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# Comparative Impact Analysis of Cyclone Ana in the Mozambique Channel Using Satellite Data

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**Abstract:** There is still insufficient information available for a streamlined impact assessment of tropical cyclones on coastal habitats, particularly in the Mozambique Channel. Using Sentinel-1 and Sentinel-2 data, along with socio-ecological parameters including mangrove forest health and population density, we modeled the extent of flooding and its impact following the 'severe tropical storm' Ana which occurred between the 20 January until 25 January over the Mozambique Channel. Focusing on regions hit by Ana, namely the Sofala and Zambezia regions and the Boeny and Melaky provinces in Mozambique and Madagascar, respectively, we adapted a model by the United Nations Platform for Space-Based Information for Disaster Management and Emergency Response (UN-SPIDER) to effectively assess storm impacts at a resolution of up to 10 m. Our results showed that in Mozambique, more than 195,977 people have been potentially affected by Ana, while in Madagascar this number was down to 79,003. The central region of Zambezia accounted for the majority of flooding occurrences, although the Boeny province accounted for most of the flooding as a proportion of its total area. The Sofala region of Mozambique displayed the highest-affected population and highest-affected urban area, with 108,400 exposed people. However, it was found that only a small proportion of affected areas in all regions of interest (ROIs) were urban areas, accounting for 1.4% of the flooded areas on average. Low mangrove normalized-difference vegetation index (NDVI) changes between before the 2021–2022 cyclone season were found throughout all ROIs, despite the appearance of degraded mangrove patches in the proximity of barren areas at a fine scale (<20 m). Finally, it was found that healthy mangrove forest ecosystems in the Mozambique Channel were effective in protecting highly populated areas from cyclonic events for up to 40 km, on average.

**Keywords:** impact analysis; tropical cyclone; Mozambique; mangrove; satellite data



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## 1. Introduction

Tropical cyclones are some of the most devastating natural disasters, with far-reaching consequences, such as human displacement, economic loss, and environmental damage and changes [1,2]. Tropical cyclones are defined as low-pressure systems with organized deep convection that form over warm tropical waters along with maximum sustained surface winds ranging between 63–118 km/h [3]. The Southwestern Indian Ocean is one of the main tropical cyclone areas in the world and the most active one in the Southern Hemisphere [1]. Favorable conditions, such as high sea surface temperature, weak vertical wind shear, and vertical profiles of humidity, lead to the high frequency of depression systems [4]. In the Mozambique Channel specifically, this is reflected in local parameters, such as high sea surface temperature (SSTs) with an average of 29.6 °C, a southerly wind shear with height, and below-normal geopotential height anomalies at 500 hPa [5]. In the Mozambique Channel, three to 12 cyclones form every year. Cyclone season in Madagascar typically occurs between November and March, with an average of 1.5 cyclones yearly, the highest number on the African continent [6,7]. In Mozambique, on the other hand, the cyclone season spans November to April and the area is estimated to suffer from 1.16 cyclones every year on average [5].

Since mid-March 2022, it has been estimated that around 960,000 people have been affected by the five extreme tropical weather events [6] that occurred in the Mozambique Channel and left displaced people in need of health, water, housing, and alternative livelihoods. Estimating the impacts of tropical weather events in a context of increases in their frequency is therefore crucial for developing climate-adapted solutions.

### 1.1. An Introduction to Flooding

A key consequence of tropical cyclones and depression systems is heavy precipitation. Flooding is defined as the event whereby precipitation falls more quickly than water can be absorbed into the ground or carried away by rivers or streams. River flow, rainfall, tide surge and topography all define the type of flooding that has occurred [8]. It is estimated that flood-related impacts will worsen by 187% by 2050 under the Hadley Centre Coupled Model (HadCM3) [9].

As such, today, and increasingly so in the near future, flooding will induce landslides, destruction of buildings, the creation of stagnant bodies of water and much more [8]. One key human cause for concern is also its alteration to food supply, sanitation facilities, water contamination, and access to healthcare due to overcrowding or destruction of facilities [10].

Although it is important to note that some floodings, particularly small- and low-magnitude flooding, can be beneficial through their capacity to recharge groundwater, wetlands, improve soil fertility and construct floodplains [11], most tropical cyclones tend to carry negative ecological impacts due to their high magnitude. Flooding tends to increase erosion, lead to eutrophication [11] and increase groundwater stores, thus making these areas more prone to further extreme flooding in the case of another high precipitation event [12]. In areas of high-exposure indexes, such as coastal areas in Mozambique and Madagascar [13], the impacts of climate change, including an increase in the frequency of storm events, is likely to feed this cycle of negative ecological impacts following flooding.

### 1.2. Relationship between Mangrove Ecosystems & Cyclones

Over the past several decades, annual global mangrove loss is estimated at 1–2%, exceeding rates in many inland tropical forests [14]. Mangroves are defined as highly productive carbon rich ecosystems that receive nutrients from both sea and land. Mangroves not only sustain local ecological ecosystems, they also support local populations that rely on them for fuelwood, construction material, medicine, food from mangrove fisheries, timber, and tannins [15]. Mangrove forests exhibit pronounced zonation, which has been attributed to the species' responses to factors such as river discharge, temperature and precipitation, land surface elevation and salinity of these ecosystems [15]. In a context of sea-level rise, mangrove ecosystems also play an important role in vertical elevation gains, owing to their aerial rooting systems and linked biological processes, such as plant litter and woody debris deposition, root accumulation, sediment trapping and algal mat development on the soil surface [16].

In Mozambique particularly, mangroves occur almost along the entire coast and act as a crucial first barrier for local populations against damaging tropical storms and sea-level rise [17]. It has one of the largest mangrove areas in Africa (with 3054 $km^2$), only second to that of Nigeria (8573 $km^2$) [18]. Mangroves are generally threatened by deforestation for firewood or construction and occasionally from oil spills [17]. Mangrove forests in Mozambique decreased in area between 1972 and 2004 from 408,000 ha in 1972 to 357,000 ha in 2004 [18]. This trend is believed to be matched by similar trends in degradation throughout the country. Madagascar on the other hand, displayed mangrove forested areas of 2800 $km^2$, Africa's fourth largest amount, and 2% of the global distribution. It, however, suffers from a 1–2% deforestation rate on average [19]. As these two countries in the Mozambique Channel represent some of the biggest African mangrove ecosystems combined and are increasingly threatened by sea-level rise and tropical cyclones, investigating the impacts of the latter on these ecosystems is vital.

### 1.3. Knowledge Gap

To assess the impacts of tropical cyclones to support management approaches, typical traditional field-survey approaches include methods such as questionnaires to affected populations, in-situ water level measurements, and surveys [8]. However, these techniques prove to be very expensive and time-consuming to fully grasp the extent of landscape and property damage when, for example, areas of interest are flooded, and communication systems are damaged [20]. Current high-resolution remote sensing (10–30 m) has the potential to be used in effective flood responses and facilitate flood prevention and/or mitigation strategies at a very fine scale.

Many studies have investigated the impacts of tropical cyclones on natural and coastal habitats using remote sensing, such as in the USA [2] or India and Bangladesh [21], but very few have offered insights into tropical cyclone impacts in the Mozambique Channel.

Studying the impacts of tropical cyclones and storms in the Mozambique Channel is therefore of the utmost importance in countries underrepresented in scientific research and applications, but overrepresented in vulnerability and exposure to climate change-related risks [8].

### 1.4. Study Objectives

This study aimed to act as a pilot for further integrative impact-analysis assessment in the Mozambique Channel. As such, it focused on tropical cyclone (TC) Ana which occurred in January 2022 between the genesis on 20 January until 25 January over Madagascar and Mozambique. Note that “tropical cyclone” is the preferred concise term used in this study, although it was classified as such for one day and is generally considered a ‘severe tropical storm’.

The main questions that the study attempted to answer included the following:

- Are there differences in the climatic and anthropogenic impacts after TCs in coastal Mozambique and Madagascar?
- Specifically, were mangrove forests degraded after the TC? Were there regional differences in the degradation extent and pattern? For example, do areas in the vicinity of the mangrove hit by the TC fare better than non-mangrove areas?

## 2. Materials and Methods

### 2.1. Study Area

The Mozambique Channel is comprised of all countries in coastal southeastern Africa, namely, Mozambique, Madagascar and the islands of Comoros and Mayotte (Figure 1). The chosen ROIs involved the two countries most affected by cyclones in the area: Madagascar and Mozambique. Specifically, both countries were the most affected with TC Ana, the tropical storm focused on in this study.

Mozambique has an area of 800,000 km$^2$, with 11 regions. It shares land borders with six countries: Tanzania, Malawi, Zambia, Zimbabwe, South Africa, and Eswatini. The country is bordered by the Indian Ocean, with main coastal cities including the capital city of Maputo, Maxixe (Inhambane province), Beira (Sofala province), Quelimane (Zambezia province) [8]. The country has 11 main international rivers, including the large Zambezi and Limpopo Rivers, and about 104 river basins that feed mangrove systems.

The neighboring island nation, Madagascar, has an area of 587,041 km$^2$ divided into 23 regions (faritras). The main coastal cities include Mahajanga (Boeny), Hell-Ville (Diana) and Maintirano (Melaky). As a result of the island’s long geographical isolation from neighboring continents, Madagascar harbors a high level of biodiversity and a species endemism of more than 80% [9]. Monitoring habitat changes, particularly in resilience-enhancing habitats such as mangroves, is consequently of the utmost importance in the face of tropical cyclones.

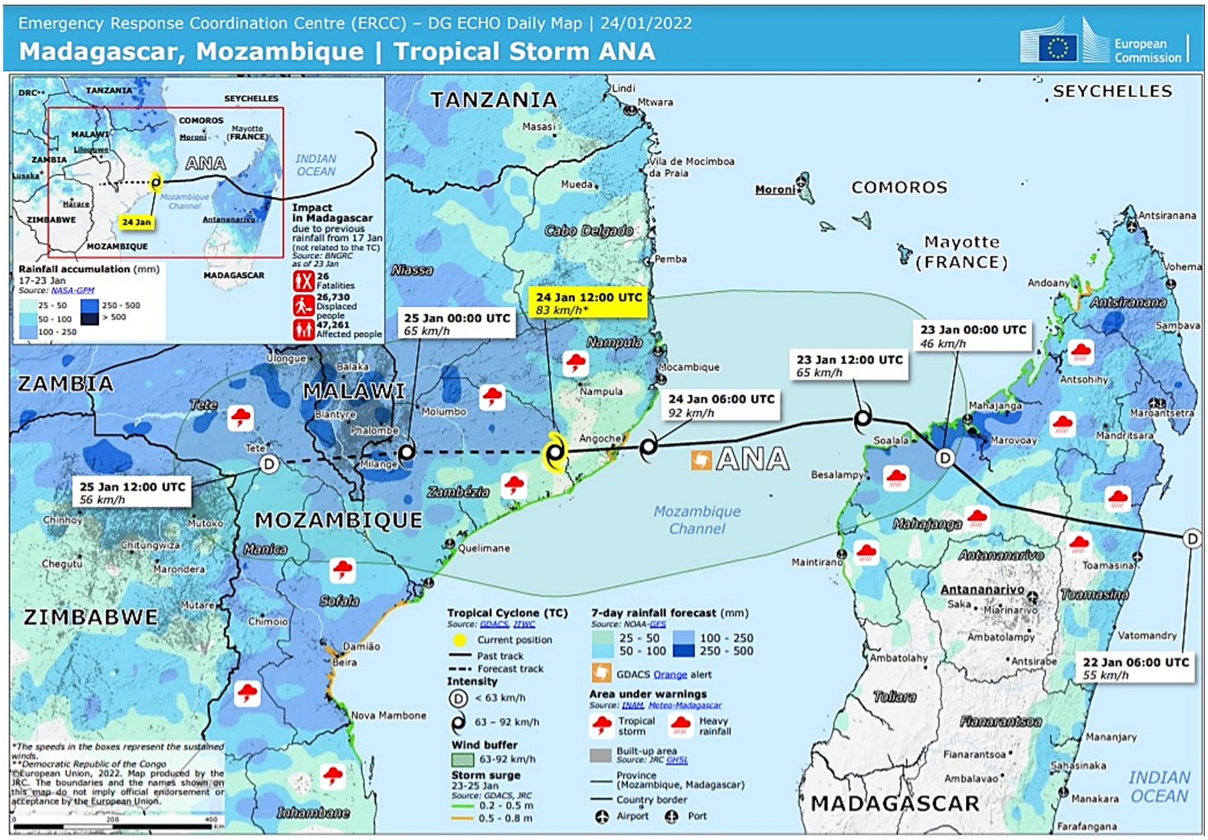


**Figure 1.** Ana tropical cyclone track, intensity and rainfall patterns over the Mozambique Channel [22].

## *2.2. An Overview of Tropical Cyclone Ana*

Tropical cyclone Ana occurred in 2022 between the 20–25 January over Madagascar, Mozambique, and Malawi. (Figure 1).

The track mostly impacted coastal regions of Madagascar and Mozambique. This included the areas of interest for this study, namely the Zambezia and Sofala provinces in Mozambique and the Melaky and Boeny regions in Madagascr. The storm's genesis occurred on 20 January as a tropical depression of approximately 1009 hPa and rapidly evolved into a 'severe tropical storm' over the western coast of Madagascar with pressure dipping below 1000 hPa on 23 January [23]. Finally, Ana was declared a tropical cyclone on the 24 January as it hit the Zambezia province, Mozambique at noon. Maximum sustained winds were recorded at 95 km/h in Mozambique and the lowest pressure recorded was 993 [23]. It is important to note, however, that as Mozambique and Madagascar have different administrative systems, called regions and provinces respectively, these all correspond to a level 1 administrative level according to the Food and Agriculture Organization Global Administrative Unit Layers (FAO GAUL) classification [24].

## *2.3. Impact Assessment*

The skeleton of the impact assessment was derived from the United Nations Platform for Space-Based Information for Disaster Management and Emergency Response (UN-SPIDER) recommended framework for flooding assessment using Sentinel 1 SAR data. This provided the basis for the flooding model. The increasing frequency of flooding events [2] in combination with the constantly increasing number of economic assets and dense population located in flood-prone sites have amplified the need to better use of Earth observation (EO)-based information for disaster management. EO-based mapping products can provide information on the flood extent and facilitates extensive spatial analysis of the flood event. A fast response to a flooding incident is vital to minimize the impact and potential damage of flooding. Decisionmakers and disaster management are often reliant on mapping products to make relief decisions. EO data can provide the relevant information with the spatial and temporal coverage to drive the decision-making in a limited time frame. UN-SPIDER recommends the use of optical imagery and radar at different spatial and temporal resolutions for flood mapping. Sentinel-based flood mapping carried out using the UN-SPIDER workflow is immune to weather conditions (as opposed to more commonly used optical data). Both data sources are established in both practical applications and in the scientific literature [25–31]. Hence, the UN-SPIDER Sentinel-1-based flood-mapping workflow was used (see Figure 2).

The tool was expanded using additional datasets to include impact parameters such as population density, high resolution land cover type and forest degradation, particularly in mangrove forests. In addition, masks were constructed to remove co-founding factors such as permanent surface water and topography parameters such as slope. An overview of the datasets used for the flooding model and impact assessment can be found in Table 1 overleaf. All the data presented below was resampled to have a 1 km spatial resolution prior to analysis.

#### 2.3.1. Flood Model

As seen in Figure 1, the image collection used for the flood extent image was taken from Sentinel-1 SAR GRD data, extracted, and processed through Google Earth Engine. This was clipped to the ROIs in Madagascar, namely the Melaky and Boeny regions, using the Human Data Exchange's Office for the Coordination of Humanitarian Affairs (OCHA) administrative boundaries at level 1. In the case of Mozambique, in the Sofala and Zambezia provinces, which have a quasi-similar extent and were also affected by the TC Ana, the Food and Agriculture Organization Global Administrative Unit Layers (FAO GAUL) were downloaded, and Sentinel-1 data were applied to it. The FAO GAUL administrative layer was used for the flood-extent study in Mozambique, as it was found that the OCHA boundaries significantly cropped the Mozambican coastal areas, including mangrove forests, which were the main topic of this study. Additional methodology on pre/post-processing, and explanations of the period of study used are further explained in the Supplementary Materials (Supplementary S1).

#### 2.3.2. Socio-Ecological Flood Impacts Model

The impact assessment of this study aimed to offer an integrative approach which looked at a diversity of sociological and ecological parameters, namely: exposed population depending on population density, the extent of potential damage in urban areas and the ecological consequences of the storm in key mangrove ecosystems.

To assess the number of potentially affected populations in Mozambique and Madagascar, population-density data were gathered from the World Population Hub at 1 km resolution (Table 1). As the flood layer derived from Sentinel-1 data was of 10 m resolution, the dataset was reprojected to a 1 km resolution to count the overlapping pixels between the flood model and the number of inhabitants per km$^2$. A reducer computing an aggregated weighted sum of those input pixels was used to obtain the number of people exposed per region and visualize spatial trends in ROIs. As such, flooded areas with low population density, under 250 inhabitants/km$^2$, were ascribed to the 'low' category, flooded areas with medium population density, between 250–500 inhabitants/km$^2$, were ascribed to the 'medium' category while flooded areas with high population density, above 500 inhabitants/km$^2$ were ascribed to the 'high' category. It is important to note, however, that this was prescribed arbitrarily and visualized to emphasize differences in population density per affected flooded area. In reality, in Mozambique for example, the mean population density of the 2020 dataset was of 40 inhabitants/km$^2$.

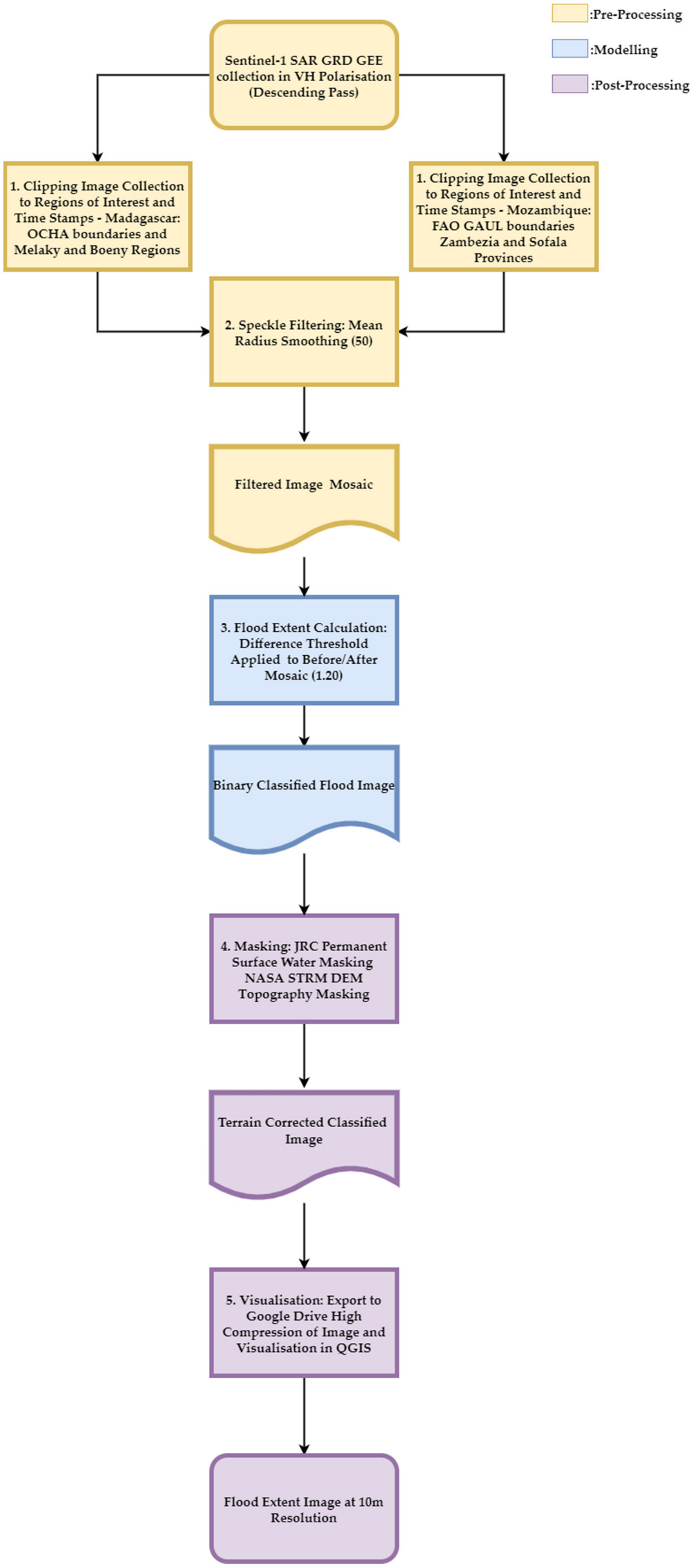


**Figure 2.** Flood model workflow. Adapted from UN-SPIDER radar-based recommended practice. All code can be found on GitHub.

**Table 1.** International Resource Panel (IRP) Dataset overview, sources, resolution, and temporal coverage.

| Data (Index Type) | Data Name | Source | Spatial Resolution | Temporal Coverage |
|---|---|---|---|---|
| Land Cover Classification | CGLOPS Land Cover Classification | Copernicus: ESA-VITO | 10 m | Static: 2020 |
| Population Density | World Population Density: Madagascar | World Pop Hub | 1 km | Static: 2018 & 2019 |
| | World Population Density: Mozambique | | | |
| Mangrove Degradation (NDVI) | Sentinel 2 | ESA | 15 m | 2013–2022 |
| | Sentinel 1 SAR—GRD | | 5 × 20 m | 2017–2022 |
| Flooding Model | JRC—Global Surface Water Mapping Layers v1.3 | EC JRC | 30 m | 1981–2021 |
| | SRTM DEM—void filled | ESA | 15 m | Static: 2015 |
| | CGLOPS Land Cover Classification | Copernicus ESA—VITO | 10 m | Static: 2020 |

Assessment of the affected urban areas in the Mozambique Channel was computed using the ESA World Cover dataset at 10 m resolution (Table 1). The tiles of interest were downloaded from the ESA World Cover viewer, which uses a random forest classification algorithm, then pre-processed in QGIS, tiled, merged and compressed. In Google Earth Engine, the same reducer technique to the population parameter was applied by doing the weighted sum of overlapping pixels between the flood model and urban class, after selecting the band associated with the land-cover class for urban areas (50) [28].

In order to assess the impact of TC Ana on the mangrove ecosystems, a NDVI was computed using a mosaic of Sentinel-2 data (Equation (1)). This used the red and NIR band, which correspond to bands B4 and B8. Equation (1) is the NDVI used to assess mangrove degradation after cyclone season:

$$NDVI = \frac{NIR - Red}{NIR + Red} \quad (1)$$

As previously mentioned, due to the high number of clouds during the period of study (cyclone season), the NDVI was computed using a median composite of images from before the start of the cyclone season vs. after the cyclone season. As such, this NDVI effectively looked at the impacts of all the cyclones that occurred between September 2021 ('before') and June 2022 ('after'). This was then applied to the ROIs and areas of mangrove forests using band 95 for the 'before' image and the 'after' image of the World Cover dataset [28]. Finally, a change analysis was computed whereby the difference between the 'before' and 'after' image was computed by dividing the 'after' image by the 'before' image, much like the flood-model methodology. The resulting difference image shows areas with light pixels displaying high change after the cyclone season and areas with dark pixels displaying consistency and no changes after cyclone season. All code and user instructions can be found on GitHub and is reproduceable in Google Earth Engine (GEE) in JavaScript, using the afore-mentioned open-source datasets.

## 3. Results

Results from this study's flood model displayed the presence of flooding during the passage of TC Ana. In total, it was found that more than 1,051,992 hectares flooded during the period of study (January–February 2022) in the Zambezia and Sofala provinces in eastern Mozambique. On the other hand, in Madagascar there were less-flooded areas, with a total of 706,715 ha flooded over the regions of Boeny and Melaky in western Madagascar.

The output from the flood model displayed significant flooding and apparent changes in the landscape between the periods of study, for example in Morrimeu National Reserve (Figure 3).

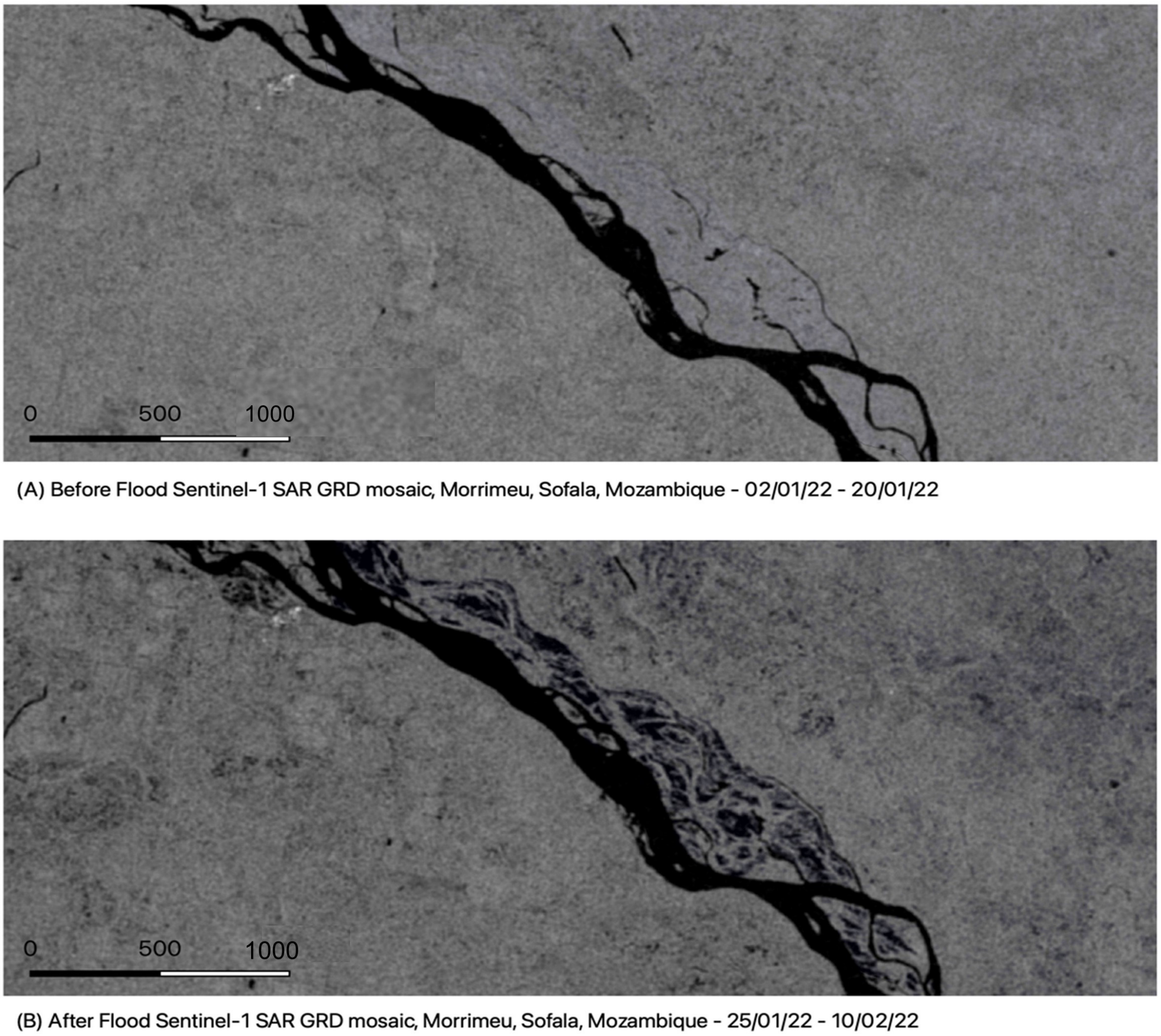


**Figure 3.** Before (**A**) vs. after (**B**) Sentinel-1 SAR mosaic of the Morrimeu National Reserve Area in Sofala, Mozambique. Areas on the eastern side of the Zambezi River can be seen to have been flooded, with stagnant water bodies caught between drier patches of land.

The overall flooding model can be seen in Figure 4 overleaf, at a high resolution of 10 m. Most of the flooding occurred throughout the Zambezia province, along the storm track, while in the Sofala province, the majority of flooding occurred in the north of the Sofala region near the Zambezi River.

In Madagascar, most flooding occurred in the north-western region of Boeny, coinciding with the storm track on the 23 January. Most of the flooding in the Boeny region was predicted to have occurred around Bombetoka Bay and further inland along the Betsiboka River, which flows into the Mozambique Channel.

The predicted output of the flooding model along with its respective land cover and population statistics can be seen in Table 2. Despite accounting for the highest hectares of flooding in Mozambique and Madagascar per region, the Zambezia province had a lower relative flooded area across all four regions of study (Table 2). In contrast, the Boeny region of Madagascar was predicted to have experienced the highest relative flooding across all regions impacted by the TC, with more than 14% relative area flooded compared to an average of 6.4% in the other regions.

When comparing both countries, it was found that the regions of Zambezia, Mozambique and Boeny, Madagascar accounted for most of the flooding area and its related damage.

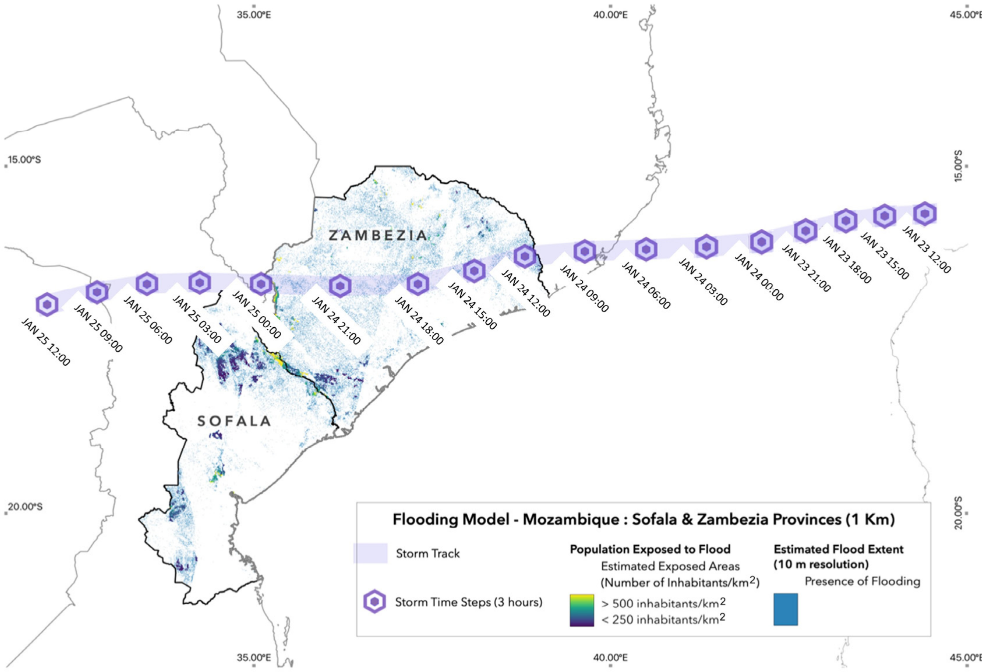


**Figure 4.** Flooding Model and Related Exposed Population in the Sofala and Zambezia Provinces, Mozambique for TC Ana between 23 and 25 January 2022 (10 m resolution). Data was predicted using Sentinel-1 SAR GRD data and World Population Hub data. The areas with the highest number of people affected per km$^2$ in Mozambique occurred in areas around the Zambezi River in the Sofala province in riverside cities such as Caia and Marromeu, which can be seen in light yellow.

As can be seen in Table 2, in the Sofala province alone, 108,400 people are estimated to have been affected by flooding linked to the TC Ana between 23 and 25 January 2022. In Mozambique overall, this number is estimated at more than 195,977 affected people, while in Madagascar, it amounted to 79,003. As such, Mozambique's potentially exposed population was 2.5 times more exposed than Madagascar's population during TC Ana. As can be seen in Table 2, the majority of urban areas affected by flooding were predicted to occur in Mozambique. However, overall, the urban areas impacted by flooding accounted for a small percentage of overall flooded areas, with a relative percentage of 1.4% in Mozambique compared to less than 1% in Madagascar. This is relatively negligible and could only be observed at a very fine scale on this study's 10 m resolution maps, and was therefore not included in visualizations.

The NDVI Index was calculated and visualized for both Madagascar and Mozambique as a measure of degradation. Changes in NDVI were observed in both countries' ROIs before vs. after the TC season.

In Mozambique, changes in mangrove degradation specifically, with a before compared to after the cyclone season method, were minute (~changes of 0.1 in NDVI). This was despite some local increases in the patchiness of mangroves near already-barren areas and some local degradation.

In Madagascar, in the Boeny region, mangrove areas displayed more degradation than the Melaky region and Mozambique overall. The majority of changes in NDVI could be seen in Bombetoka Bay, which flows into the Mozambique Channel, with differences in NDVI of 0.2–0.3. As can be seen in Figure 5, the comparison of this mangrove area shows a lower NDVI overall immediately after the cyclone season compared to before the season. Some stagnant bodies of water also appear to have been created south-west of Bombetoka Bay.

**Table 2.** Comparative Summary Table of the Flooding Model, Including Modelled Exposed Population and Urban areas. Relative areas for flooded areas, exposed population and urban areas were calculated as a percentage of total region area, total regional population, and regionally flooded area respectively.

| | Region | Area Affected by Flood (ha) | Relative Area Flooded (%) | Number of Exposed Population | Relative Exposed Population (%) | Affected Urban Areas (ha) | Relative Affected Urban Areas (%) |
|---|---|---|---|---|---|---|---|
| **Mozambique** | Zambezia | 595,872 | 5.78% | 87,577 | 1.71% | 6741 | 1.13% |
| | Sofala | 456,120 | 6.71% | 108,400 | 4.80% | 7860 | 1.72% |
| **Madagascar** | Boeny | 451,731 | 14.55% | 66,591 | 7.15% | 4042 | 0.89% |
| | Melaky | 254,984 | 6.56% | 12,412 | 4.01% | 767 | 0.30% |

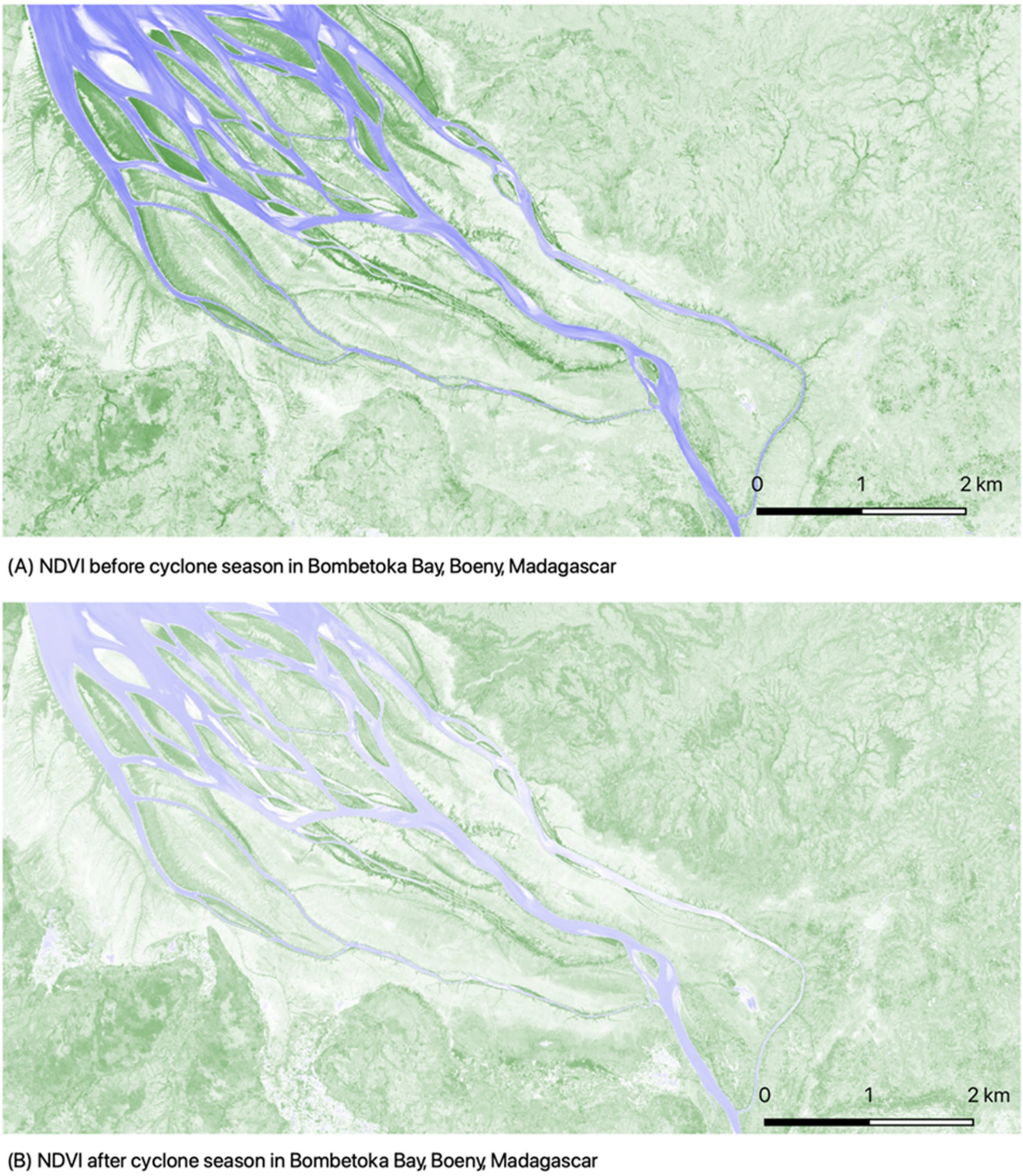


**Figure 5.** NDVI Comparison between before vs. after Cyclone Season in Bombetoka Bay, Madagascar-the country's largest remaining mangrove ecosystem using Sentinel-2 data. Areas in purple are areas with water components such as rivers or flooded areas. Dark green represents areas with high NDVI and healthy tropical vegetation, while light green represents areas that tend to be more barren, degraded and less healthy. Overall, mangrove forests tend to have been more degraded after cyclone season, patchy and bodies of stagnant flooded areas have also appeared.

The distance of exposed populations to healthy mangrove forests has been computed and can be visualized in Figure 5 below in the Sofala region.

## 4. Discussion

### 4.1. Impact Numbers in the Mozambique Channel

Ana was classified as a 'severe tropical storm' by Meteo-France La Reunion (and 'TC' by OCHA), due to its wind speed ranging 89–117 km/h, corresponding to a medium-intensity natural hazard (Meteo France Reunion, 2022). On the contrary, cyclone Idai had 10 min sustained winds ranging twice those of Ana with 166–213 km/h winds thus classifying it as an 'intense TC' [31]. The flooding impact from our model of TC Ana was then compared with the data from different sources. According to emergency reports by ReliefWeb, affiliated to the UN-OCHA initiative, more than 185,429 people were affected by TC Ana in Mozambique. This estimate concurs with our model's prediction of 195,977 affected people. However, predictions vary with immediate damage assessments published on the 31 January by the National Institute for Disaster Management and Risk Reduction (INGD) reporting 45,000 affected people in the Zambezia region, which is almost twice as less as our predictions, potentially as a result of the differences in field surveys compared to remotely sensed data [29]. In Madagascar, the National Office for Risk and Disaster Management (BNGRC3), estimated that there were more than 131,555 affected people throughout the 12 regions of the country [30]. This concurs with our estimate, particularly as most affected populations were located in the two ROIs, the Boeny and Melaky regions. National estimates in Madagascar tend to be comparable to this study as they tend to be remotely sensed Copernicus data combined with National Meteorological Services data, Meteo Madagascar.

Results from our flooding model showed that 5–15% of the study areas were flooded. When compared to past TCs, such as Idai in Mozambique in March 2019, where TC Idai had 10 min sustained winds ranging twice those of Ana with 166–213 km/h winds, thus classifying it as an 'intense TC' [31], this range was 50–60% [32]. Despite being very different events, these ranges concur with the cyclone's differences in category. As such, the study's flooding model seems proportionally less than cyclone Idai in terms of the extent of relative flooding area.

### 4.2. Spatial and Regional Trends

As the subject of this study is relatively recent and occurred only six months before the time of writing and is in an area underrepresented in scientific literature, there are very few studies or reports that may attempt to validate this study. However, it was found that this study's predicted impact and flooding model followed the storm track (Figure 4). Specifically, it was found that the majority of the flooding occurred in the areas where the depression and wind speeds were the highest, namely in Zambezia, Mozambique on 24 January with pressures as low as 994 hPa and wind speeds of 95–100 km/h [22]. Impacts were nonetheless felt in all four regions of the study, including the Boeny region, Madagascar which accounted for the majority of the relative flooded area, despite the storm being only categorized as a tropical depression [32] when it occurred in the region on 23 January. This could be because the Boeny region has a higher population of 931,171, three times the size of the Melaky region, and so has a higher number of urban areas [33]. As such, the increase of urban areas prevents rain from infiltrating into the soil underneath, causing urban impervious areas to display faster and larger hydrological responses than natural pervious areas [34].

In conjunction with a higher number of urban areas, vulnerability to flooding in Madagascar is emphasized by the lack of sustainable urban planning, insufficient capacity, and poor functioning of the drainage network because of clogging with solid waste and deterioration throughout the country [35].

In Mozambique, the flooding resulting from Ana mainly occurred in croplands, with urban areas being negligeable. This is particularly because croplands were found mainly around the Zambezi River, where the majority of production consists of easily flooded rice fields, as well as maize, sorghum, millet and cassava [24]. Long term, this may have impacts on food security and flooding recovery as lowland crops such as cassava and beans tend to be planted during the rainy season between January–March [24].

Within each country, the highest impact on population was felt in areas near rivers, namely the Zambezi River and Betsiboka River in Mozambique and Madagascar, respectively. Flooding was also caused in the Zambezia province following the Licungo River's overflow resulting in damaged bridges, transportation, and communication lines following moderate to high floods in the mainland [7].

Another key factor that also determines differences in flooded areas is topography. In the regions of Sofala and Zambezia, most of the elevation is classified as low and ranges from 0–150 m above sea-level on average [36]. In a study of cyclone Idai, it was found that areas with low elevation and close to the coast were more likely to be affected by floods [37]. As such, proximity to the Zambezi River and areas of low elevation in both Sofala and Zambezia regions may explain the spatial differences in flooding within each region and will be more likely to be flooded [37].

### *4.3. Beneficial Impact of Mangrove Forests in Flood Mitigation*

Throughout eastern Africa, both Madagascar and Mozambique show the largest proportion of highly exposed coastline to threats such as sea level rise, flooding, storms, particularly as a consequence of rising populations in urban coastal areas, due to better economic opportunities than further inland [37]. The areas of mangrove forest comprised in Sofala and Zambezia cover 50% of the total mangrove cover in Mozambique [17]. Despite a scarcity of studies in central Mozambique, it was estimated in 2017 that Sofala and Zambezia provinces had a high exposure to coastal climate hazards and erosion, through the calculation of an exposure index (EI) due to high tides, lower elevation, erosion, and high infrastructure development [13].

Globally, cyclones have been responsible for 46% of mangrove mortality. This was emphasized by cyclone Idai in 2019 which has considerably impacted Mozambique and the exposed region of Sofala. However, due to limited impact studies of cyclone Idai, little is known about the long-lasting impact of cyclone Idai on mangrove communities. In attempting to map out degradation in one cyclone season after Ana, it was found that there was no considerable degradation in mangrove forests following the cyclone in Mozambique, despite increased patchiness in areas close to already-barren areas which may have amplified mangrove vulnerability to storms [8]. As can be seen in Figure 6, most flooding in Sofala, Mozambique, occurred further inland along the Zambezi River, an area unprotected by mangrove forests. Overall, mangrove forests in both Madagascar and Mozambique displayed very low degradation levels compared to before the cyclone season in 2021, suggesting that healthy mangrove populations are present for 2022 at least. In light of this positive aspect, it was found that, despite a high population density in coastal areas in Mozambique, the majority of flooding occurred further inland, thus supporting the hypothesis that mangrove forests have successfully mitigated the impact of Ana on coastal communities [13]. However, the negligible NDVI change could also be a consequence of strong changes following cyclone Idai, which have been repercussed from 2019–2022 and cannot be appreciated through a one-year assessment.

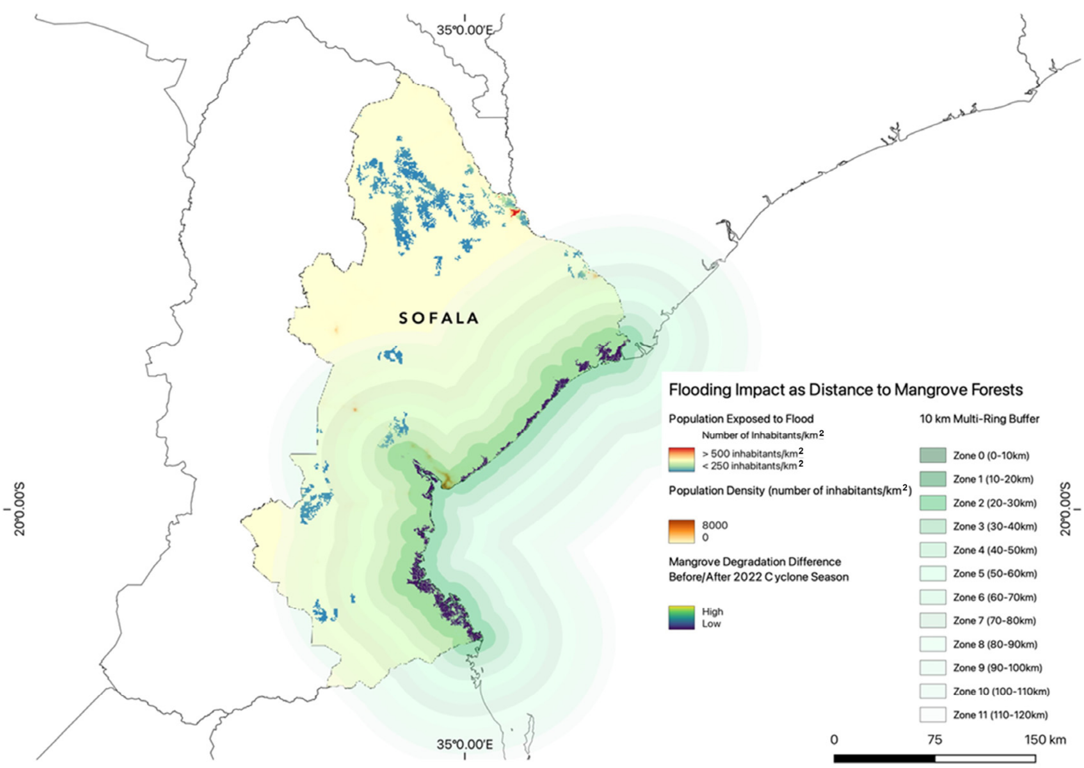


**Figure 6.** Flooding impact of TC Ana on Local Population over Sofala, Mozambique as a Measure of Distance from Healthy Mangrove Forests. In Sofala's healthy mangrove ecosystem before compared to after the cyclone season (<0.1 changes in NDVI), the majority of people exposed to flooding occurred beyond 100 km away from the coast, with the closest vulnerable people at least 40 km away from the mangrove area. Despite there being some areas of high population density, depicted in red, in the close vicinity of the mangrove areas (20 km), these populations seemed to remain unaffected by flooding.

### 4.4. Sociological Impact of Flooding

Flooding also unequally affects local communities throughout the ROIs in the Mozambique Channel. According to the INGD, 227 latrines and 24 schools were damaged in the Zambezia region alone [29]. This poses an immediate water, sanitation, and hygiene (WASH) problem, whereby impacted communities' basic needs are not met and are more vulnerable to the appearance of water-borne disease [10]. In addition, as communities become scattered, flooding places women and girls at increasing risk of organized trafficking, gender-based violence, lack of access to menstrual health management [38] and reduced access to food and resources [39]. In the future, an integrative approach to cyclone impact assessment should look at the effects of TCs on women and girls' vulnerability and gender-based violence. This is, however, currently limited by the scarcity of survey data available and being conducted in the Mozambique Channel. This has also been emphasized by COVID-19, whereby international NGOs and UN bodies did not conduct health and gender surveys for two to three years, leaving many women and girls unrepresented in data.

### 4.5. Limitations

In order to acquire land cover information, the 2020 ESA World Cover Map at 10 m resolution was leveraged. Globally, the classification map has an accuracy of 74.4%, thus meaning that more than 25.6% of the global map may be misclassified. This could imply that the mangrove extent might be different from ground validation, particularly as it dates from two years ago. In addition, the proportion of urban flooded area might equally be biased as urban settlements tend to appear differently across the globe, particularly on the African continent when compared to Europe, where the majority of the datasets' authors are from. However, validation was done by expert local end-users in many countries of interest and was mitigated for as much as possible. As this classification uses both Sentinel-1 and Sentinel-2 data, areas with persistent cloud cover in 2020 might result in misclassification at a fine scale due to the use of optical data (Sentinel-2). Cloud cover was also an issue when computing mangrove NDVI. Sentinel-2 data during the cyclone season was composited but still displayed 2.5% of cloud cover in some areas, thus affecting the NDVI change analysis at a fine scale, particularly in cloud-prone coastal areas around the city of Beira, Mozambique.

Moreover, population-density data was gathered for the year 2018 in Madagascar and Mozambique. According to the World Bank, Mozambique's annual population growth in 2022 stood at 2.8% and Madagascar's at 2.6% [40]. In addition, internal migration due to the lack of economic opportunities or forced climate change-related displacement [39] may also affect population density in 2022 compared to 2018. For example, emigration from Zambezia to Sofala, in 2010 was estimated at 31,600–79,100 people [41]. Moreover, internal displacement is likely to be emphasized following the recent series of severe cyclones that hit coastal Mozambique in 2019, namely Idai and Kenneth and in Madagascar, TC Batsirai in early 2022.

Studying the impact of cyclones and storms in terms of socio-ecological damage is vital. However, because many studies of cyclone impacts tend to be written in Portuguese, are outdated or non-existent, this hinders the potential to validate newer studies such as this one. In an attempt to provide immediate emergency response, the majority of impact assessments are enacted by humanitarian bodies and focus on immediate human impacts, and to a lesser extent the potential causes and buffers of TCs.

As such, one of the original aims of this study was to predict whether storm Ana created stagnant bodies that promoted the appearance of water-borne diseases such as malaria. However, due to the impact of COVID-19 on field survey accessibility and funding, the earliest study of malaria in the ROIs was only available in 2016 for Madagascar and 2018 in Mozambique. After contacting malaria experts, it was found that the malaria survey season for the year of 2022 had been considerably delayed due to cyclones and NGOs' financial recovery from COVID-19. Data were therefore not available at the time of the study (June–August 2022), while it typically tends to be finished by July each year [42]. Further studies should, therefore, aim to make the connection between the vulnerability of coastal communities to cyclones and malaria, as they are exposed to the loss of healthcare infrastructure, reduced access to resources and are more likely to be in the vicinity of stagnant water bodies [43].

## 5. Conclusions

This study aimed to map the impacts of TC Ana following its passage over Mozambique and Madagascar, two countries that have been most affected by the said tropical depression. It was found that there were differences in both environmental and anthropogenic impacts across all four ROIs, with the regions of Zambezia, Mozambique and Boeny, Madagascar experiencing the majority of flooding and flood-related impacts. In addition, urban areas were found to have been less likely to be flooded across all countries. Ecologically, this study established a difference in region-wide vegetation health compared to after the cyclone season. Despite this, mangrove forests across all ROIs were considered to be generally healthy in 2022. Finally, it was found that, in terms of the exposed population, areas in the vicinity of mangroves fared better than non-mangrove areas further inland. As such, this study further supports the global and local push for mangrove reforestation in tropical-coastal ecosystems to protect vulnerable communities from natural hazards worldwide.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app13074519/s1, Supplementary S1: Supplementary for Madagascar Channel. Supplementary S2: Pre-Processing. Supplementary S3: Post-Processing.

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