Exploring the potential of remote sensing to detect marine plastic debris in the South African Ocean region

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Abstract
The ocean provides various economic, environmental, and social benefits for society. In recent years there has been a threat to the ocean through the millions of tonnes of marine pollution that has been disposed into the ocean. Due to these detrimental consequences of plastic pollution on the marine environment, several governments and international governing bodies are proposing solutions to this global issue. It is therefore important to develop methods for the detection of marine plastics for more informed and targeted clean-up or prevention operations for the oceans. However, this can be challenging due to the vastness of the ocean. Remote sensing techniques such as optical and Synthetic Aperture Radar offer a unique opportunity to detect marine debris and a larger extent. In this study, we present a method to use both optical and SAR data to detect marine debris in the South African Exclusive Economic Zone (EEZ). The use of spectral indices, Plastics Index (PI), Floating Debris Index (FDI) and Normalized Difference Vegetation Index (NDVI) was derived from Sentinel-2 and RapidEye imagery. The results indicated that the higher resolution RapidEye imagery was more sensitive in detecting potential floating plastics than Sentinel-2 due to the higher resolution. Positive NDVI and PI values indicate potential floating vegetation and associated plastics. The results revealed that18% and 30% of the pixels in the NDVI and PI images respectively were positive. A threshold of 1 standard deviation showed few outliers that were confined to the edges of the study area and in the harbour, with only 0.12 % of the study area being classified as an outlier in the FDI image. Sentinel-1A GRD data was used to derive backscatter in VV, VH and VV/VH polarisations. The results showed that the VV polarisation highlighted the potential floating more significantly than the other polarisations. The integration of these two methods could provide an enhanced approach to monitoring marine plastic debris.

1. Introduction

Oceans cover approximately 71% of the Earth's surface and provide numerous services (Asiyabi et al., 2023). The ocean plays a crucial role in the global climate system, is a habitat for marine species and can provide food for a large portion of the population (Miedtank et al., 2024). Marine debris, which can also be referred to as marine pollution/litter consists of various ocean materials such as plastic bottles, fishnets, and nurdles that have been disposed of into the ocean (Waqas et al., 2023). In the marine environment, there have been millions of tonnes of plastics that enter our oceans annually as macro and microplastic litter (Biermann et al., 2020). There has been a slow rate in the degradation of plastics, and an increase in the production of single-use items that has led to an accumulation of plastic debris globally in marine and coastal environments (Topouzelis et al., 2021). The increase of marine pollution has devastating environmental consequences for the ocean such as water contamination, eutrophication of water and chemical poisoning due to heavy metals, oils and inorganic pollutants (Aretoulaki et al., 2021). For endangered species such as marine mammals, sea birds, turtles and fishes, plastics can cause serious adverse effects or death through entanglement or ingestion (Biermann et al., 2020; Waqas et al., 2023). There are also direct economic costs that include negative impacts on fishing, transportation and tourism marine industries (Arabi and Nahman, 2020).

The blue economy refers to the range of economic sectors and related policies which determine whether the use of oceanic resources is sustainable (World Bank 2017). One of the principles of a sustainable blue economy is that it restores, protects, and maintains the diversity of marine ecosystems (World Bank 2017). Due to these detrimental consequences of plastic pollution on the marine environment, several governments and international governing bodies are proposing solutions to this global issue (Waqas et al., 2023). The United Nations (UN) Sustainable Development Goals (SDG) have highlighted the importance of plastic pollution and established a target specifically related to plastic debris. According to Verster and Bouwman (2019), recent data indicated that between 15 000 and 40 000 tonnes of plastic enters oceans from South Africa per year. South Africa's coast plays an important role in the economy through tourism, fisheries, and ecosystem services. Plastic pollution threatens these economic contributions (Arabi & Nahman, 2020). It is therefore important to develop methods for the detection of marine plastics for more informed and targeted clean-up or prevention operations for the oceans within the South African Exclusive Economic Zone (EEZ).

Due to the severe environmental and socioeconomic consequences of plastic pollution, it is important to have the ability to monitor and mitigate plastic pollution (Veettil et al., 2022). Conventional approaches include the use of in situ measurements that can offer valuable insights into the presence of plastic pollution (Veettil et al., 2022). However, due to the challenging conditions and vastness of oceanic and coastal regions, conducting in situ measurements may not always be feasible. Remote sensing offers a unique opportunity to monitor oceans at a global scale and overcome the limitations of in situ measurements. There is also the potential to upscale and standardise previous attempts to monitor the distribution, size and abundance of marine floating plastics both spatially and temporally (Veettil et al., 2022).

Various airborne and spaceborne remote sensing platforms have been used to detect marine plastic debris such as Unmanned

Aerial Vehicles (UAVs), Light Detection and Ranging (Lidar), terrestrial cameras, multispectral, hyperspectral data and Radar and Sonar. However, satellite remote sensing using optical and microwave sensors such as Synthetic Aperture Radar (SAR) can be used in a cost-effective way to detect marine plastics at large spatial extents. There have been limited studies on the use of spaceborne remote sensing to detect marine floating plastics in a South African context, however.

In this study, the aim is to use optical and SAR remote sensing techniques to detect floating marine plastics within the South African EEZ. The objectives are to apply thresholding to optical and SAR remote sensing data and evaluate the data independently to potentially isolate marine floating debris. Section 2 will briefly outline the use of optical and SAR data in previous related studies. Section 3 presents the methodologies used to detect possible marine floating plastics. Section 5 presents the results, followed by sections 5 and 6 which will present the discussions and conclusions respectively.

2. Remote sensing for marine plastic debris detection

2.1 Optical/Multispectral remote sensing

Optical remote sensors can record the solar radiance reflected from the Earth's surface at visible (400-700 nm), Near-Infrared (NIR) (720-1300 nm), Short-wave-infrared (SWIR) (1300-3000 nm) parts of the electromagnetic spectrum (Amani et al., 2022). Different objects on the Earth's surface can reflect and absorb any incoming solar light differently at various spectral bands. According to Waqas et al. (2023), the Red, NIR and SWIR bands are useful in the detection of marine plastics where there was low absorption by the marine debris and high absorption by the background ocean water. Furthermore, spectral indices can be used to enhance the detection of a target by using a mathematical combination of bands. Two spectral indices that have been developed are the Plastics Index (PI) developed by Themistocleous et al (2020) and the Floating Debris Index (FDI) (Biermann et al., 2020). Furthermore, because marine debris can include a host of different materials such as marine vegetation, the vegetation can be separated using the Normalized Difference Vegetation Index (NDVI) (Biermann et al., 2020).

Recent studies have explored the use of multispectral imagery from Sentinel-2 to manually detect and identify macroplastics using the FDI and spectral signatures (Biermann et al., 2020) for five different regions. The results indicate that the FDI for Sentinel-2 allowed for the detection of materials floating on the ocean surface at sub-pixel levels. Furthermore, the study showed that the floating materials are reflected in the NIR region which can be used for differentiation of aggregated materials floating on the ocean. Advancements in the detection of marine litter using optical remote sensing have seen the use of high-resolution Unmanned Aerial Vehicle (UAV) imagery which significantly improved the detection accuracy of floating debris over that of medium-resolution Sentinel-2, allowing for the identification of individual pieces of plastic (Cortesi et al., 2022; Topouzelis et al., 2019). While higher resolution improves accuracy, UAV-based detection is limited in terms of the size of an area that can be monitored. Additionally, UAVs are affected by adverse weather conditions and would not be able to fly during times of heavy winds or rainfall. Although optical remote sensing can be useful in detecting floating plastics, one major limitation is the presence of clouds and cloud shadows (Themistocleous et al., 2020; Veettil et al., 2022). To overcome this limitation, microwave remote sensing techniques such as SAR can be used.

2.2 Synthetic Aperture Radar (SAR)

Synthetic Aperture Radar sensors are part of the active remote sensing systems that transmit electromagnetic pulses and measure the backscattered radiation from a target on the ground's surface (Moreira et al., 2013). Unlike optical sensors, SAR sensors do not rely on solar radiation and therefore, can acquire data in day-night and inclement weather (Asiyabi et al., 2023). This means that imagery is not affected by the presence of cloud cover (Veettil et al., 2022). SAR operates in several frequency bands including, increasing in wavelength, Ka-Band, Ku-Band, X-Band, C-Band, S-Band, L-Band and P-Band. These bands are suited to different applications, longer wavelength bands can penetrate through cloud cover more effectively but often operate at a lower spatial resolution while shorter wavelength bands are more affected by cloud cover but can capture finer surface features (Johansson et al., 2017). The basis for the detection of floating plastics is the separation of backscatter signals from the surrounding ocean water and the floating plastics themselves. These backscatter signals are affected by the physical properties, orientation and roughness of the surface. Areas of high backscatter can be attributed to a rougher surface, where a stronger signal is returned to the sensor, which could signify floating plastics when compared to a smooth surface, being the surrounding water (Davaasuren et al., 2018).

Simpson et al. (2022) demonstrated the use of C-band SAR data alone in the monitoring of plastic islands in a river environment through change detection algorithms, showing high accuracies. While this study does show the promise of SAR, specifically for the detection of marine plastics translating these methods to a marine setting may involve significant differences to account for the turbidity difference in the water. Despite the benefits of SAR imagery to detect plastics, the interpretation can be complex (Asiyabi et al., 2023).

3. Methodology

The methodology developed in this paper includes a quantitative approach using remote sensing datasets from SAR and optical platforms to detect marine plastic debris. A description of the study area and the data that was used is presented in Section 3.1, and Section 3.2. The methods used to detect plastics from optical and SAR are outlined in Sections 3.3 and 3.4 respectively.

3.1 Study Area

The study area is situated in the south of Durban in the KwaZulu Natal Province within the South African EEZ (Figure 1). Durban is located on the eastern coast of South Africa and is considered a densely populated metropolitan home to 3.8 million inhabitants. The economy of Durban is driven by the port and shipping industry and hosts the busiest container port in South Africa (Ryan, 2020). Two different areas for the detection of marine plastic debris have been identified within this area. The first area is situated in the waters within Durban harbour, surrounded by the shipping industry and receiving inputs from the Umbilo River which is attached. The river flows through a mix of industrial and residential areas along its banks, which acts as the channel for the input of land-based plastics into the river and is carried further downstream. The second area of interest is located 7 km north of the harbour at the Blue Lagoon River mouth where the Umgeni River converges within the Indian Ocean. An area buffer from the coast to 300 m offshore will be considered for the detection of plastics. The river is a host to large amounts of human activity, industry and informal settlements on the banks which acts as a pathway for plastics to be released into the ocean.

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This area of interest was included to account for the lack of turbidity which is prevalent in Durban Harbour. A flooding event was identified which took place on the 22nd of April 2019, on the eastern coast of South Africa. This was used as a case study to evaluate the use of optical and SAR methods.

Figure 1. Area of interest is situated on the east coast of KwaZulu-Natal Province in South Africa.

3.2 Data

In this study, three different datasets were used. Optical data from Sentinel-2 and Planet's RapidEye was used to derive spectral indices. Furthermore, C-band Sentinel-1 SAR data was used to detect plastics using the SAR backscatter coefficient. The sensor characteristics of each dataset are shown in Table 1.

Dataset	Date	Platform	Spatial Resolution	Temporal Resolution
Sentinel-2A	29/04/2019	Optical	10 m	14 days
RapidEye	30/04/2019	Optical	5 m	5.5 days
Sentinel-1A	29/04/2019	SAR	14 m	12 days

Table 1. Optical and SAR data characteristics.

The Sentinel-2 data consists of 12 bands with spatial resolution that range between 10 and 60 m. In this study, Sentinel-2A level 2A bottom of atmosphere (BOA) reflectance was used, and the image was already atmospherically corrected. RapidEye imagery was provided by Planet's Education and Research Program and consists of five different bands which are all acquired at 5 m spatial resolution.

3.3 Detection of floating plastics optical workflow

The optical workflow used in this study is shown in Figure 2. The downloaded Sentinel-2 and RapidEye images covered a larger area than is of interest to this study with features that would potentially serve as false detections of plastic, such as land-based features, it is therefore important that the images were clipped to only include a smaller area of interest.

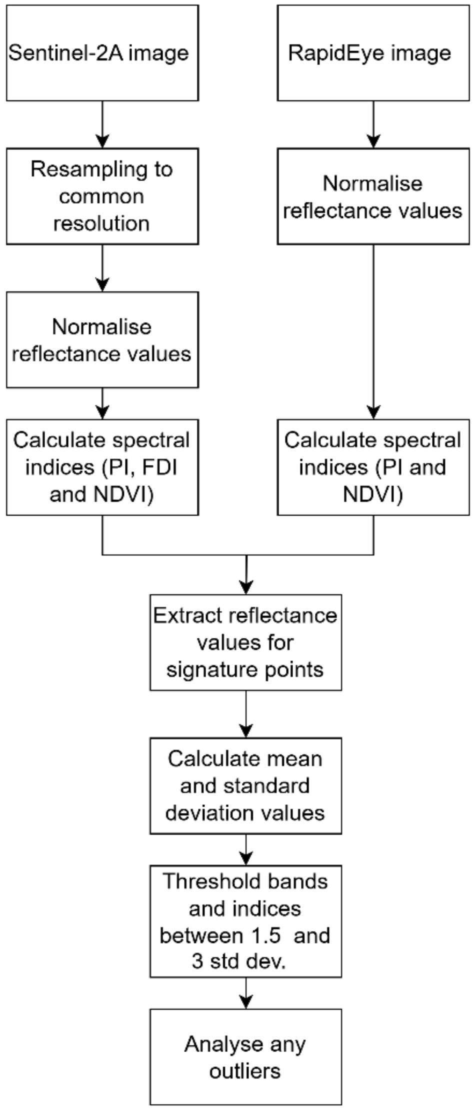

Figure 2. Workflow to detect floating plastics using optical Sentinel-2 and RapidEye imagery.

In the DUNIA sandbox QGIS software was used on the virtual desktop to generate a clipping layer. There is a spatial resolution difference between the bands for the Sentinel-2 that were used therefore spatial resampling was conducted to ensure that there is a consistent spatial resolution. All the bands were resampled to 10 m. The next part of the workflow used a minimum-maximum normalisation to standardise the reflectance values for all the bands for both the Sentinel-2 and RapidEye images. Normalisation removes the effects of non-surface target effects on reflectance at the time of image capture while allowing for reflectance values to be on a consistent scale between 0-1. The next step was to calculate the spectral indices. The Plastics Index (PI), Floating Debris Index (FDI) and Normalized Difference Vegetation Index (NDVI) indices were calculated according to Equations 1, 2 and 3. The PI can be used to highlight differences in the reflectance values in the NIR and Red bands. The FDI includes a thresholding technique for NIR reflectance using the SWIR and Red bands which allows plastics to be detected and separated from mixed floating targets by leveraging the absorption characteristics of plastics in the SWIR region. Finally, the NDVI is effective in discriminating between plastics and water in previous research.

$$PI = \frac{NIR}{NIR+RED} \quad (1)$$

$$FDI = NIR - (RE2 + (SWIR1 - RE2) * \frac{(\lambda NIR - \lambda RED)}{(\lambda SWIR1 - \lambda RED)} * 10 \quad (2)$$

$$NDVI = \frac{(NIR-RED)}{(NIR+RED)} \quad (3)$$

where *NIR* = Near-infrared band
RED = Red band
RE2 = Red Edge band
SWIR1 = Short-wave infrared band
λ = wavelength of the corresponding band

Signature points were created to aid in the classification of different materials and to better threshold reflectance and index values to separate plastics from other targets. The reflectance values for each signature point were extracted from the respective images. This was done across bands 4,6,8 and 11 for the Sentinel-2 image, according to the spectral regions of interest, and across all 5 bands for the RapidEye image. Once the reflectance values had been extracted for the targets in the study area the next step was to apply thresholds to the reflectance values to isolate outliers that do not fall within a defined range of values associated with a known target, for both the Sentinel-2 and RapidEye images. To separate the floating plastics from the background water the mean values of the spectral indices were calculated. Thereafter the standard deviation was used to highlight any difference between the mean values and the standard deviation.

3.4 Detection of floating plastics SAR workflow

Sentinel-1A Ground Range Detected (GRD) data for the 30th of April 2019, was downloaded on the DUNIA platform and processing was undertaken in ESA's SNAP toolbox. The date of this imagery coincides with the RapidEye imagery closely and is one day apart from the Sentinel-2 imagery which was taken on the 29th of April. Sentinel-1 imagery has two polarisations vertical-vertical (VV) and vertical-horizontal (VH). The pre-processing steps included applying the orbital file to ensure that geometric corrections can be applied accurately. Thereafter, thermal noise was removed. Thermal noise impacts the measured backscatter for the Sentinel-1 imagery, specifically in areas with low backscatter. The applied function subtracts noise values, stored in the product's metadata from the backscatter values in each polarisation, improving the quality of the data. The next step in the workflow includes radiometric calibration, which involves converting raw intensity values into backscatter values (sigma nought values). Speckle is a common noise found in SAR imagery which occurs when reflected radar signals combine constructively or destructively causing a granular appearance on images. The Sigma Lee Filter was used for speckle filtering. An ellipsoidal correction was performed in ESA's SNAP through the Range-Doppler approach on the SAR imagery to geocode the data in the slant range geometry as opposed to the side-look geometry. A ratio for the backscatter values in the VV and VH polarisation was also calculated.

To analyse the results, the Constant False Alarm Rate (CFAR) was used as a thresholding method. The CFAR method adjusts the detection threshold on a local noise level by using a moving window. This method has been applied to detect ships using SAR imagery. A moving window of 7 x 7 pixels was used to estimate the noise levels and pixels that exceed the calculated noise levels by 3 standard deviations were flagged as outliers. This was applied to the VV polarisation, VH polarisation and the polarisation ratio. Finally, a shape-based filter was used to filter out the rest of the ships based on a shape aspect threshold.

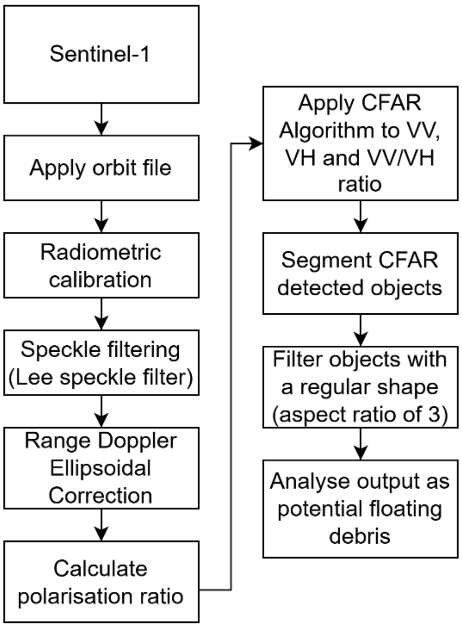

Figure 3. Workflow used to detect potential floating plastics using SAR data.

4. Results

4.1 Optical data for the detection of plastics

Three different spectral indices were calculated for Sentinel-2. The PI results are shown in Figure 4a, and the FDI map and NDVI are depicted in Figures 4b and Figures 4c respectively. For the Sentinel-2 data that was acquired on the 29th of April 2019. The PI map indicated high values in yellow and lower values in dark blue. The results show that there are some points of interest in the Durban Harbour area however, the ships in the harbour also indicate high PI values. Similarly, the NDVI values highlight floating vegetation values which may be associated with floating plastics. In this instance, the ships exhibit high NDVI values. This makes it difficult to distinguish between ships and floating plastics. For the FDI map, the SWIR band is used in the calculation which the other two indices do not consider. The results of the FDI show that overall, the majority of study area presents low FDI values (in blue) which is expected in the open ocean. Higher FDI values were found near the shoreline and in the northern region of the study area. A higher resolution RapidEye image was used to calculate spectral indices.

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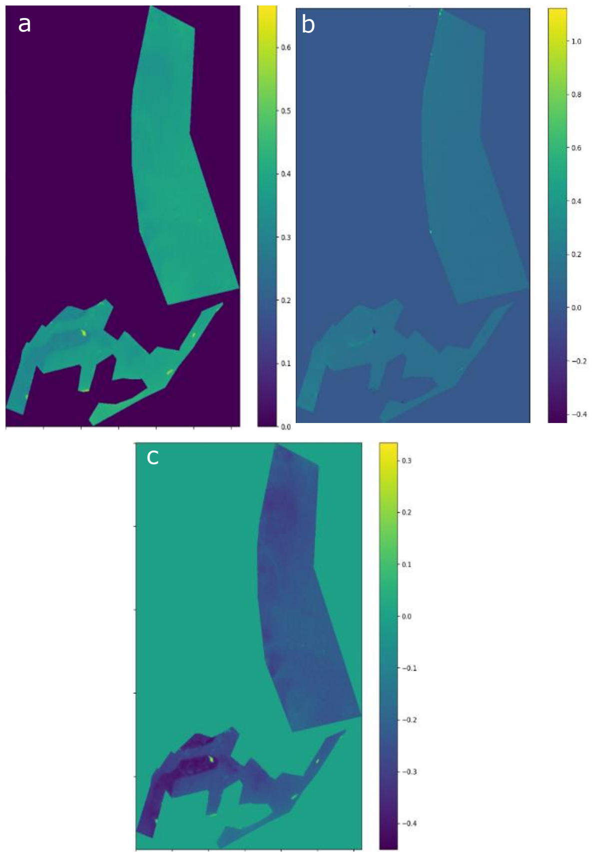

Figure 4. a) PI map for Sentinel-2, b) FDI map for Sentinel-2 and c) NDVI map for Sentinel-2. The high values are represented by the yellow colour scale and the lower values are represented by the darker blue colour scale.

The results for the 5 m RapidEye imagery that was acquired on the 29th of April 2019 are presented in Figure 5a and Figure 5b. The RapidEye image does not have a SWIR band so the FDI could not be calculated for this dataset.

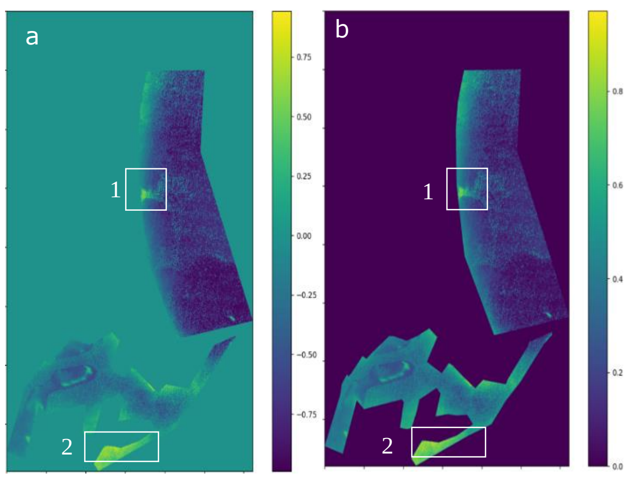

Figure 5. a) NDVI calculated for RapidEye b) PI calculated for RapidEye.

There are some notable patterns from the NDVI and PI maps that were derived from the RapidEye imagery. There is a clear flow of the material which could represent marine plastic debris in the area around the Umgeni River mouth, highlighted in the boxlabelled 1. This is indicated by high NDVI and PI values. High values were also found in the corners of the harbour and along the boundary towards the shore, highlighted in box 2. Positive NDVI and PI values indicate potential floating vegetation and associated plastics. The results revealed that 18% and 30% of the pixels in the NDVI and PI images respectively were positive.

To analyse these results further, and to separate the potential floating plastics from the background water thresholding was applied (Figure 6a, 6b and 6c). The results from the Sentinel-2 NDVI map show that a threshold of 1 standard deviation flagged many outliers which could be floating plastics (Figure 6c). This suggests that water with high levels of chlorophyll which is in the floating vegetation may not be sufficient to separate the floating vegetation alone. The FDI and PI threshold maps are more sensitive to the floating debris than the vegetation in the study area. A threshold of 1 standard deviation showed few outliers that were confined to the edges of the study area and in the harbour, with only 0.12 % of the study area being classified as an outlier in the FDI image.

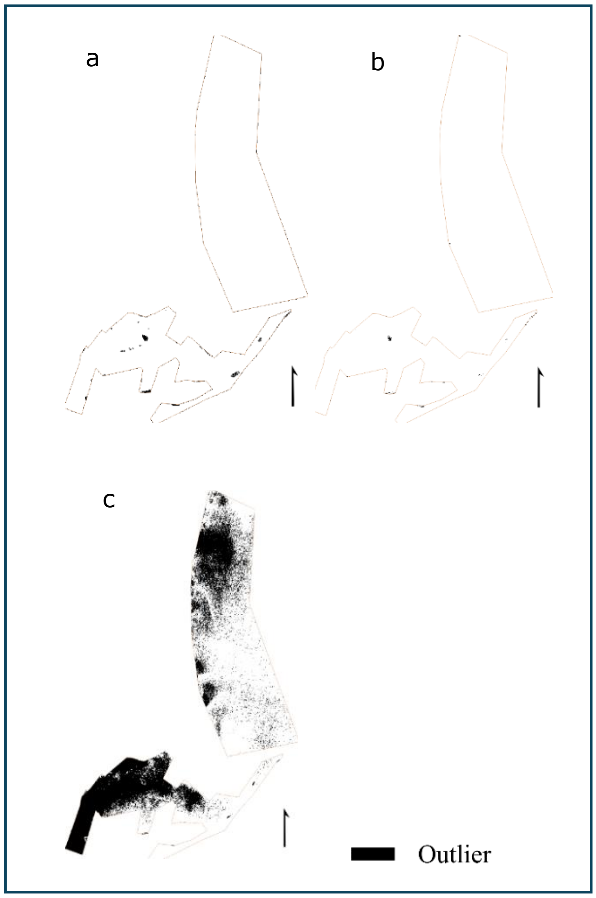

Figure 6. Outliers that could represent plastics in at 1 standard deviation a) PI threshold map, b) FDI threshold map and c) NDVI threshold map.

The RapidEye threshold maps for the NDVI and PI are shown in Figures 7a and 7b. The results indicate that the location of the outlier pixels is scattered across the harbour, highlighted in red in box (labelled 2), and on the coast which corresponds to the outflow potential of the Umgeni River, as seen in box 1.

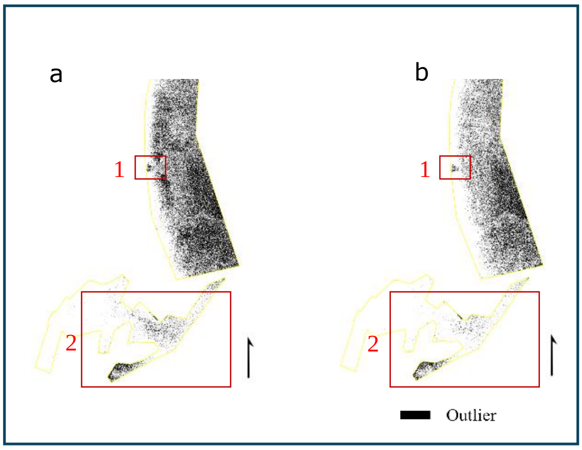

Figure 7. a) NDVI threshold map for RapidEye and b) PI threshold map for RapidEye

4.2 SAR data for the detection of plastics

For the detection of floating plastics using SAR the backscatter from Sentinel-1A was calculated in both the VV, VH polarisation and the VV/VH ratio. The CFAR detection applied to the VV polarisation provided the clearest result. After shape-based filtering, outliers, which could potentially represent floating debris or plastics, are highlighted in white in Figure 8. The VV polarisation was more sensitive to isolating relevant features within the study area. There was floating plastic debris near the shoreline and harbour as well as collections of outliers along lines which could be collections as currents.

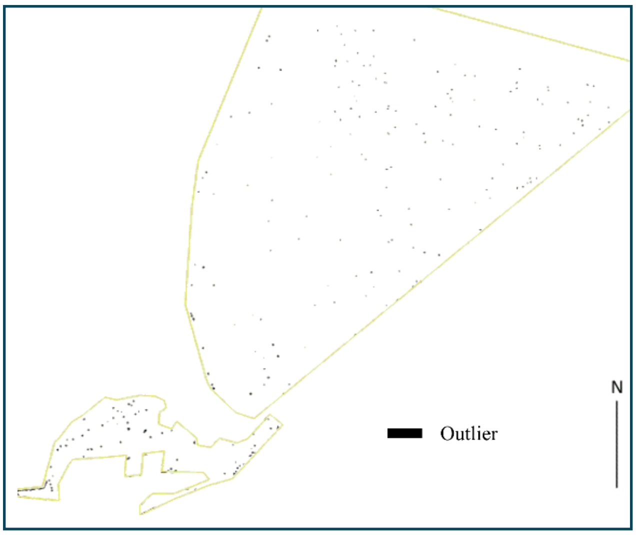

Figure 8. CFAR detection threshold for the VV polarisation.

The CFAR detection results for both the VH polarisation and the VV/VH ratio have what appears to be a large amount of speckle with no coherent patterns in detected outliers. The VH polarisation is sensitive to surface roughness, which in theory should allow floating debris to be detected, however, this makes it prone to variations on the sea surface such as waves and roughness caused by wind. The speckle found in the results for the VH image may be due to the fact that noise is being detected instead of meaningful floating debris detection.

5. Discussion

Three spectral indices were calculated namely, the Normalized Difference Vegetation Index (NDVI), Plastic Index (PI) and the Floating Debris Index (FDI). These indices were selected based on their theoretical ability to highlight floating debris from background marine water as well as their proven effectiveness in previous studies (Biermann et al., 2020; Themistocleous et al., 2020). The results of the Sentinel-2 NDVI and PI were spatially correlated showing high values near the shoreline and scattered within the harbour indicating potential zones of accumulation for vegetation and therefore associated marine debris which are consistent with the scenes described in the harbour after the flooding event. However, ships exhibited high NDVI and PI values which complicated the differentiation between potential debris and other floating features. The high NDVI values observed for ships may be explained by high reflectance from the metal present on the ships in the NIR region of the spectrum, leading to false high NDVI values not correlating to floating vegetation. The higher spatial resolution of the RapidEye imagery, of 5m, provided more detailed patterns in the NDVI and PI indices than that of the Sentinel-2 imagery. High NDVI and PI values were observed along the Umgeni River mouth as well as in the harbour corners, correlating to an outflow of the Umbilo River. This is consistent with expected distributions of debris with rivers being a major source of marine debris. The thresholding technique also highlighted collections of outliers that could represent floating plastics on the edges of Durban harbour and near the Umgeni River mouth, particularly in the RapidEye imagery. The results from the RapidEye threshold maps also highlight the value of using high-resolution optical data to detect floating plastics. While the thresholding methods successfully excluded unwanted targets such as ships from index detections, a limitation was presented in the fact that it is difficult to pinpoint the threshold value that balances the exclusion of unwanted targets and sensitivity in detecting marine debris. Therefore, there is a need for more advanced techniques such as machine learning to validate whether the detection corresponds to debris or not.

SAR backscatter from Sentinel-1 data on the 30th of April 2019 was used to detect floating plastics. The main advantage of using SAR data for ocean applications is that it has an all-weather image capability. The results indicated that in this study VV polarisation was more sensitive to detecting outliers using the CFAR method. This is consistent with the findings of de Fockert et al. (2024), who demonstrated that the VV polarisation was more sensitive in separating floating litter from background water in a controlled test environment. Future work will also include evaluating different thresholding methods other than CFAR to discriminate floating plastics from the ocean. The limitations of using SAR data are that the composition and size of the floating plastics and the interaction with the ocean background may make it challenging to obtain direct measurements (Simpson et al., 2022). Furthermore, the scattering mechanism from objects is strongly dependent on the size, shape and dielectric constant (Simpson et al., 2022). This will influence the way the floating plastics are detected because the scattering mechanisms may differ depending on these properties. One limitation of this work is that no ground truth was available and therefore, the detections cannot be validated for both the optical and SAR results.

Previous research has indicated that optical imagery can be used to detect marine debris though this technique faces challenges with cloud cover. SAR shows promise to address these challenges however complexities arise from the interaction of floating plastics and background ocean altering backscatter. The fusion of these two datasets could see an increase in detection accuracy while allowing for more consistent monitoring. Fusion does however present challenges in the form of acquisition date differences and spatial resolution mismatch. Floating plastic in a marine environment is not a static feature and is exposed to movement via current and tidal influences. Future work is needed to overcome these challenges, taking the dynamic behaviour of floating plastics into account.

6. Conclusion

Marine plastic debris is a major threat to both coastal and marine environments. Therefore, continuous monitoring could be valuable in detecting and mitigating these threats. The use of remote sensing can monitor large portions of the ocean which can overcome limitations of in situ measurements. In this study optical and SAR remote sensing techniques were used to detect floating plastics in Durban, South Africa. For the optical methods, spectral indices were calculated for both Sentinel-2 and RapidEye imagery. The advantage of using spectral indices to detect marine plastics is that is it simple to apply which provides a cost-effective way to detect clusters of plastics. However, this relies on using imagery that is acquired during cloud-free conditions. If cloud-free conditions are not available backscatter derived from SAR could be used as an alternative. The integration of these two methods could provide an enhanced approach to monitoring marine plastic debris.

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