National Oceanography Centre

PASS-SWIO

Portagauge and Satellite Sea Level Monitoring System for the Southwest Indian Ocean

Implementation Road Map

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Acronyms

Acronym	Definition	Further Details
APMF	Agence Portuaire Maritime et Fluviale, Madagascar	National body responsible for management and operation of ports and harbours in Madagascar https://www.apmf.mg/en
BNGRC	Bureau Nationale de Gestion des Risques et des Catastrophes	National Office for Risk and Disaster Management, Madagascar https://bngrc.gov.mg/
CCI	Climate Change Index	ESA CCI+ is a series ESA programmes to establish satellite data based indices for Essential Climate Variables
CFIM	Centre de Fusion d'Information Maritimes	https://cfimmadagascar.org/
CNRO	Centre National de Recherches Océanographiques	Madagascar Oceanographic Research Organisation http://cnro.recherches.gov.mg/
C-RISe	Coastal Risk Information Service	Name of Project - website here: http://www.satoc.eu/projects/c-rise/
DGM	Direction Générale de la Météorologie	Madagascan Met Office http://www.meteomadagascar.mg/
EO	Earth Observation	-
ESA	European Space Agency	www.esa.int
FTM	Institut Geographique et Hydrographique National, Madagascar	National geographic and hydrographic agency
GFDRR	Global Facility of Disaster Reduction and Recovery	https://www.gfdrr.org/
GLOSS	Global Sea Level Observing System	https://gloss-sealevel.org/
GNSS-IR	Global Navigation Satellite System interferometric reflectometry	
IHO	International Hydrographic Organization	https://iho.int
IOC	Intergovernmental Oceanographic Commission	https://www.ioc.unesco.org/en

Acronym	Definition	Further Details
IOC	Indian Ocean Commission	https://www.commissionoceanindien.org/en/
IH.SM	Institut Halieutique et des Sciences Marines	Madagascar http://www.ihsm.mg/
NGO	Non-Governmental Organisation	
NOC	National Oceanography Centre	https://noc.ac.uk/
POLTIPS	Tidal Prediction Software	Developed at the National Oceanography Centre, UK
PSMSL	Permanent Service for Mean Sea Level	Global data bank for long term sea level change information from tide gauges and bottom pressure sensors, https://psmsl.org/
SatOC	Satellite Oceanographic Consultants Ltd	Project Partner http://www.satoc.eu/
SDG	Sustainable Development Goal	See e.g. http://www.un.org/sustainabledevelopment/sustainable-development-goals/
SHOM	Service hydrographique et océanographique de la marine	A French public administrative establishment under the supervision of the Ministry of the Armed Forces https://www.shom.fr/index.php/en
TASK	Tide gauge data processing and analysis software	Developed at the National Oceanography Centre, UK
TG	Tide Gauge	
UNESCO	United Nations Educational, Scientific and Cultural Organization	unesco.org
WIOMSA	West Indian Ocean Marine Science Association	https://www.wiomsa.org
WMO	World Meteorological Organisation	wmo.int

1. Introduction

The PASS-SWIO project is funded by the European Space Agency (ESA) under the EO4Society programme. It aims to establish a sea level monitoring system for Madagascar, based on the deployment of a low-cost relocatable tide gauge (Portagauge), which uses a radar gauge alongside Global Navigation Satellite System interferometric reflectometry (GNSS-IR) technology, combined with the analysis of satellite altimeter sea level data to provide validation and wider scale knowledge on sea-level variability.

The project partners have worked closely with the national Madagascar Meteorological Agency (DGM – Direction Générale de la Météorologie) who have taken responsibility for the local maintenance and operation of the Portagauge, and who have been trained to carry out the data processing and analysis (for tide gauge and satellite altimeter data).

The ESA project funding supported the design, build, transport and initial installation of the NOC Portagauge at Toamasina Port (as well as capacity building and stakeholder engagement). The initial deployment at Toamasina in June 2023, has enabled the collection of sufficient data to allow an accurate calculation of the main tidal constituents at that location, and to support a cross-validation against satellite altimeter data (reported in the Validation Report D3.2 and summarised in Section 2, below). This deployment has served as a proof of concept of the Portagauge system. In order to progress sea level monitoring in Madagascar it is necessary to implement the next phase of the project by moving the Portagauge to a new location.

This document, developed through discussion with key stakeholders in Madagascar, presents a Road Map for the sustainable long-term implementation of a national sea-level monitoring system for Madagascar, through redeployment of the Portagauge at additional locations around the coast of Madagascar, with consideration of current developments in permanent tide gauge installations and the need to secure funding to support these deployments and maintain the system.

We begin by introducing the Portagauge system and examining the current state of permanent Tide Gauge installations in Madagascar. In Section 2, the results of the deployment in Toamasina are briefly discussed. Sections 3 examines the need for sea level monitoring, particularly in the context of Madagascar, with input from stakeholders. We develop the Road Map in Section 4, by reviewing future locations for Portagauge deployment, with respect to sea level variability, coastal vulnerability and site suitability. We consider the cost of future deployments along with potential sources of funding in Section 5 and, finally, present our conclusions and recommendations in Section 6. It is hoped this can serve as a model for other island states and coastal countries in the Southwest Indian Ocean and beyond.

1.1. The Portagauge

The Portagauge is a self-contained portable tide gauge that facilitates rapid deployment and ease of installation.

Traditional tide gauges require a substantial investment in hardware to install a system in one fixed location. A tide gauge installation is designed and constructed to suit the requirements of a specific location; this is then installed and robustly anchored to the land to prevent movement. It is usually not possible, or desirable, to move this installation and reinstate it at a new location. In contrast, the Portagauge has been designed to provide the qualities of a permanent tide gauge installation, in a package that permits transportation and relocation around various sites.

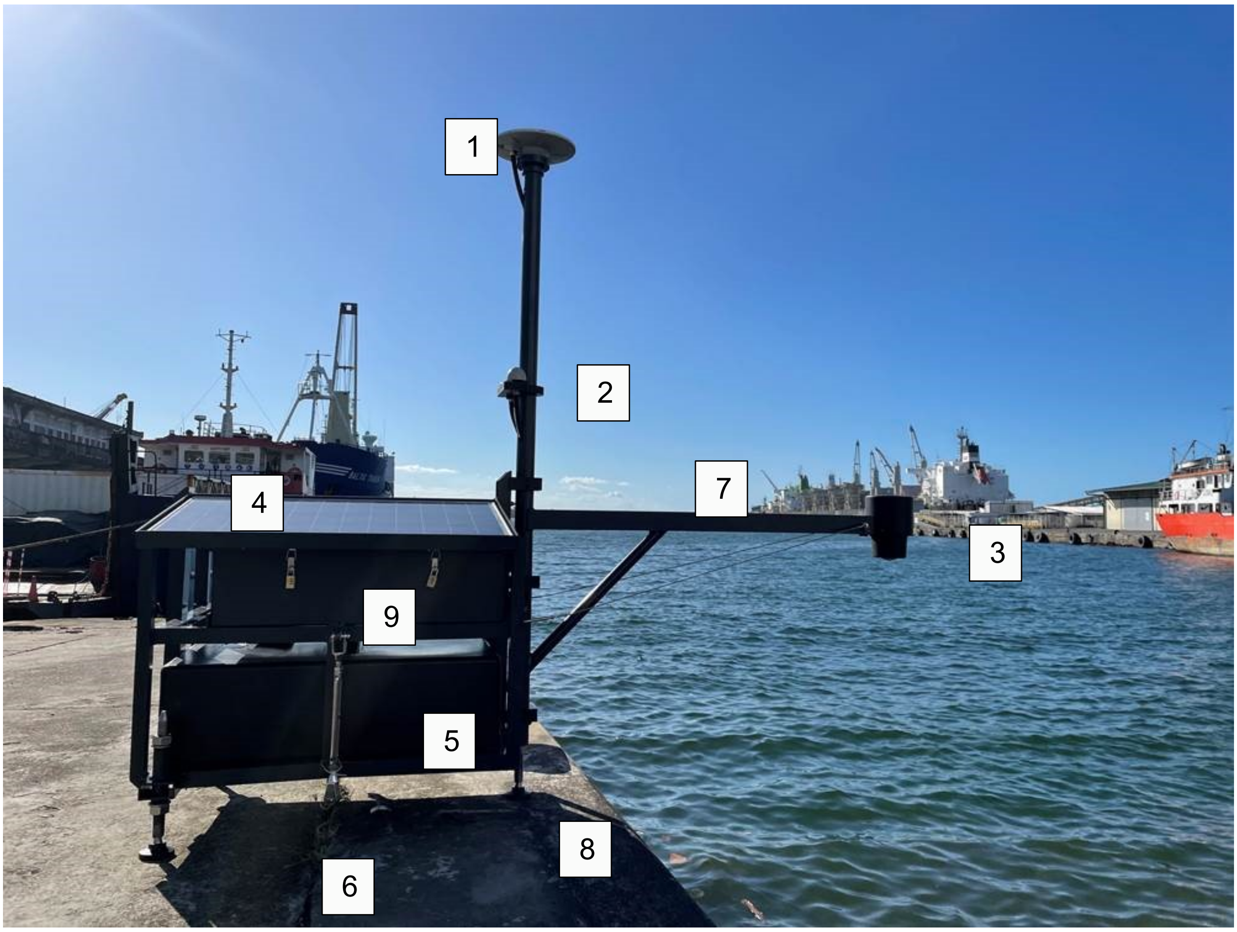


Figure 1 The Portagauge installed at Toamasina Port, with the key components identified

1. Trimble Zephyr GNSS antenna 2. GPS and 4G antennas for data logger time and communications 3. Vegapuls 6X radar sensor shown with protective cover 4. Solar panels 5. Water ballast tank 6. Turnbuckle anchoring point 7. GNSS mast / radar arm 8. Levelling feet 9. Instrument box

The design of the Portagauge is based on the NOC's permanent tide gauge installations, but uses lighter materials to ensure portability. It consists of the following key components (Figure 1):

- Vegapuls 6X radar sensor
- Trimble Zephyr GNSS antenna
- Trimble Alloy GNSS receiver
- Satlink3 data logger
- Vaisala PBT110 Barometer
- Mobile data communication

The equipment is housed inside two glass reinforced plastic (GRP) enclosures which in turn are located inside a steel protective case, this, in conjunction with the angled solar panels, protects the instruments from water ingress from wave overtopping or rainfall. The Portagauge is anchored to the ground with two steel turnbuckle anchors and further stabilised by filling the water ballast tank. The dimensions of the Portagauge are shown in Figure 2. It weighs 180kg when the water tank is empty and 460kg when full.

Power is supplied by a battery which is charged by solar panels, no external power supply is required.

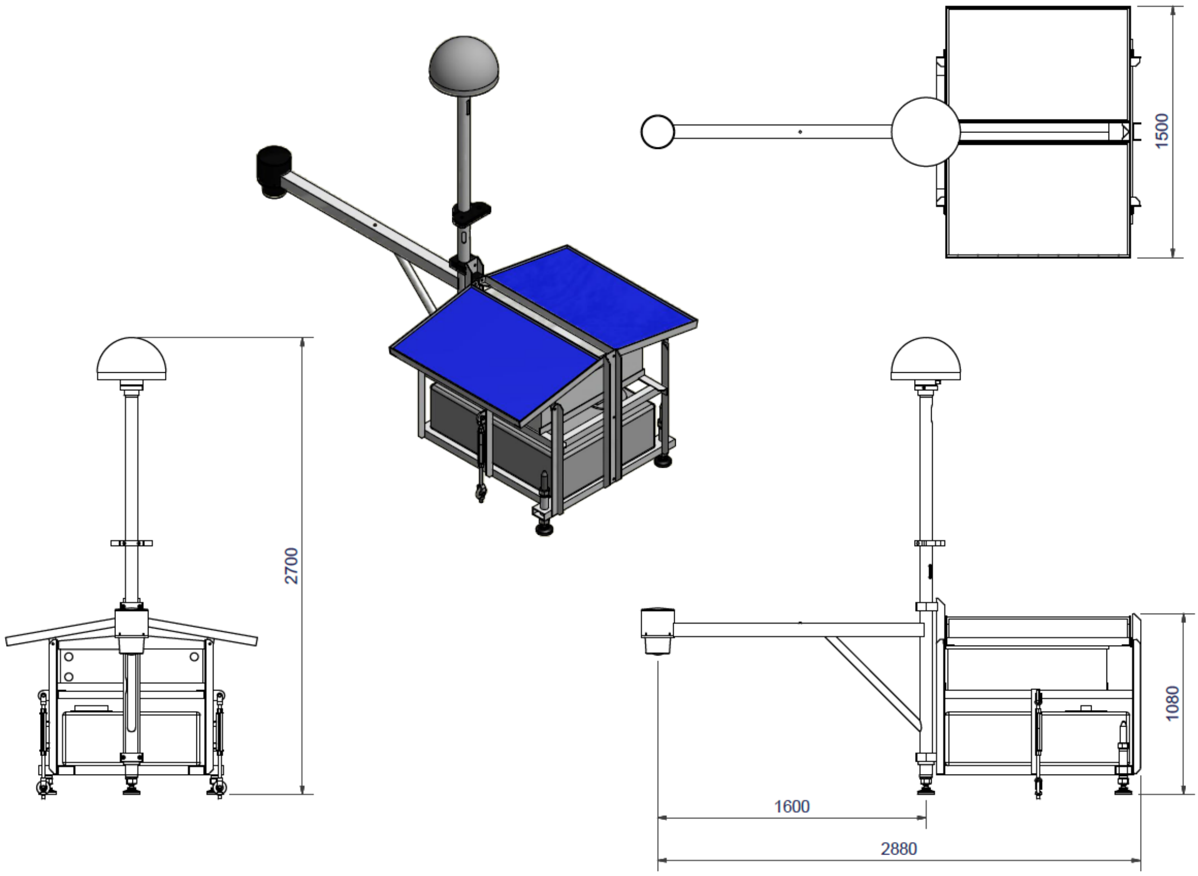


Figure 2 Design drawing for portagauge, dimensions in millimetres

The Vegapuls 6X radar sensor accurately measures the distance to the sea surface. As the sea level varies due to the tide, the radar sensor measures the distance to the sea surface continuously. The GNSS antenna continually receives signals from satellites overhead, which are logged by the Trimble Alloy GNSS receiver. These data provide information on the location of the Portagauge and provide an indication of any vertical land movement experienced by the gauge. The GNSS also receives reflected signals from the sea surface, which through an innovative analysis technique, GNSS-IR, can be used to infer sea-level.

1.2. Tide Gauges in Madagascar

Madagascar currently has very limited tidal prediction capability (based primarily on model data) and no national sea level monitoring capability. At the inception of the PASS-SWIO project, there was only one functioning tide gauge station, at Toamasina Port. This had been installed by SHOM and was operational from January 2010 to March 2022 when it was removed to accommodate development of the port. An earlier tide gauge, at Nosy Be in the cyclone-prone north of the island, was operational until May 2003, then in 2004 the pier on which it was located was badly damaged by a storm. We are aware that there have also previously been tide gauges at Toliara and Taolagnaro (Fort Dauphin), but there is no data available from these installations (see Section 3.2).

Over the last few years there has been some work to improve this situation. IH.SM have been working with the First Institute of Oceanography, China to install new permanent tide gauges at Toliara and Taolagnaro (Figure 3). The team at IH.SM are currently developing a methodology to share the collected data. In addition to these tide gauges, IH.SM hope to install two further tide gauges in the North of Madagascar by the beginning of 2026 (one of which will be at Nosy Be).

The DGM are also currently working on a proposal to secure funding from the European Union to install a network of permanent tide gauges around the coast of Madagascar.

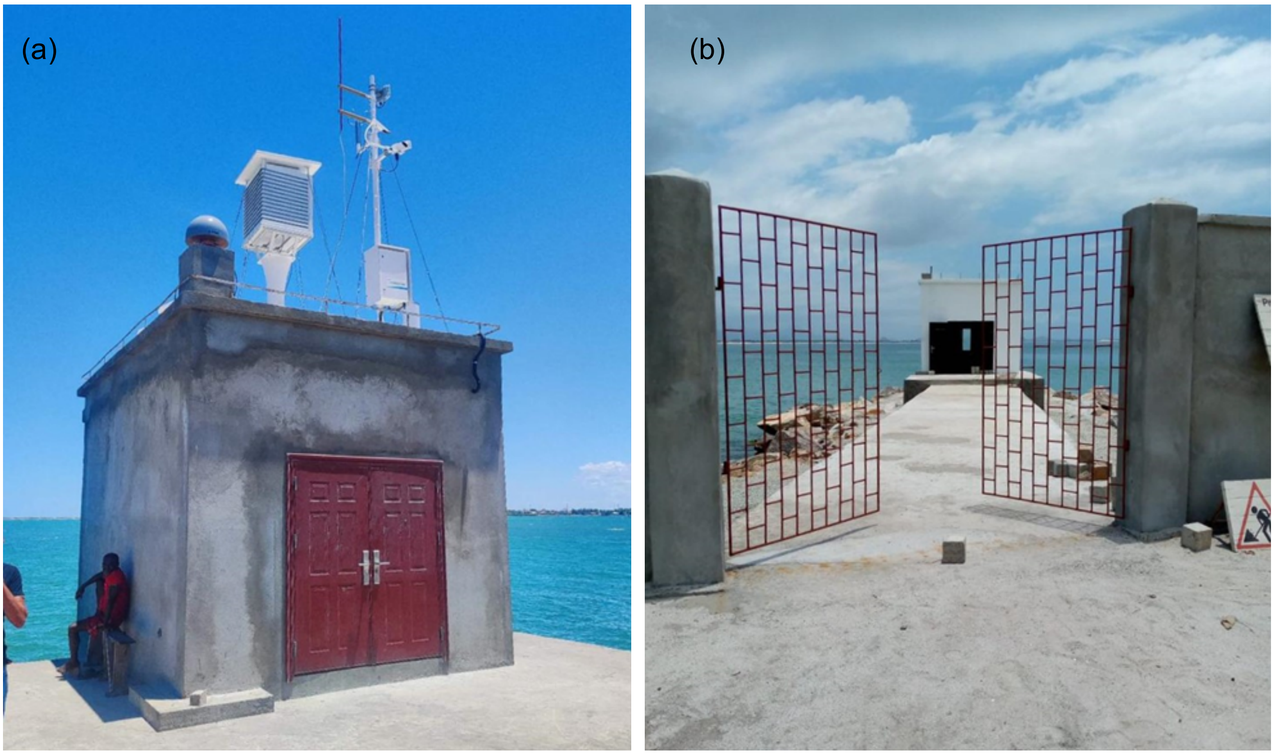


Figure 3 New permanent tide gauges installed by IH.SM at (a) Toliara and (b) Taolagnaro

2. Deployment of the Portagauge at Toamasina

The Portagauge was installed at Toamasina Port on 13th June 2023 (Figure 4). A validation study (Cotton et al, 2024a) was carried out to:

- Quality control and validate the Portagauge radar gauge data.
- Establish the accuracy of the satellite measurements of sea-level with respect to the SHOM Toamasina tide gauge measurements.
- Establish the accuracy of the Toamasina GNSS-IR measurements with respect to the Toamasina Portagauge radar gauge measurements.
- Confirm if a reliable cross-validation can be made between Portagauge radar and satellite altimeter data with a limited period of data (in this case 8 months).

Three separate cross-validations were carried out:

- Cross-validation of historical (SHOM) Toamasina tide gauge data against satellite altimeter data (01/01/2010 to 29/03/2022).
- Cross-validation of Toamasina Portagauge radar gauge data against satellite altimeter data (13/06/23 to 31/01/24).
- Cross-validation of Toamasina Portagauge radar gauge data against Toamasina Portagauge GNSS-IR sea-level data (13/06/23 to 31/01/24)

Figure 4 Installation team from NOC, SatOC and DGM with the Portagauge at Toamasina Port

The Portagauge data (for 13/06/2023 to 31/01/2024) were quality controlled and validated using the NOC TASK software. Tidal Harmonics were extracted from the sea level data, and model predictions generated. Residuals were then inspected for evidence of any large outliers or long-term trends. The data were found to be good quality, with no significant outliers (Figure 5).

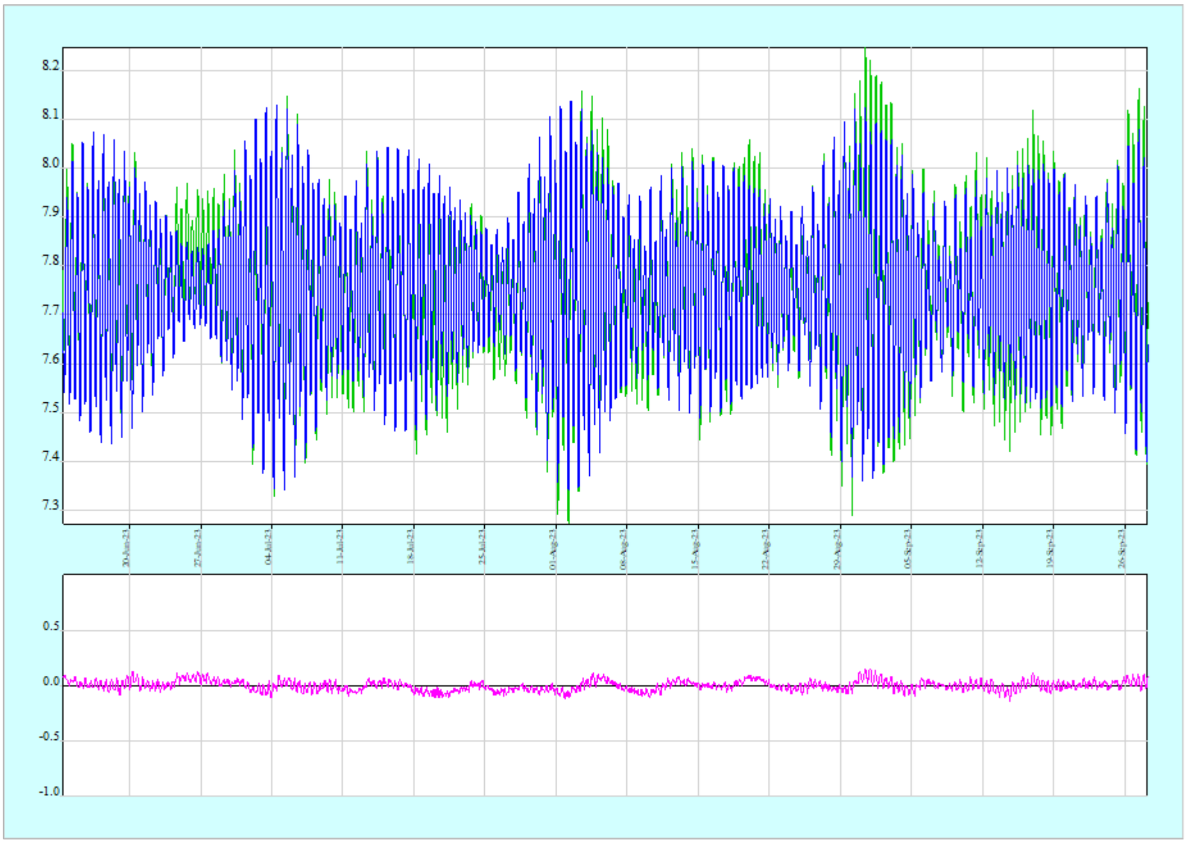


Figure 5 Portagauge radar gauge data (blue) overlaid on model tidal predictions (green) and residuals (magenta) for eight months from 13/06/2023 to 31/01/2024

Taken over 27 months (01/01/2020 to 29/03/2022), measurements of sea level anomaly from the Jason-3, Sentinel-3a and Sentinel-3b Level 3 data validated against Toamasina tide gauge sea level residual (Figure 6) showed a root mean square error of 4 to 5cm. This shows a high level of agreement between the satellite and tide gauge data and suggest a low natural variability in sea level at this location in the Madagascar coastal region. These results also provide confidence that the altimeter data provide an accurate measurement of sea level close to the Madagascar coast.

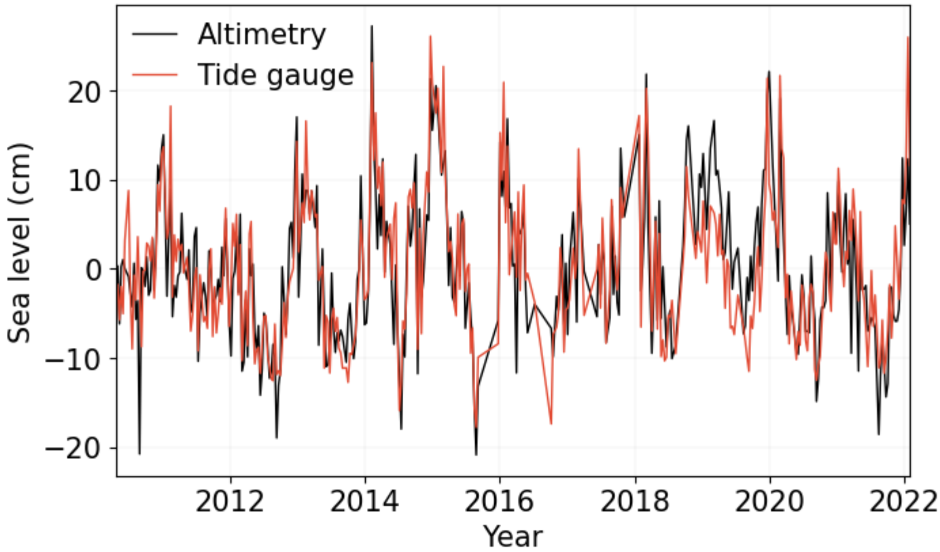


Figure 6 Time series of altimeter sea level anomaly (Jason series satellite data, including Sentinel-6a-MF) and SHOM tide gauge residual sea level at point of highest correlation (relative orbit 094)

Over a period of 8 months (13/06/2023 to 31/01/2024), measurements of total sea level from the Sentinel-6a MF, Sentinel-3a and Sentinel-3b satellites validated against Portagauge tide gauge sea level show root mean square error of between 5 to 10cm (Figure 7).These results give confidence that a data set over a limited period can be used to validate altimeter data against a temporary tide gauge. There is an offset of between 18.45 to 20.15m between the satellite altimeter and Portagauge sea level measurements.

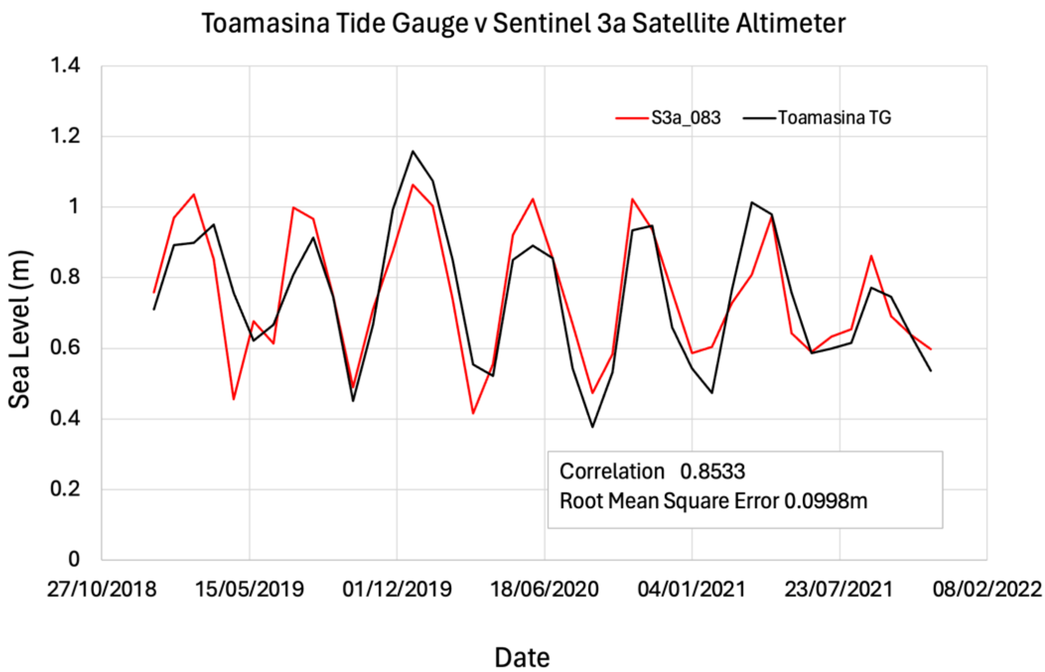


Figure 7 Time series of Sentinel-3a altimeter and tide gauge total water level from relative orbit 083, at the point of maximum correlation

An investigation looking into the possible benefits of using specialised coastal processors (Cotton and Shaw, 2023), indicated that coastal processing would provide more valid data very close to the coast (within 5km of the coastline), but did not provide improvements to the standard EUMETSAT L2 product in the range 5-10km from the coast.

Finally, comparison between the GNSS-IR and radar gauge daily mean sea levels (both instruments on the Portagauge installed at Toamasina) show a very high level of agreement (root mean square error of 9.2mm, Figure 8). This demonstrates that the GNSS-IR instrument is able to provide an accurate measurement of water level, even when it has a severely restricted field of view (Figure 9).

Together these findings help us to conclude that a relatively short-term deployment of the NOC Portagauge can provide sufficient data for a reliable cross-validation against satellite altimeter data.

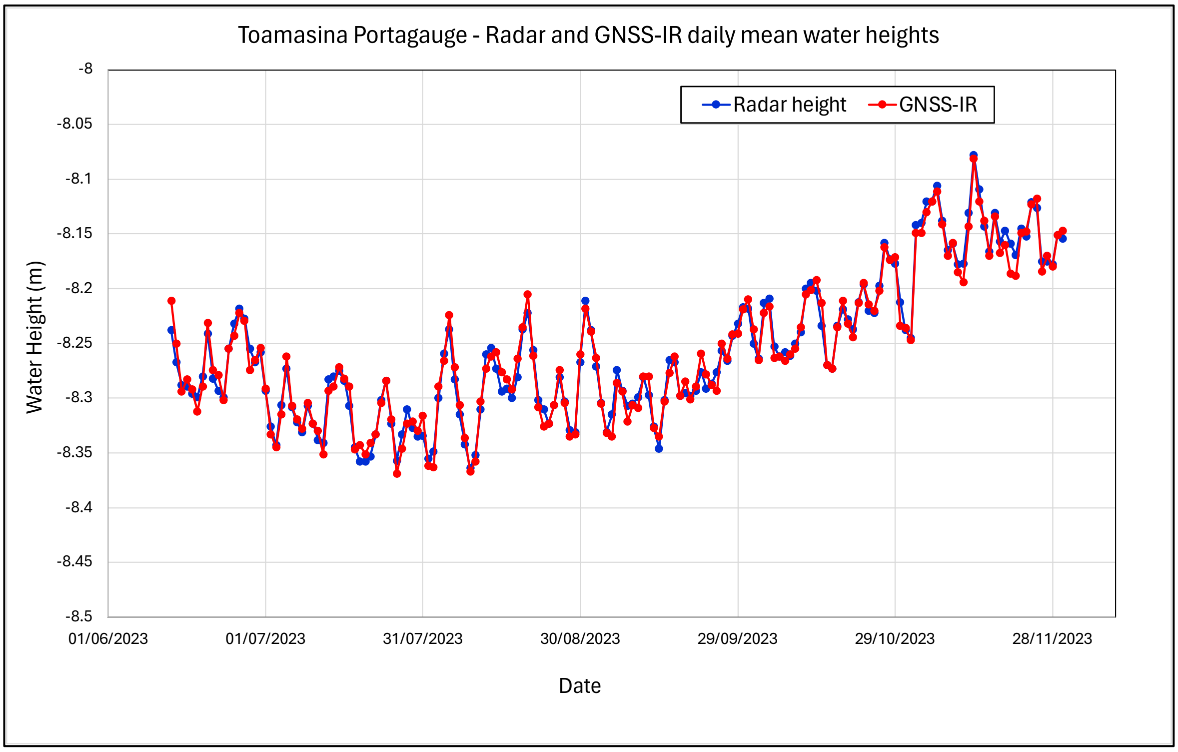


Figure 8 Daily mean water height measurements from the Toamasina Portagauge radar sensor and GNSS-IR

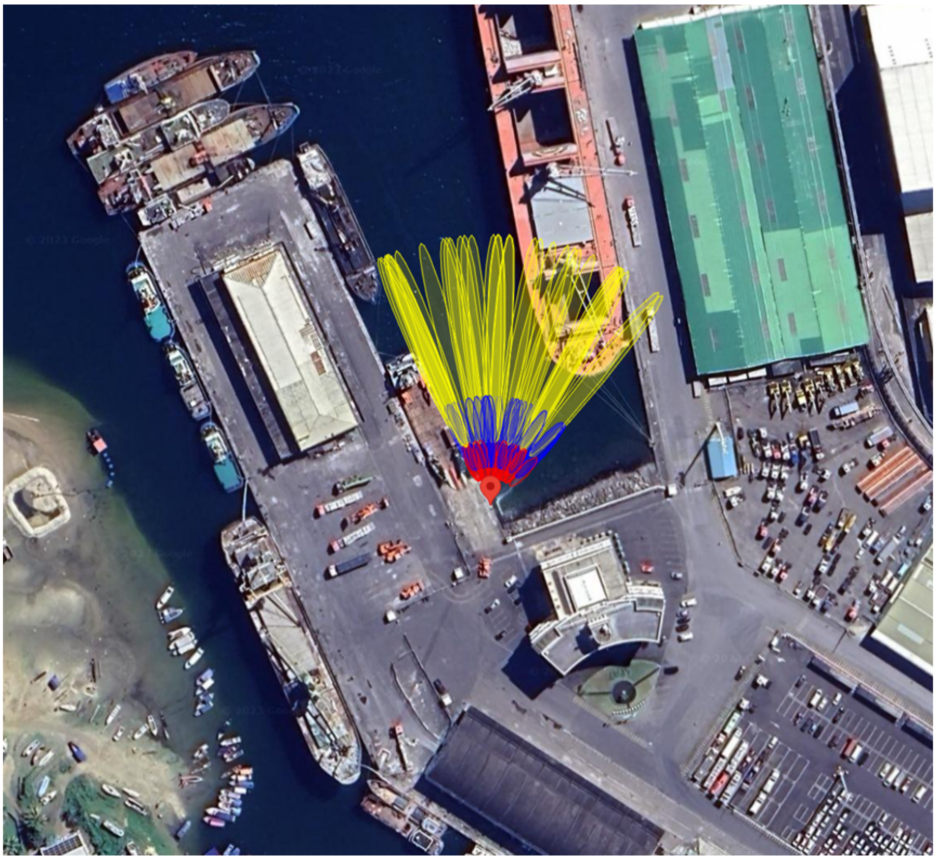


Figure 9 Field of view for GNSS-IR measurements in Toamasina Port

3. Requirements for Sea Level Monitoring

3.1. Why do we need to understand sea level?

Sea level is one of the most useful and widely used oceanographic variables (Figure 10). These data are vital to scientists studying fluctuations in major ocean currents and improving our understanding of global climate change. Sea level is used by engineers designing coastal installations, by those involved in operational oceanography (for example, providing flood warnings from storm surges or tsunamis), and in local applications such as provision of tide tables for port operations or leisure activities.

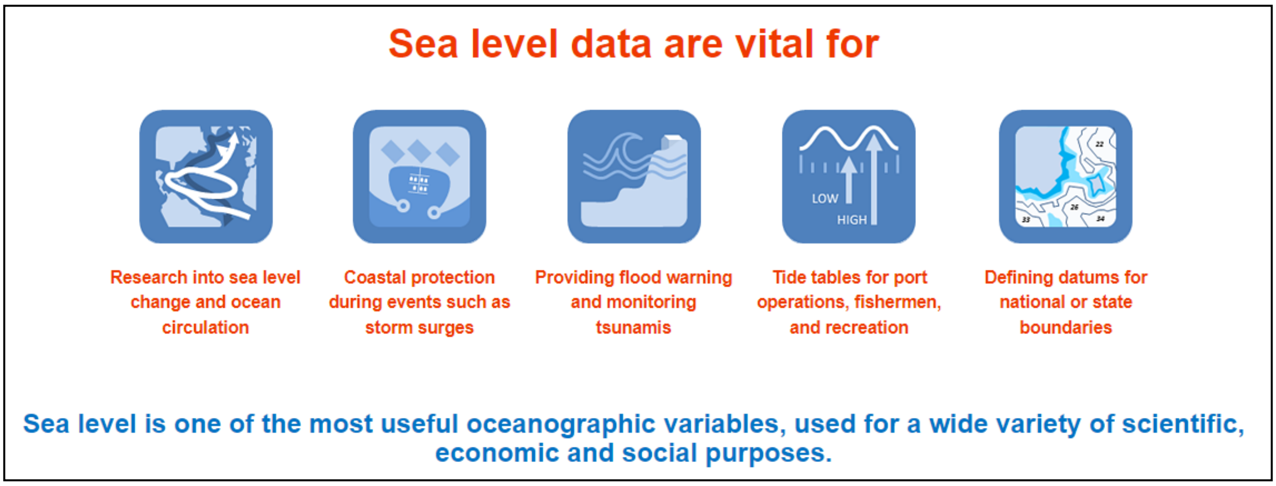


Figure 10 Importance of sea level data (GLOSS, 2024)

There are limitations to the geographical coverage of sea level data, with a significant geographical bias in long term records (required for applications such as climate change studies) towards the Northern Hemisphere (Figure 11).

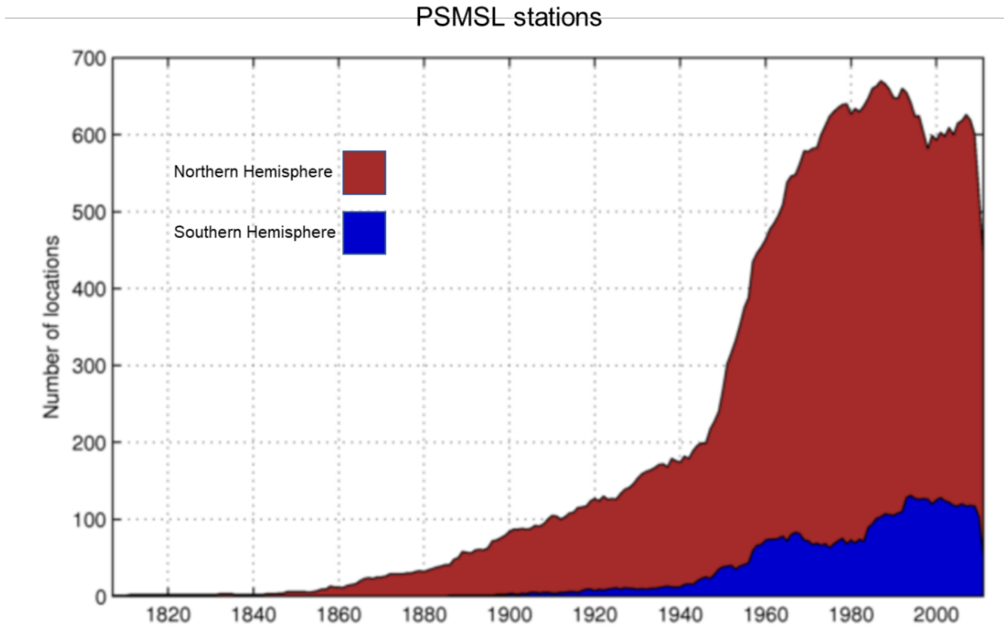


Figure 11 Number of Permanent Service for Mean Sea Level stations with Revised Local Reference data. Adapted from PSMSL, 2012

3.2. Previous reports on sea level requirements

A good understanding of all hazards related to sea level requires long-term, high-quality observations, which can only be assured through dedicated funding and skilled local operators (Hibbert, 2021). There have been four previous reports on the requirements for sea level monitoring for Madagascar, two written for the Intergovernmental Oceanographic Commission (IOC, Razakafoniana, 1999 and Razakafoniana, 2001) and two written as part of the UK Space Agency funded C-RISe project (C-RISe, 2020 and C-RISe, 2021).

The national reports (Razakafoniana, 1999 and Razakafoniana, 2001) noted that, following the end of the colonial era, when the French Hydrographic Service (FHS) was responsible for Madagascar's tide gauges, sea level monitoring was recommenced when Madagascar joined the GLOSS program in the mid-eighties. At this time a tide gauge network of 3 gauges was established by the Centre National de Recherches Océanographiques (CNRO) working with Foibe Taosarinranin'I Madagasikara (FTM). These were located at Nosy-Be, Toliara and Taolagnaro (Fort Dauphin), see Figure 16. CNRO was responsible for the processing of the data using a software package provided by the University of Hawaii. However, the reports note that most of the data from Taolagnaro and Toliara were of poor quality with many data gaps due to technical problems, thus only data from the Nosy-Be gauge were processed. The reports also note that Madagascar suffered from a lack of manpower working on physical oceanography and related subjects, and that the training of a scientist working on this field would have been useful for the processing and analysis of the sea level data. The collection of data from gauges for processing and distribution to the external data archives was problematic for CNRO, and assistance with data transmission and computer facilities was requested.

The 2001 report notes a proposal for the installation of two additional tide gauges at Morondava and Manakara (Figure 16), to support coastal erosion studies. In support of this proposal it was noted that the regions around both Morondava and Manakara have been affected by erosion, which has impacted the harbour at Morondava and endangered coastal properties and infrastructure. However, we have been unable to find any record of tide gauges at either location.

The C-RISe (Coastal Risk Information Service) project held a workshop in February 2020 in Antananarivo to review the project and discuss coastal risk priorities for decision makers; how satellite data can complement other data sources to address priorities; and how to increase local capacity to use satellite data in providing scientific support in strategy development and management of coastal areas. The workshop had 45 participants from across Madagascar, including representatives from government agencies, NGOs and research institutions. Priority areas included marine planning, coastal erosion and protection, impacts on marine ecosystems, tropical cyclone tracks, and impacts of all aspects of climate change on human activities and livelihoods. All of these would benefit from availability of sea level data.

The workshop highlighted a need for data (and more effective data sharing), but also the need to increase the capacity to work with and use these data, with a need for both training and IT resources. This need for capacity development, in order to achieve a fully operational national tide gauge network and make data available to end users, was also raised by Razakafoniana (2001).

The C-RISe policy brief on *The Importance of Sea Level Monitoring for Madagascar* (C-RISe, 2021) highlighted the potential to use satellite altimetry measurements in combination with tide gauge and GNSS data to enhance knowledge of sea level change. This approach was recommended in order to address the reasons, identified by Hoguane (1999), that tide gauges are often non-operational in developing states. These are:

- Lack of equipment (and difficulty acquiring replacement parts (Mundlovo et al., 2007));
- Lack of qualified maintenance personnel;
- Lack of funds to maintain tide gauges;
- Difficulty in accessing remote tide gauges due to poor transport infrastructure, poor roads and insurgency.

3.3. Users Requirements from PASS-SWIO Questionnaire

To investigate the interests and requirements of users of sea level data in Madagascar, a questionnaire was issued in the early stages of the PASS-SWIO project. There were 17 respondents, representing a wide range of users and applications (Table 1) of sea level data. This has enabled a broad overview of what data are currently being used and what the needs are in terms of both data and capacity building.

A large proportion of respondents were at management level, and work for government in some capacity. This is reflected in the recorded applications of interest and requirements, which tend to relate to the needs for coastal management applications.

It was not possible to draw strong conclusions in terms of specific detailed requirements for sea level data from the questionnaire responses. This is due to the current extreme lack of data availability and the range of areas from which our respondents were drawn (although this may not represent all potential users of sea level data in Madagascar). The current lack of sea level data for Madagascar, due to an absence of tide gauges, has resulted in limited capacity to use these data and the need for data for a wide range of locations.

We provide a summary of responses below, more detail is available in the *PASS-SWIO User Requirements Survey – Summary of Results* (Cotton, 2022).

Priority Requirements for Sea Level Data

Priority requirements in terms of applications, what derived products were needed, and key data product characteristics are summarised in Table 1.

Table 1 Priority requirements for sea level data

Applications	Derived Products	Characteristics
Risks Disasters Coastal retreat Marine erosion Coastal protection work Livestock and marine culture Hotels Urban planning	Sea level rise Tidal predictions Cyclone surges Tide gauge data Satellite data Sea level at specific times and places	Interoperable Daily data Regularity Timely and high resolution Easy to handle formats

A separate question provided more detail on the applications for which sea level data were used. The responses indicated that applications that sea level data were used for were slightly biased towards coastal management, planning and conservation (57%), as opposed to research or operational applications (43%). Just under 30% of respondents needed sea level data for both management and planning applications and scientific research.

Important Locations for Sea Level Data

Respondents were asked what the most important locations in Madagascar were for sea level data. These are listed in

Table 2 and identified on a map in Figure 12.

Table 2 Important Locations for Sea Level data from the PASS-SWIO Questionnaire

Scale	Location
Large scale	All Coasts; Western parts; shrimp fishing zone; maritime emergency zones; Madagascar Exclusive economic zone
Regional areas	Diana; Northern Diana region; Boeny region; Sava region; Manambolo-Tsiribihina region, North-East (Sainte Marie); North-West (Maintirano) coast; West coast - Maintirano to Mahajanga; Northwest - Radama archipelago to Nosy Hara; East coast - Toamasina to Eastern Cape
Specific locations	Diego Suarez, Toamasina, Mahajanga, Manakara, Toliara, Morondava, Nosy-Be, Sainte-Marie, Manakara, Fort Dauphin, Vangaindrano, Mananar, Cap Est, Antalaha, Sava

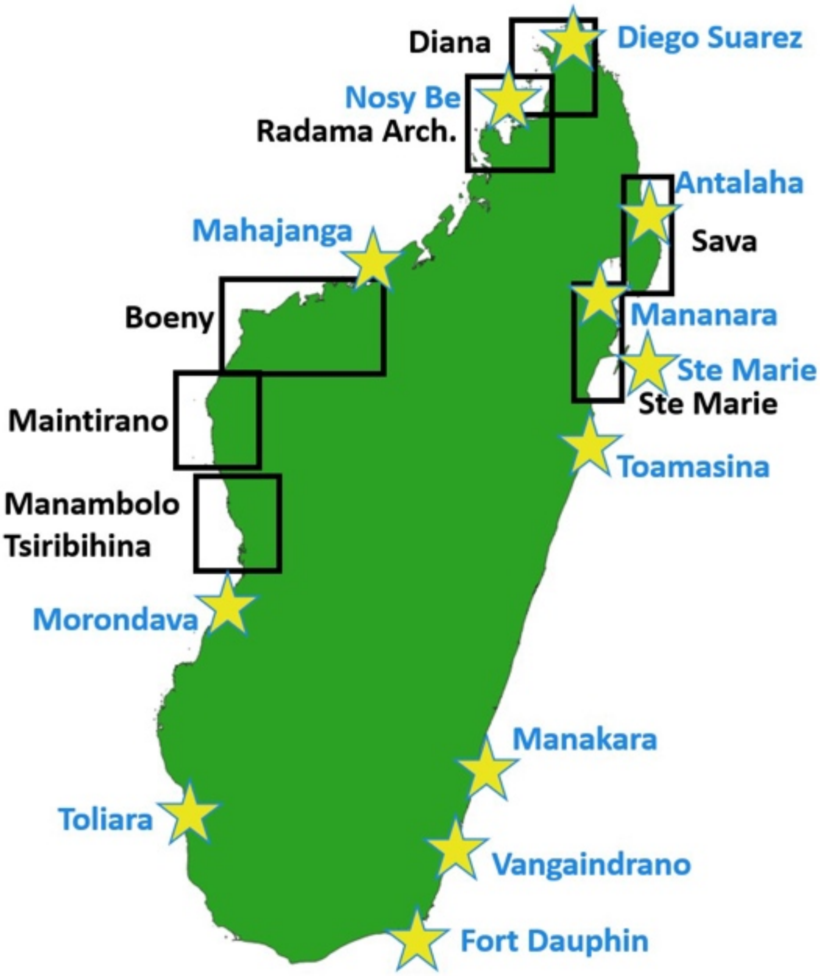


Figure 12 The locations of the regional areas (black boxes) and specific sites (stars) for which sea level data was required by respondents to the PASS-SWIO Questionnaire

Problems and Gaps in Sea Level Data

The main problems with sea level data could be separated into issues with the data themselves and issues related to resources and capacity. Data were generally seen to be sparse, with limited or no access to real time data and a lack of data for specific locations, or difficult to access. There is a lack of resources, in terms of technical and IT equipment and a lack of capacity, in particular knowledge in data analysis. In addition to an improvement in the availability of and access to sea level data, it is essential to develop the capacity of local users to process and apply these data products in the range of applications listed in Table 1.

3.4. Summary of Requirements for Sea Level Data

There is a widespread recognition of the need for sea level data in Madagascar and a strong interest in improving data coverage and accessibility, for use in a wide range of applications and locations. Thus, there is a need to improve the coverage of sea level measurements at the Madagascar coast, through the installation of tide gauges and the use of satellite altimetry. There is also a requirement to improve the capacity to process, disseminate and apply sea level data by providing training and access to suitable IT resources.

4. Review of Potential Portagauge Locations

4.1. Introduction

In this section we review possible future locations for the Portagauge, considering the sea level variability and the vulnerability of the locations, as well as site requirements, availability of necessary supporting resources and input from stakeholders.

4.2. Site Requirements

In selecting the next location for the Portagauge we must first consider the importance of having accurate sea level measurements at that location. We therefore consider:

- The sea level variability
- Which locations prone to flooding and erosion
- Where there are vulnerable populations
- Where there is vulnerable infrastructure
- Locations of ports

The NOC has many years' experience of installing tide gauges, and has identified some key requirements for an ideal tide gauge location (see also UNESCO, 2006). An ideal location for a tide gauge:

- Is away from risks of shipping and construction
- On flat, solid, stable ground
- Does not dry out at low water
- Exposed to the open ocean (i.e. not up-river, in an estuary or behind sand banks or lagoons)
- Away from large buildings and vessels that could interfere with the GNSS signal

Harbours are suitable locations for tide gauges as they are exposed to the ocean, but also provide some protection from extreme conditions. However, they are slightly risky due to shipping and construction and therefore the location within the harbour should be selected with care.

There are some other practical considerations to be borne in mind.

- Is the location secure?
- Is it accessible so that it is feasible to transport the Portagauge to that location (a large crate 255cm x 145cm x 180cm, weighing approximately 300kg)?

- Are staff available to install and maintain tide gauge, to regularly check the operation and download data as necessary?

These practical requirements reinforce the idea that ports are the most suitable location as they can provide the necessary security and access.

4.3. Characteristics of Sea Level Variability

Here we provide a brief overview of tidal and non-tidal sea level variability in the region of Madagascar, from model, tide gauge and satellite altimeter data. The report uses new analysis carried out for the PASS-SWIO project and refers to results from other relevant analyses. The objective of the overview is to identify regions where the patterns of variability are coherent, and where they are different, to support the identification of future tide gauge locations in the development of a sea level monitoring system for the Southwest Indian Ocean, see *D3.3 Sea Level Variability Report* (Cotton, 2024) for more detail.

Tidal Variability

Tidal parameters vary around the coast of Madagascar. The tidal range varies from 4m in the northwest coast to less than 1m on the east coast.

Tidal parameters for locations around the Madagascar coast were extracted from the POLTIPS model (NOC, 2024) and used to analyse tidal variability around the coast of Madagascar.

The largest tidal range (4.03m) is for Mahajanga in the northwest, this range decreases for locations to the south on the west coast (Morondava 3.91m; Toliara 2.96m). The tidal range is much lower on the east coast: 0.72m at Toamasina and 0.55m at Mananjary. Note that these tidal ranges are not referenced against a local datum, but against a nominal mean sea level.

Non-Tidal Variability

Long term trend

Long term trends in sea level also vary around the coast of Madagascar, from 3.9 mmyr^{-1} in the northwest to 2.1 mmyr^{-1} in the southeast (Figure 13). From analysis of 20 years' altimeter data, the sea level at the Madagascar coast is estimated to have risen by 42 – 780 mm over that time period. These trends calculated from satellite altimeter data are expressed relative to a mean sea level, so do not include any changes in the land at the coast (for instance vertical land movement and erosion), which should be investigated.

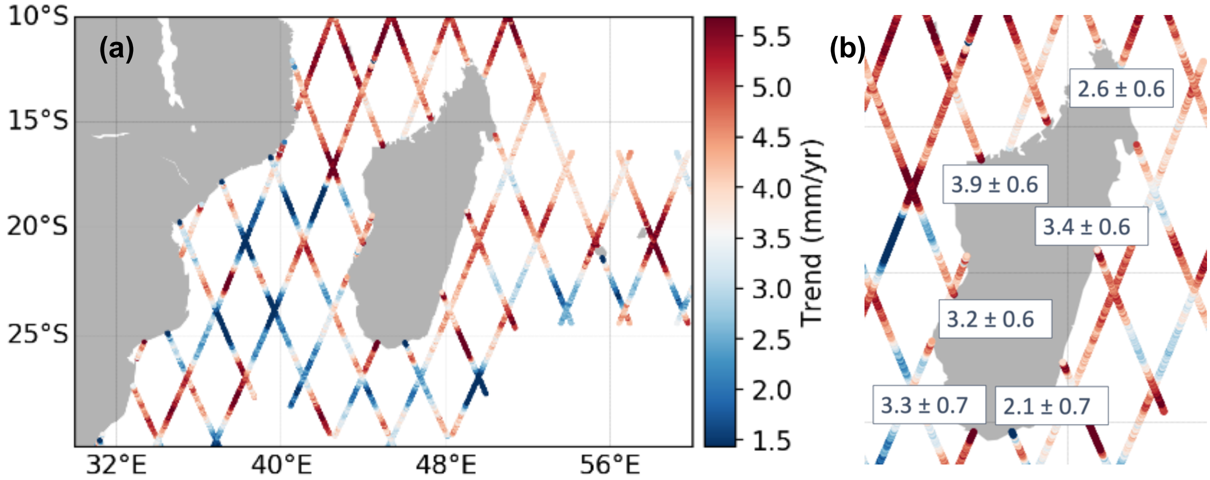


Figure 13 (a) Annual increase in sea level (2000-2020) calculated from satellite altimeter data (Jason-1, Jason-2, Jason-3), (b) Zoom of right panel to Madagascar coast. Inset values are annual increase within 3km of the coast, calculated for the ESA CCI+ sea level project (Cazenave et al., 2022)

Seasonal cycle

The seasonal cycle in sea level is mostly caused by variations in ocean circulation driven by the different monsoon seasons. The amplitude of the semi-annual cycle was under 2cm, and 5-10cm for the annual cycle, largest at the southwest coast. It is much lower than the tidal range, even for the east coast. This is more important for oceanographic investigations and unlikely to be an important practical consideration for most coastal applications.

Extreme Events (Storm Surges and Tsunami)

The number and intensity of tropical storms in the Southwest Indian Ocean varies from year to year, but on average, in the order of 10 named storms occur each year and one of those will make landfall on Madagascar (Langlade, 2013). The associated storm surge can be up to 2m (GFDRR, 2016).

The NOC modelled the storm surges from 66 named tropical storms in the Southwest Indian Ocean between 1990 and 2015, and found there is a risk to storm surge at all coastal locations, with perhaps maximum risk at the north eastern and central western coasts.

The GFDRR classifies the risk to the Madagascar coast from Tsunami as medium (GFDRR, 2020). This means there is more than a 10% chance of a potentially damaging tsunami occurring in the next 50 years. The north, east, and southern coasts are classified as being at medium risk, the western coast from Morombe north to Ambanja is classified as low risk.

Okal et al (2006) reported that the maximum runup on the Madagascar east coast following the 2004 Boxing Day tsunami was 5.4m at Betanty in the southeast. No casualties were reported, though there was some damage to infrastructure (roads).

4.4. Vulnerability

The developing nations of the Southwest Indian Ocean are particularly vulnerable to sea level extremes, due to intense tropical cyclone activity from October to March each year. Madagascar often experiences multiple tropical cyclones each year, with an average annual direct loss of USD 87 million (GFDRR, 2016). In 2015 tropical cyclone Chedza caused 68 fatalities and affected over 80,000 people (GFDRR, 2016). Tropical cyclones have been found to account for about 85% of average annual losses (USD 100 million) experienced by Madagascar due to adverse natural events (World Bank, 2017). A recent study showed 26% of Madagascar's coastline to have high or very high levels of exposure to coastal hazards (Ballesteros & Esteves, 2021). It is projected that the average intensity of tropical cyclones will increase, that rising mean sea levels will contribute to higher extreme sea levels associated with tropical cyclones, and that coastal hazards will be exacerbated (IPCC, 2019).

Esteves and Ballesteros (2019) developed an index of exposure to coastal change for East Africa (including Madagascar). The index was based on seven variables: geomorphology, relief, wave exposure, wind exposure, surge potential, presence of natural habitats with an important coastal protection role (mangroves, coral reef and seagrass meadows) and relative sea-level change rate. However, they could not include sea-level change and geomorphology in the final analysis due to the scarcity of comparable data that could meaningfully reflect variations across the study area.

The index highlighted that the East coast of Madagascar had very high exposure to coastal change, with the south eastern region of Fianarantsoa having the greatest percentage (~50%) of its coastline highly exposed to coastal hazards and the Toamasina region (with a longer coastline) having the greatest length of coastline exposed to hazards (261km), Figure 14.

A further study (Ballesteros and Esteves, 2021) investigated the social vulnerability to coastal hazards in East Africa, unfortunately there was not enough socio-economic data available to include Madagascar fully, but it was reported that 1,156,800 people in Madagascar are at higher exposure to coastal hazard (within 5km of coast). The region with the greatest number of people at higher exposure to coastal hazard is Androy, the most southerly Region of Madagascar, 71,800 people within 5km (Figure 15). As Figure 15 shows, the highest exposure is on the east coast, with much lower exposure to the north and west. These areas will become more exposed with loss of protective habitat. Toamasina for example, is highly exposed to wind and wave hazards, loss of coral reef would increase this exposure (Ballesteros and Esteves, 2021).

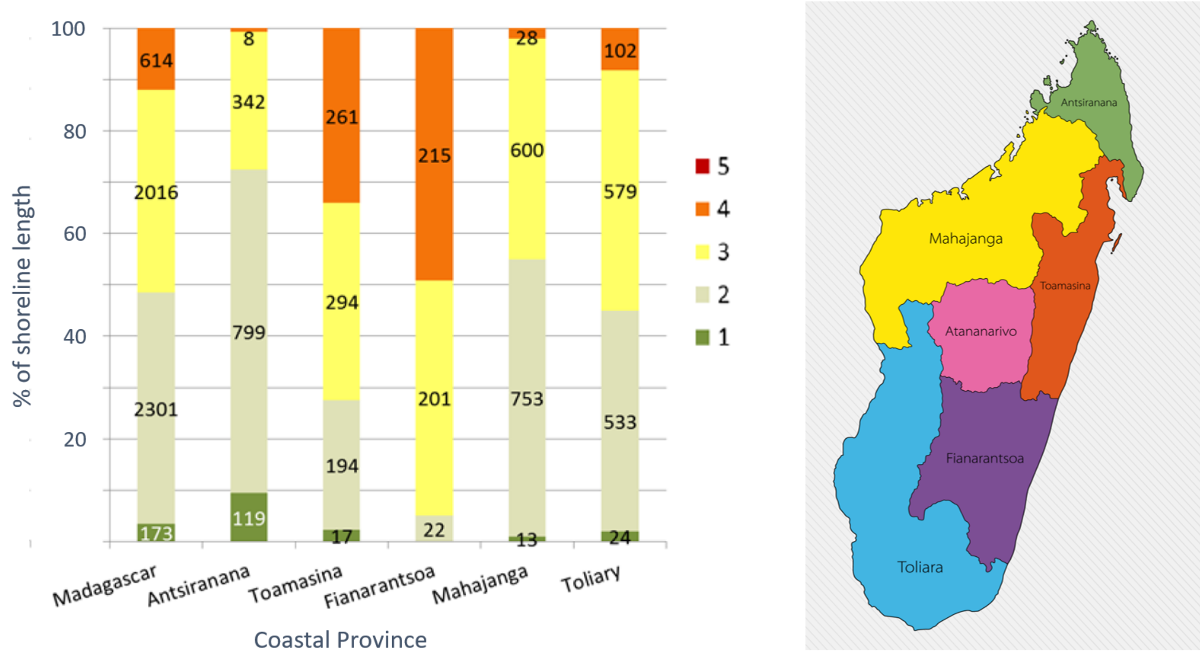


Figure 14 Distribution of the five classes of the index of exposure to coastal hazards (5 = very high exposure, 1 = very low exposure) in percentage of shoreline length (Esteves and Ballesteros 2019). The map shows the locations of the Provinces, these were abolished as administrative areas in 2007, with the creation of smaller regions

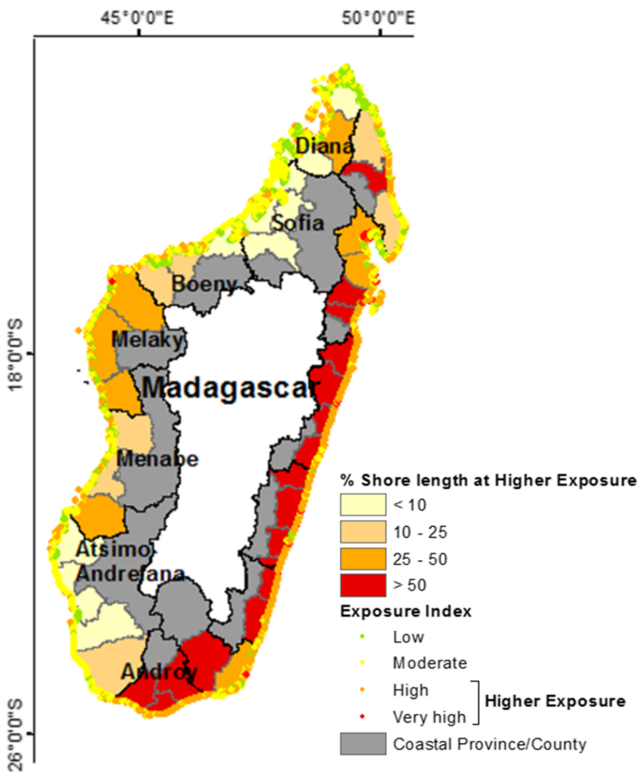


Figure 15 Exposure index ranking and proportion of district shoreline length at higher exposure (Ballesteros and Esteves, 2021)

According to a recent report (Rakoto, 2022), approximately one million Malagasy people are dependent on fishing for their livelihood, with 83% of those living at the coast and working in small scale, artisanal fisheries.

Several areas of the Madagascar coastline are subject to erosion. Razakafoniaina (2001) noted that the regions around both Morondava and Manakara have been affected by erosion, which has impacted the harbour at Morondava and endangered coastal properties and infrastructure. That report noted a proposal to install tide gauges at these locations to support erosion studies, however, we have been unable to find any further record of this work. Fort Dauphin (Taolagnaro) has also been identified as suffering from coastal erosion (Rahobisoa et al., 2014), with fears expressed that this could impact tourism in the area.

The NOC carried out a Madagascar Shoreline Detection exercise as part of the ESA-funded EO4SD Marine and Coastal Resources project (https://eo4sd-marine.eu/). This produced information on the annual position of the shore, change rate (total in meters, m/yr.) and forecasted shorelines (10- and 20-year position, including uncertainty bands) for all of Madagascar's sandy shoreline using Landsat 7 and 8 imagery. However, further analysis of these data would be required to identify the most vulnerable locations.

In the PASS-SWIO User Requirements Survey (Cotton, 2022), respondents identified the greatest risks to the Madagascar coastline in two categories, events and impacts.

Events:

- Tsunami,
- Rising seas,
- Cyclones,
- Human activities,
- Forest destruction

Impacts:

- Coastal erosion;
- Flooding;
- Destruction of coastal areas;
- Displacement of villages;
- Lifestyle impacts;
- Food insecurity/seafood availability;
- Habitat loss;
- Hyper sedimentation;
- Dangers to shipping;
- Collisions;
- Marine pollution;
- Loss of revenue;
- Environmental degradation.

The ability of coastal communities in Madagascar to resist or adapt to climate change impacts of sea level rise and changes in storms and cyclones was seen to be low by our respondents. This was due to low incomes and the lack of alternative livelihoods in fishing communities. However, traditional knowledge and expertise on the environment and climate were recognised as an advantage.

The need for targeted support to enable communities to develop adaptation strategies and improve resilience was noted, as well as the requirement to improve infrastructure, integrating risk and disaster models into planning and implementing new construction techniques. The importance of education and awareness raising, and of improved communication was also highlighted by a number of respondents, as was the need for improved early warning systems.

4.5. Ports

As noted previously, the security and physical requirements strongly indicate the need for the Portagauge to be located within a managed port environment, with personnel to provide maintenance and repair close by.

The International Hydrographic Organization (IHO, 2023) identified four Ports of National Interest in Madagascar, and 13 ports of regional interest. Discussions with APMF in February 2024 confirmed the status of the original four national ports, with the addition of Ehoala (Fort Dauphin) and Nosy Be due to recent and planned developments (Figure 16). These ports have a wide range of facilities and levels of infrastructure (**Error! Reference source not found.**Table 3).

Ports of International Interest: Toamasina, Toliara, Antsiranana (Diego Suarez), Mahajanga, Nosy Be and Ehoala (Fort Dauphin)

Ports of National Interest: Taolagnaro, Mananjary, Manakara, Morondava, Morombe, Maintirano, Antsohihy, St Louis, Vohemar, Antalaha, Maroantsetra, Ste Marie

River Ports: Vatomandry, Mahanoro

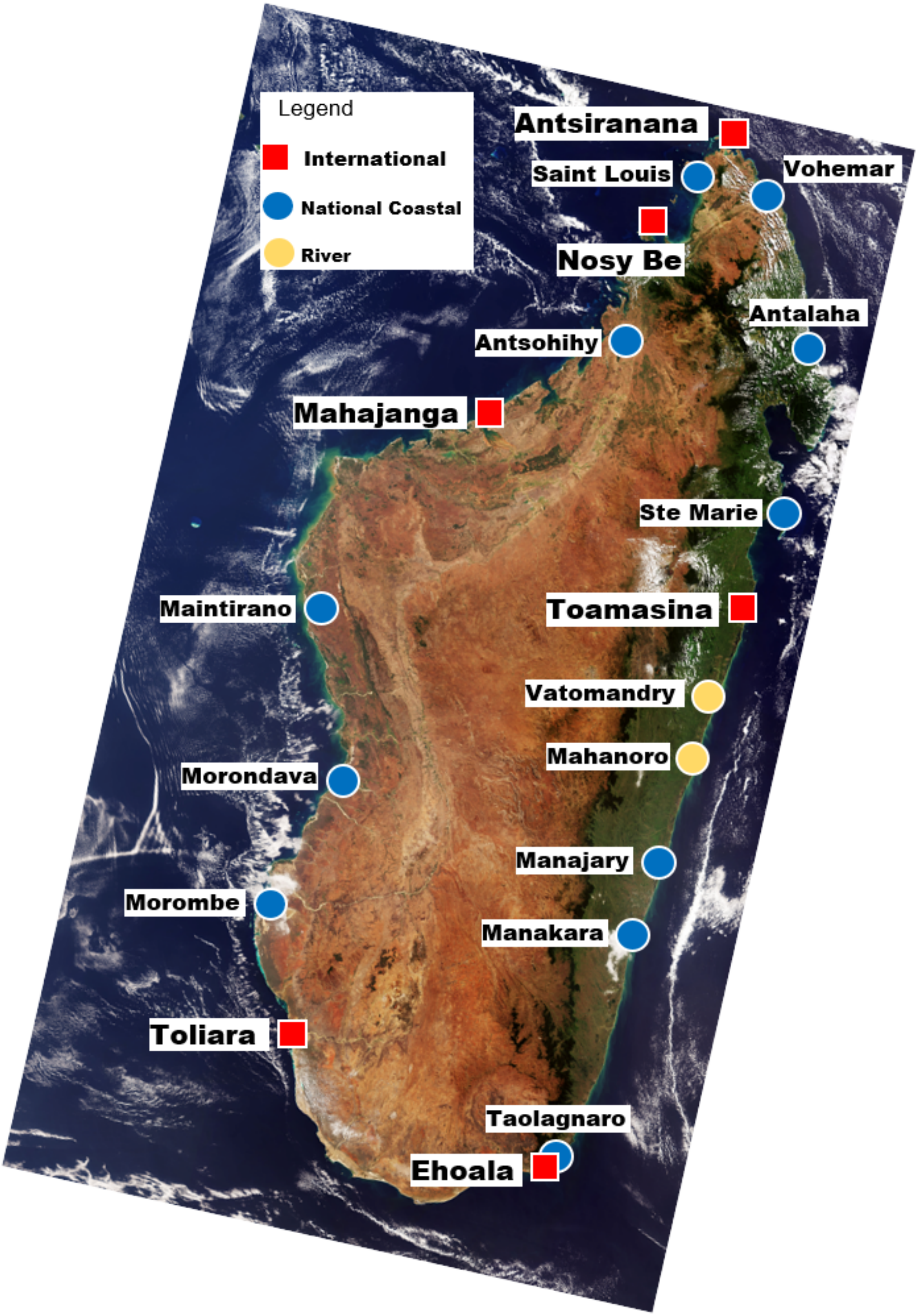
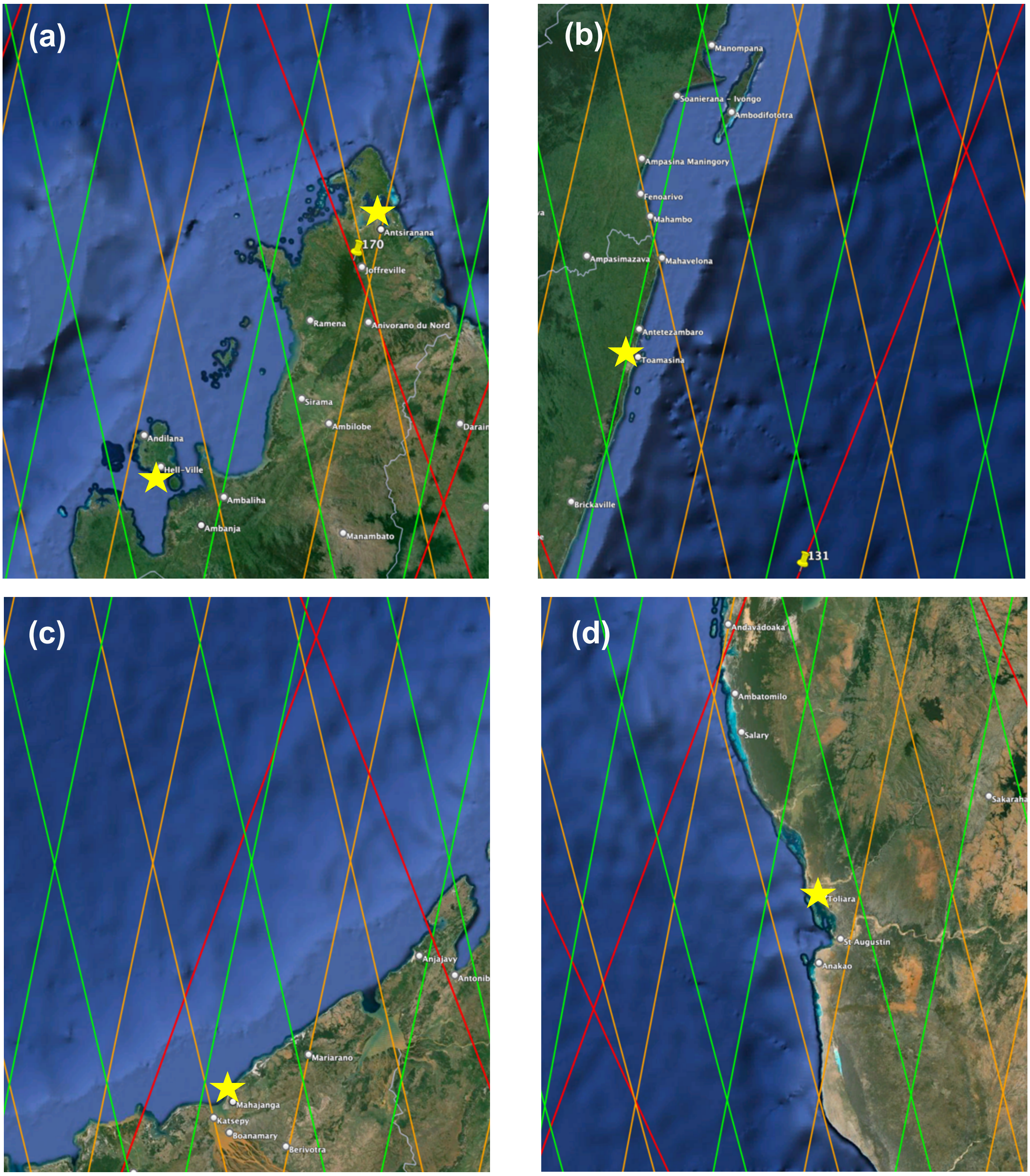


Figure 16 Madagascar Ports, information provided by APMF

4.6. Availability of satellite altimeter data for validation

An important aspect to be considered is the availability of satellite altimeter data close to the Portagauge location to support cross-validation. Figure 17 shows the locations of the major ports and the ground tracks of the Sentinel 3a, Sentinel 3b and Sentinel 6a MF satellites.

Sentinel 3a and Sentinel 3b tracks are re-sampled every 27 days, Sentinel 6a MF every 10 days. The location of Sentinel 6a cross-overs will provide the best sampling (twice every 10 days). No individual port appears to be better located than any of the others for this consideration



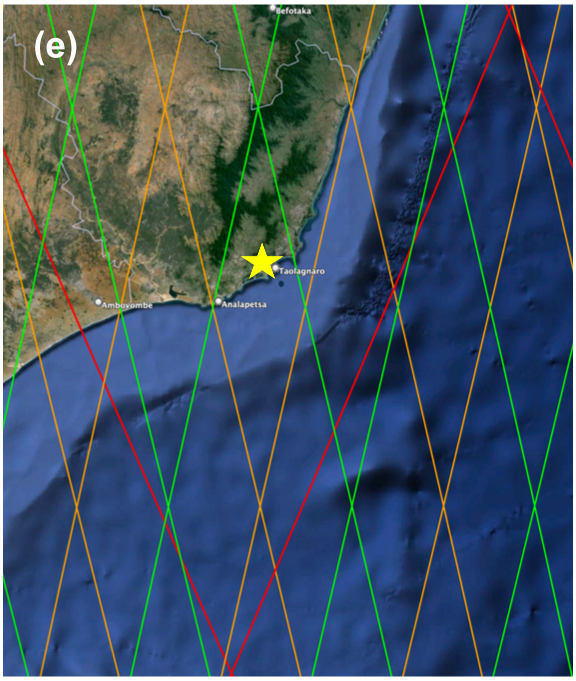


Figure 17. Ground tracks of Sentinel 3a (Brown), Sentinel 3b (green) and Sentinel 6a MF (red) satellites near the major ports (Yellow stars) of Madagascar: (a) Antsiranana and Nosy be, (b) Toamasina, (c) Mahajanga, (d) Toliara, (e) Taolagnaro /Ehoala.

4.7. Locations of DGM Offices

In order to support the installation and operation of the Portagauge, which will be installed, maintained and operated by DGM staff, it should be sited at a location where there are DGM staff available. We understand that there are now DGM offices in all regions, but we are not certain of the proximity of all DGM offices to all the port facilities. We know that at Mahajanga the DGM office is 2.5km from the port and at Nosy Be the DGM office is at the airport, 12 km from the port.

4.8. Site Access

The Portagauge will need to be transported across Madagascar, which has a limited and poor road network. It may be more practical to transport the Portagauge by sea.

4.9. Discussions with Stakeholders in Madagascar

During a visit to Antananarivo on 12-16 February 2024, PASS-SWIO project team members visited various stakeholders to report on the PASS-SWIO project and the performance of the Portagauge. During these meetings we also sought to solicit opinion on the most appropriate location for future deployment of the Portagauge. Discussions with IH.SM were held online in advance of the visit.

IH.SM – Institut Halieutique et des Sciences Marines

IH.SM is based in Toliara in the South of Madagascar and hosts the National Oceanographic Data Centre.

IH.SM has been working with the First Institute of Oceanography, China, to install two permanent tide gauges in Toliara and Taolagnaro (Fort Dauphin). These installations were completed in January (Toliara) and February (Taolagnaro), with float and pressure gauges, together with GNSS and weather stations at both locations. There are (currently unconfirmed) plans for two further tide gauge installations in the north of Madagascar by 2026, with one of these one probably at Nosy Be. It is understood that the data from the tide gauges will not be freely distributed and that an MoU would be needed to access these data.

IH.SM are keen to maintain a relationship with the PASS-SWIO project and to have access to data generated by it.

DGM -Direction Générale de Météorologie

DGM is the Madagascar National Meteorological Agency.

Alongside the delivery of training to DGM staff, discussions were held with DGM staff around the experience of installing and operating the Portagauge as well as future locations.

In terms of the experience of the installation and operation of the Portagauge in Toamasina, the following points were highlighted:

- There were no major problems in the installation process. The installation manual was clear and comprehensive.
- It is a long distance from the DGM office to the port, so it is time consuming and difficult to make many repeat visits in a short time. A lightweight tablet to test Wi-Fi connections and download the data would be a very useful asset.
- The base of the packing case has sustained some damage and so would need repair before further use.
- It was queried if any spare parts would be needed over a longer period of installation.

We were advised by the Chef de Service de la Maintenance et Installations Techniques, Ms Miorah Linah Rakotonirina, that DGM was working with APMF on a proposal to an EU forum which is planning investment in the Western Indian Ocean, to be provided through the Indian Ocean Commission. They were considering requesting instrumentation including twelve tide gauges.

FTM - FOIBEN-TAONTSARINTANIN' I MADAGASIKARA

FTM is the national geographic and hydrographic agency. FTM has been involved in the past in the operation of tide gauges, as detailed in IHO (2023). A meeting was held with FTM staff to discuss their interest in sea level data, and understand their priorities.

FTM are responsible for Marine charts, they require accurate datum. They are interested in accessing the GNSS data from the Portagauge but require that it be levelled to a local benchmark.

The Portagauge was not levelled against this benchmark during installation, but the point taken for the vertical reference was recorded and could be referenced to the FTM Toamasina benchmark, which is at the Port administration building. There is some difficulty processing GNSS data at FTM, due to the low precision of the local geoid model for Madagascar and they requested advice on this.

Benchmarks are available along roads and railways in Madagascar, they are also available at the ports. It was agreed that FTM could carry out levelling to benchmarks for future installations of the Portagauge.

In terms of priorities for future locations of the Portagauge, Morondava was suggested, due to the local erosion issues. We were advised that 10km had been lost from the coast and that erosion is ongoing. Mahajanga was also proposed, as it has a larger, more secure port, which may be better suited to site the Portagauge.

There was a suggestion that the measurements being made using the GNSS on the Portagauge could be used to improve local information and feed into global initiatives.

Ministry of Spatial Planning

The Ministry of Spatial Planning (Ministère de l'Aménagement du Territoire, de l'Habitat et des Travaux Publics) has responsibility for coordinating marine activities including tourism, aquaculture, and fishing. Its main interest is in locations where there is most erosion, and where coastal protection is needed. Madagascar is currently developing its Blue Economy Strategy and many activities, such as seaweed and sea cucumber cultivation are expected to expand. It would be useful to better understand sea level and tides in the planning and execution of these activities. They would like tidal information that would support the identification of the most suitable locations for tourism/recreation activities such as kite surfing and also need information to support construction of infrastructure at the coast.

It was noted that most marine activities and habitats are on the west coast as well as a large number of coastal communities. On the east coast the priority is coastal ecosystem conservation and protection (specifically mangroves), this is particularly the case in the north east at locations such as Isle St Marie Island and Ambodivahibe Bay.

There was some interest in obtaining sea level information at Isle St Marie as there is erosion occurring in the south part near the meteorological station. Beaches and coconut trees have been lost.

The importance of data being shared and easily available was emphasised. One of the Ministry's biggest problems is in getting information to support planning.

APMF – Agence Portuaire Maritime et Fluviale

APMF is the national body responsible for the management of ports, maritime areas and rivers in Madagascar.

APMF were very interested in the project and were ready to collaborate and coordinate with any follow-on activities. For the next location of the Portagauge they recommended one of five other major ports of Madagascar (in addition to Toamasina). These all have managed security access into the port.

The APMF is currently finalising a master plan for further development of Madagascar's Ports. We understand this will involved the development of a new port at Ehoala (near Fort Dauphin/Taolagnaro) and includes plans to develop the port at Nosy Be.

BNGRC – Bureau Nationale de Gestion des Risques et des Catastrophes

BNGRC are particularly interested in Tsunami risk, but also other risks at the coast. They are working with the IOGA (Institute of Oceanographic and Geophysical Analysis) at the University of Antananarivo to better understand risks by modelling flood depth and extent. It was suggested that the IOGA should also be involved in future discussions.

They would be interested to talk to NOC about tsunami warning systems and are very willing to assist with any practicalities in the future.

CFIM – Centre De Fusion D'Information Maritimes

CFIM is a national and regional centre for integrating maritime information to support operational activities. It has an interest in receiving real-time sea-level information and tidal predictions. Currently CFIM does not have access to any tidal predictions to support their operations.

In terms of preferred future locations for the Portagauge, CFIM suggested a location on the west coast where there was a larger tidal range. Initial thoughts were Nosy Be, Mahajanga or Toliara, as there were major ports at those locations that perhaps would be most suitable. Morondava could also be an option, but it is a smaller port and the suitability of the situation there is not clear.

4.10. Summary

Table 3 provides a list of potential locations with indications of suitability, key characteristics and strategic priority. We have only included existing international ports, as other coastal and river ports will not meet the basic requirements in terms of security and access for a Portagauge.

The discussions in the previous sections have highlighted the following key considerations:

- Only the ports of international interest are expected to be able to meet the physical and security requirements for hosting a tide gauge.
- Erosion is a concern in several locations in Madagascar.
- Tidal range is small on the east coast (less than 1m), larger on the west coast (up to 4m). Note that sea level measurements from tide gauges on their own cannot provide information on erosion.

- Locations most vulnerable to storm surge associated with tropical cyclones are on the north eastern and central western coasts of Madagascar.
- IH.SM has recently installed new tide gauges at Toliara and Fort Dauphin (Ehoala).
- It is important to have DGM staff available at the new location to provide local support for maintenance and operation.

Our recommendation for the next location of the Portagauge is to install it at a port of international interest on the west coast of Madagascar. The two candidates are therefore:

1. Mahajanga - Port of International Interest, high tidal range, can experience storm surges from tropical cyclones.
2. Nosy Be - Port of International Interest, high tidal range, can experience storm surges from tropical cyclones. Currently under development. Possible location for next IH.SM tide gauge.

Table 3 Potential locations for future deployment of the Portagauge

Location	**Physical Suitability of location**	**Availability of logistic support**	**Tidal Range (m)**	**Long-term Sea-Level trend (mm/yr)**	**Vulnerability to storm surge**	**Tide Gauge History**	**Strategic Priority**
Toamasina	Secure large port environment, sheltered harbour. First port of MDG. Security (ISPS level 1)	DGM Office	0.72	3.3 ± 0.6	High	2010-2023 (SHOM - radar)	Port of International Interest
Toliara	Medium Port, 2nd of MDG, 2 wharves. Port facilities in good condition and well-maintained	IH.SM Office DGM Office (7km)	2.96	3.2 ± 0.6	Medium	1991-93 (FTM-float), 2024- (IH.SM)	Port of International Interest
Antsiranana (Diego Suarez)	Medium sized port, single wharf, large ship facilities. Security (ISPS level 1)	DGM Office	1.91	2.6 ± 0.6	High	None	Port of International Interest
Mahajanga	Third port in MDG. Small vessel commercial port, One cargo berth (151m). Security (ISPS level 1)	DGM Office (2.5km)	4.03	3.9 ± 0.6	High	None	Port of International Interest
Ehoala (Fort Dauphin)	Deepwater port, newly developed (2009), 3 wharves, protected by breakwaters. Security (ISPS level 1)	DGM Office (8km)	0.60	2.1 ± 0.7	Medium	1985-1989 (CNRO-float), 2024- (IH.SM)	Port of International Interest
Nosy Be	Small, open roadstead. Has an oil terminal. APMF has plans for development.	DGM Office (12km)	4.00	2.6 ± 0.6	High	1958-2014 (CNRO-float)	Port of International Interest

5. Costs and Funding Sources

5.1. Introduction

The model proposed in PASS-SWIO, for a sea level monitoring system for Madagascar, is based on the installation and deployment of a low-cost relocatable tide gauge (Portagauge), moved to a series of coastal sites, each for a minimum of six months. The six-month minimum deployment period is required to provide sufficient measurements to establish accurate tidal coefficients to support reliable tidal predictions, and cross-validation against satellite altimeter sea level data.

Following the successful demonstration of the PASS-SWIO concept with the deployment at Toamasina, we are now proposing to install the Portagauge at each of the five remaining Madagascar ports of international interest (listed in Section 4.5), for a minimum period of six months. Allowing for two months between each deployment to uninstall, transport and reinstall the Portagauge, this would require a programme of four years. We would recommend that the next instalments are on the north west coast (Mahajanga and Nosy Be). The order of the remaining three deployments (Toliara, Antsiranana and Ehoala) could be determined later and would consider any new developments. At the end of this period, there would be reliable tidal predictions for all major ports in Madagascar, and the foundation for long-term sea level measurements based on satellite data cross referenced against coastal benchmarks.

We noted in Section 1.2 that IH.SM has installed new tide gauges at Toliara and Ehoala, and is planning two further tide gauge installations over the next two years. We also noted that DGM are currently working on a proposal to secure funding from the European Union to install a network of permanent tide gauges around the coast of Madagascar. The future Portagauge deployments would be complementary to these installations.

5.2. PASS-SWIO Implementation Costs

We have estimated that the cost for the transport, installation and operation of the Portagauge (for 6 months) at each new location to be €15,000. This allows for site survey to identify a suitable location for the Portagauge within the port, transport to the new location, installation by DGM and FTM staff and de-installation, operational costs, data management and project management from the UK. It is estimated that this will require 36 days of staff time from DGM and 4 days from FTM staff, per deployment. The costs include travel and subsistence expenses for these staff, but does not include salary costs.

In case of any failure of the Portagauge equipment over the 4-year deployment period, we have costed in two one-week visits by a NOC engineer (working alongside a Malagasy representative), plus the cost of parts for repairs. This would cost an estimated €30,500.

In addition, there is a one-off cost for new computer hardware and TASK and Poltips licenses, which we estimate at €9,000 and €10,200 data management costs from BODC.

Finally, we have costed stakeholder engagement, including a single visit from NOC and SatOC staff to Madagascar, to maintain and build relationships with the stakeholders we have developed in the course of the PASS-SWIO project. This will allow us to share information on the data available and its uses, as well as consulting on further needs. The cost of a five-day visit is estimated at €25,000.

Thus, the cost for the full implementation plan for five further deployments would be €150,200 over four years.

An itemised costing is provided in an annex to this report.

5.3. Data Management

The implementation of good data management practice will be essential to ensure the delivery of the main benefits of this project. Discussions with stakeholders and the responses to the User Questionnaire have established that there is a wide interest in accessing the Portagauge data. Future plans must also include actions to make the Portagauge data quickly and freely accessible. This is also a key capacity building requirement.

Visits to Madagascar by the IHO (IHO, 2011 and IHO, 2023) have highlighted this issue. IHO (2023) emphasised the importance coordinating activities for data collection and information on projects of shared interest, noting that the "collection of data is only economically conceivable" if these are widely shared, resulting in a requirement for national level coordination of data management. The same report also notes that the FTM is the national authority in charge of Hydrographic Data Infrastructure.

We therefore recommend a parallel capacity building programme, involving DGM, IH.SM, APMF and FTM, to support the development of a robust sea level data management infrastructure for Madagascar. This would involve a workshop in Antananarivo, to provide capacity building and plan the management of these data within Madagascar and the sharing of the data globally. We estimate the full cost of this to be €31,000, which would bring the cost of the PASS-SWIO implementation to €181,200.

5.4. Statement of Benefits

By deploying the Portagauge at the five locations indicated above, we could achieve a minimum of 6 months sea level data from radar and GNSS-IR instruments at all major Madagascar ports, which will allow:

- Generation of accurate tidal constituents, and accurate tidal predictions at all of Madagascar's International ports.
- Linking the Portagauge sea level measurements to long-term satellite altimeter measurements around the coast of Madagascar.
- Monitoring of sea level associated with unusual events such as tropical cyclone related storm surges, or tsunamis.

The benefit to local stakeholders and communities includes provision of essential information regarding the timing and magnitude of high and low waters. This would facilitate port and fishing operations, as well as improve recreational and tourism activities and benefit aquaculture and mariculture. It would, importantly enable preparedness of low-lying communities for extreme tidal events and allow for better planning both terrestrial and marine. All of this will enhance disaster mitigation, safety, food security, livelihoods and economic growth.

There are also important global benefits to better understanding sea level around Madagascar, particularly considering the absence of sea level measurements in the Southern Hemisphere (Figure 11). The data collected by PASS-SWIO will be made widely available for scientific use and should assist in the understanding of a wide spectrum of ocean processes, as well as in the monitoring and understanding of global sea level rise.

5.5. Funding Sources

We have looked at a number of possible funding sources, but have not yet identified any relevant programmes currently inviting bids. Possible funding sources include:

UNESCO Intergovernmental Oceanographic Commission (IOC)

2020 to 2030 is the UN Decade of Ocean Science for Sustainable Development. It has a new call - Call for Decade Actions No. 07/2024 – which aims to fill gaps in funding and resources, as well as to incentivise new initiatives in capacity development as part of the Ocean Decade Capacity Development Facility to support Decade Actions. The call is open until 31 August 2024. Projects are required to contribute to one of the 26 endorsed Decade programmes. Full details are available at https://oceandecade.org/news/new-cfda7-resource-mobilization-and-capacity-development-sustainable-ocean-management/

PASS-SWIO has registered to take part in an online Q&A session to understand what opportunities are available.

International Hydrographic Organization (IHO) Capacity Building Work Programme

The IHO has a work programme dedicated to capacity building (https://iho.int/en/capacity-building-and-technical-cooperation). This sets high level priorities for capacity building activities, which include technical visits, education programmes, training and workshops, but not, so far as we understand, direct support for implementation of new measuring capabilities or instrumentation. The visit of IHO representatives to Madagascar reported in IHO (2011) and IHO (2023) were supported under this activity and provided recommendations for further capacity development and training programmes.

This Implementation Road Map will be provided to the IHO Capacity Building programme with a request for information on any relevant IHO programmes or funding opportunities.

WIOMSA

At present we do not see any potential funding from WIOMSA. In general, WIOMSA programmes are focussed on marine conservation, fisheries research and management, coastal and marine ecosystems and climate change. Nonetheless we will continue to monitor WIOMSA communications for any relevant funding opportunities.

Indian Ocean Commission

The Indian Ocean Commission maintains a website for funding opportunities.

- https://www.commissionoceanindien.org/opportunites-et-carrieres/
- https://www.commissionoceanindien.org/projets-en-cours/

At the time of writing this report, there were no suitable opportunities available.

This Implementation Road Map will be provided to the IOC with a request for information on any relevant IHO programmes or funding opportunities.

Other

Other possible sources for funding will also be continue to be investigated and considered.

For example, the UK FCDO website for Madagascar has a page on development (https://www.gov.uk/government/publications/uk-madagascar-development-partnership-summary/uk-madagascar-development-partnership-summary-july-2023), which lists the Blue Planet Fund. It states that:

"This new programme will provide targeted technical assistance to the Government of Madagascar as part of the Oceans Partnership and a Social Capital Challenge Fund for Small Island Developing States, including Comoros."

We will continue to follow this opportunity and the other potential sources of funding.

6. Conclusions and Recommendations

6.1. Conclusions

The PASS-SWIO project has successfully demonstrated the concept of a low-cost sea level monitoring system for Madagascar which combines data from a relocatable tide gauge (Portagauge) with satellite altimeter sea-level measurements and analyses. Data from an 8-month deployment of the Portagauge have been assessed and demonstrated to be of high quality, and tidal parameters extracted from these data can be used to generate accurate tidal predictions (Section 2, Figure 5). These data have also been cross validated against satellite altimeter sea level data and shown a good level of agreement between the tide gauge data and the satellite altimeter measurements. In addition, sea level data from the GNSS instrument, also located on the Portagauge, have been found to show very close agreement with the radar gauge data (Section 2).

Staff from DGM have been trained in the installation of the Portagauge, and in the processing and analysis of tide gauge and satellite altimeter sea level data. The DGM staff reported no major problems in the installation process and expressed confidence they would be able to repeat the installation at other locations in Madagascar.

Discussions with stakeholders in Madagascar have confirmed a high level of interest in accessing sea level data for a range of applications and have emphasised the importance of data sharing (Section 4.8).

We now recommend a long-term implementation of the Portagauge system, as outlined in Section 5, and suggest that this approach can provide a model for application in similar developing island states and coastal nations with limited existing capability and resources.

6.2. Recommendations

Full Implementation of Portagauge based sea level monitoring system

We recommend the implementation of a rolling programme of installation of the Portagauge at the five remaining Madagascar Ports of National Interest, for a minimum of 6 months at each, with the next two installations on the north west coast at Mahajanga and Nosy Be. The order of the remaining three deployments (Toliara, Antsiranana and Ehoala) could be determined later and would consider any new developments. DGM would be responsible for the deployment and maintenance of the Portagauge and for data management. They would work in co-operation with the national mapping agency (FTM) and the national port and harbours agency (APMF).

We estimate the total cost of this programme would be €181,200 over a minimum period of four years.

Madagascar Sea Level Data Management infrastructure

A key part of this implementation will be the establishment of a co-ordinated national data management infrastructure for sea level data, linked to international sea level data measurement systems, to ensure the sea level data are available nationally and internationally. This should include the provision of tidal predictions for the sites where tidal harmonics are available. This should involve discussions between all interested agencies, specifically DGM, IH.SM, FTM and APMF. The recommended programme detailed in Section 5 includes a capacity building component to address this need.

Other Recommendations

Following on from the work of the PASS-SWIO project, and discussions with national stakeholders, we provide a number of additional recommendations:

1. The PASS-SWIO Implementation Road Map should be provided to the relevant Madagascar stakeholder agencies, to the IHO, the Indian Ocean Commission and WIOMSA.
2. The GNSS data should be made available to the FTM for analysis and processed to provide information on Vertical Land Movement at coastal locations. The issue of the low precision of the local geoid model for Madagascar should be addressed.
3. BNGRC and NOC should hold discussions regarding Tsunami warning systems for the Southwest Indian Ocean.
4. Noting that the Esteves and Ballesteros (2019) study, which developed an index of exposure to coastal change, could not include sea-level change and geomorphology in their analysis for Madagascar due to lack of comparable data, and the fact that the east coast of Madagascar was assessed to have a very high exposure to coastal change, we recommend a scientific programme to provide improved data on these key parameters.
5. The Pangalanes Canal on the northeast coast of Madagascar (south of Toamasina) is a series of link inland lakes and waterways and provides an important safe transport link instead of the open Indian Ocean which is vulnerable to large swells. However, it is subject to changes in water level following prolonged rain, which can flood coastal villages. There is a Sentinel 3A track that runs along this canal for much of its length, and the use of FFSAR processing to provide accurate water levels could be of interest.

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8. Annex – Detailed Costing Basis for PASS-SWIO Implementation Phase

Item	**Details**	**Estimated cost (Euro)**
Installation of Portagauge at new port location	Local DGM staff to liaise with port authorities to identify a suitable location for Portagauge installation. Two DGM staff to install Portagauge FTM staff (with assistance from local DGM staff) to level Portagauge to local benchmark Hire of forklift and possible storage costs prior to installation	10,500 (per installation x5)
De-installation of Portagauge	Two DGM staff to de-install and pack Portagauge. Hire of forklift and cost of packing case repairs or packing materials	7,500 (per de-installation x5)
Transportation of the portagauge between locations	It is expected that this will be by ship	2,000 (per move x5)
Operational cost	Local DGM staff to check on Portagauge Cost of SIM card/data transfer Data checking and processing by DGM Project management from NOC and SatOC	57,000 (per deployment x5)
	Total repeat costs	**75,000 (15,000 per deployment)**
Data Management	Computer hardware Computer Software (TASK and POLTIPS licences) BODC Data Management	19,200

Survey at Toamasina	One off cost at Toamasina to carry out levelling to local benchmark. FTM staff, with assistance from local DGM staff.	500 (one off cost)
Portagauge Maintenance	Visit to Portagauge for maintenance/repair by NOC staff Assistance from in-country staff Portagauge parts	30,500 (two visits)
Stakeholder engagement	Visit of NOC and SatOC staff to Madagascar for meetings with stakeholders, knowledge exchange and data sharing	25,000 (one visit)
Capacity building in data management with DGM, IH.SM and FTM	Creation of training material Visit of NOC and SatOC staff to Madagascar to host capacity building workshop Hire of venue Expenses of Malagasy attendees	31,000 (one off cost)
	Total estimated cost for 4-years	**181,200**

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