then used to fill in the formula by Hedley et al. (2005) (eq. (1)) to create the deglinted images. In Figure 9 a deglinted satellite image of Bonaire is presented as an example. The deglinted image was created using the masked glinted image (shown in Figure 8).



Figures 7a, b, and c: Scatterplots with regression lines between the visible bands on the Y-axis and the NIR band on the X-axis. Values are given in reflectance \* 10.000.

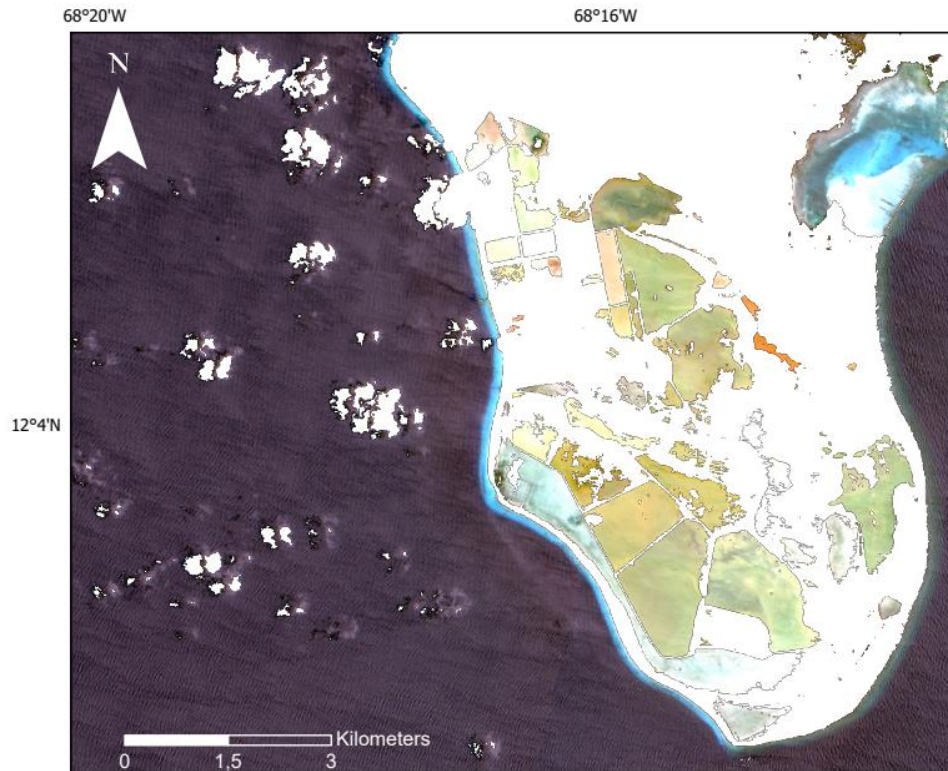


Figure 8: Glinted masked image of Bonaire. Sun glint is clearly visible in the sea, recognizable by the white spots and waves. The satellite image was acquired on 2019-08-21.

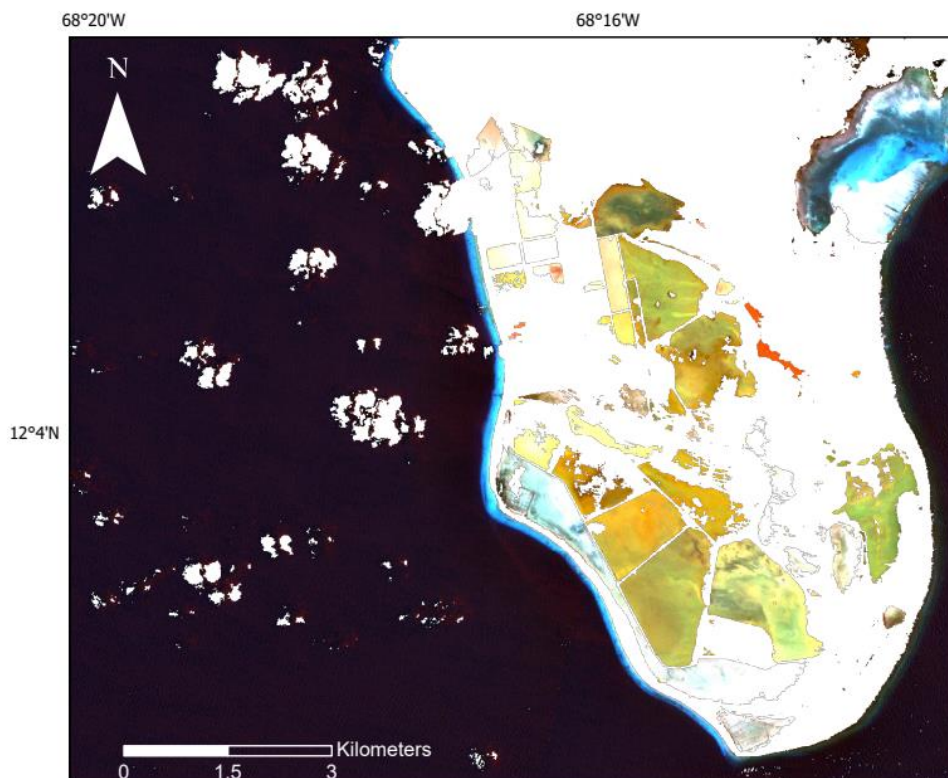
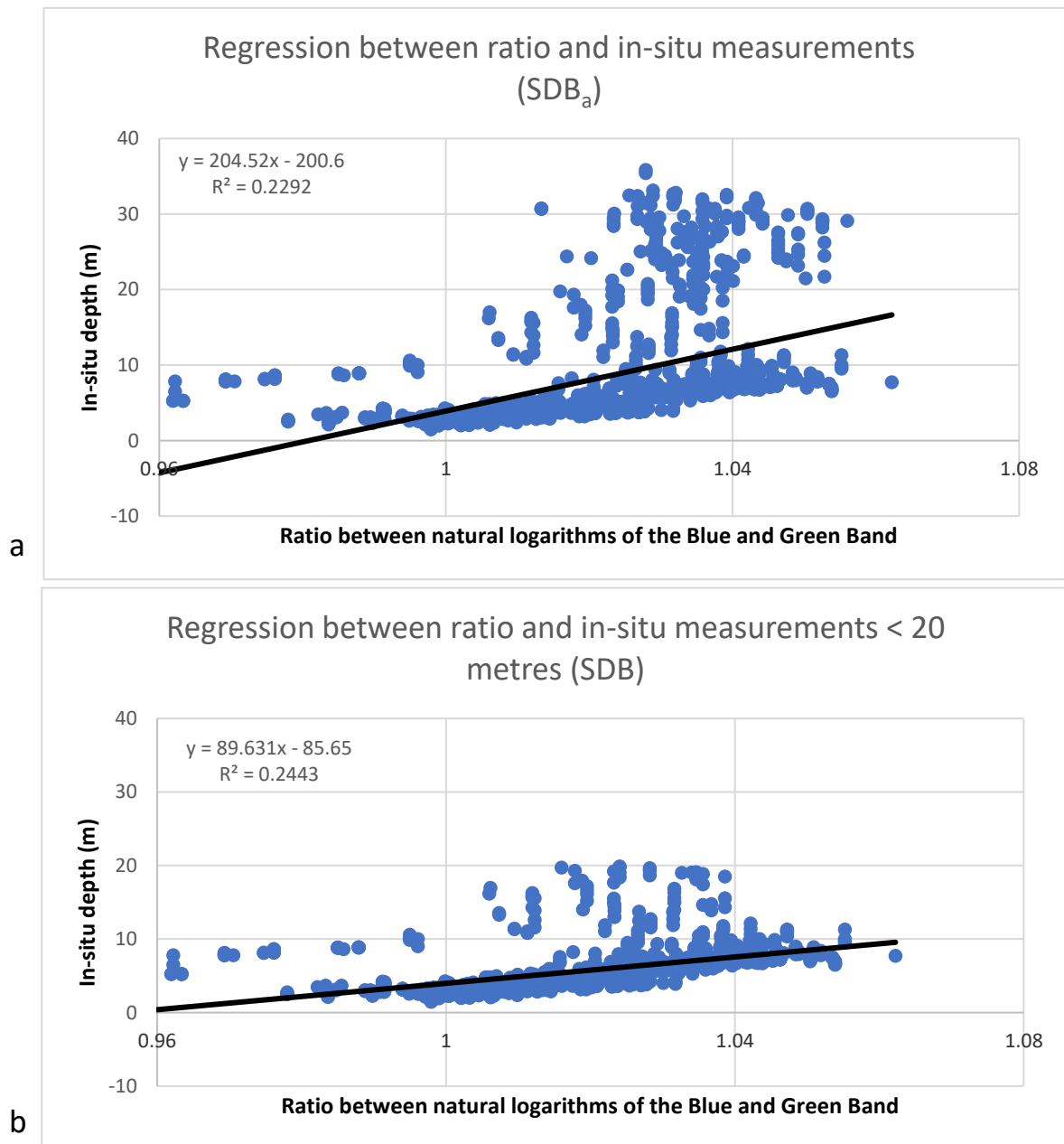


Figure 9: Deglinted image of Bonaire created using the deglinting method by Hedley et al. (2003). The sun glint (white spots and waves over the sea) from the previous image are now much less present. The satellite image was acquired on 2019-08-21.

### 3.4 Bathymetry calculation

The bathymetry was calculated, for both a glinted masked image and a deglinted masked image. In order to do this, it was first necessary to create the scatterplots necessary to calculate the  $m_1$  and  $m_2$  in the formula of Stumpf et al. (2003) (eq. (2)). In Figure 10a a scatterplot is shown with on the X-axis the ratio between the natural logarithms of the Blue and Green, and on the Y-axis the depths of the in-situ measurements over sand. The formula of the regression line can be used to complete  $SDB_A$ . Another scatterplot was created which only took into account the in-situ depths of less than 20 metres, so the formula of this regression line was used for  $SDB_B$  (Figure 10b). It is interesting to see that the  $R^2$  of the second scatterplot is a bit higher than the first one. Despite this difference being small, this could suggest that the bathymetry model calculated with  $SDB_B$  could be slightly more accurate than the bathymetry model calculated with  $SDB_A$ . In Figure 11 an example of a finished bathymetric model is shown, which was created using Graph 10b.



Figures 10a and b: Scatterplots used for the regression between the in-situ depths on the Y-axis and the ratio between the natural logarithms of the Green and Blue band on the X-axis.

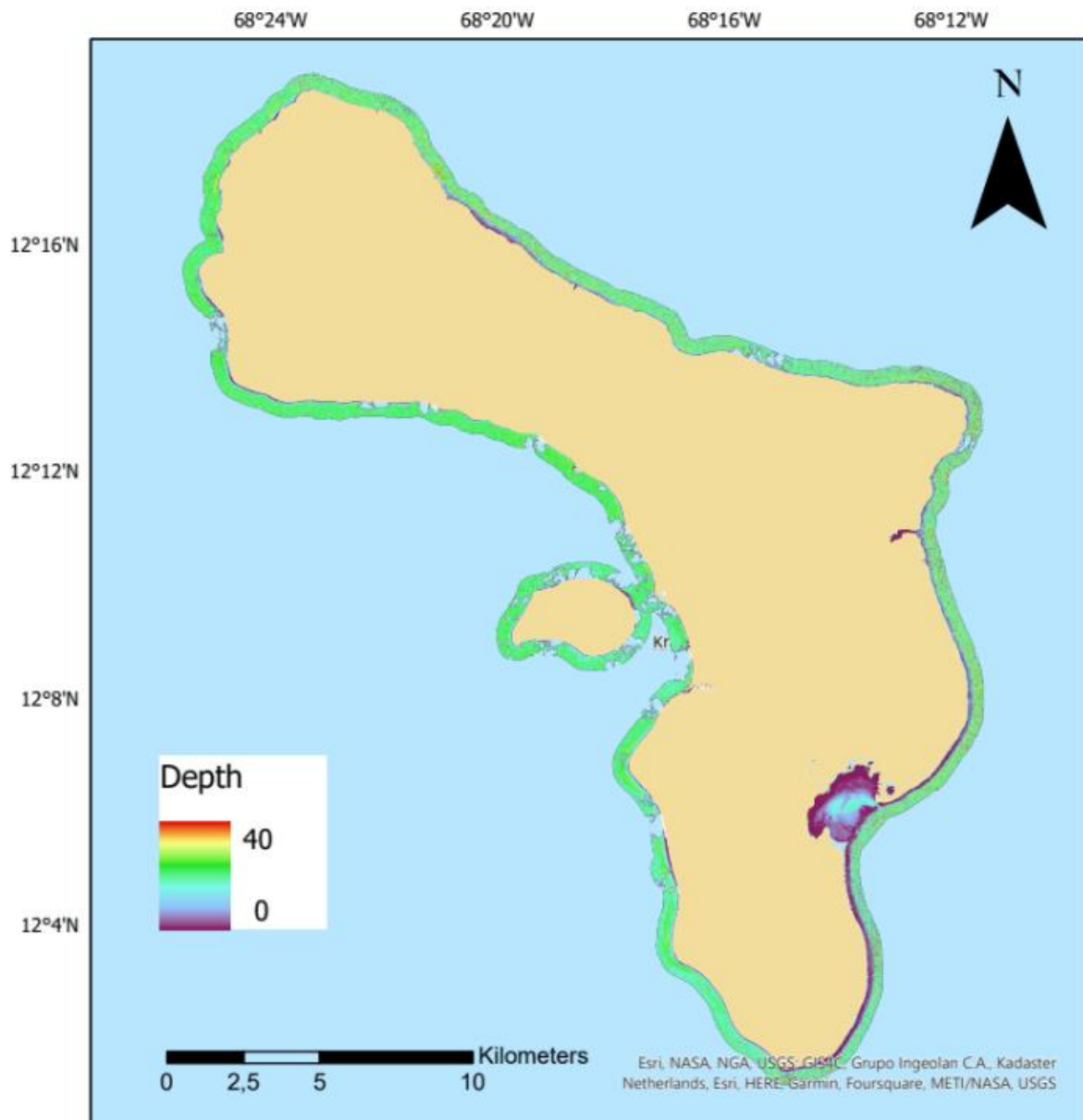


Figure 11: Bathymetric model created using a deglinted satellite image and calculated using formula  $SDB_B$  based on Stumpf et al. (2003). The satellite image was acquired on 2019-08-01.

### 3.5 Bathymetry RMSE

After the calculation of all the bathymetric models, they were validated based on total RMSE and depth class RMSE (Table 3). Interesting to note is that the total RMSE of all four models of satellite image 3 was much lower than the total RMSE of images 1 and 2. Moreover, the highest accuracy for the 1-10m depth class was present in satellite image 1, using a deglinted image and formula SDB<sub>B</sub>. This suggests that deglinting and only using depths less than 20 metres for the calculation of the bathymetry model could be the most accurate method for shallow waters. The depth class of 1-10m is important because many coral reefs occur in this region. Lastly, it is interesting to note that the lowest RMSEs for all depth classes except 1-10m were present in satellite image 3, which was deglinted and calculated using the formula SDB<sub>A</sub>. This in contrast to the highest RMSEs, which were all except one present in satellite image 1, which was glinted and used SDB<sub>B</sub>.

Table 3: Calculated RMSE for the complete images, and per depth class. In yellow are the lowest RMSEs and in red the highest RMSEs.

Satellite Image 1 (2019-08-01)				
	Deglnted SDB <sub>A</sub>	Glinted SDB <sub>A</sub>	Deglnted SDB <sub>B</sub>	Glinted SDB <sub>B</sub>
20-30m RMSE	247.18	280.22	354.02	372.91
10-20m RMSE	37.24	46.99	72.96	80.8
1-10m RMSE	7.96	5.82	3.58	3.86
Total RMSE	61.79	69.45	89.02	94.8

Satellite Image 2 (2019-08-21)				
	Deglnted SDB <sub>A</sub>	Glinted SDB <sub>A</sub>	Deglnted SDB <sub>B</sub>	Glinted SDB <sub>B</sub>
20-30m RMSE	263.62	273.87	354.97	364.79
10-20m RMSE	53.38	49.28	77.27	79.03
1-10m RMSE	9.63	6.61	4.94	4.57
Total RMSE	65.45	64.5	84.88	86.84

Satellite Image 3 (2019-01-08)				
	Deglnted SDB <sub>A</sub>	Glinted SDB <sub>A</sub>	Deglnted SDB <sub>B</sub>	Glinted SDB <sub>B</sub>
20-30m RMSE	96.9	133.93	179.04	237.06
10-20m RMSE	31.8	37.12	32.34	46.42
1-10m RMSE	12.58	9.75	4.62	3.89
Total RMSE	33.96	40.99	45.77	60.3

### 3.6 Comparison between methods

The shallow waters are specifically interesting for this research due to the occurrence of coral reefs. Therefore, in this section, the bathymetric models of satellite image 1 will be visually compared for shallow waters. In order to visually validate these models, Figures 12a, b, c, and, d show zoomed-in parts of the bathymetric models of satellite image 1. Interesting is the big difference between Figures 12a and 12c, and 12b and 12d. 12a and c are both calculated using a glinted image, whereas 12b and d were both calculated using a deglinted image. The only variable that differs is the used formula;  $SDB_A$  was used for 12a and 12b, and  $SDB_B$  was used for 12c and 12d.

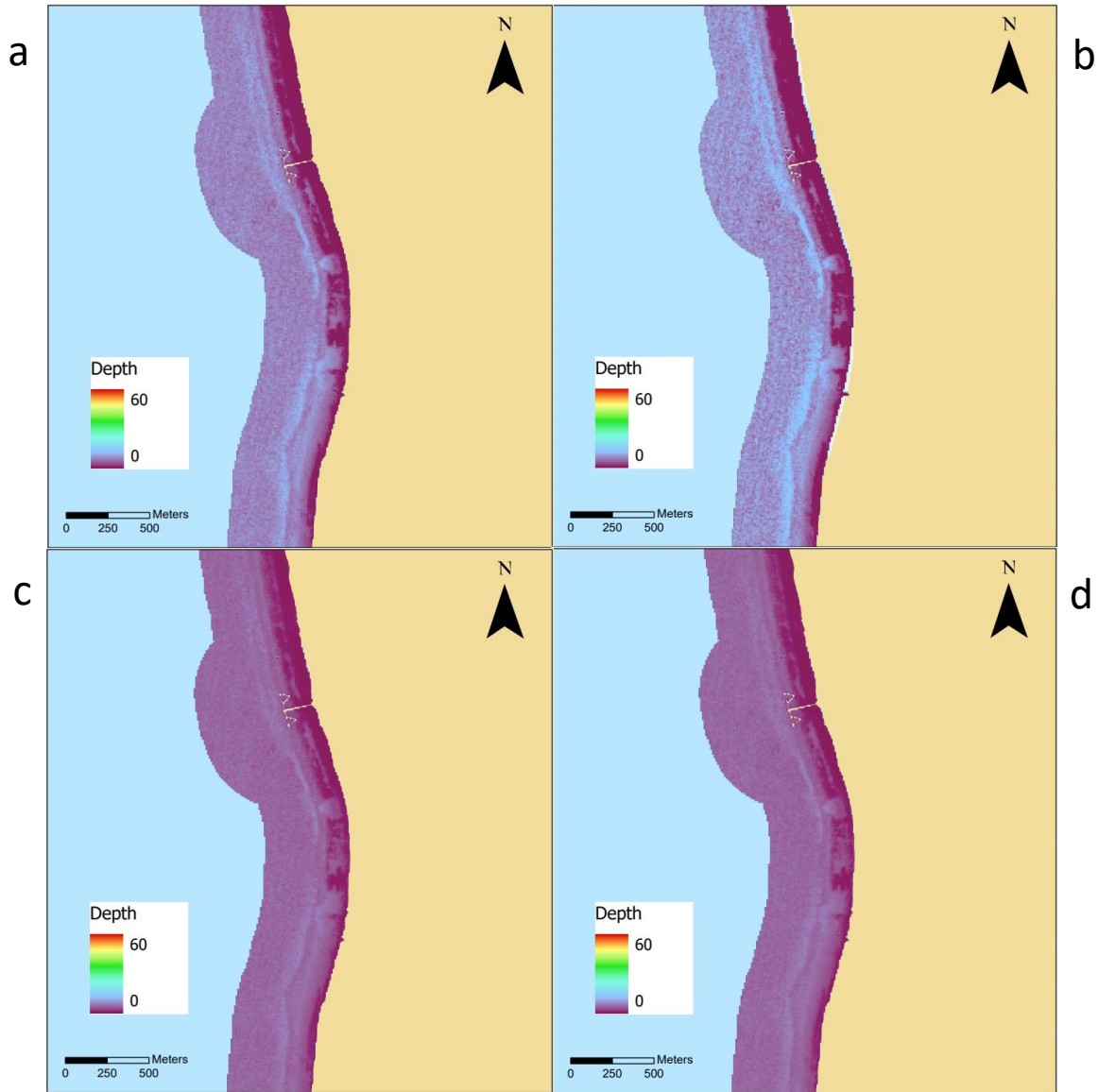


Figure 12: Zoomed-in parts of the bathymetric model. 12a was calculated by keeping the image glinted and applying formula  $SDB_A$ . For 12b the image was deglinted and again formula  $SDB_A$  was used. The model in 12c was formed by keeping the image glinted and applying formula  $SDB_B$ . And lastly, 12d was deglinted and formula  $SDB_B$  was used for the calculation of the bathymetry. The satellite image was acquired on 2019-08-01.

These abovementioned differences between the methods are also visible by looking at the RMSEs for satellite image 1 (Table 3). The RMSEs for 12a, b, c, and d are 5.82, 7.96, 3.86, and 3.58, respectively. Images 12c and d have the most similar bathymetric model, and their RMSEs are also the closest to each other.

### 3.7 Determining the most accurate method

Next, it is important to find out which method provides the most accurate bathymetric model. Again, since the shallow waters are the most interesting, this is where the focus of this comparison lies. With an average RMSE of 4.11 for the glinted method using formula  $SDB_B$ , it can be concluded that this method yields the most accurate results for depth class 1-10m (Table 4).

Table 4: The average of the RMSEs over the three satellite images for each used method. By calculating this, it is possible to determine for each depth class which method had the lowest average of RMSEs over the three images, so which method gives the most accurate results. In yellow is the lowest average RMSE marked.

The average RMSEs over the three satellite images				
	Deglnted $SDB_A$	Glinted $SDB_A$	Deglnted $SDB_B$	Glinted $SDB_B$
20-30m RMSE	202.57	229.34	296.01	324.92
10-20m RMSE	40.81	44.46	60.86	68.75
1-10m RMSE	10.06	7.39	4.38	4.11
Total RMSE	53.73	58.31	73.22	80.65

### 3.8 Comparison with reality

Next, a visual comparison is made between the most accurate bathymetric model for the shallow waters (Figure 13a) and an RGB image (Figure 13b). It is interesting to see that the bathymetric model shows patterns in the water that are also visible in the RGB imagery.

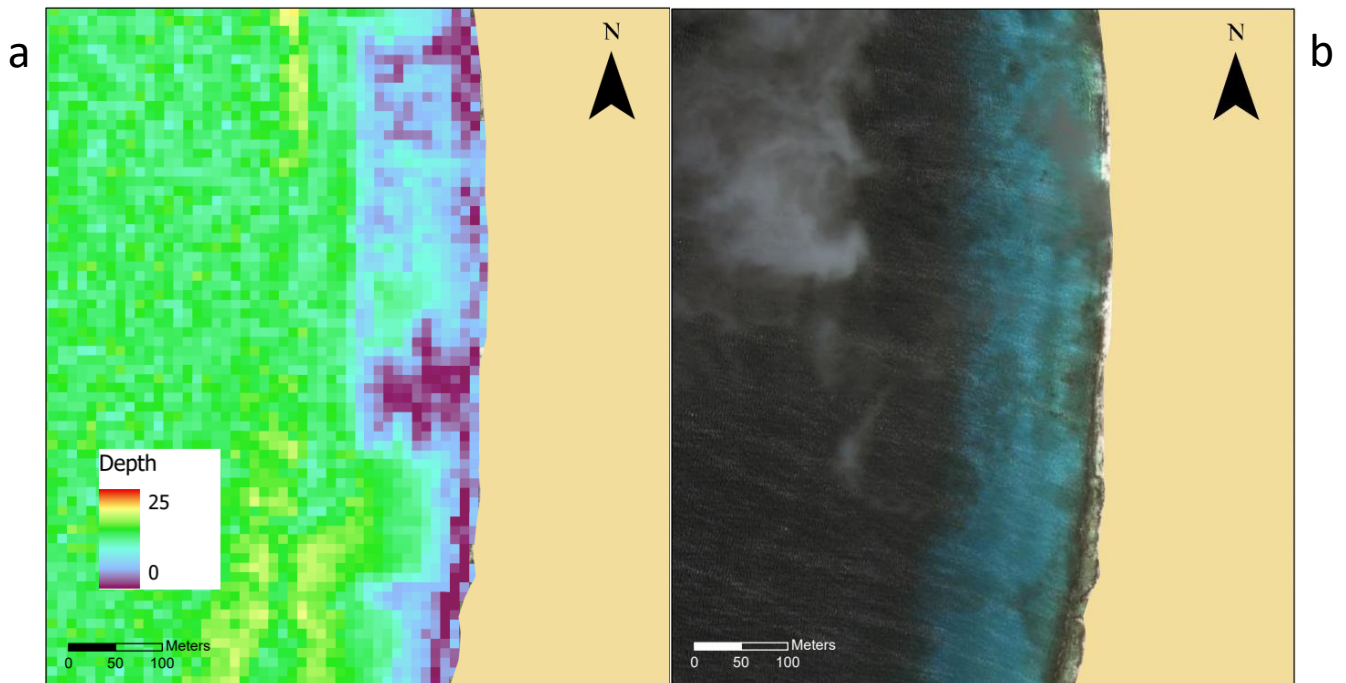


Figure 13a and b: Visual comparison between the most accurate bathymetric model (a) and an RGB image (b). The satellite image was acquired on 2019-08-01.

### 3.9 Comparison with Hydrografische Dienst

Lastly, the most accurate bathymetric model created in this research is compared to the bathymetric model of the Hydrografische Dienst. As can be seen in Figures 14a and b, the absolute values of the two bathymetric models are not similar to each other. However, visually, a resemblance is more present. As can be seen in the red squares, the bathymetric models share some similarities regarding the depth patterns in the coastal waters.

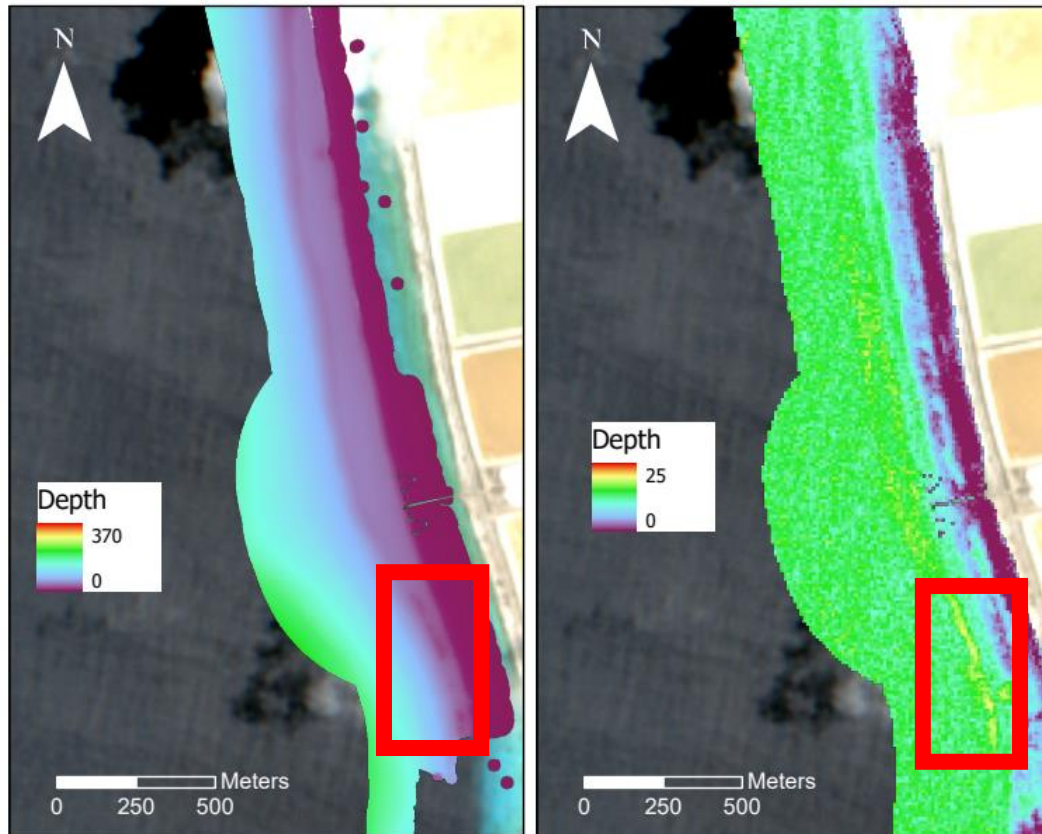


Figure 14a and b: Figure 14a shows a zoomed-in image of the calculated model in this research using a deglinted image and formula  $SDB_b$ . Figure 14b displays a zoomed-in image of the bathymetric model created by the Hydrografische Dienst. The satellite image was acquired on 2019-08-01.

For the results, some sections only provide a visualisation of one of the satellite images. The visualisations of the other images are available in the Appendix.

## 4. Discussion

Regarding the deglinting process, the results show that the regression line of the Red band has a very low  $R^2$  of 0.25, especially compared to the Blue and Green Bands which were both approximately 0.76. This means that the regression lines of the Blue and Green Bands fit the data much better than the regression line of the Red Band. However, it is important to note that the deglinted Red Band is only used for the visualisation and is not actually applied in the calculation of the bathymetry. This is in comparison to the Blue and Green Bands, these are both essential for the derivation of the bathymetry and therefore it is important that these regression lines have a good fit of the data. Another thing to keep in mind is the resolution: the bands used in this research have a spatial resolution of 10 metres. This spatial resolution could result in a variation in sub-pixel sunglint, and the correction of the sun glint could lead to noise (Wicaksono et al. 2021).

For this thesis, two formulas were used for the calculation of the bathymetry:  $SDB_A$  and  $SDB_B$ .  $SDB_A$  is the original formula created by Stumpf et al. (2003). However, because this research focuses on shallow waters, it was decided that another formula would be created, which was more applicable to these waters. The results confirm that  $SDB_B$  is indeed more applicable to shallow waters, compared to  $SDB_A$  (Table 3). For all satellite images, the RMSEs of the 1-10m depth class are lower for  $SDB_B$  than  $SDB_A$ , meaning  $SDB_B$  provided more accurate bathymetric results for the 1-10m depth class. However, when looking at the 10-20m depth class, the results were more accurate for  $SDB_A$ . Furthermore, the total RMSEs were also lower for  $SDB_A$ . This shows that the used formula should depend on the application. If the focus lies on only the shallow waters, it might be more beneficial to modify the formula of Stumpf et al. (2003) by calibrating it on lower depths.

It is interesting to see that the deglinting did not improve the accuracy for all depth classes. The deglinted images provided a lower total RMSE and lower RMSEs for depth classes 10-20m and 20-30m, compared to glinted images (Table 3). However, for depth class 1-10m, the results show that the model was almost for all images more accurate when using a glinted image. This suggests that sun glint might be dependent on water depth, and that sun glint plays a larger role in deeper waters. The RMSEs for the methods that used a glinted image are mostly lower than the RMSEs for methods that used a deglinted image. However, this is not the case for satellite image 1. Here, the deglinted image provided the most accurate result for depth class 1-10m with an RMSE of 3.58. A possible explanation could be that more sun glint was present on the acquisition day of satellite image 1 compared to the other two images.

The lowest average RMSE for the three satellite images was found for the method which uses a glinted image (Table 4). This suggests that for the calculation of the bathymetry of shallow waters, it is not necessary to deglint the image. However, the difference between the RMSEs of glinted and deglinted using  $SDB_B$  is 0.27m and this is only based on three images so it could be caused by chance. There are many different processes and factors that could influence the accuracy of the images, and because of the small sample size (of 3 images), the conclusions of this research may not be completely accurate to reality.

Moreover, when looking at the RMSEs, it is visible that the method applied in this research is more accurate for the lower depths. The RMSEs of a few hundred for depth class 20-30m suggest that the methods of this research are not feasible for these depths. This is in line with Stumpf et al. (2003) who state that this methodology yields accurate results for depths up to 20-30 metres. However, you could discuss an RMSE of 10 metres for the depth class 10-20m is also not accurate. If we compare the RMSEs of this research to similar studies, they are in the same order of magnitude. A study by Dewi and Rizaldy (2021) used the formula of Stumpf et al. (2003) to determine the bathymetry for an area with depths up to 15 metres and found the lowest RMSEs to be 3.624 for a deglinted image and 4.878 for a glinted image.

Furthermore, the lowest RMSE of the study by Chybicki (2017) was a bit lower at 1.653m. Lastly, a study by Yunus et al. (2019) gave an RMSE between 1.99 and 4.74m. With the lowest average RMSE of 3.58, it is visible that the results of this research achieved a similar accuracy compared to other studies.

### **Limitations**

However, even though the accuracy of this research is similar to other studies, there are certain factors limiting the accuracy. First of all, the Sentinel bands used for the calculation of the bathymetry all had a spatial resolution of 10 metres. This is in contrast to the point measurements of the in-situ data, which have a much higher spatial resolution. This means that there could be multiple point measurements in one Sentinel-2 pixel, meaning that these point measurements will have the same reflectance values. This could result in inaccuracies regarding the depths.

Furthermore, it is important to discuss whether the in-situ measurements are accurate. The in-situ point measurements were achieved using a sonar on a small boat. The rocking of the boat might cause inaccurate measurements to take place because the sonar would measure the depth that is not exactly below the boat. Furthermore, due to the tide and differences in sea level, the depth measurements might be less accurate. Moreover, human error is a possible cause of inaccuracies. However, when compared to the data of the Hydrografische Dienst (for which we can assume it is accurate because it was done using high-quality equipment), the in-situ point measurements seem to be quite similar and therefore accurate with an RMSE of 0.33m.

The environment of Bonaire also poses certain limitations. Firstly, the creation of the mask for the land/clouds. This mask is formed by looking at the reflectance values of the visible bands and applying thresholds. However, crests that are caused by the wind might cause a higher reflectance value for certain parts of the sea, meaning that these do not apply to the thresholds on which the mask is based. For example, the crests could be masked as clouds even though it is water. Furthermore, in shallow waters with clear conditions, the seafloor can have a high reflectance, resulting in bright spots which could be masked even though they are actually water. Moreover, a big limitation for the calculation of the bathymetry is present for the east of the island of Bonaire. The east coast of the island has to endure trade winds, causing the sea to be wild. These waves result in much noise in the satellite image, making it impossible to accurately calculate the bathymetry for these areas.

Lastly, turbidity due to rain could limit the possibilities of bathymetry calculation (Chybicki, 2017). Bonaire has a climate where most precipitation falls in the months of October, November, and December. Therefore, it is predicted that satellite imagery acquired during and directly after these months could be less usable for the calculation of the bathymetry due to higher turbidity in the water. However, when looking at Table 3, the results show the opposite. Except for depth class 1-10m, the RMSEs of all other depth classes are the lowest for satellite image 3. Satellite image 3 was acquired in January, whereas images 1 and 2 were acquired in August. Keeping in mind the climate of Bonaire, you would predict that images 1 and 2 would be more accurate. However, for this research, this was not the case. This difference could be caused by a multitude of factors and because of the small sample size, it is not possible to give an accurate reason for the higher accuracy for image 3.

In spite of the limitations, this research provides new knowledge about satellite-derived bathymetry, especially its application in Bonaire. The accuracy of the results suggests that there are possibilities for SDB in Bonaire. It also provides a workflow that could be used as a baseline for future bathymetric studies in Bonaire. This research gives insights into the factors that could pose limitations for SDB in Bonaire, and also which factors should be held into account. Furthermore, it argues why certain choices are made and how these choices can be made dependent on the application.

## 5. Conclusion

This research calculated the bathymetry of Bonaire using optical satellite data. This was achieved for both glinted and deglinted images, using the formula created by Stumpf et al. (2003). Two formulas were used ( $SDB_A$  and  $SDB_B$ ). This research focuses on shallow waters, and therefore depth class 1-10m. The most accurate result for depth class 1-10m had an RMSE of 3.58 m and was achieved by calculating the bathymetry of a deglinted image, using the formula  $SDB_B$ . However, when looking at the average RMSE of the three satellite images of this research, using glinted images and  $SDB_B$  provided the most accurate bathymetric models (with an average RMSE of 4.11m). However, the difference between glinted and deglinted depends on the image and therefore it is difficult to say if deglinting improves accuracy or not. On the other hand, the use of the formula  $SDB_B$  showed more accurate results for depth class 1-10m for all images. Therefore, it can be concluded that the most accurate bathymetric model of Bonaire is achieved using the method of Stumpf et al. (2003) and calibrated using in-situ depths of less than 20 metres. Whether the image should be deglinted or not cannot be concluded from this research due to a too-low sample size.

According to Stumpf et al. (2003), the methodology used in this research is applicable to depths up to 20-30 metres. However, when looking at the results, the depth class 20-30m has an average RMSE of more than two hundred metres which is not accurate. The obvious reason for this high RMSE is the fact that the method used in this research is not applicable to the deeper depths. The reflectance might not be able to penetrate the water column of 30 meters which makes it impossible to accurately calculate the bathymetry. Moreover, the depth class 10-20m has an RMSE of more than 40 metres, which is also not accurate. So, concluding from the results of this research, the methodology can only yield accurate results in the depth class of 1-10 metres. This accuracy still has an RMSE of 3-4 metres. However, it has to be said that there are improvements possible for the methodology of this research. This could reduce the RMSE of the 1-10m depth class and might provide accurate results for deeper depths.

## 6. Recommendations

As previously mentioned, this research faced some limitations which might be circumvented in future research. A sample size of 3 images is not enough to create definitive conclusions, therefore future studies should increase the sample size. If there is a large sample size, it may also be possible to determine whether deglinting has an added value for the calculation of shallow waters or not. Furthermore, the formula  $SDB_B$ , which provided the most accurate results for shallow waters, was calibrated through the use of in-situ depths of less than 20 metres. However, future research could explore whether it is possible to achieve more accurate results by calibrating the formula on even less deep depths, for example on depths less than 10 metres.

Moreover, this research used the ratio of the green and blue band to determine the bathymetry. These bands were chosen because they have the lowest attenuation over depth. However, this is not completely true. According to Caballero and Stumpf. (2019), the Sentinel-2 bands with the lowest attenuation are the coastal blue band (B1) and the blue band (B2).

However, the coastal blue band has a spatial resolution of 60 meters so resampling has to be applied. Future research can use the formula by Stumpf et al. (2003) and the ratio between the coastal blue band and the blue band. This might yield more accurate results or maybe accurate results to a larger extent due to the lower attenuation. Lastly, future research could focus on a specific area in Bonaire. Some comparable bathymetric studies determine the bathymetric calculation of a smaller area and end up with more accurate results (Caballero and Stumpf, 2019). The complete coast of Bonaire is quite a large area which increases the complexity of the calculation.

This research showed that satellite-derived bathymetry has possibilities for the island of Bonaire. It is a feasible method to obtain information crucial for the conservation of biodiversity in shallow waters. However, future research needs to be done in order to further explore the possibilities in terms of accuracy and extent.

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## 8. Appendix

The accompanied zip file contains the following:

- A PDF and Word version of this report
- A PowerPoint presentation of both the Midterm and Final presentation
- All datasets used and created during this research