




## Future socioeconomic development along the West African coast forms a larger hazard than sea level rise

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Sea level rise will exacerbate the vulnerability of low-lying coastal regions around the world in the coming decades, posing a severe threat to coastal populations. Here, we assess the future population and asset exposure of West Africa (WA) to normal and extreme coastal flooding based on the projected sea level rise scenarios reported in the IPCC Sixth Assessment Report using a bathtub modeling approach, MERIT DEM and gridded population gross domestic product datasets that are consistent with the Shared Socioeconomic Pathways. We find that socioeconomic development will be responsible for the maximum increase in future coastal flooding along the WA coast towards the end of the century. While contributions from climate-induced sea level rise will dominate and be responsible for changes in coastal flooding events in some countries, exposure to these events is likely to dominate in many countries if the ongoing horizontal infrastructural development and economic-oriented transformation continue. These results have important implications for both sustainable coastal planning and flooding risk mitigation for WA's coastal areas and should be considered as a cautionary tale for managing increasing socioeconomic development and coastward migration at the expense of the region's coastal ecosystems.

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It is certain that in the coming decades, sea level rise (SLR) will exacerbate the vulnerability of many low-lying, densely populated coastal regions of the world, and will highly likely become a major threat to human existence<sup>1,2</sup>. Global damage costs from floods and storms have been trending steadily upward in the 21st century<sup>3</sup>. This increased economic loss is caused mainly by socioeconomic change and changing climate patterns in areas of higher hazard<sup>3</sup>.

According to<sup>4</sup>, the difference of 11 cm (between a median global sea level rise for a temperature rise of 1.5° and 2° C) global sea level rise in 2100 could result in additional global annual flood costs and losses of US\$ 1.4 trillion per year (which is about 0.25% of global GDP) if no additional adaptation is implemented. It further stated that if warming is not kept below 2 °C under RCP8.5, the global annual flood costs without additional adaptation could increase to US\$ 14 trillion per year and US\$ 27 trillion per year for median and 95th percentile global SLR of 86 and 180 cm, respectively, reaching 2.8% of global GDP in 2100<sup>4</sup>. The risks and impacts of SLR and flooding will be disproportionately borne by poor people<sup>5</sup>, especially those from poor and developing countries such as those found in Africa.

Besides, the impacts of SLR may be worsened by land subsidence<sup>6,7</sup>, which may further increase the *effective* or *relative* SLR. More than half (51–70%) of present-day relative SLR experienced by human populations is caused by subsidence<sup>8</sup>, and predominantly (>70%) caused by anthropogenic actions that create or enhance coastal subsidence<sup>9</sup>. As such, human activities, intrinsically tied to socioeconomic developments in coastal zones, will further exacerbate relative SLR and coastal flood risk.

On the global scale, coastal water flooding and sea level are bound to increase with potentially severe consequences for coastal populations<sup>10</sup>. West Africa (W.A.; Fig. 1) coastal countries, comprising Mauritania, Senegal, Gambia, Guinea Bissau, Guinea, Sierra Leone, Liberia, Cote d'Ivoire, Ghana, Togo, Benin, and Nigeria, are threatened by sea level rise and coastal flooding. Thus, being very low-lying areas where coastal areas (i.e., the land below 10 m elevation) host about one-third of the total population and generate 56% of its GDPs<sup>11</sup>, coastal flood hazard is expected to increase<sup>12</sup>.

Besides, SLR may be worsened by the region's low capacity to act in response to such challenges<sup>13</sup>. The fast-growing population,

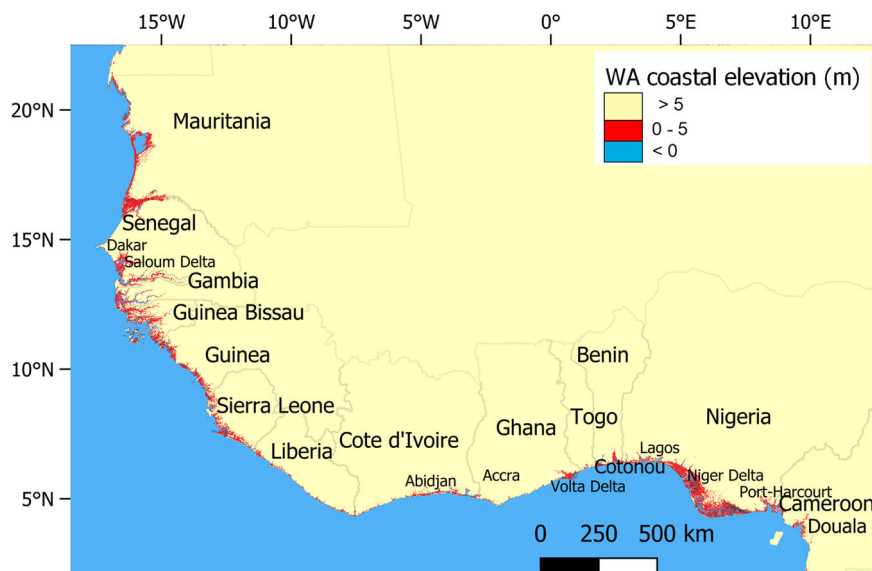
coast-ward migration, urbanization, and unrestrained and unregulated socioeconomic development are increasingly exposing people and assets to SLR<sup>13</sup>, while potentially also creating human-induced subsidence as witnessed elsewhere<sup>14</sup>. For instance, rising sea levels and coastal flooding has forced people to abandon public infrastructure and homes in Saint-Louis, a city in northern Senegal near the mouth of the Senegal River<sup>15</sup>. As a result, freshwater and wetland fisheries and agricultural production have been radically altered by saltwater intrusion in the region<sup>16</sup>. As most parts of the WA coastal zone consists of low-lying areas that experience rapid population growth and intense economic development, understanding future SLR and coastal flooding (both normal and extreme) events are critical in informing and formulating policy directions. Such an investigation will help identify regional “hot spots” where a more detailed study is required.

Here, following earlier studies, e.g. refs. 17–21, we determine the populations and the value of assets that would be exposed to coastal water levels (CWLs) in the absence of coastal defenses and protection along the West African coastlines. We estimate the normal (i.e., median values) and extreme (98th percentile) CWLs from the contributions of different components of sea levels using Eq. (1) at every 50 km (at 244 locations) along the West African coast (“Methods” section):

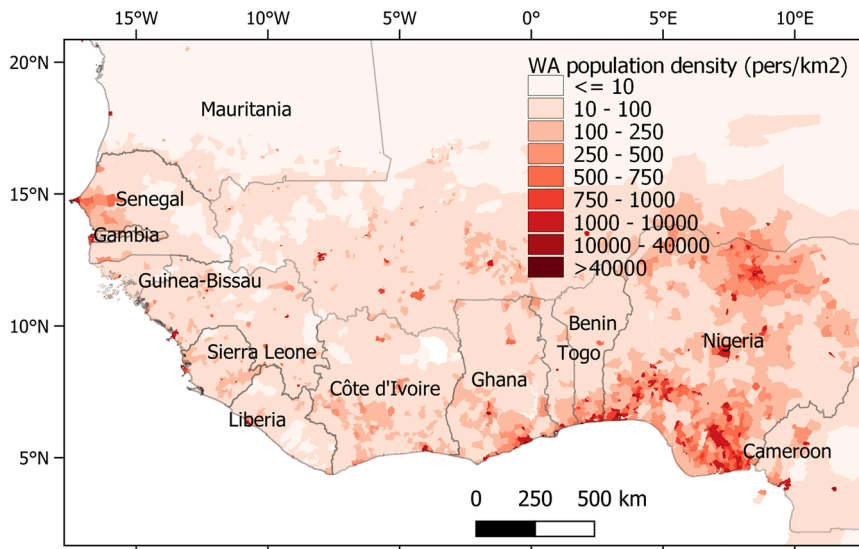
$$CWL_{(t,i)} = T_{(t,i)} + Ws_{(t,i)} + S_{(t,i)} + SLA_{(t,i)} \quad (1)$$

where tide  $T$  is tide,  $Ws$  is wave setup,  $S$  is storm surge due to atmospheric pressure and winds,  $SLA$  is the regional sea level anomaly,  $CWL_{(t,i)}$  is coastal water level which is a function of time,  $t$  at a study location,  $i$  (“Methods” section). The term extreme coastal water level (hereafter referred to as ECWL) is used here to denote the value of the CWL that has a return period of 100 years. Aside from the fact that the selection of locations is based on the even distribution and the availability of data at the selected locations, it is also based on the socio-economic or environmental relevance of the locations, such as coastal cities.

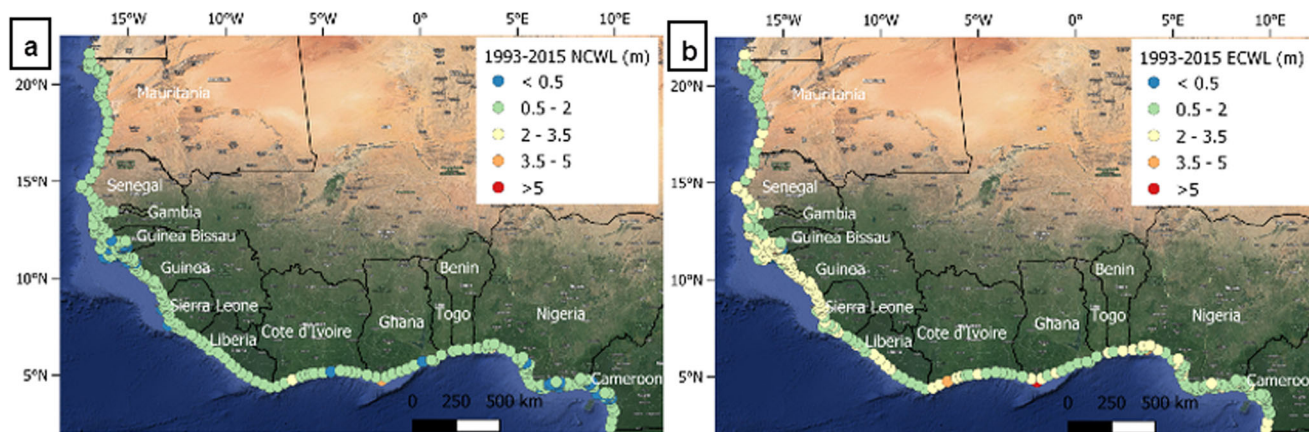
To obtain future projections, the normal and extreme estimates of CWL are coupled with four (4) of the five IPCC 6th Assessment Report Sea Level Projections Shared Socioeconomic Pathway-Representative Concentration Pathways (SSP-RCP) scenarios: SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 scenarios (Methods). The resulting present and future projections of



**Fig. 1 West African coastal elevation (m).** Coastal elevation below 5 m is in red (Data source: <sup>95</sup>MERIT DEM). Maps in Fig. 1 were generated using data acquired from MERIT DEM ([http://hydro.iis.u-tokyo.ac.jp/~yamada/MERIT\\_DEM/](http://hydro.iis.u-tokyo.ac.jp/~yamada/MERIT_DEM/)) in QGIS v.3.24.0 environment (<https://www.qgis.org/>).



**Fig. 2 West African coastal population density distribution in 2015 (person/km<sup>2</sup>).** (Data source: <sup>107</sup>CIESIN). Maps in Fig. 2 were generated using data acquired from CIESIN (<https://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-density-rev11>) in QGIS v.3.24.0 environment (<https://www.qgis.org/>).



**Fig. 3 Regional distribution of historical coastal water levels.** Historical (averaged 1993–2015) coastal water levels (CWLs) for **a** median/normal coastal water levels (NCWL); and **b** 98th percentile/extreme coastal water levels (ECWL). (The map images used in producing these figures were generated using the Google Satellite Hybrid plugin in QGIS v.3.24.0 environment, <https://www.qgis.org/>).

normal and extreme coastal water levels (hereafter referred to as the NCWL and ECWL, respectively) are then combined with global topographic data to assess the potential population and assets affected by coastal flooding along the West African coastline in 2015-, 2050-, and 2100-time steps (Methods). The distribution of normal and extreme coastal floodings (hereafter referred to as the NCWF and ECWF, respectively) is then used to determine the hotspots of coastal water flooding (hereafter referred to as CWF), where an increase in flooding at the country level is projected at the end of the century. Finally, we estimate the total population and value of exposed assets at risk at present/baseline (2015) and future (2050 and 2100-time steps) (“Methods” section).

**Results and discussion**

**Results**

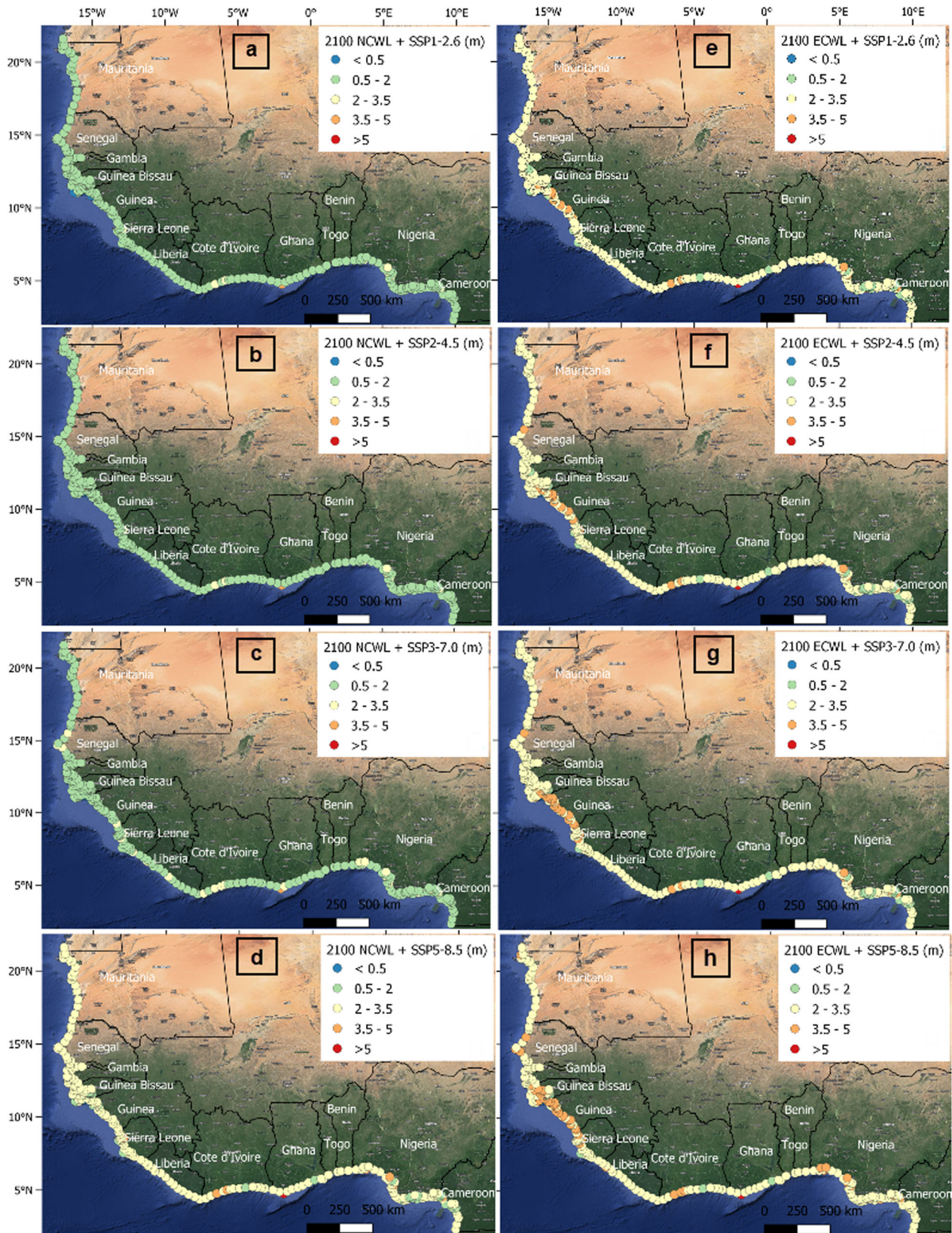
*Coastal water level projections using mean 1993–2015 as the baseline.* The mean NCWL and ECWL along WAC are projected from 0.83 and 1.97 m between 1993 and 2015 (Fig. 3) to 1.05 and 2.25 m (under both SSP1-2.6 and SSP2-4.5), and 1.07 and 2.28 m

(under SSP3-7.0), and 1.08 and 2.28 m (under SSP5-8.5) in 2050, respectively (Supplementary Fig. 1). Further, the mean NCWL and ECWL are projected to accelerate during the present century under these scenarios, reaching 1.31 and 2.62 m (under SSP1-2.6), and 1.32 and 2.73 m (under SSP2-4.5), and 1.56 and 2.95 m (under SSP3-7.0) and 2.62 and 3.17 m (under SSP5-8.5), respectively by the year 2100 (Fig. 4).

Under different scenarios, country average values in 2015 for NCWL and ECWL vary from a maximum of 1.18 and 2.17 m in Ghana to a maximum of 2.4 and 3.5 m in Nigeria under SSP5-8.5 in 2100 (Fig. 4d, h). Apart from Nigeria, other countries with events above the WAC mean CWL in 2100 under SSP5-8.5 are Benin (2.92 and 3.25 m), Ghana (2.91 to 3.42 m), Liberia (2.61 and 3.2 m), and Guinea Bissau (2.86 and 3.16 m) (Fig. 4d, h).

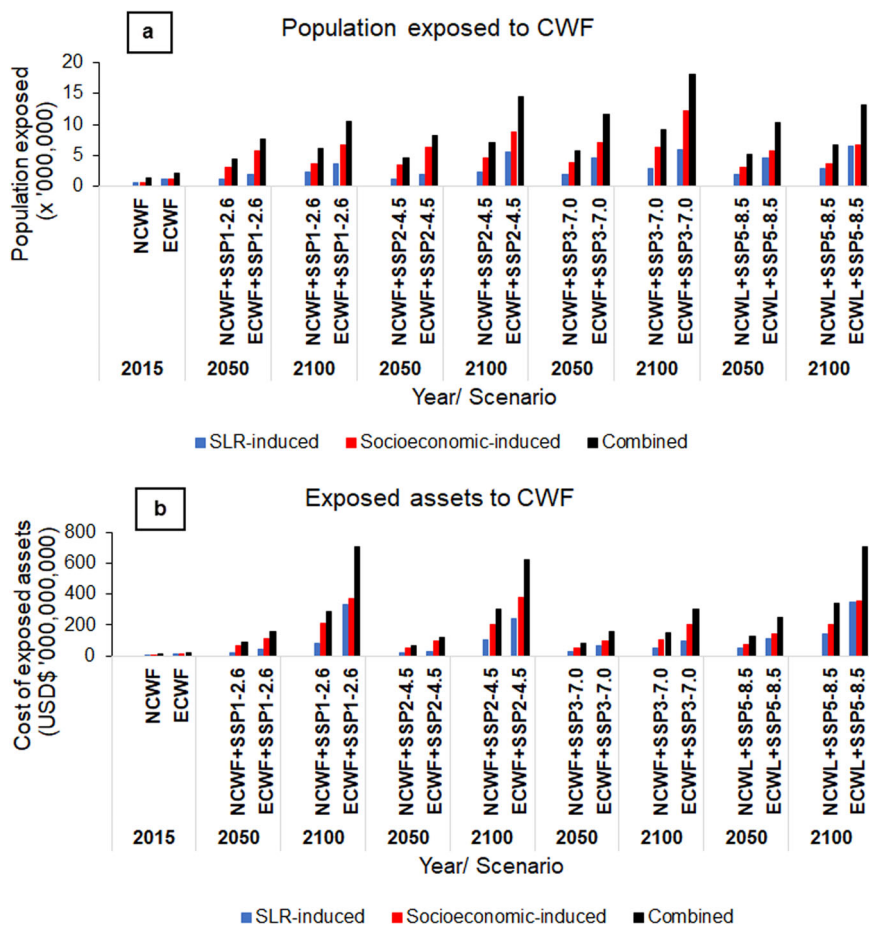
*Exposed population and assets to coastal flooding.* Fig. 5 shows the exposed population and assets to CWF for the present (2015) and future (2050 and 2100) under different climate change scenarios. For instance, the WA population that is potentially exposed to coastal flooding events (NCWF-ECWF) increased from 0.7 to 1.1 million in 2015 to 6–10.3 million people under SSP1-2.6, 7–14.4





**Fig. 4 Regional distribution of projected coastal water levels.** Projected (2100) coastal water levels (CWLs) for **a-d** 50th percentile/ normal coastal water levels (NCWL) under SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5, respectively; and **e-h** 98<sup>th</sup> percentile/ extreme coastal water levels (ECWL) under SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5, respectively. CWLs are estimated every -50 km along the West African coastline according to<sup>78</sup>. (The map images used in producing these figures were generated using the Google Satellite Hybrid plugin in QGIS v.3.24.0 environment, <https://www.qgis.org/>).





**Fig. 5 Exposed population and assets to the present and future coastal floodings.** The **a** exposed WA population; and **b** exposed WA assets to CWF caused by sea level rise, socioeconomic development change, and their combined effect under various climate change scenarios in 2050 and 2100.

million people under SSP2-4.5, 9.2–18.1 million people under SSP3-7.0, and 6.6–13.2 million people under SSP5-8.5 (Fig. 5a). This corresponds to a 9- to 16-fold increase in absolute exposed population in 2100 across the considered scenarios compared to 2015. The exposed assets increased from US\$7.8–11.5 billion in 2015 to US\$464–580 billion under SSP1-2.6, US\$303–620 billion under SSP2-4.5, US\$153–302 billion under SSP3-7.0 and US\$593–655 billion under SSP5-8.5 (Fig. 5b). This corresponds to a 100- to 300-fold increase in absolute exposed assets in 2100 across the considered scenarios compared to 2015. Our results underscore the high vulnerability of the WA population to sea level rise.

In terms of the percentage of the total exposed WA population to exposed population per country and total exposed WA assets to exposed assets per country in 2100, our results indicate that the countries with the largest coastal population at risk of coastal flooding in 2100 are Nigeria, Senegal, Cote d'Ivoire, Benin and Ghana (Table 1). These five countries contain about 82 and 87% of the population and assets exposed, respectively, to ECWL in the entire WA under SSP5-8.5 in 2100. Nigeria is especially striking as it holds more than 50% of the coastal population at risk (Table 1). This can be attributed to the population concentration in the region's low-lying, densely populated coastal cities and deltas.

*SLR-induced coastal flooding vs. socioeconomic-induced coastal flooding.* To evaluate the relative importance of socioeconomic and sea level rise to the future risk of WA coastal areas, we compared the impact of coastal flooding due to sea level rise with that of the impact due to socioeconomic development. As shown in Fig. 5, irrespective of the climate change scenario,

socioeconomic development will be the dominant factor of exposure to the CWF events at the regional level. In contrast, it varies at the country level (Fig. 6 and Tables 2, 3). For instance, climate-induced SLR will be the dominant factor of exposure to CWF events in countries like Guinea Bissau, Mauritania, Guinea, Cameroon, and Togo. In converse, socioeconomic will be the dominant factor of exposure to the CWF events in countries such as The Gambia, Benin, Senegal, Cote d'Ivoire, Nigeria, Sierra Leone, Liberia, and Ghana (Fig. 6 and Tables 2, 3).

## Discussion

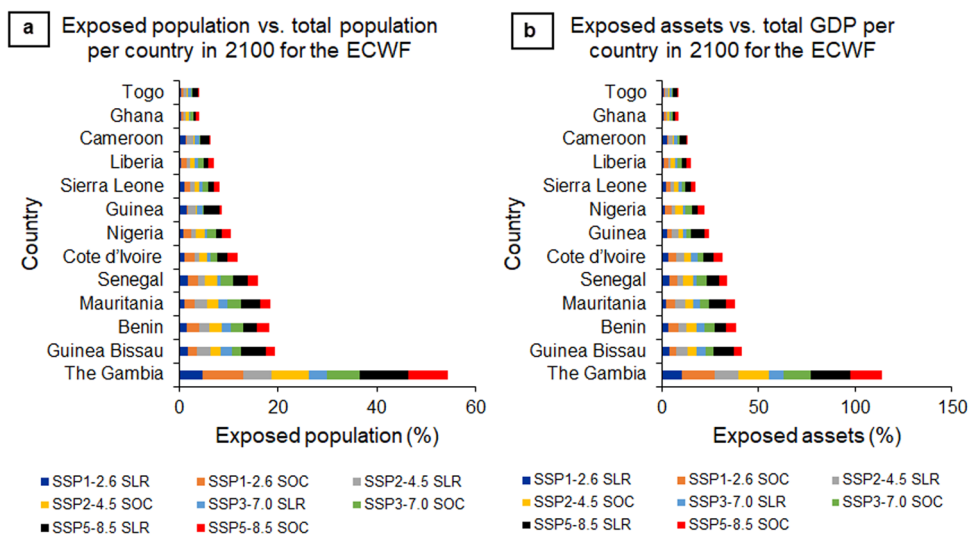
**Our results.** Our assessment of the exposed population and assets enables us to evaluate the relative contribution of socioeconomic development and SLR to the future CWF risk of WA coastal areas. We found that more people will be exposed to the CWF events under SSP3-7.0 and fewer events under SSP1-2.6, reflecting the highest and lowest affected population, respectively, under these scenarios (Fig. 5). Whereas the exposed assets to the CWF events will have the lowest cost under SSP3-7.0 and the highest under SSP5-8.5 (Fig. 5). These results are similar to the findings of refs. 1,22,23. For instance, the findings of ref. 22 show that while the exposed population is highest under SSP3-7.0, the exposed assets are lowest under this scenario.

Further, our results suggest that future CWF caused by increasing socioeconomic development in the WA coastal zone will dominate at the regional level. Albeit this will vary at the country level (Fig. 6 and Tables 2, 3). For instance, climate-induced SLR will be the dominant factor of exposure to CWF events in

**Table 1** The relative percentage of the present and projection for 2100 under SSP5-8.5.

Country	% Exposed population per country to total exposed WA population	Rank	% Exposed population per country to total exposed WA population	Rank	Country	% Exposed assets per country to total exposed WA assets	Rank	% Exposed population per country to total exposed WA assets	Rank
(a)	2015		2100		(b)	2015		2100	
Nigeria	55.3	1	57.3	1	Nigeria	32.2	1	69.4	1
Senegal	13	2	8.9	2	Senegal	14.8	4	4.7	2
Cote d'Ivoire	1.8	9	6.5	3	Cote d'Ivoire	21.5	2	4.6	3
Benin	7.7	3	5.8	4	Benin	5.3	5	4.2	4
Ghana	4.1	6	3.5	5	Ghana	3	6	4.2	5
Cameroon	5.2	4	3.4	6	Cameroon	16.5	3	2.9	6
Mauritania	2	8	3.1	7	Gambia	0.8	10	2.7	7
Gambia	2.3	7	2.9	8	Guinea	2.4	7	2.1	8
Guinea	4.9	5	2.8	9	Mauritania	0.9	9	1.7	9
Sierra Leone	0.9	12	1.9	10	Sierra Leone	0.7	11	1.3	10
Liberia	0.3	13	1.8	11	Liberia	0.2	13	1.1	11
Guinea Bissau	1.2	11	1.2	12	Guinea Bissau	0.4	12	0.8	12
Togo	1.3	10	0.8	13	Togo	1.3	8	0.4	13

(a) Total exposed WA population compared to the exposed population to ECWF at the country level. (b) Total exposed WA assets compared to the exposed assets to ECWF at the country level.



**Fig. 6** Exposure (population and assets) to coastal floodings in different countries by 2100. The **a** exposed population, and **b** exposed assets at the country level to CWF caused by both sea level rise and socioeconomic development change under various climate change scenarios in 2050 and 2100.

countries like Guinea Bissau, Mauritania, Guinea, Cameroon, and Togo. In converse, socioeconomic development will lead to increasing future CWF events in countries such as The Gambia, Benin, Senegal, Cote d'Ivoire, Nigeria, Sierra Leone, Liberia, and Ghana (Fig. 6 and Tables 2, 3). The results of the present study should be regarded as a caution to regulate future coastal developments effectively along the WA coastline.

According to our results, the countries with the largest coastal population at risk of coastal flooding in 2100 are situated in the Bight of Benin: Benin, Cote d'Ivoire, and Nigeria (Table 1). These three countries contain about 73% of the average annual people exposed to coastal flooding in WA under SSP5-8.5 in 2100 (Table 1). As stated earlier, the Nigeria case is exclusively conspicuous as it holds more than 50% of the coastal population at risk. Likewise, in terms of exposed assets, irrespective of the scenario, Nigeria, Benin, Cote d'Ivoire, and Ghana topped the list of coastal assets at risk of coastal flooding in 2100, comprising 74.4% of the entire exposed assets of the region (Table 1). Our results agree with the<sup>24</sup>, which state that the coastal countries of west and central Africa, like

Senegal, The Gambia, Sierra Leone, Nigeria, Cameroon, Gabon, and Angola, have low-lying lagoonal shores that are endangered by sea level rise, especially since the majority of these nations have fast-growing coastal towns where most of the populations are poor people residing in potentially hazardous areas<sup>1,23-25</sup>.

**The future implications to WA coast.** Earlier studies have shown that flood risks could be driven by socioeconomic change, as the number of people, assets, and value of economic activities increases over time<sup>26</sup>. In the absence of risk-mitigating measures, socioeconomic growth could result in the absolute damages from flooding increasing by a factor of 20 by 2100<sup>27</sup>. Climate change and risky urbanization patterns are expected to further aggravate the flooding risks before the end of the 21<sup>st</sup> century<sup>28-31</sup>. It is expected that an entire stretch of West Africa, between Abidjan and the Niger Delta, will become a megacity before the middle of the century. Future land subsidence owing to unsustainable extraction of fluids such as gas, oil, and water will occur at locations with high

**Table 2 The relative percentage of the exposed population compared to the total population per country in 2100 for the ECWF.**

**Exposed population vs. total population per country in 2100 for the ECWF**

Country	SSP1-2.6		SSP2-4.5		SSP3-7.0		SSP5-8.5		Dominant factor
	SLR (%)	SOC (%)	SLR (%)	SOC (%)	SLR (%)	SOC (%)	SLR (%)	SOC (%)	
The Gambia	4.8	8.1	5.8	7.6	3.6	6.7	9.8	7.9	SOC
Guinea Bissau	1.8	1.8	2.7	2.1	2.2	2	5	1.8	SLR
Mauritania	1.1	2.1	2.4	2.4	1.8	2.6	4	2.1	SLR
Benin	1.5	2.6	2	2.5	1.8	2.6	2.7	2.6	SOC
Senegal	1.7	2.2	1.3	2.4	0.8	2.6	2.9	2.1	SOC
Cote d'Ivoire	1	2	1.1	1.6	0.7	1.2	2.2	2.1	SOC
Nigeria	0.7	1.8	0.8	1.8	0.6	1.7	1.3	1.8	SOC
Sierra Leone	1	1.1	0.9	1	0.8	1	1.3	1	SOC
Guinea	1.4	0.3	1.6	0.3	1	0.3	3.3	0.3	SLR
Liberia	0.3	1.2	0.6	1.1	0.6	1.1	1	1.2	SOC
Cameroon	1.3	0.3	1.2	0.3	0.9	0.3	1.7	0.3	SLR
Ghana	0.3	0.6	0.4	0.6	0.3	0.6	0.6	0.7	SOC
Togo	0.4	0.3	0.8	0.3	0.6	0.3	1.1	0.3	SLR

**Table 3 The relative percentage of the exposed assets in 2100 to the total GDP per country in 2100 for the ECWF.**

**Exposed assets to total GDP per country in 2100 for the ECWF**

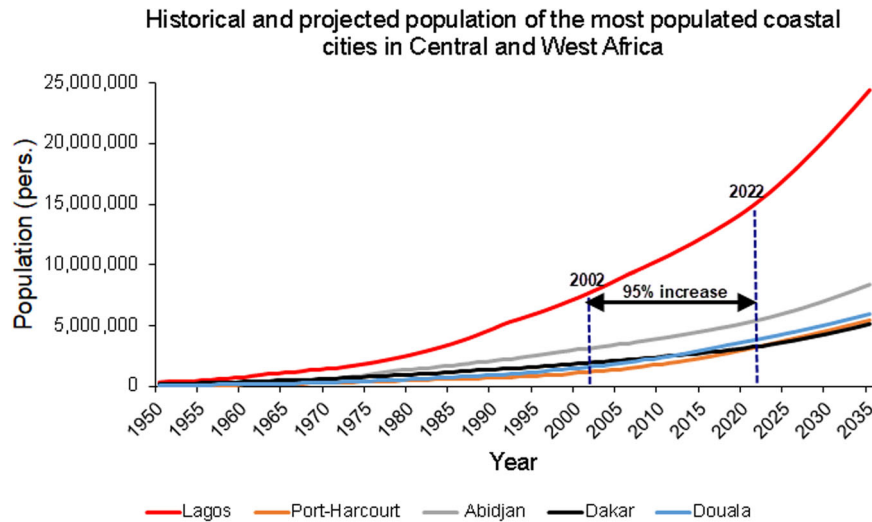
Country	SSP1-2.6		SSP2-4.5		SSP3-7.0		SSP5-8.5		Dominant factor
	SLR (%)	SOC (%)	SLR (%)	SOC (%)	SLR (%)	SOC (%)	SLR (%)	SOC (%)	
The Gambia	10	17	12.2	15.9	7.6	14	20.6	16.7	SOC
Guinea Bissau	3.8	3.8	5.7	4.4	4.6	4.2	10.6	3.9	SLR
Mauritania	2.3	4.5	5	4.2	3.8	4.7	8.4	4.8	SLR
Benin	3.1	5.4	4.1	5.3	3.8	5.5	5.7	5.4	SOC
Senegal	3.6	4.6	2.8	5.1	1.6	5.5	6.1	4.5	SOC
Cote d'Ivoire	3.1	4.3	4.1	3.3	3.8	2.5	5.7	4.5	SOC
Nigeria	1.5	3.7	1.7	3.8	1.3	3.5	2.7	3.8	SOC
Sierra Leone	2.1	2.2	1.9	2.2	1.6	2.2	2.8	2.2	SOC
Guinea	2.9	2.2	3.5	2.2	2	2.2	6.9	2.2	SLR
Liberia	0.7	2.5	1.3	2.4	1.2	2.2	2.1	2.4	SOC
Cameroon	2.7	0.5	2.5	0.6	1.9	0.6	3.6	0.6	SLR
Ghana	0.7	1.2	0.8	1.3	0.5	1.2	1.3	1.4	SOC
Togo	0.8	0.7	1.6	0.7	1.2	0.6	2.3	0.7	SLR

population pressure and economic activities<sup>8,32,33</sup> and increase coastal flood risks at a rate four times faster than sea level rise<sup>8</sup>. This suggests that although CWF caused by sea level rise will continue to increase, land subsidence at the local level will dramatically aggravate the problem<sup>8</sup>.

It is indubitable that the African continent will drive the future of urbanization, and it is a strip along the coast of West Africa where the biggest changes will happen. This is because most of the economic activities that form the backbone of the national economies of these coastal countries are situated in the coastal zone<sup>34</sup>. Considering the United Nations projection, Africa which was less than one-tenth of the world's population in 1950, will be home to 3.9 billion people, or 40% of humanity by the century<sup>35</sup>. The rapid growth of WA's coastal populations would place a new demand for infrastructure, housing, and other physical structures, and amenities before the end of the century. However, it remains uncertain how the West African nations would manage urbanization and socioeconomic development in the long term<sup>34,36-38</sup>. At present, coastal wetlands are considered in terms of their economic worth rather than their environmental importance<sup>39,40</sup>. Governments allocate coastal wetlands to real estate developers and grant permits to provide exclusive residential areas and use them to build public infrastructure, bringing billions of internally generated revenue to the government coffers<sup>41,42</sup>. In some cases, most developers build in the wetlands without acquiring government

building permits<sup>43</sup>. Cities throughout the region have tended to sprawl outwards, rather than upward<sup>38,44</sup>.

The Cote d'Ivoire-Ghana-Togo-Benin-Nigeria section is fast becoming the world's most rapidly urbanizing region, a megalopolis in the making<sup>45,46</sup>. As of 2022, Lagos-Nigeria, Abidjan in Cote d'Ivoire, Douala in Cameroon, Dakar in Senegal, and Port-Harcourt in Nigeria occupied the 16th, 77th, 119th, 149th, and 150th positions among the first 150 most populated cities in the world (Fig. 7). It is expected that the coastline between the Cote d'Ivoire-Ghana-Togo-Benin-Nigeria section will become a continuous urban megalopolis before the middle of the 21st century<sup>46,47</sup>. Lagos is where the most dramatic changes are evident. As a state in Nigeria, Lagos is the African fourth-biggest economy and largest city in Africa<sup>46</sup> (Fig. 7). For instance, between 2002 and 2022 (in 2 decades), the population of Lagos, almost doubled, increasing from 7,875,000 to 15,388,000 (about a 95% increase: Fig. 7). Looking at the United Nations projection, Lagos will be home to 24.5 million people by 2035 and 40 million by 2050<sup>35</sup> (Fig. 7). But it may be difficult to accommodate this population by 2050 because, with the ongoing horizontal infrastructural development, every bit of environmental sanctuary would have been ripped off before then. By the end of the century, it is anticipated that the coastal length between Abidjan and Lagos would contain somewhere about half a billion people, making it the world's largest continuous, densely populated area<sup>35</sup>.



**Fig. 7 The most populated coastal cities in West Africa.** Historical and projected population of the first 5 most populated coastal cities in Central and West Africa (Data source: [111www.macro trends.net](http://www.macro trends.net)).

As coastal West Africa's urbanization continues to gather pace, and populations and regional socioeconomic development surge across countries' borders, the region's governments must set their sights higher to address the sweeping demographic and social changes in the WA coastal zone<sup>46,48,49</sup>. This is because as shown in our study, population pressures and increasing exploration and exploitation of coastal resources will lead to coastal degradation<sup>39,50</sup>. The Greater Accra Metropolitan Area, which is the most urbanized area in Ghana, has witnessed the destruction of its wetlands as a result of urban expansion and development. This wetland degradation has been linked to the perennial flooding in the metropolitan area<sup>43</sup>. In Lagos, about four decades ago, water supply was available in most residences. But the story has since changed as pipe-borne water is no longer available in those neighborhoods.

Today, Lagos residents have now gone into sinking boreholes in individual houses<sup>51–54</sup>. This proliferation and continuous abstraction of groundwater via borehole sinking can lead to the depletion of groundwater levels and eventually to land subsidence<sup>55,56</sup>. Land subsidence has already been known to occur often in Lagos, with estimates ranging from 2 to 87 mm/year, with the highest rates found along the coast and where large structures are constructed on landfills<sup>57</sup> and land subsidence linked to an unprecedented collapse of buildings<sup>58</sup>. The rate of subsidence in Lagos is anticipated to increase dramatically in the upcoming years due to continuous indiscriminate groundwater exploitation, urbanization, and rapid population growth, which may further exacerbate the flood rate and other related geohazards<sup>57</sup>.

As the coastal population grows human activities will increase, putting more pressure on coastal ecosystems such as mangroves, estuaries, deltas, and coral reefs that form the basis for important economic activities such as tourism and fisheries<sup>59–61</sup>. Further exploration and exploitation of other natural resources in the coastal zone, especially over-exploitation of groundwater withdrawal, oil and gas extraction, sand mining, and the construction of flood barriers around rivers will result in the sinking of the coastal land<sup>8,62</sup>. The WA's coastal cities are dealing with interrelated issues, including sea level rise, rapidly expanding populations, land pressure, and a lack of affordable housing<sup>63–65</sup>. As populations are pushed further into the wetlands and shorelines surrounding cities, they are increasing their vulnerability to floods and reducing the protection that these natural ecosystems and barriers offer<sup>43,66,67</sup>. Therefore, to mitigate the

effects of sea level rise, it will be necessary to simultaneously address other causes of vulnerability (such as balancing between high-end developments that displace residents and affordable housing options).

**Uncertainties/limitations of the study.** The results obtained in the present study are comparable to those of earlier research, e.g.<sup>1,22,23</sup>, but there are some inherent uncertainties in the methodology used, thus this should be seen as a first-order evaluation of the potential course of the adaptation commitment. The flood risk assessment used here is subject to uncertainties related to elevation data<sup>68,69</sup>, inundation model<sup>70–73</sup>, population change<sup>74–76</sup>, and socio-economic developments<sup>77</sup>.

Here, AW3D30 has been used to derive local coastal slopes (and wave setup) while MERIT was used for regional topography (and flooding maps). While AW3D30 has the potential for high resolution and can capture fine-scale features<sup>78</sup> necessary to derive fine parameters such as coastal slope, it contains noise on a regional level which makes its use for flooding maps less appropriate than MERIT which noise has been reduced and regional biases reduced by combining it with IceSat data. Indeed, uncertainties on the DEM used here are large, and it is in the same order for every global DEM available globally. This study highlights the current uncertainty regarding flood risk to the coastal population due to the provenance of DEMs. Therefore, this study is also a call for future missions<sup>79,80</sup> to better monitor coastal zones, in particular in Africa that mostly miss ground surveys and count on satellite observations for the coastal zone<sup>36,81</sup>.

While high-resolution satellite-derived DEMs are possible with submeter accuracy<sup>82,83</sup> with on-demand satellites such as Pleiades (French Space Agency CNES/Airbus), they are limited to local to regional scale. Global monitoring will be feasible with new missions such as the French Space Agency (CNES)'s Constellation Optique 3D (CO3D) for higher resolution DEM with a revisit for temporal evolution, which is still out of reach. Indeed, morphology can change within a single storm and such revisit is key and progressively accessible with new techniques and missions, in particular when considering the topography-bathymetry continuum<sup>84–86</sup>, which is of paramount importance when accounting for the complexity of waves' contribution to sea level at the coast<sup>87,88</sup>. However, we use a widely validate DEM already employed for such flooding exercises. And while it would



be inaccurate locally to resolve the dune-beach system, due to its necessary coarse resolution, the regional patterns are correct as they are corrected with IceSat missions.

Our findings can be utilized as a first-order assessment by decision-makers at the national and regional levels to focus on and coordinate adaptation and development efforts. However, because adaptation is implemented locally, decision-makers need to employ the best finer-resolution data that are currently available to assess the commitment to adaptation over time and support reliable and adaptable decisions.

## Conclusions

We have examined the distribution of projected coastal water flooding impacts on the coastal population and assets following temporal changes in sea level rise and socioeconomic development on the West African coast. Under different climate change scenarios, country-wise, the impact of future coastal flooding induced by SLR will be a dominant factor on the coasts of some WA countries. However, at the regional level, CWF events are likely to be dominated by socioeconomic development, especially if the conservation of the coastal environment is not put on the front burner of the socioeconomic development and economic-oriented transformation that is ongoing in the region.

Thus, to preserve future WA coastal areas, policy and decision makers must develop and put into action a plan that includes relocation, adapting current development to account for flood risk, restricting developments in high-risk areas, and encouraging the society to take steps that will lessen impacts of the likelihood of rapid rises in coastal flooding over a longer period. Further, the rising socioeconomic development and coastward migration must be regulated and managed sustainably. To mitigate future coastal flooding risks, implementation of adaptation must start now.

## Methods

Using the data and methods described below, we conducted an elevation-based assessment of coastal inundation vulnerability for the West African coastline. The empirical analysis we undertake in this study is based on combining information from geospatial data from different sources. Geospatial data are analyzed in the Quantum Geographic Information Systems (QGIS 3 v.26) environment.

**Components of coastal water levels.** Data on components of coastal water levels (CWLs) are obtained from<sup>78</sup> at every 50 km alongshore (at 244 locations) along the West African coast, from Mauritania in the northwest down to Cameroon in the southeast. Apart from the fact that the selection of locations is based on the even distribution and the availability of data at the selected locations, in addition, is based on the economic or environmental importance of the locations, such as coastal cities. According to<sup>78</sup>, altimetry-based sea-level time series anomalies (SLA in Eq. (1), with reference to WGS84, are extracted at the closest points to the coast from the gridded daily maps produced by the SSALTO/DUACS multi-mission<sup>89</sup> and distributed by the Copernicus Marine Environment Monitoring Service<sup>90</sup>. Atmospheric variables (surface winds, sea level pressure) and wave data (significant wave height,  $H_s$  and peak wave period,  $T_p$ ) are extracted from the ERA-interim reanalysis<sup>91</sup>, developed by the European Centre for Medium-Range Weather Forecasts model (ECMWF), at 0.5° and 6 hourly temporal resolutions between 1993 and 2015. The ERA-interim reanalysis uses a coupled ocean wind-wave and atmospheric model, which has been extensively validated<sup>91–93</sup>.

Storm surge ( $S$  in Eq. (1)) time series for the same period (1993 and 2015) are extracted from the MOG2D-G barotropic model forced by ERA-interim surface winds and atmospheric pressure with 6 hourly outputs. Astronomical tidal levels ( $T$  in Eq. (1)) for the 1993–2015 period are obtained at an hourly resolution from the global tide model FES30 at the closest points to the coast. Here, wave setup ( $R$  in Eq. (1)) is determined using the<sup>94</sup> approach, where  $R$  is given as a function of deep-water significant wave height  $H_s$ , wavelength ( $L_o$ ), and sub-aerial coastal slope ( $\beta$ ) using the dataset from<sup>78</sup>. All the components feeding into Eq. (1) are ultimately interpolated to an hourly resolution to account for the compound nature of extreme coastal water levels. These CWL estimates have been thoroughly validated against extensive global tide gauge data (for more details about data acquisitions and procedures followed, see<sup>78</sup>). CWLs are subsequently used as forcing for coastal flood inundation estimates.

**Coastal topographical data.** This is from the multi-error-removed improved-terrain (MERIT) digital elevation model, a 3-arcsecond global terrain dataset that is

the most accurate freely available global terrain dataset for flood modeling<sup>95</sup>. It is known as a global DEM that provides a good predictor of flood extent<sup>96–98</sup>. It has been proven to resolve many errors in flat floodplains that are present in other satellite-based terrain datasets<sup>95</sup>. MERIT-DEM combines elevation data from several sources (SRTM, ASTER, ICESat), which are then processed to remove vegetation, stripe noise, random noise, and absolute biases.

To remove data at cells classified as urban in areas of low gradient, the DEM is filtered using a global urban footprint dataset. The corrected elevations at these locations are then interpolated from the remaining neighboring elevation data. The original MERIT DEM has a resolution of 3 arc-seconds (~90 m at the Equator). To be consistent with 1 km spatial resolution population/GDP data and for a computationally expensive inundation modeling of many SLR increments and population changes, we use 30 arc-seconds (1 × 1 km at the Equator)<sup>96</sup>. The datum for the estimates of median and extreme CWLs is the mean sea level while the datum for the MERIT DEM is the geoid. To bring these datasets to the same datum (i.e., mean sea level), we apply the mean dynamic ocean topography (MDOT)<sup>17</sup>. Further, we use the high-resolution (~0.2 km) coastline dataset of global self-consistent hierarchical high-resolution geography (GSHHG) to define the West African coastline for calculations of flooding extent.

**Historical and projected sea level rise.** Based on the linear assumption (1), an historical time series of  $TSL(t)$  at each point for the period 1993–2015. To obtain future projections for the end of the 21st century, we consider four scenarios of SLR based on the IPCC 6th Assessment Report Sea Level Projections which incorporated the global land movement into its estimation. In addition, we use published data from<sup>8</sup> and<sup>62</sup>, respectively, for some locations (e.g., deltas and coastal cities) that are known to be highly susceptible to subsidence.

Here, we consider SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5, respectively, for low, intermediate, high, and very high in terms of future Greenhouse Gas Emissions<sup>24</sup>. The Shared Socio-economic Pathway (SSP) label in each scenario gives information about the change in socioeconomics, including population, and the RCPs (Representative Concentration Pathways) give the radiative forcing scenario. These datasets are extracted for the 244 locations from the National Aeronautics and Space Administration (NASA) Sea Level Projection (<https://sealevel.nasa.gov/>). The IPCC projection of sea level for the study locations is obtained at the closest points to these locations. The median and extreme value estimates of CWL are coupled with these selected global projections of RSLR. The resulting projected future median (normal) and extreme CWLs are then used in conjunction with topographic data to assess the potential extent of episodic coastal flooding along the West African coastline in 2050 and 2100.

**Coastal inundation modeling.** We assess coastal flooding based on a bathtub method, following the same approach as<sup>17</sup>. The bathtub inundation model posits that a region with an elevation below the expected flood level will be inundated like a “bathtub”. The elevation in each cell of a DEM is evaluated against an anticipated sea level in a GIS context, and all cells with values lower than the predicted sea level are regarded to be in floodplains<sup>72</sup>.

Using static (bathtub) flood modeling technique<sup>99,100</sup>, we estimate areas that are hydraulically connected with the ocean for each averaged value of CWLs over the entire coastline<sup>22</sup>. A flood-fill algorithm using 8 nearest neighbors determines grid cells that are flooded at each estimated flood height<sup>101</sup>. The whole process is repeated for each estimated flood height in three-time steps (2015, 2050, 2100).

We acknowledge that the bathtub model may have some limitations in its use for flood risk assessment due to the vertical uncertainty of DEMs in the order of meters, thereby underestimating the coastal flood risk, especially in low-lying coastal zones<sup>70,71,102</sup>. However, several studies have applied it to map coastal flood inundations around the globe (e.g.<sup>17,70,103–105</sup>). Moreover, the DEM we use here, MERIT, is found to have a vertical error of not more than 2 m<sup>96,106</sup>.

**Population and asset exposure.** For determining the number of people exposed to flooding for the 2015 baseline, we use the NASA Socioeconomic Data and Applications Center (SEDAC) 1-km resolution GPWv4 Rev. 11 population counts dataset<sup>107</sup> available at (<https://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-count-rev11>). To calculate future flood exposure, we use the SEDAC’s 1-km resolution global population projection grids based on Shared Socioeconomic Pathways (SSP) dataset<sup>108</sup> for 2050 and 2100 (<https://sedac.ciesin.columbia.edu/data/set/popdynamics-1-km-downscaled-pop-base-year-projection-ssp-2000-2100-rev01/data-download>). To determine the value of assets potentially exposed to flooding for both the present period (2015 baseline) and future projections (2050 and 2100) for the selected SSPs, we use the global gridded gross domestic product (GDP) consistent with the Shared Socioeconomic Pathways (SSPs) recently developed<sup>109</sup> and available at (<https://zenodo.org/record/5880037#.Y2F-znrMLre>). These datasets are used to determine the potential population and assets’ exposure to flooding<sup>110</sup>. The year 2015 is considered as the reference year with consequent time steps of 2050 and 2100. For each point in time, the potential exposure is estimated for the considered return period and each grid cell under the baseline and future climate conditions.

**Estimating the exposed population and assets.** First-order estimates of population exposure to CWL are estimated by combining the above data with the population dataset. These datasets are used to calculate occupant coastal population counts for areas vulnerable. To assess the relative contributions of climate-induced SLR and socioeconomic drivers of CWF, the following cases are studied: static climate combined with dynamic exposure, which expresses the change in impacts from economic (GDP) growth and population dynamics; dynamic climate (considering both the dynamic CWLs and climate extremes) combined with static exposure, which expresses the impacts of future climate on present society; dynamic climate and exposure, which expresses the impacts of future climate on future WA coastal population.

The relative contributions of the climate-induced SLR and socioeconomic factors to CWFs are quantified following<sup>19</sup>. To determine the exposed asset to CWF, we assume that the asset values are directly proportional to population per area. Thus, the exposed population is translated into exposed assets by applying individual WA countries' GDP per capita rates to the population data, followed by applying an estimated assets-to-GDP ratio of 2.1 that is considered appropriate for the countries considered in this study (see Supplementary Methods and Supplementary Fig. 2 on how assets-to-GDP ratio is derived), using the equation<sup>17</sup>:  $A = 2.1 \times P \times G$ , where A is the value of the asset exposure to coastal flooding (US\$), P is the population (for either constant or increasing population) and G is the Gross Domestic Product per head of population (US\$/head). Despite that this relationship has been successfully applied in several studies (e.g. refs. <sup>17,107,110</sup>), there will be uncertainty since assets cannot be evenly spaced amongst the population.

### Data availability

The SSALTO/DUACS altimeter products were produced and distributed by the Copernicus Marine Environment Monitoring Service (<https://www.aviso.altimetry.fr/en/data/products/sea-surface-height-products/global/ssalto/duacs-experimental-products.html>). Dynamical atmospheric corrections were acquired from AVISO and can be accessed via <https://www.aviso.altimetry.fr/en/data/products/auxiliary-products/dynamic-atmospheric-correction.html> (<https://doi.org/10.24400/527896/a01-2022.001>). FES2014 tidal data are produced by LEGOS and can be accessed via <https://www.aviso.altimetry.fr/en/data/products/auxiliary-products/global-tide-fes/description-fes2014.html>. Tide gauge data were downloaded from the University of Hawaii Sea Level Center (<https://uhslc.soest.hawaii.edu/data/>). ERA-Interim data were produced by the European Centre for Medium-Range Weather Forecasts (<https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim>). MERIT data were acquired from Institute of Industrial Sciences, The University of Tokyo ([http://hydro.iis.u-tokyo.ac.jp/~yamada/MERIT\\_DEM/](http://hydro.iis.u-tokyo.ac.jp/~yamada/MERIT_DEM/)).

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### Author contributions

O.A.D. conceived the study together with R.A.; R.A. and E.W.J.B. produced the coastal water level datasets while O.A.D. produced the figures and drafted the manuscript. R.A., E.W.J.B., P.M., D.B.A., and P.S.J.M. contributed to the discussions at different stages and responses to reviewers' comments.

### Competing interests

The authors declare no competing interests.

### Additional information

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