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Coastal Zone Changes in West Africa: Challenges and Opportunities for Satellite Earth Observations

Rafael Almar¹ · Thomas Stieglitz² · Kwasi Appeaning Addo³ · Kader Ba⁴ · Gregoire Abessolo Ondoa⁵ · Erwin W. J. Bergsma⁶ · Frédéric Bonou^{7,8} · Olusegun Dada⁹ · Donatus Angnuureng¹⁰ · Olivier Arino¹¹

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Abstract

The West African coastal population and ecosystems are increasingly exposed to a multitude of hazards. These are likely to be exacerbated by global climate change and direct impacts from local human activities. Our ability to understand coastal changes has been limited by an incomplete understanding of the processes and the difficulty of obtaining detailed data. Recent advances in satellite techniques have made it possible to obtain rich coastal data sets that provide a solid foundation for improving climate change adaptation strategies for humanity and increasing the resilience of ecosystems for sustainable development. In this article, we review West African coastal layout and current socio-environmental challenges together with key parameters that can be monitored and several coastal management programs that rely on satellite techniques to monitor indicators at the regional level. The social, technical and scientific problems and difficulties that hinder the interest of coastal practitioners and decision-makers to use the satellite data are identified. We provide a roadmap to precisely respond to these difficulties and on how an improved satellite earth observation strategy can better support future coastal zone management in West Africa.

Keywords Satellite Earth observations · Coastal hazards · Vulnerability · Monitoring · Coastal zone management

Article Highlights

- We review West African coastal layout and current socio-environmental challenges
- We identify key parameters that can be monitored through satellite and several coastal management programs in West Africa
- We provide a roadmap on how satellite imagery can support sustainable coastal zone management in West Africa

Extended author information available on the last page of the article

1 The West African Coastline: Layout and Drivers

The low-lying West African coast from Mauritania to Nigeria can be classified into three main sectors (Fig. 1; Ibe and Awosika 1991; Alves et al. 2020; Dada et al. 2021):

- The northwestern sector of Mauritania, Senegal, and the Gambia is characterized by a narrow continental shelf with sand dunes and their generally narrow spits delineating river arms (with the exception of the cliff-bound southern coast in the Gambia River estuary),
- The western sector of sand and mud from Guinea-Bissau to Sierra Leone with estuaries rich in mangroves and a wide continental shelf favoring the amplification of the tides,
- The Gulf of Guinea coast from Liberia to Nigeria with a narrow shelf and straight barrier of sandy beaches, river inlets and lagoons (Anthony and Blivi 1999; Feka and Morrison 2017; Alves et al. 2020).

The West African coast has a subtropical to tropical climate, primarily influenced by the Atlantic Ocean and the Sahara Desert (Lewis and Buontempo 2016). The West African monsoon, a seasonal low-level atmospheric circulation pattern, represents, along with the Harmattan system, the primary driver of climate variability in the region. The most important rivers originate in the Guinea highlands and include the Niger, Volta, and Senegal rivers (Diop et al. 2014; Anthony 2015; Anthony et al. 2016). For hydroelectric power generation, irrigation, and flood control purposes, most of these large rivers as well as smaller ones have been dammed in recent decades, significantly altering their hydrology

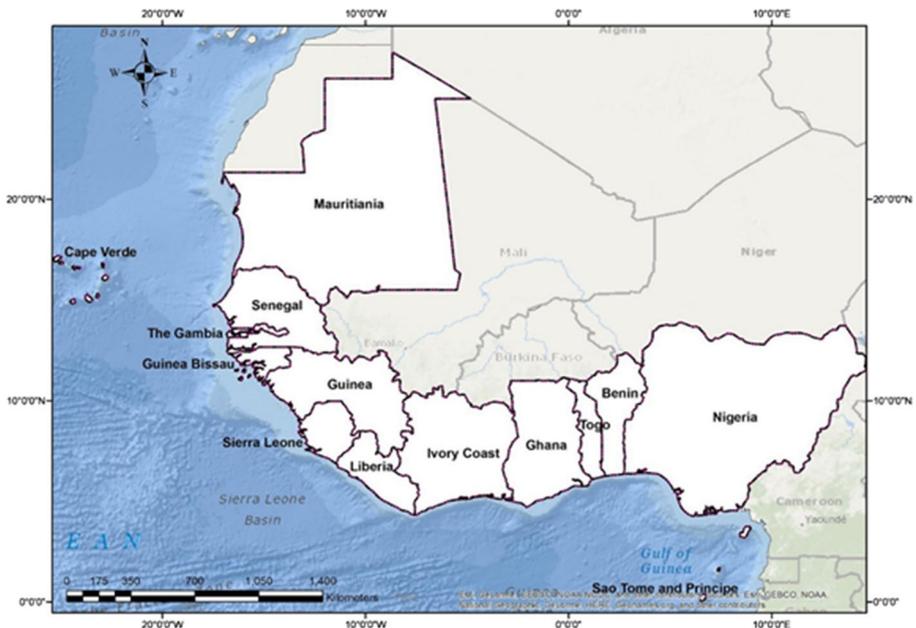


Fig. 1 The West African coast (from Dada et al. 2021)

and sediment flows, accelerating coastal erosion downstream (Ly 1980; Anthony 2015; Diop et al. 2014; Anthony et al. 2016, 2019; Dada et al. 2015, 2016a, b, 2018; Abessolo et al. 2021).

The West African coast is generally considered a storm-free environment, dominated by North Atlantic distant swells (Sadio et al. 2017; Almar et al. 2019; Ndour et al. 2020) with their interannual fluctuation described by the North Atlantic Oscillation (Almar et al. 2019). The wave regime in the Gulf of Guinea area is mainly driven by extratropical storms, and their variability is modulated by the South Atlantic Annular Mode (SAM) (Almar et al. 2015; Melet et al. 2016; Abessolo et al. 2020). The evolution of the sandy coast is controlled by strong longshore sediment drift resulting from oblique waves. (Laibi et al 2014; Almar et al. 2015, 2019; Giardino et al. 2017a; Anthony et al. 2019;). Tidal amplitude is typically micro- to meso-tidal, with the highest amplitudes recorded in Guinea, Guinea-Bissau and Sierra Leone (2.8–4.7 m; Diop et al. 2014).

There is a wide variety of ecosystems and habitats along the West African coast. The richness of estuaries, deltas, coastal lagoons, and nutrient-rich cold water upwelling contributes greatly to the diversity of fish life in this region. These habitats include (1) wetlands, particularly those surrounding mangroves in a succession of deltas and estuaries, providing key habitats for migratory birds (Diop et al. 2014); (2) coastal freshwater lagoons, deltas and estuaries, and a wide range of tidal marshes and seasonal swamps, also counting with seagrass beds located off some estuaries, archipelagos and deltas; (3) sandy beaches, considered important nesting ecosystems, especially for sea turtles.

The dominant factor affecting the waters of the continental shelf is coastal upwelling, which is the source of the rich fish production of the region (Fig. 2).



Fig. 2 Coastal vulnerabilities in West Africa: Illustration of coastal erosion and flooding, destruction of the mangrove for smoked fish and shrimps, water contamination and eutrophication, and Sargassum landing in Ghana (from Marsh et al. 2021)

2 Socio-Environmental Threats

The rapid emergence of new infrastructure, urban expansion and densification, superimposed on the effects of climate change, is rapidly accelerating the deterioration of coastal ecosystems and their ecological service functions. Today, there is increasing demand for natural hazard management in coastal areas (Goussard and Ducrocq 2014; Alves et al. 2020; Dada et al. 2021). Low-lying coastal areas, estuaries, and deltas are most vulnerable to coastal flooding (Nicholls and Tol 2006; World Bank 2020; Duku et al. 2021). Sea-level rise, coupled with an increase in the intensity or frequency of extreme events, will have severe effects on coastal development (IPCC report, Oppenheimer et al. 2019). Many coastal and island areas will be submerged or subject to increasingly frequent flooding, causing considerable damage (Goussard and Ducrocq 2014; Dada et al. 2020).

Along the West African coast, a rise above the global average is expected (World Bank 2020; Marti et al. 2016). This could have dramatic consequences for some coastal areas located just above current sea level. Major coastal cities and historical heritage in the region are at great risk (Ouikotan 2017; Vousdoukas et al. 2022). Saltwater intrusion into coastal aquifers will be more frequent and could gradually render aquifers unsuitable for consumption and agriculture. The assumption of a 1 m rise in sea level would lead to a considerable increase in coastal hazards, mainly affecting low-lying sandy and muddy coasts and mangroves. Major lagoon systems will also be affected (Chaigneau et al. 2022).

Some areas of the region, especially along deltas and megacities, are progressively subsiding due to human activities such as oil and gas development, freshwater extraction for agriculture, and urban densification, exacerbating the effects of sea-level change there. Subsidence and mangrove clearing have increased erosion to about -30 m/yr in Nigeria (Ebisemiju 1987; Dada et al. 2016b, 2019; Anthony et al. 2019; Alves et al. 2020). Indeed, the main source for smoking fish and shrimp is mangrove wood.

The African population is the fastest growing in the world (Denis and Moriconi-Ebrard 2009). The coastal fringe accounts for about 56% of the gross domestic product (GDP) of West African countries (UEMOA/WAEMU 2011; Goussard and Ducrocq 2014; Diop et al. 2014). The highest population density hotspots are located in some key megacities along the coast, including Dakar, Abidjan, Accra, Lomé, Cotonou, and Lagos.

Due to rapidly changing environmental conditions, the increasingly dense human population now faces the challenge of adapting its habitats and activities, but public governance generally fails to support it (Dada et al. 2021). The situation is further exacerbated by the lack of a legal framework for land use, planning and coordination for environmental protection. These heavily and densely populated West African coastal areas depend on the biological resources of the marine and coastal areas. Coastal fisheries are an important source of income in the region, employing 6.7 million people (Thomas 2020). However, overexploitation of marine resources and degradation of nurseries will likely lead to gradual and significant depletion of fish stocks (Diop et al. 2014).

Water pollution is also a major aspect of environmental degradation in marine, coastal, and freshwater areas of the West African coast (Diop et al. 2014; World Bank 2020; Croitoru et al. 2019). Agricultural runoff from irrigation, including elevated nutrient and pesticide concentrations, contributes to increased eutrophication of estuaries, deltas, coastal and freshwater environments (Diop et al. 2014). There are occurrences of seasonal invasive aquatic weeds in most freshwater aquatic areas, including coastal lagoons (Diop et al. 2014; Ndour et al. 2018). Sargassum beach landings are becoming an increasingly prevalent problem in the region (Gower et al. 2013; Franks et al., 2016; Wang and Hu 2016).

Coastal erosion is widespread in the region, with significant effects on coastal ecosystem functioning and livelihood support. Although the coastline is highly sensitive to natural erosion and sedimentation processes due to natural changes in wave regime, strong longshore drift transport, and river flow due to rainfall variability, human activities have intensified coastal erosion, including sand mining, disruption of hydrological cycles, construction of dams on rivers, construction of ports, dredging and deforestation of mangroves, etc., 2009; Laibi et al. 2014; Ozer et al. 2017; Sadio et al. 2017; Angnuureng et al. 2018; de Boer et al. 2019; Giardino et al. 2017a; Ndour et al. 2018; Almar et al. 2019; Anthony et al. 2019; Abessolo et al. 2021).

Finally, tourism is also an important industry in some West African countries, with its impacts on coastal areas. The construction of infrastructure such as ports, hotels, and other recreational facilities directly on the coast has been responsible for clearing coastal vegetation, filling wetlands, and increasing sewage and solid waste loads (Giardino et al. 2017a) and, in some cases, has contributed to accelerated coastal erosion (Appeaning 2009; Andrieu 2018; Angnuureng et al. 2020; Dada et al. 2021).

3 Satellite Observation to Support the Management of Coastal Areas and Marine Activities

Coastal areas are notoriously expensive and difficult to measure and monitor using in situ techniques (Benveniste et al. 2019; Melet et al. 2020; Cesbron et al. 2021). Due to the lack of consistent mapping regimes, the evolution of West African coasts is partially known and the processes driving these dynamics are poorly described (i.e., global climate change is still perceived as the dominant driver of coastal evolution, while local human pressure is often dominant and rather poorly documented; Dada et al. 2021). Thus, it is in these regions that EO data have a particularly vital role to play; in many cases, there are few viable and cost-effective alternatives for assessing critical information for decision making and management.

Satellite Earth observation (EO) represents a powerful tool for generating regionally consistent information. It provides a unique source of information that can help monitor and link hazards, exposure, vulnerability factors, and a wide range of potential risks. Most EO programs are moving toward free and open source policies so that the data generated can be used without restriction, making it more accessible today (Le Traon et al. 2019). EO data can provide unprecedented understanding of the coastal environment. EO also provides valuable information in support of risk and disaster management, such as exposure mapping in support of preparedness and mitigation, early warning, and response; tracking of up-to-date, synoptic, and objective information on the infrastructure of assets at risk; early warning and tracking of a range of natural hazards, disaster response, and support for crisis mapping and damage assessment; and support for recovery/reconstruction/rehabilitation. Despite the high potential for coastal practitioners and scientists, these EO data are still only minimally used. We list the main EO geo-environmental variables that can be monitored and discuss the social, technical, and scientific issues or challenges that hinder the interest of these actors in using satellite data and how satellite observation of these geo-environmental variables can better support coastal zone management in West Africa (Table 1). Below, we briefly review the main EO-derived observations used in coastal research today, illustrating each parameter with an example from West Africa.

Table 1 Examples (non-exhaustive) of monitored variables from EO and their level of maturity and implementation in WA. Cell color indicates the maturity/level of implementation (green: operationally used by practitioners, yellow: first showcases and pilot use, orange: pioneer studies at the research level)

Type	Geo-environment variables	Vulnerability/resources	Status of implementation in West Africa
Geomorphology	Shoreline	Erosion	Operational — used for indicators in the West African Coastal Observatory
	Topography	Protection to flooding	Used as pre-operational state—showcase
	Bathymetry	Sediment scarcity, erosion, aqua life nesting	Research level
	Land motion	Subsidence and flooding	Used as pre-operational state — showcase at urban areas and deltas
Sea-land waters	Sea level	Flooding	Operational (from altimetry) but of low frequency and distance from the coast. Models are effective
	Waves	Flooding and erosion, risk for offshore infrastructures, blue economy and power	Operational but not used in West Africa (SAR- Sentinel-1)- of low frequency and distance from the coast. Models are effective
Land cover/land use	Rivers	Flooding at estuaries and delta- compound effect with ocean drivers	Largest rivers/estuaries only can be monitored through altimetry and too low frequency of revisit (10 days)
	Water color	Pollution and contamination	Research level
	Classes of water, mangroves, forests, beaches, urban areas and infrastructures, etc	Deforestation, flooding, illegal or uncontrolled urban extension, algae and Sargassum landing, sustainable management	Operational — used for indicators in the West African Coastal Observatory

3.1 Land Cover–Land Use

EO land cover algorithms (reviewed in Pandey et al. 2021) can be used to determine the status of beaches/dunes, forests, and other vegetation types such as crops and mangroves, land artificialization (Zanaga et al. 2021). Many EO programs such as Landsat, Sentinel, SPOT, and Pleiades produce a huge volume of medium to high-resolution multispectral images every day that can be organized into time series. These time series provide a powerful tool for detecting and measuring spatial and temporal changes in anthropogenic and natural features. In addition, the temporal information provided by image time series allows for increased accuracy in land cover classification, producing up-to-date maps that can help identify changes in land over time and space.

Coastal land cover types can be generated by combining optical data (Sentinel-2, Landsat-8) and SAR data (Sentinel-1). A supervised classification method can then be applied to several spectral band indices derived from the optical data and backscatter information statistics from several SAR acquisitions (Thomas et al. 2018). An illustration is given in the West African Coast 2020 Assessment Report of the Schéma Directeur d’Aménagement du Littoral Ouest Africain (SDLAO)/West African Economic and Monetary Union (UEMOA/WAEMU) in a study of land use on the coast of Benin, with the aim of differentiating mangroves, forests, and agriculture for vegetated areas (Fig. 3). This information can be linked to in situ observations such as information on water quality, e.g., turbidity or the occurrence of algal blooms.

Urban area detection, in particular, benefits from combining optical and radar data into a common classification system. Especially in areas where cloud cover limits the acquisition of suitable optical data, radar data have a great advantage because they are independent of cloud conditions (Parker 2012). Further research and experience in combination

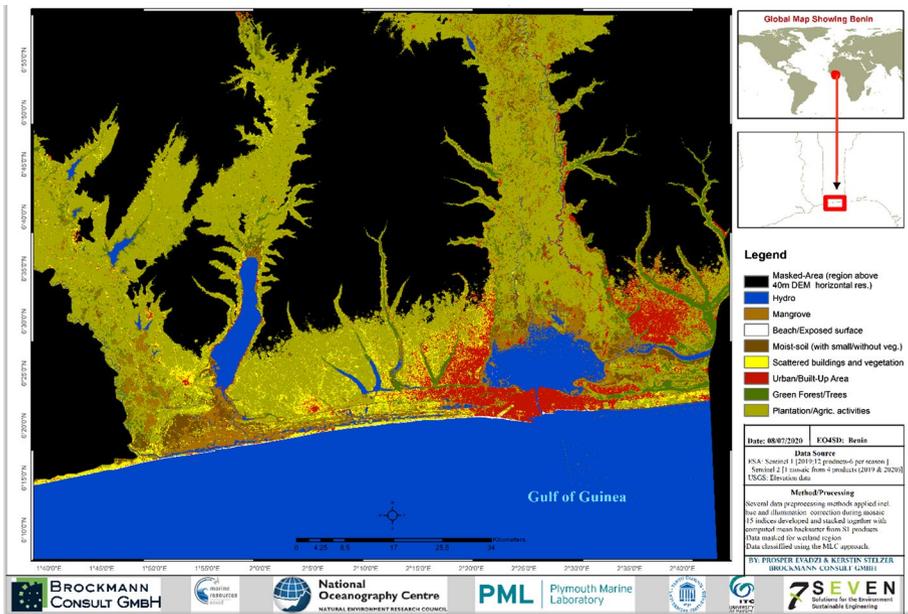


Fig. 3 Coastal Land Cover Map of Benin showing urban, vegetated and water surfaces (from SDLAO/UEMOA/WAEMU 2020 report on West Africa Coast)

with ground truth data would provide better results and therefore a better basis for change detection analyses. A primary objective in the Benin example in Fig. 3 is the identification of mangroves. Differentiating them from forests remains difficult, especially for very dense vegetation (because the water below cannot be seen). However, advances in satellite technology, as well as the availability of freely available datasets and open-source software, have produced increasingly accurate and comprehensive datasets on the extent, structure, and condition of mangroves, which can contribute to ecosystem service assessments and stimulate conservation and rehabilitation efforts (Worthington et al. 2020).

The European Space Agency's Earth Observation for Sustainable Development (EO4SD) disaster risk reduction (DRR) product—mapping the condition and evolution of built-up areas for Greater Banjul—provides discrete information on the spatial distribution and shape of human settlements and urban expansion. New settlements are increasingly located in hazard-prone areas and are sometimes occupied by dwellings with building typologies that are particularly vulnerable to hazards. The EO4SD DRR products provide information on features at risk, which can be used to estimate exposure to a given hazard. A methodology for extracting built-up areas from Copernicus Sentinel-2 imagery is illustrated here by a processing chain using a deep learning model (Kamdem De Teyou et al. 2020; James et al. 2021). It uses a semantic segmentation algorithm based on convolutional neural networks as a central piece of decision making on an annual time series of Copernicus Sentinel-2 images with 10 m resolution (channels: R, G, B, NIR). It is particularly interesting to see how the model can detect built-up areas from 10-m resolution images in areas virtually impossible for a human interpreter to grasp: The model sees beyond what is observable to the naked eye in the imagery (Fig. 4). The model is adaptable to the computation of entire regions due to its processing efficiency. It can be customized for certain

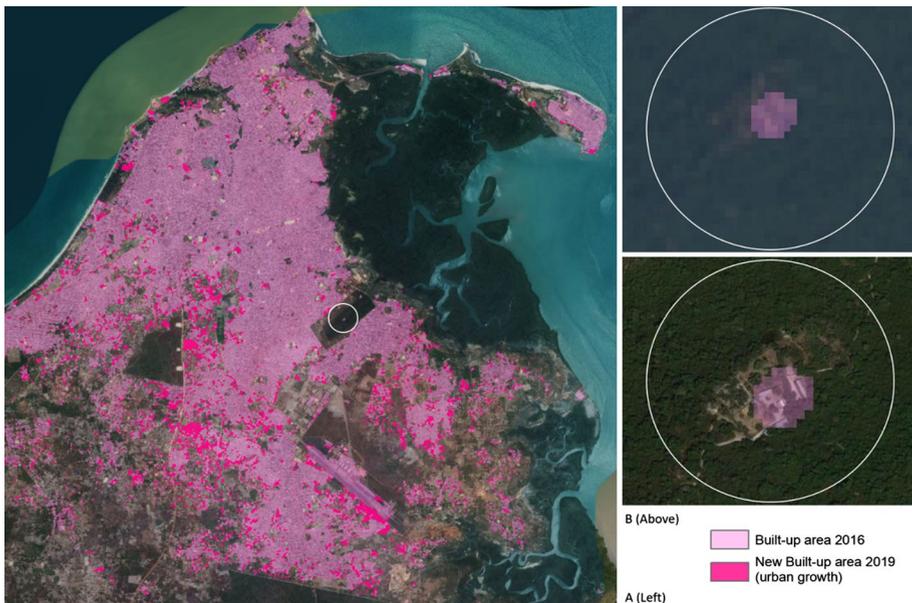


Fig. 4 A built up-area in 2016 and evolution between 2016 and 2019 generated with Copernicus Sentinel-2 imagery in the EO4SD DRR project. **B** Example of the product accuracy with built-up area superimposed over Copernicus Sentinel-2 imagery (**B**) and over a very high-resolution imagery (**A**) (SDLAO assessment report 2020)

geographic contexts and can learn and improve its accuracy with each new area analyzed and extracted.

Multispectral optical and Synthetic Aperture Radar (SAR) satellite data (e.g., PALSAR or Sentinel-1) are used to map and monitor coastal mangrove forests worldwide, including in West Africa (Bunting et al. 2018; Giri et al. 2011; Goldberg et al. 2020; Nwobi et al. 2020; Thomas et al. 2018). However, significant inconsistencies remain among the mangrove extent data products. Sargassum beach landings are also becoming an increasingly prevalent problem in the region. Since 2011, innovative satellite remote sensing analyses have provided strong evidence for the growth and spreading of Sargassum in the equatorial Atlantic (Gower et al. 2013; Franks et al. 2016; Wang and Hu 2016). For example, based on an “alternative floating algal index” (FAFI), “FA density” maps are now provided daily as an average of the previous 7 days. (Marsh et al., 2021).

3.2 Geo-Morphology

3.2.1 Shoreline

A number of methods can be used to monitor the location of shorelines from space, all using optical or radar data processing techniques. For country-scale mapping (e.g., as requested by the West African Coastal Area Management (WACA) program), annual median cloud minimum optical data composites can be downloaded from Google Earth Engine and used to delineate shoreline changes using open-source tools such as Coastsat (Vos et al. 2019a; Bergsma et al. 2020; Almeida et al. 2021) and the Digital Shoreline Analysis System (DSASv5) (Himmelstoss et al. 2018).

For example, along the coast of Benin, shorelines are synthesized through a classification and thresholding process using Landsat 7, 8, and Sentinel-2 pan-sharpened images between 2000 and 2020 (Fig. 5). A baseline is extracted using the first shorelines to plot transects at 50 m intervals along the coast. The process can be repeated over many regions of interest along the coast to allow for rapid large-scale (i.e., country/region-wide) analysis over a period of several decades.

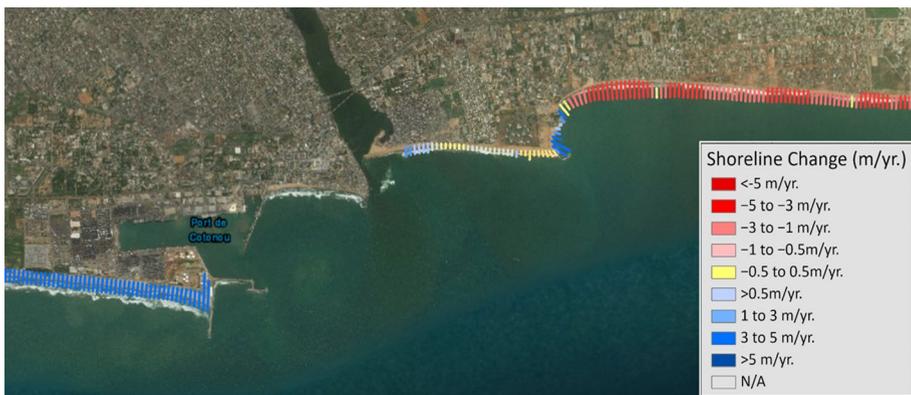


Fig. 5 Shoreline change rates at Port de Cotonou, Benin (SDLAO/UEMOA/WAEMU 2020 West Africa Coastal Areas assessment report)

3.2.2 Topography–Digital Elevation Model (DEM)

Remote sensing techniques now offer a good alternative for constructing digital elevation models (DEMs) over large spatial areas with sufficient resolution (< 100 m). They include global DEMs such as the 90 m resolution Shuttle Radar Topography Mission (SRTM) collected in the early 2000s (Farr et al. 2007; widely used for large-scale flood modeling, e.g., Ettritch et al. 2018; Neumann et al. 2015; Kulp et al. 2018), as well as the commercial 5 m ALOS AW3D30 DEMs (JAXA, Tadono et al. 2016; 30 m free resolution used for coastal overtopping in Dada et al. 2019; Almar et al. 2021a), and 8 m resolution WorldDEM (Airbus, on request). However, these DEMs are often several years old and do not reflect rapidly changing coastal areas.

By analyzing stereo pairs of optical satellite images using photogrammetry (Tateishi et al. 1992; Youssefi et al. 2020), it is possible to construct large-area DEMs, including the key intertidal zone, with vertical errors less than 0.5 m (Collin et al. 2018; Almeida et al. 2019; Taveneau et al. 2021)—see Fig. 6.

3.2.3 Bathymetry, Toward a Shoreface Land-Sea Coastal Morphology Continuum

To derive nearshore bathymetry, ocean color can be derived from optical missions such as Sentinel-2 and Landsat, from which water depth, seafloor features, and turbidity can be derived simultaneously or independently (Caballero et al. 2019; Salameh et al. 2019; Monteys et al. 2015; Li et al. 2021; Cesbron et al. 2021). The calculated bathymetry is not the depth of the consolidated sediment bedrock, but the depth of the suspended sediment layers in the mud. On muddy coasts, the data provide information on both constant suspended sediment and fluid sediment layers. As an alternative, bathymetry can be derived from satellite wave kinematics (Fig. 7), which has the potential to be independent of the water column and bottom spectral characteristics (Bergsma et al. 2019; Daly et al. 2021; Baba et al. 2021; Almar et al. 2021b) to depths of 35–50 m, depending on wave conditions (Bergsma and Almar 2020, Daly et al. 2021).

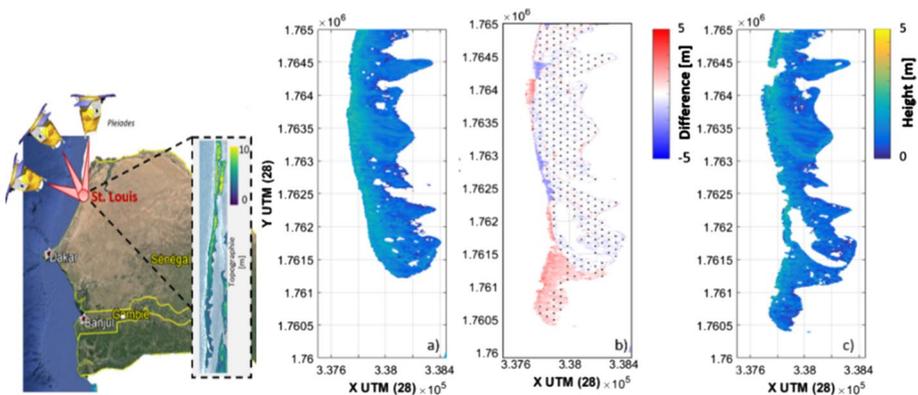


Fig. 6 (left) Saint Louis city (Senegal) location with the insert illustrating a Pleiades satellite acquisition showing an overview of the Languede Barbarie. (right) Sand spit topography derived from Pleiades—03/2019. DEMs difference (03/20–03/19). Sand spit topography derived from Pleiades—03/2020 (from Taveneau et al. 2021)

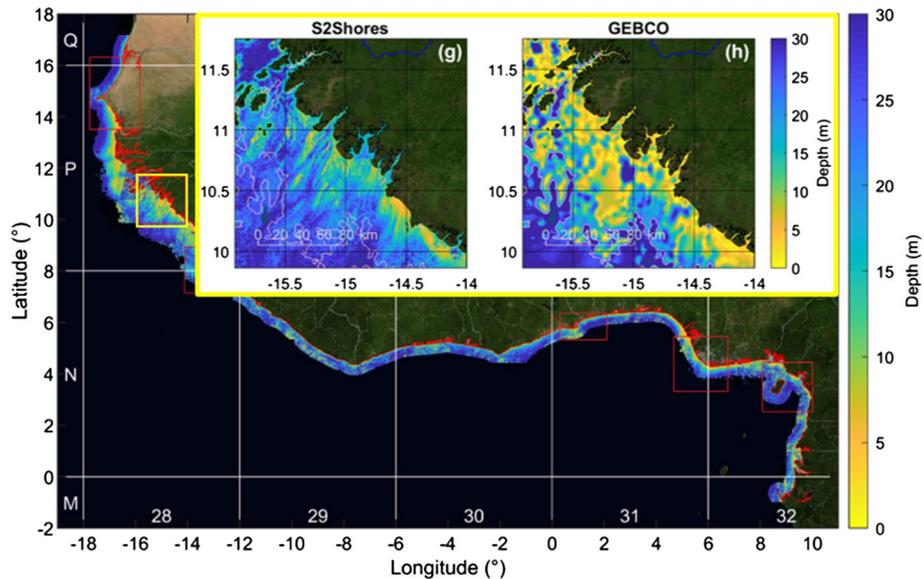


Fig. 7 West African bathymetry from Sentinel-2: inset shows the estimate and GEBCO product (from Daly et al. 2021)

The nearshore of coastal areas includes within the same cell and morphological profile both emergent and submerged portions that rapidly exchange sediment. This is a critical area to monitor to reduce uncertainty in predicting the impact of storms and climate change (Ranasinghe et al. 2020; Almar et al. 2021a, b). New opportunities are provided by on-demand satellite video (e.g., Planet, Jilin, Pleiades, etc.) that allows for combined topography and bathymetry in a single pass (Bergsma et al. 2021; Almar et al. 2022). This unlocks the problem of lack of decades-old data or surveys in West Africa, with significant potential in coastal engineering (coastal infrastructure design—see Turner et al. (2021)).

3.2.4 Vertical Land Motion—Subsidence

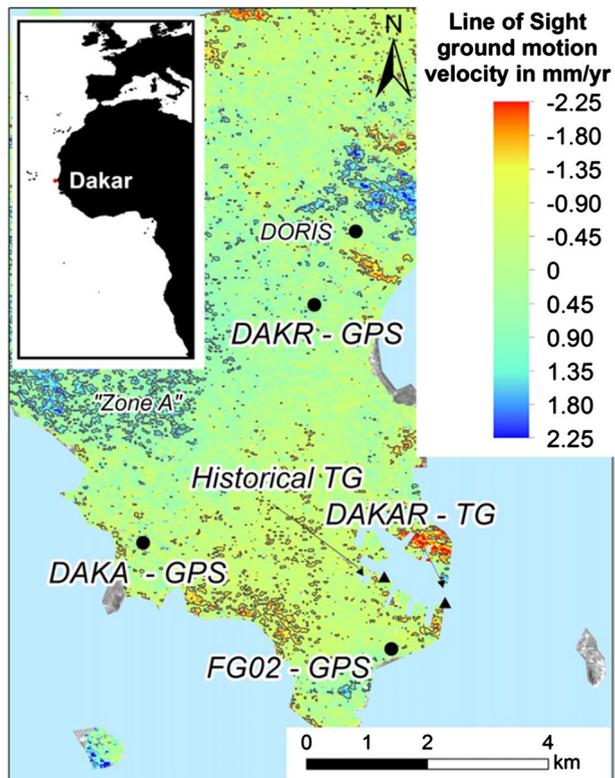
In the context of increasing intensity and frequency of disasters related to soil instability, it is important to accurately assess the potential impact of events such as landslides and subsidence (Dealbera et al. 2021; Nicholls et al. 2021a, b). To achieve this goal, cost-effective techniques can be useful for monitoring soil and infrastructure stability over a wide area (regional and global), avoiding large initial investments and increasing risk management capabilities to reduce losses.

As an example, the Geologic Risk Operations Platform (GEP—<https://geohazards-tep.eu>) is a cloud-based environment that provides a set of EO processing services to map hazard-prone land surfaces and monitor ground deformation. The platform is constantly expanding and includes a wide range of systematic and on-demand products and services to help EO practitioners and end users better understand geohazards and their impact (Foumelis et al. 2019). The GEP aims to improve the acceptance of online EO services and products for geohazard assessment and their adoption in decision making.

Being a collaborative platform, it allows users to control how they engage and interact with other users, to share and promote their assets and/or results. As an example, a total of 352 Copernicus Sentinel-1 images covering Dakar, Senegal were processed using the Parallel Small Baseline Subset (P-SBAS) on-demand processing service provided by CNR-IREA (<https://terradue.github.io/doc-tep-geohazards-v2/tutorials/gep-sbas-s1.html>). The P-SBAS algorithm is a technique for retrieving Earth surface displacement time series and mean velocity maps from a synthetic aperture radar (SAR) data set (Casu et al. 2014; Manunta et al. 2019). Details of the Copernicus Sentinel-1 SAR mission are available at Sentinel Online—ESA (<https://sentinel.esa.int/web/sentinel/home>).

The results in Fig. 8 highlight the status of the Greater Dakar coastal zone with respect to ongoing subsidence or uplift events. Inspection of the displacement time series provides additional information on the temporal behavior (displacement history) of each measurement point. Ground displacements measured by the interferometric synthetic aperture radar (InSAR) are measured along the satellite line of sight (LoS), expressing a combination of vertical and horizontal motion. Each measurement corresponds to the average motion in a 90×90 m area at the surface. The geospatial accuracy of the results is about 15 m, while the expected measurement accuracy is 1–2 mm/yr (e.g., Manunta et al. 2019).

Fig. 8 Line-of-sight ground motion velocity in mm per year-1 for the entire 1993–2010 period (ERS1, ERS2, and Envisat). Negative values indicate subsidence (Le Cozannet et al. 2015)



3.3 Sea-Land Waters

3.3.1 Sea Level

Contemporary sea-level changes along the West African coast are routinely obtained from a dedicated reprocessing of satellite altimetry data as part of the ESA Climate Change Initiative sea-level project. High sampling rate (20 Hz) sea level data from the Jason-1 and Jason-2 missions over a 14-year period (July 2002 to June 2016) are considered. The data are first tracked using the adaptive leading-edge sub-probe tracker ALES (Cazenave et al. 2020). The X-TRACK processing system developed to optimize the completeness and accuracy of corrected sea level time series in coastal ocean areas is then applied (Marti et al. 2016).

From the 14-year sea-level time series, sea level trends along the Jason-1 & 2 tracks can be estimated, quantifying regional variations in sea level trends, with a focus on observed changes between the open ocean and the coastal zone. Compared to conventional 1-Hz sea level products dedicated to open ocean applications, the reprocessed 20-Hz measurements used in coastal studies allow the retrieval of valid sea level information much closer to the coast (within 3–4 km of the coast, depending on the satellite track; Fig. 4).

At shorter time scales of days to years, sea-level variability is characterized by poleward propagation of coastal disturbances triggered by Kelvin waves trapped on the coast. These transient sea-level changes have been observed, described (Polo et al. 2008) and their impact studied (Abessolo et al. 2020) along the West African coast using a 1 Hz sea level product.

4 Coastal Flooding

A particularly important application of DEM is the investigation of coastal flood risk. Combined with hydrological data, inundation water levels can be mapped to evaluate the impact of floods. Scenario mapping allows the prediction of future inundation risk, as illustrated in Fig. 9 for Banjul area, Gambia (Foumelis et al. 2021). Based on DEM information, floods can reach 1.6 m today and between 1.9 and 2.7 m in the next 100 years, depending on three IPCC scenarios considered (RCP 2.6, RCP 4.5 and RCP 8.5) (Fig. 9). The provisional result is valid for the current storm climate, taking into account only a mild evolution of the weather due to climate change, i.e., excluding unprecedented extremes; for a stable shoreline, with no erosion, i.e., the retreat of the coast that could reduce significantly the surface of the city; and for a 2100 pessimistic prediction of 2.7 m rise above the land vertical datum, combining the Intergovernmental Panel on Climate Change (IPCC) worst scenario, spring tides and the maximum-known meteorological effects (Fig. 10).

The quality of flood predictions can be improved by (a) improving the quality of tide predictions essentially by retrieving or programming extended tide observations (tide gauges whose vertical movements are monitored by GPS); (b) checking compatibility between DEM precision and water-level observations; (c) a better knowledge of extreme sea level statistics; and (d) a better knowledge of wave set-up and runoff.

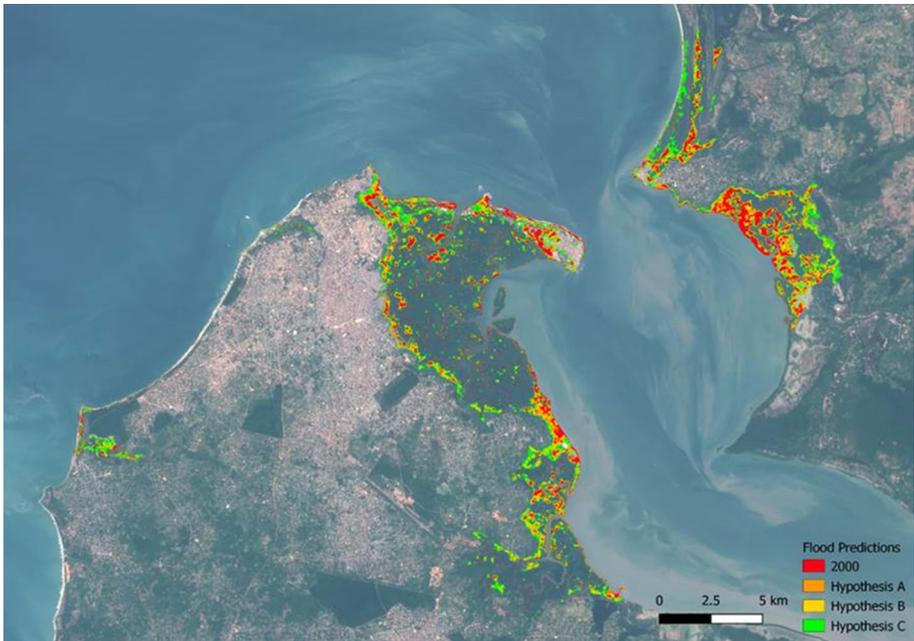


Fig. 9 Flood chart of Great Banjul (Gambia) with different flood predictions performed under the Earth Observation for Sustainable Development Disaster Risk Reduction (EO4SD DRR) project (Foumelis et al. 2021)

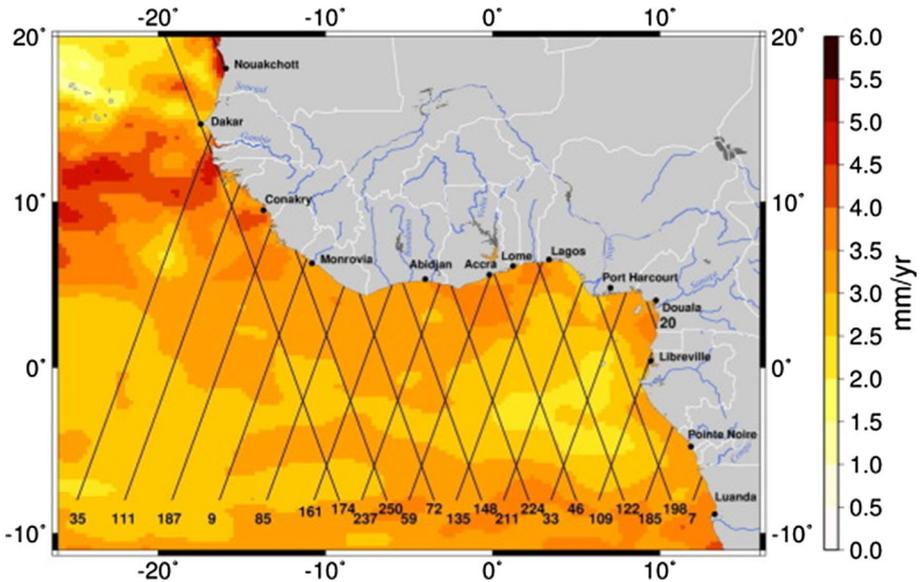


Fig. 10 Sea-level rise at the coast from the C3S gridded product from July 2002 to June 2016 in West Africa. Jason satellite tracks (identified by numbers) are overlaid (from Marti et al. 2016)

4.1 Water Quality

EO4SD—Earth Observation for Sustainable Development—is an ESA initiative that aims to achieve a step increase in the uptake of satellite-based environmental information. The EO4SD portal (<https://eo4sd.eofrom.space>) contains Sentinel-3 Ocean and Land Colour Instrument (OLCI) water quality data at 300 m resolution for the entire coast of Africa from both Sentinel-3A and B satellites (Fig. 11), using a polymer atmospheric correction (Steinmetz et al., 2011).

Satellite-derived chlorophyll concentration can be used to study seasonal and interannual phytoplankton dynamics, as well as monitor coastal water quality, eutrophication and harmful algal blooms. High Chlorophyll-a concentrations can indicate high nutrient concentrations in the surface waters and can be due to the eutrophication of coastal waters. For example, in the Gulf of Guinea off Côte d’Ivoire, research by Kassi et al. (2018) combines remotely sensed observations of ocean color with in situ observations of *Sardinella aurita* catch, temperature, and nutrient profiles, as well as reanalyses of wind and sea surface temperature, to investigate the relationships between catch and oceanic primary producers (including phytoplankton biomass and phenology). Kassi et al. (2018) discuss how predictive models can provide powerful tools to support the assessment and monitoring of fishing activity, which can contribute to the development of the fisheries information and management system.

5 Water Pollution

EO can be used to identify different types of land-based pollution (LBP) in the coastal or marine environment such as untreated sludge or sewage nearshore dredging, near-shore oil spill (this is discussed in the next section), tourism activities and illegal rubbish dumping (to be detected before being washed out).

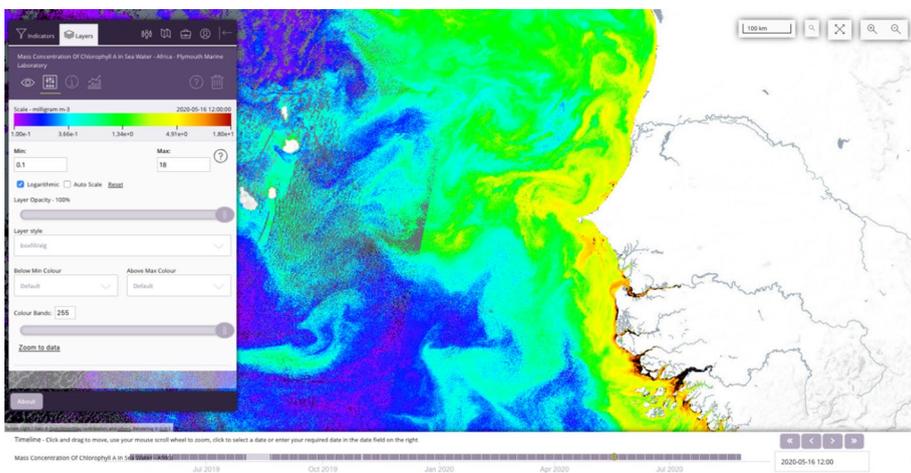


Fig. 11 View of the EO4SD Marine Portal satellite-derived chlorophyll concentration off the west coast of Africa on May 16, 2020. In this area, upwelling of nutrient-rich deep water occurs and leads to high productivity (accessed on <https://eo4sd-marine.eu>, SDLAO assessment report, 2020)

The indirect runoff of wastewater is combined with river runoff, and due to the high rates of advection and diffusion, the effluents are well-mixed in the water, and their direct detection is challenging. The direct runoff of untreated wastewater is detectable by satellite images as it has three distinctive imprint features on the surface of coastal waters: color, temperature, and surface roughness. Only the first feature, color, is detectable at a fine spatial resolution of ~10 m. Satellite products of sea surface temperature are merely available at coarse resolution > 500 m which is unfit for the fine-scale of land-based pollution.

Pollution methods typically use the color feature to detect and quantify the discharge of untreated sludge in coastal waters. The color of untreated sludge is commonly dark and can be detected in the visible part of the solar spectrum. In an example study from Senegal, the discharge of sewage pipelines into coastal waters of the Senegalese coastline south of Dakar is apparent (Fig. 12). This image is from the Sentinel-2 Multispectral Instrument (S2-MSI). This sensor observes the reflected sunlight in the visible part at a 10-m resolution and a 5-day revisit. This type of “visible” sensor is affected by cloud cover.

S2-MSI is used to quantify the discharge of untreated sludge along the coastline and up to 500 m offshore. The service provides probability maps [from 0 to 1] of solid waste, and dissolved waste for cloud-free observations. The probability values are estimated from water quality indicators and light penetration depth. For this purpose, the 2SeaColor model (Salama and Verhoef, 2015; <https://github.com/suhybsalama/2SeaColor>) is employed. The service uses Sentinel-1A and Sentinel-1B SAR satellite images provided by the European Space Agency. SAR sensors are very sensitive to variations of sea surface roughness and can successfully detect oil slicks that effectively dampen sea waves. The slicks are visible as dark spots in the SAR images. The system uses a machine-learning approach to delineate potential oil slicks from “lookalikes” associated with variations of the wind field, currents or algal blooms.

By combining the evidence from a series of processed images with vessel-tracking data (i.e., AIS) authorities can be alerted to request Port State Inspections at the subsequent port arrival of the vessel, during which records can be checked and evidence gathered for possible breaches of international law. Such a service extension would require a regional/international collaborative approach.



Fig. 12 Color composite (red, green, blue) from Sentinel-2 MSI image acquired on April 24, 2020 (using 2SeaColor model of Salama and Verhoef 2015) (SDLAO assessment report, 2020)

The service has been successfully applied for monitoring an oil leak at Mbaou in Dakar, Senegal (in the SDLAO assessment report 2020). Marine pollution was originally reported in this area by local fishermen, who observed thick oil slicks scattered in the area from Large Mbaou to Small Mbaou on July 16, 2020. These oil slicks are automatically detected in satellite images two days earlier, on July 14, 2020. Figure 12 shows in red the location and extent of the detected pollution areas. The largest oil slick in the image originates at the coast just opposite a refining plant.

6 Examples of Satellite EO Initiatives in Better Management of Coastal Zones

Recently, efforts have been made at the countries and regional levels to address some of the challenges facing the West African coast. These programs are largely based on EO. Here, we showcase two of them: (1) the West African Coastal Areas Management Program (WACA) which was developed by the World Bank Group in partnership with the coastal countries in the region; (2) the Space Climate Observatory (SCO), with several sites in West Africa, aims to study, monitor and adapt to the impacts of climate change, especially at local scales, using EO tools in combination with field data and models. These programs also search at developing the regionally human capacity of current managers and train future West African coastal experts and young researchers on developing the right tools and models to improve the sustainable management of the West African coastal region.

6.1 West African Coastal Areas Management Program (WACA, World Bank Group)

The program targets countries that want to improve the management of natural and man-made risks affecting coastal communities. It provides countries with access to technical expertise and financing to support sustainable development in the coastal zone, using coastal erosion and high-risk flood management as a starting point (Giardino et al. 2017b). The World Bank and its partners are pioneering this first-of-its-kind regional approach to addressing severe coastal erosion. Other partners are expected to join this effort through the new platform launched in November 2018 in Dakar, Senegal (World Bank 2018).

One of the WACA projects is the \$210 million WACA Resilience Investment Project (WACA ResIP), which aims to address coastal erosion, flooding, and coastal pollution in selected target areas in six West African countries, namely Benin, Côte d'Ivoire, Mauritania, Sao Tome and Principe, Senegal, and Togo. The project was developed in collaboration with four regional institutions—the West African Economic and Monetary Union (WAEMU), the Abidjan Convention, the Ecological Monitoring Centre (EMC) based in Dakar, and the International Union for Conservation of Nature (IUCN). It is jointly funded by the Nordic Development Fund and the French Global Environment Facility (FFEM). Other partners are joining the effort through a new WACA platform that has been set up to stimulate knowledge transfer, mobilize additional funding, and foster policy dialog between countries and protect the West African coast.

The WACA platform has created a coastal master plan through knowledge exchange, investment crowding-in, and policy dialog between countries (World Bank 2018). It also established the West African Regional Coastal Observatory (WARCO) to improve accurate

information on the state of the coast. WARCO is set up in collaboration with WAC countries to support, improve, and promote scientific and technical knowledge; provide tools for understanding and managing coastal phenomena; and establish sustainable and integrated coastal policy. Another program is the establishment of the African Center of Excellence for Coastal Resilience (ACECoR) hosted by the University of Cape Coast (UCC), Ghana, to support the development of technical and scientific capacity of young African professionals to develop integrated solutions to coastal degradation through short- and long-term professional and academic training programs. Finally, the “blue economy” has become a key pillar of the African Union’s continent-wide Agenda 2063.

The Abidjan Convention, established in 2019, provides countries in the region with the tools and information they need to safeguard fragile coastal ecosystems and the people and biodiversity that depend on them. The 18 parties to the convention have signed four protocols designed to improve the management of their respective coastal zones. The Pointe-Noire protocol proposes sustainable approaches to integrated coastal zone management (ICZM), while the Calabar protocol provides a technical framework to ensure the sustainable management of mangroves. The Malabo protocol sets minimum standards for addressing pollution risks from oil and gas activities, and the Grand-Bassam protocol focuses on regulating land-based and air-based sources of contamination.

6.2 Space Climate Observatory (SCO, International Space Agencies)

The Space Climate Observatory (SCO), a global initiative that focuses on observing the impacts of climate change, was established in late 2017. It is made up of a group of 27 space agencies and international organizations and has an objective to provide local decision-makers with operational tools, using satellite, in situ and local socio-economic data to help them draw up climate change mitigation policies on a local scale. SCO operates through projects led by consortia bringing together the scientific community, public authorities and private sector companies. In 2020, it certified 15 projects on coastal dynamics, mangroves, floods, urban climate, agriculture, epidemiology by remote sensing, etc.

For example, a SCO demonstration project in Senegal focuses on the coastline of Saint-Louis, an area particularly vulnerable to coastal erosion and flooding (Sadio et al. 2017; Almar et al. 2019; Bergsma et al. 2020; Taveneau et al. 2021). It aims to improve our knowledge and raise awareness of stakeholders on the hazards and risks in coastal areas in the context of climate change and to propose tools and indicators of the vulnerability of populations and economic activities (e.g., Koroglu et al., 2019). Coastal erosion here is estimated at between 0.5 and 2 m per year, flooding due to heavy rainfall, river flooding and/or storm surges, industrial and domestic pollution, saline intrusion, and mangrove degradation. To respond to these different drivers, and to find a balance between ecosystem preservation and economic development, it is essential to carry out precise monitoring of physical, ecological and sociological key parameters.

The Saint-Louis project has four complementary objectives, (a) to improve knowledge of the multiple hazards (flooding by storm inundation and Senegal River flooding and coastline recession) and associated risks encountered in coastal areas, based on an approach combining existing in situ monitoring (e.g., water-level data, DGPS surveys), dedicated population surveys and multi-sensor satellite (including coastal altimetry) and shore-based video camera, statistical processing and cartographic simulations; (b) to define current and future hotspots at risk in relation to climate change (in relation to sea-level rise); (c) propose tools and indicators of vulnerability of populations, economic activities

and infrastructures from a cross approach of satellite, in situ and socio-economic data processing and cartographic simulations; (d) to sensitize the actors toward a multi-risk vision as it approaches the coast based on existing elevation data, map simulation of flooding with several sea-level rise scenarios, reference DEM of shallow water bathymetry and intertidal topography, automatic coastline detection algorithm, a geospatial database of risk areas and risk features, including mapping of current and future hot spot areas.

The final product will include the identification of past major flood damage events, the definition of scenarios for the mapping simulation of floods, quantification of sea-level rise as it approaches the coast based on existing elevation data, map simulation of flooding with several sea-level rise scenarios, reference DEM of shallow water bathymetry and intertidal topography, automatic coastline detection algorithm, a geospatial database of risk areas and risk features, including mapping of current and future hot spot areas.

7 Roadmap on How Satellite Imagery Can Support Sustainable Coastal Zone Management in West Africa

A major challenge in the coming decades will be to predict how coasts (land, sea, and ecosystems) will evolve under the effects of global change, especially in low-lying and urbanized West Africa, which exposes it disproportionately (Oppenheimer et al. 2019; Almar et al. 2021a; Vousdoukas et al. 2022). Descriptive and predictive models typically rely on numerous historical observations, making their application difficult in regions such as West Africa due to the lack of detailed information. With recent advances in satellite remote sensing techniques, it is now possible to obtain rich data sets, often also retrospectively if satellite data are available for earlier periods. These data can provide a solid foundation for the development of data-driven models and management strategies (Ranasinghe et al. 2020). EO has already begun to better assess climate impacts and provide valuable information to coastal communities that lack historical data sets, such as in West Africa and the tropical Atlantic. Of primary importance for adapting coastal development or even natural resource exploitation includes sand mining and renewable ocean energy harvesting. The use of EO for monitoring is still rare along the West African coast for metocean conditions, coastal hydro-geo-morphological parameters and hazards, although data availability has increased considerably with the growing number of satellites. Today, Copernicus is the largest producer of freely available EO data (Sentinels) in the world (Le Traon et al. 2019).

Currently, EO data acquisition alone is not sufficient to address dynamic, short-scale coastal ocean and hazard monitoring. Coastal processes and hazards can be highly localized in space and time, for example, flash floods with a typical duration of a few hours cannot be observed with a typical satellite revisit time of several days. These hydro-dynamic/oceanic variables can be monitored by satellites (SST, SSH, wind, currents, waves, ocean color, etc.—see e.g. Arduin et al. 2019; Gommenginger 2019; Rodriguez 2019; Villas Bôas et al. 2019), as well as coastal hazards (e.g., floating debris and pollutant pathways, larval dispersal, marine navigation safety, etc.). Coastal geomorphic processes and features (e.g., land subsidence, topography) are generally characterized by low temporal variability but significant spatial heterogeneity. These specificities of the coastal zone pave the way for future missions, revisit and resolution requirements for new observing strategies (Turner et al. 2021; Bergsma and Almar 2020; Bergsma et al. 2022).

In order to provide relevant information for coastal zone management, there is a need for cross sectional, coherent, synoptic spatio-temporal monitoring of the coastal ocean, where EO is assimilated jointly with in situ or other remotely sensed observations into operational numerical models. Such integrated systems form the backbone of geo-environmental forecasting, which, by itself or through back-to-back forecasting or early warning systems, is critical to reducing exposure to coastal hazards and related risks. Coastal forecasting skills have been shown to increase when near real-time EO is assimilated. They would further benefit from (a) joint observations of different variables, especially in the development of more integrated and coupled operational numerical monitoring and forecasting systems, (b) better exploitation of EO by using more types of observations and more efficient and potentially coupled data assimilation techniques for model development and validation.

These satellite data are now mostly good alternative to traditional surveys in certain for developing countries, which lack historical data, making it difficult to implement numerical models and science-based policies. Using these new observations will make it possible to determine whether rising seas are the primary threat to the West African coast and whether the assumption of resilience in the face of anthropogenic and climatic pressure is likely (Dada et al. 2021; Hzami et al. 2021). The influences of important processes such as changes in river flow driven by changes in precipitation and land uses such deforestation and urbanization are particularly important in developing countries, with possible mitigation strategies such as dikes, nature-based solutions, and set back (Lincke and Hinkel 2018; Morris et al. 2020; Tiggeloven et al. 2020).

Overall, the West African coastal system can be better managed through EO:

- Strengthen monitoring by Earth observation, in a holistic and uniform manner across West Africa. Quantify what is happening on the coast, what protections and actions are needed and also monitor the effectiveness of applied solutions and identify potential socio-environmental bottlenecks: satellite data provide such variable multi-geo-environmental solutions,
- Promote the observation network and generalize data centralization and open data sharing (Find, Access, Interoperate, Reuse) such as COPERNICUS platform and common tools such as those developed by ESA (SNAP) or free-to-use chains (e.g., for stereotopography CARS—CNES, AMS-ASP—NASA, etc.) developed by spatial agencies and laboratories (S2Shores, by LEGOS-CNES),
- Establishment of a roadmap/strategy for future EO missions to support coastal zone management in West Africa, including appropriate revisit, resolution and priority variables monitored,
- Strengthen capacity development and networking of coastal EO skills: The creation of networks of scientists and engineers and companies. Strengthen the existing education system (e.g., masters, PhDs, thematic workshops on concrete problems and solutions),
- Establishment of a common policy for all West African countries, based on decision-making adapted to regional hazards.

8 Conclusions

The evolution of the West African coast is little known up to now, and the processes driving these dynamics are poorly described (e.g., climate change is still seen as the main driver of coastal change, which is incorrect, as human pressure and local infrastructure often

dominate). The low-lying and urbanized West African coast is one of the most vulnerable regions in the world to hazards due to socio-economic development and climate changes. As compared with other observation means, most of the satellite-derived data are a free source and can be used to monitor an increasing number of variables, at an increasing frequency and resolution. They face, however, a double bottleneck of the lack of ground truth and a certain level of the technical complexity of use for regional implementation. Better use of EO data in West Africa for improving sustainable coastal zone management requires investing in developing these multiple EO-derived techniques, designing future missions, promoting these EO data and techniques available and reinforcing capacity building for the practitioners and young scientists of the region.

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