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A methodological framework of quantifying the cost of environmental degradation driven by coastal flooding and erosion: A case study in West Africa

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ABSTRACT

Coastal environmental degradation – or the reduction of the capacity of coastal environments to meet social and ecological objectives and needs – is both a driver and a consequence of climate-induced disasters. In the West African coastal areas of Côte d'Ivoire, Ghana, Togo and Benin the major drivers of environmental degradation are found to be primarily originating from rapid, inadequately planned and managed urban development – mirroring economic growth – concurrent with high-exposure to coastal flooding and erosion hazards. In addition to decreasing the resilience of coastal ecosystems, the context of widespread coastal environmental degradation in West Africa will undeniably have direct and indirect consequences for economic development and human wellbeing in the region. Furthermore, climate change will place additional increasing pressure on certain West African coastal frontages. The research presented in this paper focuses on the development and implementation, at country level and pilot-site level, of a methodological framework of quantifying the impact of coastal flooding and erosion on environmental degradation in economic terms. Specifically, this framework values the impacts of degradation that occur as a result of flooding and erosion – in absolute (US $, number of people affected) and in relative (as percentage of the countries' GDP) terms. Overall, the aggregated Cost of Coastal Environmental Degradation (CoCED) in the four countries driven by coastal flooding and erosion could amount to over US $ 3 billion by 2100, based on the worst case scenario of regional relative sea-level rise, corresponding to RCP 8.5. Moreover, the number of people affected could in some of the countries experience a 400% increase by 2100 when accounting for demographic growth.

1. Introduction

Decision-making for the future depends on anticipating change [27] – however, the present state is that development is generally long-lived and development rights are granted permanently, which leaves little room for managing for adaptation and, therefore, the capacity to anticipate and adjust to changing circumstances in the context of disaster risk remains very limited. The term disaster risk is used herein to refer to the complex interaction between coastal development processes that generate conditions of exposure and vulnerability to hydro-meteorological hazards – specifically, coastal flooding and erosion. One problem is that conflating short-term decisions with long-term objectives and future projected climate-change impacts is seldom possible under the present state. Another problem is that conforming to short-term decisions would cause environmental degradation, which is costly – to individuals, to societies, and to the environment. Poor-quality coastal environments are leading to a decline in the economic and social value of ecosystem services as well as to the destruction of important coastal habitats – however, this remains largely unquantified in economic terms (see e.g. Ref. [46]). These two problems go together and could be mitigated by a pro-active and strategic approach to coastal climate change adaptation and disaster risk reduction, one that uses insight and foresight to identify and mitigate emerging risks through a four step approach – i.e. understanding risks,

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deciding on which risks to act, anticipating new risk and knowing when to act.

The research presented in this paper focuses on developing a methodology for quantifying the impact of coastal flooding and erosion driven environmental degradation in economic terms. The methodology builds on the guidance and recommendations from various international organisations, among others the EC, World Bank, UN and the US National Science and Technology Council. It also builds on a vast research underpinning: the role of natural capital on economic development (see e.g. Refs. [3,18]); the opportunity of increasing the use of green infrastructure in coastal areas to protect the coastline against both future storms and climate-change related impacts (see e.g. Refs. [12,41,48]), on the one hand, and, on the other hand, the threat of having green infrastructure yet to be fully mainstreamed into development policy and practice [11] as compared to more conventional coastal protection structures; the fact that societies are excessively discounting risk in development choices [41], particularly in coastal areas. The methodology further recognises, that a paradigm shift in coastal development requires a change in the way in which land use and development trade-offs are conceptualised and evaluated [11], because conventional economics are not well suited to valuing ecosystem services because of the need to convert a diverse range of values into money [9].

An understanding of the impact of environmental degradation is therefore limited because of a combination of *(i)* an emphasis on economic growth alone, and *(ii)* a lack of a consistent methodology or framework to assess the cost of environmental degradation to individuals, to societies, and to the environment. As a consequence, investments tend to continue to be heavily skewed towards 'grey' infrastructure for which a monetary return can easily be calculated [13]. In contrast, natural capital is often undervalued or simply not taken into account in most cost-benefit analyses. The small number of cases where economic methods are used to assess ecosystem-based approaches tend to confine themselves to direct, physical costs and benefits – thus massively underestimating the gains and value-added that can be secured as compared to, or in combination with, 'grey' infrastructure options [11]. There remain very few real-world instances where broader ecosystem values and development co-benefits are factored into calculations [45].

1.1. The case study

The West African coastal zone contains most of the region's capital cities, which together account for more than one third of the region's Gross Domestic Product (GDP), and are home to more than one third of its population and likely more than half by 2050 [47]. The coastal zone in this region is one of the most rapidly urbanising areas in the world and hub of critical infrastructure, major industries, tourism, agriculture and fishing activities, as well as human settlements and its forerunners – e.g. communication routes – that form the backbone of national economies, drive economic growth and provide the livelihoods of many poor people. However, population growth in turn leading to rapid urbanisation, unsustainable land-use and pollution, the increasing exploitation of coastal resources, namely from fishing and sand and gravel mining activities, and an overall poor environmental governance, have all contributed to the depletion of ecosystem services and biodiversity, and to the consequent environmental degradation that is now prevailing in West Africa coastal ecosystems.

High-impact low frequency storm events, interacting with such exposed and vulnerable human and natural systems, are exacerbating individuals, communities, economies and environment predicaments. Furthermore, because of social and economic drivers of risk increase and climate change, including rising sea levels and increases in the frequency and severity of extreme weather events, coastal risks are projected to rise in coming years and decades at West African coastal areas, or on coastal regions worldwide for that matter.

In response to those challenges, the World Bank Group and the Nordic Development Fund (NDF) launched the WACA management programme technical assistance that aims at promoting sound coastal management practices. The creation of the WACA management programme further recognises the need to improve management at the regional level, as highlighted by e.g. Ref. [1]. As part of that programmatic technical assistance, the methodology developed in present research has been tested in Côte d'Ivoire, Ghana, Togo and Benin (Fig. 1), and can be applied elsewhere in West African coastal regions.

WACA in general, and coastal areas in the case study in particular, are home to natural habitats at the interface between land and sea including beaches, wetlands (some of which declared to be Ramsar sites, e.g. the Keta Lagoon Complex Ramsar Site in Ghana) and mangrove forests, which are valuable and in some instances transboundary (e.g. the Mono Transboundary Biosphere Reserve, Benin/Togo). However, poor-quality coastal environments are leading to a decline in the economic and social value of ecosystem services as well as to the destruction of such important coastal habitats.

Major drivers of coastal environmental degradation in the coastal areas of Côte d'Ivoire, Ghana, Togo and Benin are found to be primarily originating from rapid, inadequately planned and managed urban development, mirroring economic growth (see e.g. Ref. [46]). The growing rate of urbanisation and the increase in population density (in urban and peri-urban coastal areas) is leading to agricultural land conversion, pollution – which stems from household activities, industry, agriculture and transportation – and natural habitat destruction. At the same time, it is very often the case that growing concentrations of people and economic activities overlap with areas of high-exposure to coastal flooding and erosion hazards. In addition to decreasing the resilience of coastal systems, the context of widespread environmental degradation in West Africa will undeniably have direct and indirect consequences for economic development and human wellbeing in the region. Climate change will add increasing pressure on certain West African coastal frontages.

The research focuses on assessing the coastal areas' vulnerability to climate variability and change, estimating in monetary terms the cost of coastal environmental degradation (CoCED), at country level and pilot-site level, and conducting a cost-benefit analysis of CoCED remediation and climate adaptation options at pilot-site level. This goal has been achieved by developing a methodological analysis framework to go from quantifying coastal erosion and flood impacts – which are identified as being the hazards prevailing in the coastal areas of interest – to estimating in monetary terms the cost of coastal environmental degradation in order to capture its real value and reflect that value on decision making and policy development for future adaptation. A detailed estimate of the cost of other factors in environmental degradation is out of the scope of the present research.

2. Methodology

2.1. Index-based risk assessment at country level

A coastal flood and erosion risk assessment has been conducted at the country level in order to rank coastal areas on their level of vulnerability to climate variability and change and sort out the hotspots from the less vulnerable areas. For that purpose, an index-based approach to screen the entire coastline of the four countries, segment by segment, is used.

The definition of the segments as well as their number and reference generally concurs with that of the *Union Economique et Monétaire Ouest Africaine* (UEMOA) and the International Union for the Conservation of Nature (IUCN) – *Mission d'Observation du Littoral Ouest Africain* (MOLOA) studies [39,40], hereafter collectively referred to as UEMOA/IUCN studies. In total 75 segments of varying lengths, ranging from a couple to several tens of kilometres, have been defined.

The index-based methodology consists of combining several indicators into a single index – the so-called Coastal Index (CI) – thereby allowing a rapid comparison of coastal segments. This is a well-

Fig. 1. Coastal areas of the West African countries covered by the present study.

established methodology to delimit several hotspots along the coast (e.g. Refs. [2,14,16,28,31,38,44]); however, the type of indicators considered in the index, the way they are ranked and the formula used to combine these variables may differ between studies (see, e.g. Ref. [38]).

Based on the combination of variables proposed by Ref. [14] and the framework in Ref. [44] – selected because of their suitability in the evaluation of coastal flooding and erosion risks at the regional and hotspot scale and because they have been extensively tested and validated (e.g. Refs. [5,10,26,30,43]) – the CI in the present research scores two variables:

- the (multi-)hazard indicator on a scale of 0 (none) to 5 (very high); and
- the exposure indicator on a scale of 1 (none or very low exposure) to 5 (very high exposure).

2.1.1. *The (multi-)hazard indicator*

The multi-hazard indicator ($I_{(multi-)hazard}$) scores the erosion ($I_{h\_erosion}$) and the coastal inundation ($I_{h\_inundation}$) specific-hazard indicators together. Each individual hazard indicator is also ranked from 0 to 5. The likelihood of erosion and inundation occurring from both present climate variability (indicated by the '_pc' subscript, e.g. $I_{h\_inundation\_pc}$) and future projected conditions (indicated by the '_fc' subscript, e.g. $I_{h\_multi\_fc}$) is assessed.

The coastal erosion hazard indicator is based on existing qualitative data or anecdotal evidence of erosion in recent years in each of the four countries [22–25], available erosion-rates as well as expert judgement.

The top segments per country with respect to $I_{h\_erosion}$ are shown in Fig. 2. These are: 'Frontière du Togo - Grand-Popo' (BJ1-a), 'Grand Popo – Ouest Cotonou' (BJ2-d), and 'Cotonou' (BJ1-b) in Benin; 'Fresco – Assagny' (CI3-c), 'Abidjan – Port-Bouët' (CI5-a and CI5-b), 'Terrasse sableuse et cocoteraie de l'Est Ivorien' (CL7-b), and 'Zone périurbaine Est Abidjan – Grand Bassam' (CI6-a, CI6-b and CI6-c) in Côte d'Ivoire; 'Accra zone périurbaine et périphérie Est' (GH8-b and GH8-c), 'Accra zone périurbaine et périphérie Est' (GH8-e), 'New Ningo – Lekpoguno' (GH9-a), and 'Delta de la Volta rive gauche' (GH10-a, GH10-b and GH10-c) in Ghana; and 'Togo' (TG1-c, TG1-d) and 'Togoville – Agbodrafo – Aného' in Togo.

No erosion hazard is assumed for a few segments, e.g. 'BJ2-b' in Benin to the west of the port of Cotonou where accretion is reported in the study by UEMOA and MOLOA [40].

The coastal inundation hazard indicator is based on the combination of topographic data (SRTM data) with (rather limited) available data on extreme water levels (here taken at more or less MHWS) – for which the value 1.8 m is adopted all along the coast of the four countries, and being based on data for Ghana [4], and a storm surge of 1.5 m (100-year return period) based on Ref. [29]. The relative sea-level rise is assumed to be 0.1 m by 2015 slowly increasing to 0.30 m by 2050 and 0.70 m by 2100 based on the worst case scenario of regional relative sea-level rise, corresponding to RCP 8.5, as proposed by Ref. [8]. Note here that 2015, 2050 and 2100 were the time horizons of the research, for which the reference baseline was 2014.

The highest rank, 'high to very high', was assigned to areas showing some inundation under present climate variability, being the areas in and around the delta of the Volta river the only place where this is

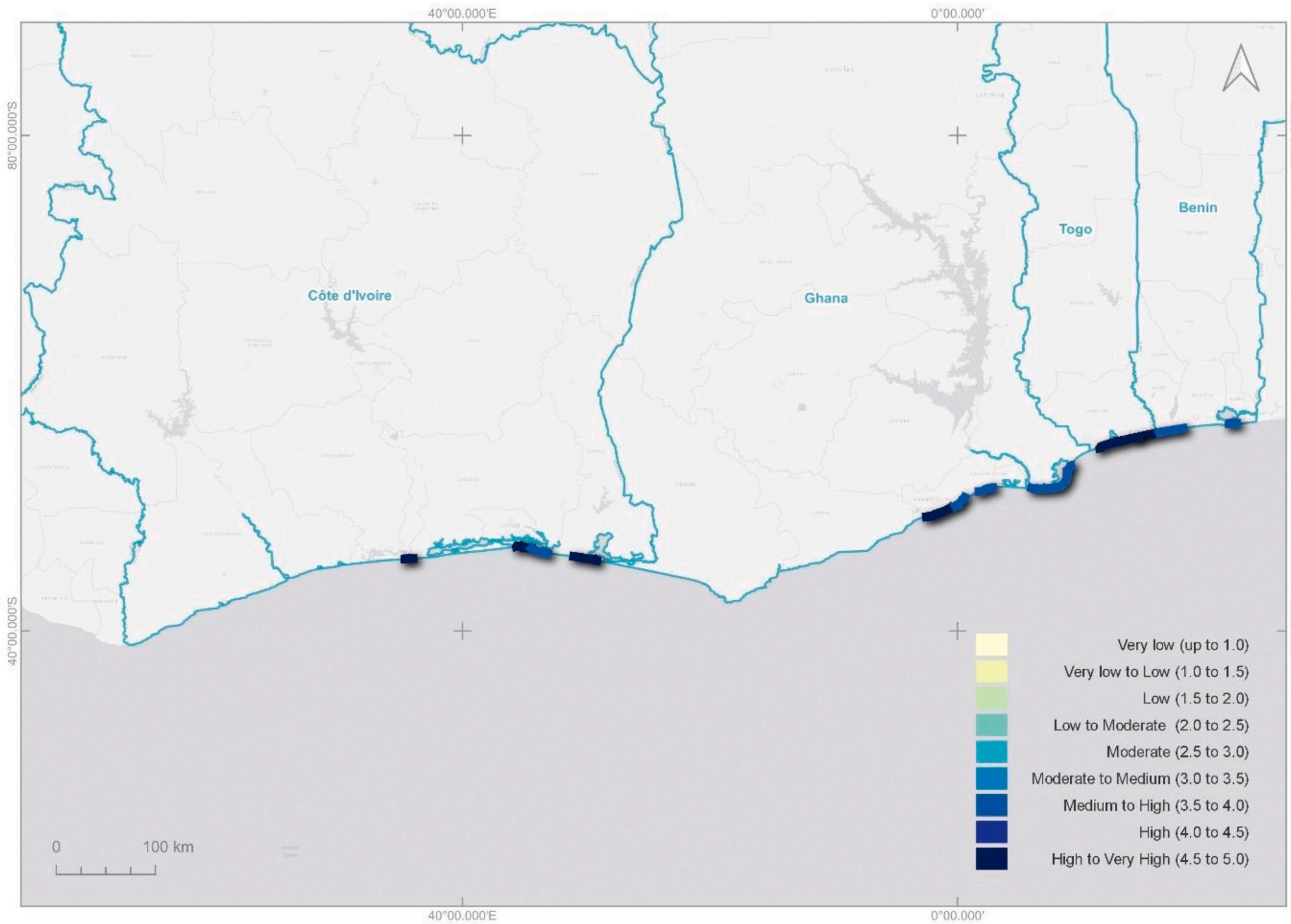


Fig. 2. *Top segments per country on the coastal erosion hazard indicator ranking – i.e. segments scoring 4* or more *on this indicator*.

estimated to happen (Fig. 3). Then the 'high' rank is assigned to low-lying areas along the coast showing inundation above the assumed extreme water level and without some kind of lagoon in the backshore. The identified segments in these conditions are '*Grand Popo – Ouest Cotonou*' (BJ1-b) in Benin, '*Zone périurbaine Est Abidjan – Grand Bassam*' (CI6-b) in Côte d'Ivoire, and '*New Ningo – Lekpoguno*' (GH9-a), which coincide with segments identified in UEMOA/IUCN studies as being inundation-prone. Lastly, the ranks of 'medium' and 'low' are assigned by intensity to areas with a water body in the backshore. The 'very low' is assigned to the remaining areas, as the lowest rank 'none' had not been assigned because of the uncertainty in the data.

The coastal inundation hazard indicator is expected to increase under future projected conditions for a number of segments in Côte d'Ivoire – namely '*Est San Pedro – Sassandra – Fresco*' (CI2-c) and '*Fresco - Assagny*' (CI3-a), as well as in Ghana – namely 'Delta de la Volta rive gauche' (GH10-c, GH10-d and GH10-e), '*Secteur urbain et extension periurbaine de Sekondi – Takoradi*' (GH3-a and GH3-d), 'New Ningo – Lekpoguno' (GH9-a).

For each segment the multi-hazard indicator under both present ($I_{h\_multi\_pc}$) and future projected climate conditions ($I_{h\_multi\_fc}$) is as given in Eq. (1). As expected, the increase in $I_{h\_multi\_fc}$ for certain segments compare with the increase in $I_{h\_inundation\_fc}$.

$$I_{h\_multi} = \sqrt{I_{h\_erosion} \times I_{h\_inundation}} \tag{1}$$

2.1.2. The exposure indicator

The exposure indicator measures the relative exposure for different receptor types. On the basis of the data readily available from the studies of the exposure of West African social, economic and natural systems to coastal climate stressors by UEMOA/IUCN studies [39,40] and USAID [42], the following three types of exposure indicators are considered:

1. Social Vulnerability Indicator (SVI) – calculated as given in Eq. (2), scores on a scale of 1–5 the following three variables:

$$SVI = \sqrt[3]{i_{exp\_population\_density} \times i_{exp\_population\_growth} \times i_{exp\_poverty}} \tag{2}$$

- population density, $i_{exp\ population\_density}$, scored as 1 for non-built areas and open spaces, 2 for hub intersections, 3 for very loose urban fabric, 4 for loose urban fabric or 5 for dense urban fabric based on predominance – according to the classes in UEMOA/IUCN studies [39,40];
- population growth, $i_{exp\ population\_growth}$, scored on a scale of 1–5 on the basis of the data and classification in the USAID study [42]; and
- subnational poverty and extreme poverty, $i_{exp\ poverty}$, scored on the basis of the USAID study layer on extreme poverty and subnational poverty [42] according to the following poverty class ranges: 1 from 0 to 20%, 2 from 20 to 40%, 3 from 40 to 65%, 4 from 65 to 85% and 5 from 85 to 100%.

2. Economic Systems Indicator (ESI) – calculated as given in Eq. (3), scores the following four variables:

$$ESI = \sqrt[4]{i_{exp\_tourism} \times i_{exp\_fisheries} \times i_{exp\_infrastructure} \times i_{exp\_crops}} \tag{3}$$

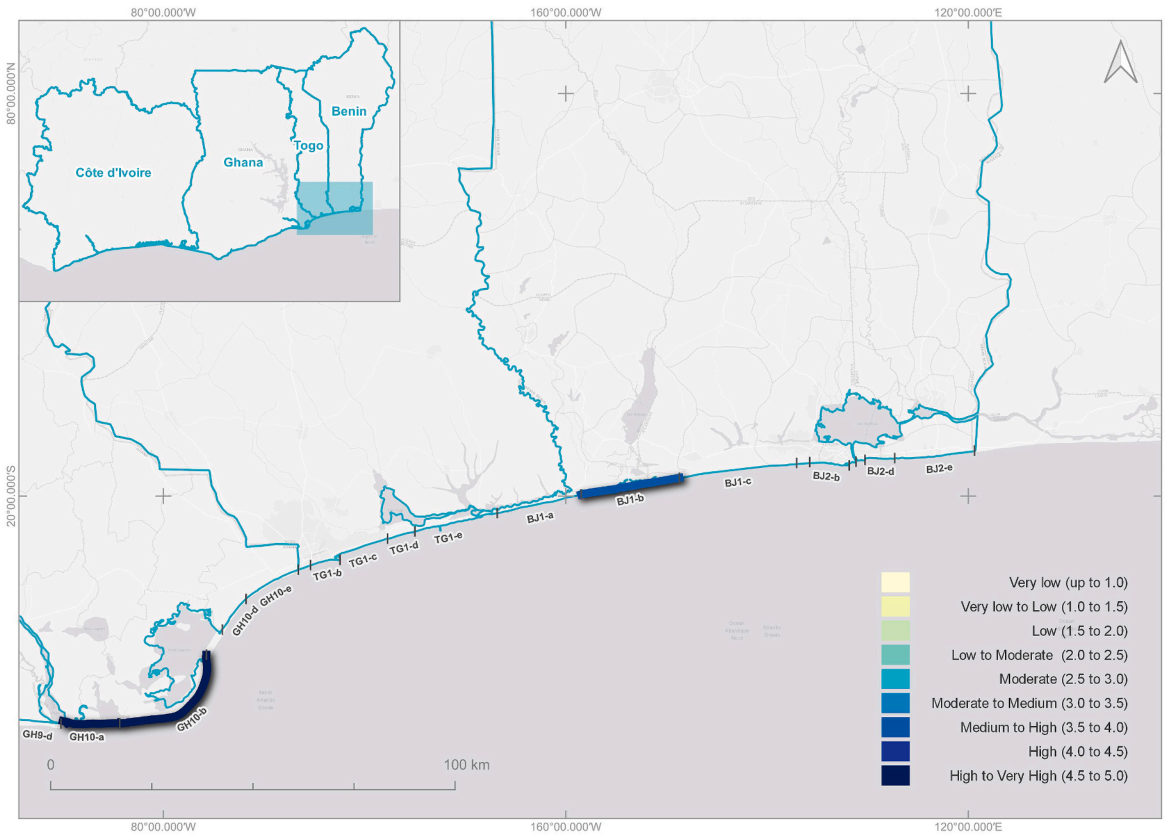


Fig. 3. Coastal inundation hazard indicator ranking per segment – top segments under present climate conditions.

- tourism, $i_{exp\_tourism}$, scored only on the basis of a binary classification of 5 assigned to areas with tourism or 1 assigned to areas without tourism because of a scarcity of data;
- fisheries, $i_{exp\_fisheries}$, score on the basis of the UEMOA/IUCN studies [39,40] according to density ranges over a specified length along the coast: 1 none, 2 if 0 to 0.1 per linear kilometre of coast, 3 if 0.1 to 0.2/km, 4 if 0.2 to 0.4/km and 5 if over 0.5/km.
- transport infrastructure, $i_{exp\_infrastructure}$ scored on the basis of a binary classification of 5 assigned to areas with ports and/or airports or 1 assigned to areas without any of those, without discriminating against relative importance; and
- commercial crops, i_{exp_crops}, all available crop layers from the USAID spatial data [42], namely rubber, oil palm, coconut, cocoa and banana crops, have been classified into 5 classes on a scale of importance.

3. Natural Systems Indicator (NSI), ranks existing coastal ecosystems within a buffer zone of 20 km from the coastline on a scale of 1–5 by importance categories; the ranking used is given in Table 1; when two or more ecosystems were present in the same segment the highest was assigned.

The overall exposure indicator ($I_{exposure}$) is calculated as given by Eq. (4).

$$I_{exposure} = \sqrt[3]{SVI \times ESI \times NSI} \quad (4)$$

An overview of the exposure indicator for the top 5 segments per country is shown in Table 2. The selected results provide evidence of how the highest exposure indicators are influenced by several combinations of type of exposure – i.e. social, economic and natural.

2.1.3. Coastal Index

The Coastal Index, used to sort out the hotspots from the less vulnerable areas, is calculated as given by Eq. (5). The multi-hazard indicator ($I_{(multi\text{-})hazard}$) in Eq. (5) can either represent one or multiple hazards.

Table 1
Natural Systems Indicator ranking.

Category based on [40]	Rank
Ramsar Sites, Biosphere Reserve	5
National Park	4
Classified Forest and site of biological interest	3
Alluvial plain, water body or lagoon, mangroves and site of interest for nature conservation or restoration	2
Saltmarshes and site of interest for ecological restoration	1

$$CI = \sqrt[2]{I_{(multi-)hazard} \times I_{exposure}} \quad (5)$$

2.2. Analysis of the cost of coastal environmental degradation (CoCED)

The CoCED analysis comprises two consecutive stages. In the first stage a risk assessment is carried out following well-established methodology and agreed definitions, as used by e.g. Refs. [14,15] for assessing coastal and flood risks in OECD countries over different spatial scales, or Refs. [20,21] for assessing coastal flood damages globally, or e.g. Ref. [19] for looking at sea-level rise impacts in Africa at continent and country levels. The followed four-step risk assessment process is explained in Fig. 4. The second stage is the analysis of the cost of coastal environmental degradation itself. The CoCED analysis is based on the land-use categories – i.e. rural, urban, economic and natural – affected by erosion or flood hazards if considered individually or in combination, as well as on the impacts on people and livelihoods, including loss of assets (houses, infrastructure) and damages to critical coastal ecosystems. The CoCED analysis – which reference baseline is 2014 – is done from 2015 through 2100 at both country level and pilot-site level.

Table 2
Exposure indicator – top 5 segments per country.

Country	Segment	SVI	ESI	NSI	$I_{exposure}$
Benin	BJ2-e: *Cotonou*	2.7	1.5	5.0	2.7
	BJ2-b: *Cotonou*	4.3	2.0	2.0	2.6
	BJ1-b: *Grand Popo - Ouest Cotonou*	2.7	1.2	5.0	2.5
	BJ1-a: *Grand Popo - Ouest Cotonou*	2.5	2.5	2.0	2.3
	BJ2-c: *Cotonou*	4.3	1.5	2.0	2.3
Côte d'Ivoire	CL7-b: *Terrasse sableuse et cocoteraie de l'Est Ivorien*	2.2	1.8	5.0	2.7
	CI2-b: *Est San Pedro – Sassandra – Fresco*	2.3	3.2	2.0	2.5
	CI3-a: *Fresco – Assagny*	2.0	1.3	5.0	2.4
	CI1-g: *Frontière du Liberia-San Pedro*	2.5	1.8	3.0	2.4
	CI4-c: *Secteur rural Assagny – Jacqqueville – Abidjan Ouest*	2.0	1.5	4.0	2.3
Ghana	GH8-a: *Accra zone urbaine et périphérie est*	2.2	2.0	5.0	2.8
	GH6-b: *Hinterland rural des zones urbaines de Cape Coast et Accra*	2.3	1.7	5.0	2.7
	GH10-c: *Delta de la Volta rive gauche*	2.3	1.6	5.0	2.6
	GH2-b: *Cap des Trois Pointes*	1.4	2.2	5.0	2.5
	GH10-b: *Delta de la Volta rive gauche*	2.3	1.4	5.0	2.5
Togo	TG1-c: *Togo*	3.4	2.1	5.0	3.3
	TG1-b: *Togo*	3.4	1.8	5.0	3.1
	TG1-d: *Togo*	1.6	1.9	5.0	2.5
	TG1-e: *Togoville – Agbodrafo – Aného*	2.7	2.8	2.0	2.5
	TG1-a: *Togo*	3.4	1.4	2.0	2.1

Very low (up to 1) | | High to very high (4.5 to 5)

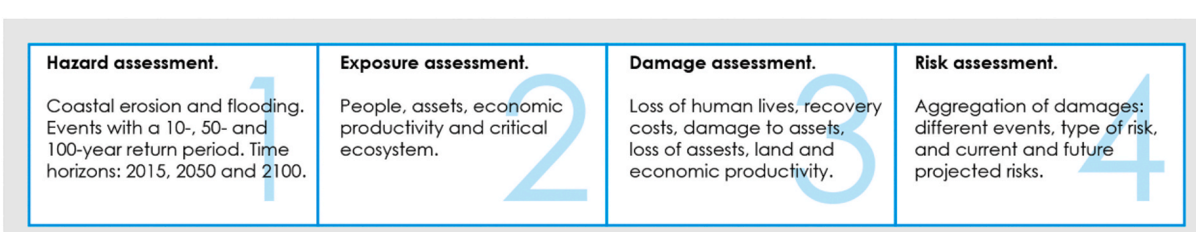


Fig. 4. Four-step risk assessment process.

2.2.1. Risk assessment

The assessment of the intensity and spatial extent of the coastal hazards in erosion- and flood-prone areas is based on numerical modelling of event-driven (storm duration time scale) and long-term (annual to decadal) erosion resulting in permanent losses of land to the sea – using XBeach (e.g. Ref. [33]) and ShorelineS (e.g. Ref. [35]) – as well as event-driven and long-term inundation – using TELEMAC (e.g. Ref. [36]). The analysis indicates that the total integrated coastal flood damage in the case study area is dominated by the 10-year return period flood, which illustrates the high vulnerability to frequent coastal flooding. The implications of projected sea-level rise for West African coastal regions include a progressive worsening of coastal erosion and flood hazards, most notably rising sea-levels will accelerate coastal erosion and low-lying areas may be permanently inundated (Fig. 5).

The effect of demographic change and economic growth per country on future damages is considered when assessing the exposure of people, assets, economic productivity and critical coastal ecosystems. Detailed or more simplified land use and land cover change can be integrated into the exposure assessment model, depending on data availability.

The flood damage assessment is based on damage functions from literature derived from a meta-analysis of a worldwide review of damage functions [21]; with respect to damages from erosion, a new method accounting for direct impacts – i.e. relocation of inhabitants and infrastructure – and indirect impacts – loss of productivity – is developed. The method accounts for the differences in GDP per hectare of land eroded.

The vulnerability of an asset to a climate hazard or stressor is linked to its potential for, or its susceptibility to, damage, and is often assessed in terms of exposure, sensitivity, and adaptive capacity. The risk assessment in the present research considers: *(i)* the vulnerability of selected assets to projected sea-level-rise in order to exclude less vulnerable assets; *(ii)* the likelihood of coastal inundation due to future climate projections; *(iii)* the consequences of impacts, not just in terms of what the impact would do to a particular asset, but also how it would affect the surrounding community and beyond; and *(iv)* the risk rating of the consequence and its likelihood of occurrence.

Damage and risk are assessed per grid cell of 1 ha in size. For a single event – e.g. one flood event – the damage per grid cell is calculated as given by Eq. (6).

$$Damage = [maximum\ value\ at\ risk]\ x\ [damage\ function] \tag{6}$$

with,

maximum value at risk, including the value of the assets – e.g. houses, infrastructure – in United States Dollar per hectare (US $/ha), economic productivity in United States Dollar per hectare per year (US $/ha per year) and ecosystem services in United States Dollar per hectare per year (US $/ha per year); and

- damage functions per hazard type – e.g. erosion, flood, sea-level rise.

Risk is reflected in absolute terms (i.e. US $ and number of people affected) as well as in relative terms (i.e. as a percentage of the countries' GDP).

2.2.2. CoCED analysis

The method developed for CoCED analysis is suitable to be implemented at different levels of detail and at different geographic scales and complements more qualitative local assessments. The analysis at both country and pilot-site levels identifies the areas prone to erosion and/or coastal flooding, estimates the number of people at risk, and assesses expected damages. At the pilot-site level a finer calculation grid cell of the land-use categories at risk and more detailed risk modelling is used. The analysis accounts for the fact that some areas are only exposed to one hazard – i.e. coastal erosion or coastal flooding – where others are exposed to multi-hazard. Furthermore, it assesses the evolution of the expected impacts from realized risks and distinguishes between the impact of sea-level-rise, population growth and economic growth.

To implement the CoCED analysis, 30 classes of land-use categories have been identified. The classes are established based on: number of inhabitants per hectare (ranging from 0.5 to more than 125) on the basis of world population databases; presence of specific assets – e.g. buildings for schools, health care, churches, monuments – and/or transport infrastructure – e.g. roads, airports – on the basis of open source maps; areas with presence of specific economic activities – e.g. industry, services, ports, quarries.

For tangible damages – i.e. material damages in rural and urban areas and areas of specific economic interest – a method to define the value at risk per country and land-use category, in which the value of the assets at risks is based on the GDP/ha and the ratio between assets value/GDP from the literature (see e.g. Ref. [17]), was developed. The GDP/ha is based on the GDP per capita for each country, and the estimated number of inhabitants per hectare. The GDP per capita is differentiated between urban, sub-urban and rural land-use categories in order to account for the difference in value per employee between different main segments (agriculture, industry and services), and the lower share of agriculture in employment for urban areas. As mentioned, the number of inhabitants per hectare is taken from world population databases, that attributes inhabitants in a region to grid cells based on information about land-use categories.

For grid cells with industry and services, country-specific estimates

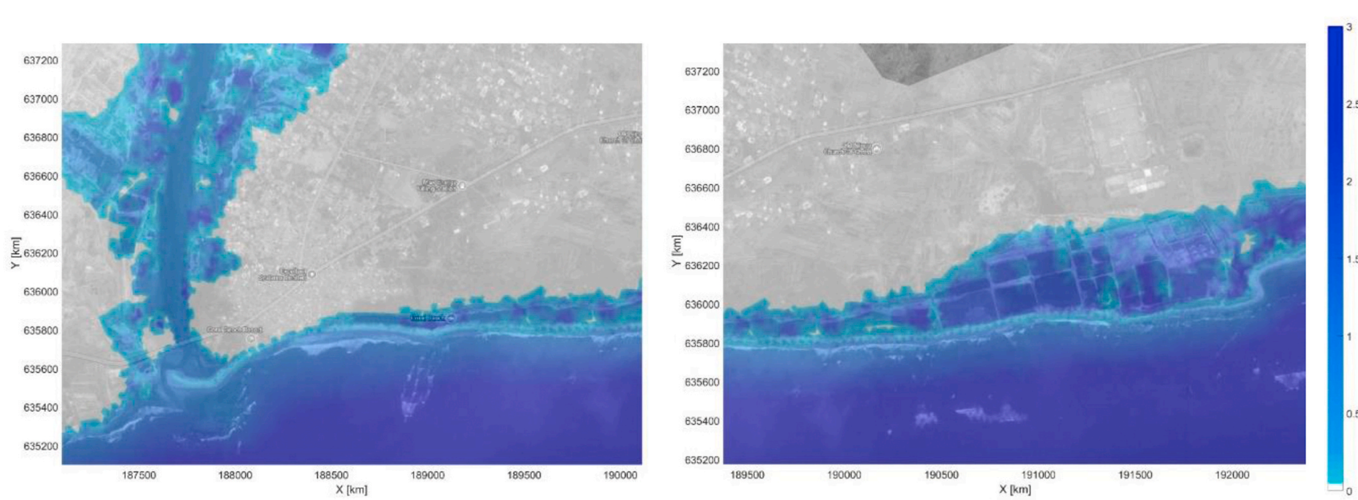


Fig. 5. Example output results on coastal flood hazard intensity at the Ghanaian pilot-site, 100-year return period storm and future projected climate conditions under RCP 8.5.

for values at risk per hectare are estimated from the literature (see e.g. Ref. [21]), and reviewed taking into account differences in GDP per capita between countries.

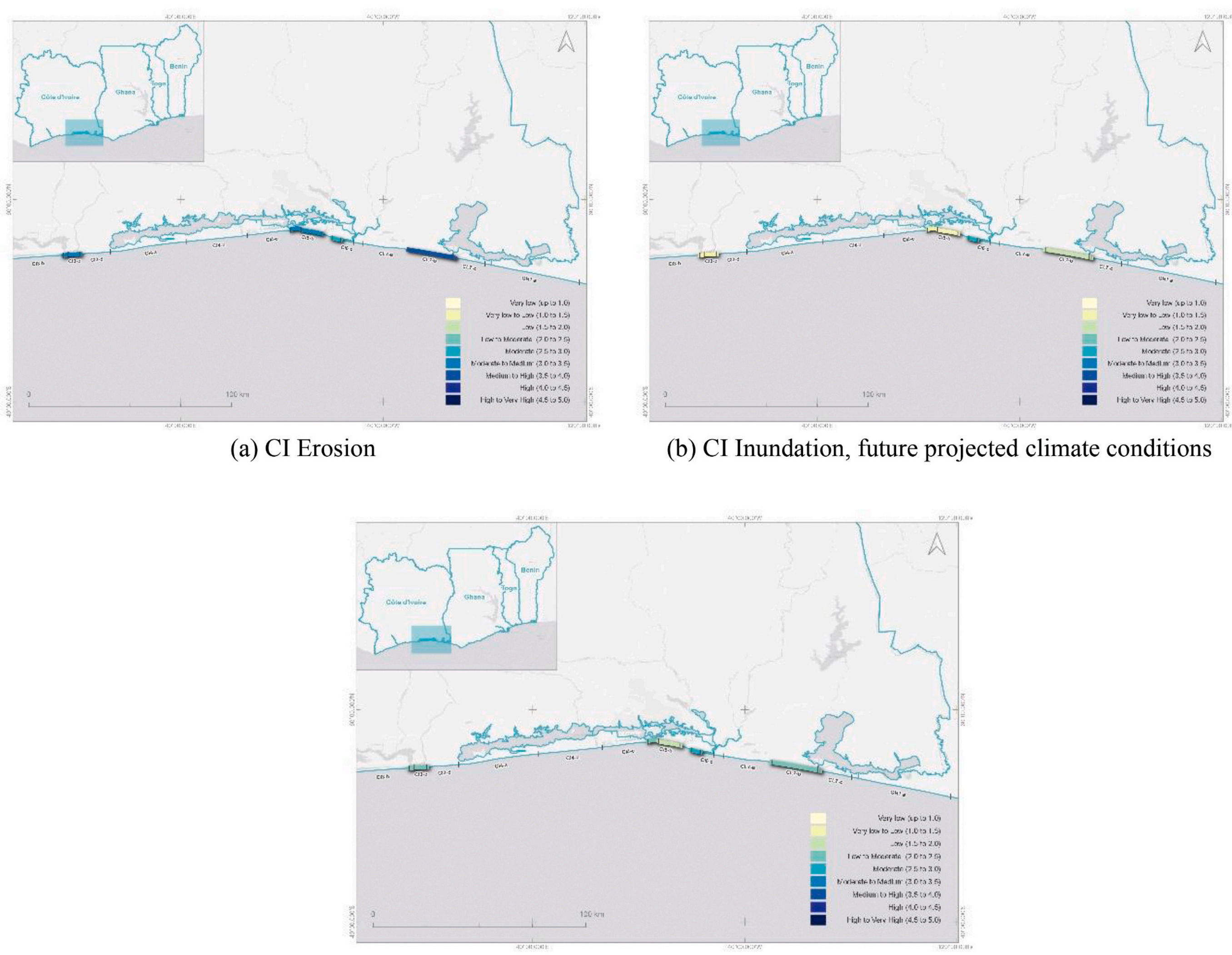
Methods and data in case of natural areas are much more uncertain – however a dollar value is attributed to the maximum value of ecosystem services lost due to erosion or flooding in order to test the relative importance of the impacts on natural land-use categories versus material damages in other land-use categories. Given the broad range of probable values and the lack of other and more precise analyses, median figures from the literature [6,7,34]. Furthermore, due to the uncertainty in the valuation, one single dollar value in 2015 US $ is attributed to the valuation of ecosystem services for all of the four countries in study.

Although little information is available on coastal flood impact on human health and on natural areas, a methodology has been developed to test to what extent these impacts are likely to be significant, using a simplified dose-response relationship for fatalities and country-specific data from literature on valuation of fatalities – i.e. the value of a statistical life.

The number of people at risk of erosion in 2050 (2100), is the number of people living in 2015 in areas that are expected to be eroded in 2050 (2100) with the assumption that no disaster risk management measure is undertaken; whereas the number of people at risk of coastal flooding in 2050 (2100) for a specific event (e.g. T100), is the number of people living in 2015 in areas that are expected to be flooded in a 100-year return period event in 2050 (2100), but are not at risk of erosion before 2050 (2100).

For areas that are both at risk of erosion and flooding in 2050 (2100), it is assumed that some areas are likely to be permanently inundated – i.e. loss of land due to coastal erosion – and are consequently not accounted for as flooded area. It is assumed that the people living in these areas in 2015 are relocated to areas not exposed to erosion or flooding. This analysis is done on a yearly basis in order to determine the year in which the people in those areas are relocated. In the following step, demographic and economic growth are taken into account. The total area – i.e. loss of land due to coastal erosion and areas subjected to coastal flooding – and people at risk are indicators used in the text to provide an overall picture of risk evolution – however, it should be noted here that the total area and the people at risk refers to two indicators with a different meaning; while the number of people at risk of erosion in 2050 (2100) refers to people that will be obliged to relocate between 2015 and 2050 (2100), the people at risk in 2050 under a 100-year flood event are people facing an event frequency of 1% – i.e. a likelihood of 1 in 100 – to suffer coastal flood damages.

Cultural values located in the coastal areas – e.g. the historic town of Gran-Bassam in Côte d'Ivoire or the Elmina castle in Ghana – were not explicitly considered in the present research, however the CoCED analysis is suitable to be expanded to assess impacts on those from realized erosion and/or flooding risks e.g. by integrating the



(a) CI Erosion

(b) CI Inundation, future projected climate conditions

(c) CI Multi-hazard, future projected climate conditions

Fig. 6. Coastal Index for the top segments in Côte d'Ivoire.

methodology proposed by Ref. [32].

To account for the high importance of the coastal flooding and erosion impacts in the future, the present value of future damages is assessed using two different discount rates, namely 4 and 6% based on Ref. [49].

3. Results

3.1. Selection of pilot-sites based on hotspots for coastal erosion and flood risks

The top segments (or hotspots) for coastal erosion and/or flood risk under future projected climate conditions are presented in Figs. 6–8. The ranking is based on the index-based approach earlier described, that was used to screen the entire coastline of the four countries in study, segment by segment, and from which a Coastal Index (CI) is computed.

The final selection of pilot-sites is based not only on the CI ranking, but also on additional consideration relevant to the cost-benefit analysis of coastal environmental remediation and climate change adaptation options at pilot-site level that followed the CoCED analysis, namely:

- the coastline beach front of a large city – i.e. 'CI5-a: *Abidjan – Port Bouët Ouest*' and 'CI5-b: *Abidjan – Port Bouët Est*', Fig. 9;
- a unprotected segment at present time – i.e. 'GH9-a: *New Ningo – Lekpoguno*', Fig. 10; and
- a continuous segment across two countries – i.e. 'TG1-e: *Togoville – Agbodrafo – Aného*' in Togo and 'BJ1-a: *Frontière du Togo – Grand-Popo*' in Benin, Fig. 11.

3.2. CoCED analysis

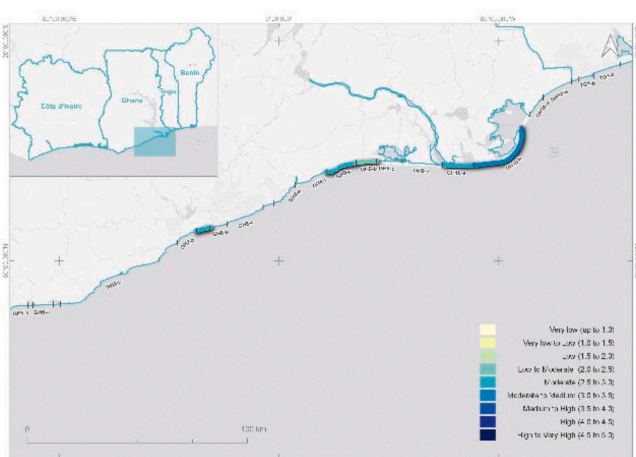
3.2.1. Côte d'Ivoire

By 2100, almost 8600 in hectares – 0.9% of the coastal zone – of Benin's coastal area is estimated to be eroded (Fig. 12). The number of people affected could increase from a hundred in 2015 to more than 20,000 in 2100. The eroded area is more or less comparable with the rest of the coastal zone in terms of population density and economic value in GDP per hectare.

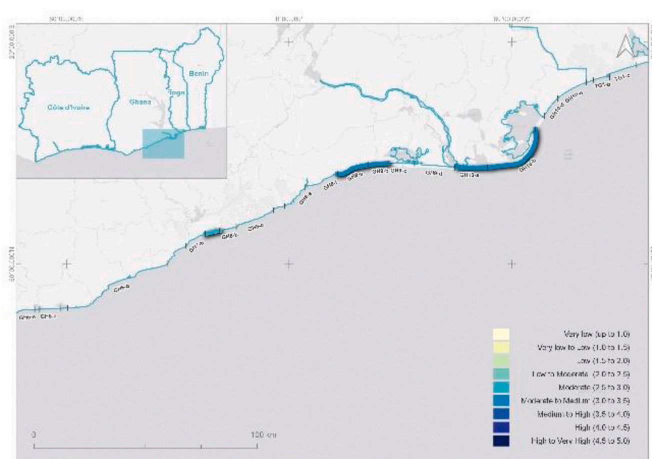
In 2050 and 2100, the importance of land-use categories is comparable. The most affected areas in terms of size (ha) are rural areas. The urban area is the largest in terms of people affected. The importance of industry and services is negligible in terms of area (ha), but high as far as impacts per hectare are concerned, accounting for 3% of damage. After 2050, the share in urban land-use category increases and becomes the main contributor to damage.

By comparison, impacts on natural areas are low, both in terms of hectares and damage. It should be noted here that data on their economic importance and damage estimates are more uncertain, and that comparability with indicators for other areas is limited.

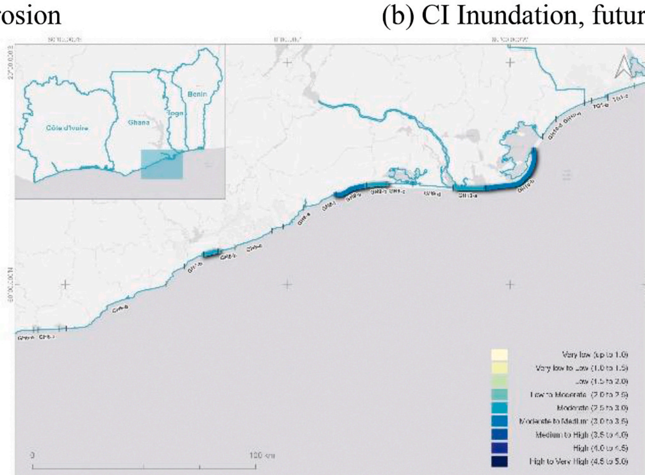
In 2015, 1400 ha – nearly 0.14% of the coastal zone – are exposed to the risk of coastal flooding. Since part of the flooded area is eroded by



(a) CI Erosion



(b) CI Inundation, future projected climate conditions

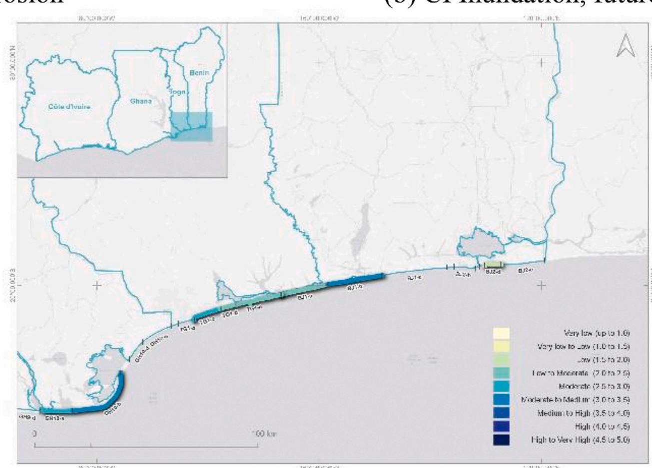


(c) CI Multi-hazard, future projected climate conditions

Fig. 7. Coastal Index for the top segments in Ghana.

(a) CI Erosion

(b) CI Inundation, future projected climate conditions



(c) CI Multi-hazard, future projected climate conditions

Fig. 8. Coastal Index for the top segments in Togo and Benin.

2050, the area affected in 2050 is only half of the eroded area in 2015 – however, by 2100, the flooded area increases to 0.27% of the total coastal area due to sea-level-rise.

The land-use categories in affected areas are mixed, which is comparable to the average land-use in the coastal area. The urban area is the largest category in terms of people affected and damage (+70%). In addition, the long-term zone at risk after 2050 is more populated and the importance of the economic zones becomes greater.

Natural areas are important in terms of hectares, especially before 2050, but not in terms of damage – however, it should be noted that these figures are bound to higher uncertainty and comparability with indicators for other types of land-use categories is limited.

The total number of people exposed to erosion and/or flood risks each year could increase sharply over time – up to 15 times between 2015 and 2100 – and is dominated by coastal flood risk, especially in the long-term.

Total estimated risks – i.e. multi-hazard risk of coastal erosion and flooding – amounted to US $ 2.1 million per year in 2015 – i.e. 0.07% of the estimated GDP of the coastal zone and 0.006% of Côte d'Ivoire's GDP. Over time, this risk increases to 0.15% of the coastal area's GDP in 2100.

Results in Table 3 indicate that, at the 6% discount rate, the present value of the total material damages between 2015 and 2030 (15 years) is US $ 31 million, of which damage due to erosion has the largest share. The number of victims of coastal flooding is estimated at about 13. If this impact is monetised using the statistical value of a human life for Côte d'Ivoire, 2%–3% is added to material damage.

At pilot-site level (Fig. 13), the total area exposed to erosion and/or flooding risks increases from roughly 400 ha in 2015 to 700 ha in 2100, or from 6 to 9% of the total surface of the pilot-site (7400 ha). When population growth is taken into account, the number of people affected would increase from a bit under 2000 in 2015 to more than 6000 in 2075. Impacts are dominated by coastal flood risks.

In the period between 2050 and 2100, erosion at pilot-site level could account for only 2.6% of that at country level in hectares, but for more than 50% of it in terms of people affected and 40% in terms of damage – clearly indicating how largely populated is the pilot-site.

With respect to flooded area, it remains similar in the period between 2015 and 2050 and increases a little – in the range of +17% – by 2100. While most of the affected areas fall in the rural land-use category, the share of urban areas affected is quite large. On average, the population density and the average value of the areas being flooded, expressed in GDP per hectare, is comparable to that at the country level but the people affected per hectare and the damage per hectare are higher. Urban areas account for more than 80% of the damage. Economic land-use categories – 3% of impacts in terms of area in hectares – represent 18% of the damages, which is explained by the fact that the pilot-site includes part of the industrial area of the port of Abidjan. Natural areas account for 5% of impacts in terms of area in hectares but the damage per hectare is very limited.

The risks of erosion and/or flooding amount to US $ 2.4 million per year in 2015 – i.e. 1.8% of the estimated GDP of the pilot-site. With a

Fig. 9. Pilot-site in Côte d'Ivoire 'Port Bouët Ouest – Abidjan – Port Bouët Est', CI5-a and CI5-b.

share of ±80%, coastal flood is the most important hazard at pilot-site level and is expected to increase over time. Table 4 indicates that at a 6% discount rate, the present value of the total material damages between 2015 and 2030 (over a period of 15 years) amounts to amount to US $ 36 million. Risks for human health are expected. Though it is difficult and too uncertain to monetise, a rough estimate looking at fatalities from flooding suggests that the total number of expected fatalities is limited (1.5–3.6) and expected to add only a few percentual points – in the range of 2–4% – to the material damages.

3.2.2. Ghana

The CoCED analysis shows that erosion will increase significantly during this century. In 2100 26,000 ha–2.6% of the coastal zone – of Ghana's coastal area is estimated to be eroded (Fig. 14). In addition, the affected area is more densely populated than the average for the coastal area and has a higher share of economic activities in both industry and services. The erosion risk is twice as high in the first period up to 2050 – +400 ha per year – than in the period after 2050–200 ha per year.

In 2015, 42,000 ha – nearly 4.2% of the coastal zone – are at risk of coastal flooding under a 100-year return period flood event. With sea-level-rise a much larger area is expected to be affected in 2050 under the same flood event – however, as part of the flooded area is eroded by 2050, the area affected in 2050 is more or less similar to that of 2015. By 2100, however, the impact of sea-level-rise dominates and the area which is exposed to coastal flood risks enlarges to 14% of the total coastal area.

The total risks are estimated to amount to US $ 47 million per year in 2015 – i.e. 0.8% of the estimated GDP of the coastal zone and 0.04% of Ghana's GDP. Coastal erosion accounts for 57% of those impacts. Before accounting for demographic and economic growth, risks would decrease because the size of the area affected by erosion decreases after 2050 – however, the decrease in realized erosion risks after 2050 is compensated by economic growth.

Results in Table 5 indicate that, at 6% discount rate, the present value of the total material damages between 2015 and 2030 – period of 15 years – is US $ 620 million. Risk for human health is expected to increase – however there is much uncertainty in their quantification and monetisation; a rough estimation based on literature about fatalities from flooding, suggests that the number of fatalities is limited and adds a few percentage points to the material damages that can add up to 1.3%.

At pilot-site level (Fig. 15), the total area at risk of erosion and/or coastal flooding increases from 840 ha in 2015 to 1250 ha in 2100, which corresponds to an increase from 21% to 32% of the pilot-site (3900 ha). While in 2015 coastal flood was the most important risk at the pilot-site, but by 2100 erosion becomes the most important instead.

Economic and natural land-use categories are mostly absent at the pilot-site, where the rural land-use category dominates in the hazard-prone areas. The type and shares of land-use categories are in line at both country and pilot-site level. Urban areas account for a share of 90% in people affected and 70% or more in damages. Throughout the century, the urban land-use category is expected to become more relevant when looking at erosion impact measured in terms of area. Population density and damage impacts per hectare due to erosion are lower at pilot-site level compared to country level; whereas for flooding those impacts are higher at pilot-site level.

The risks of erosion and/or flooding amount to US $ 0.9 million per

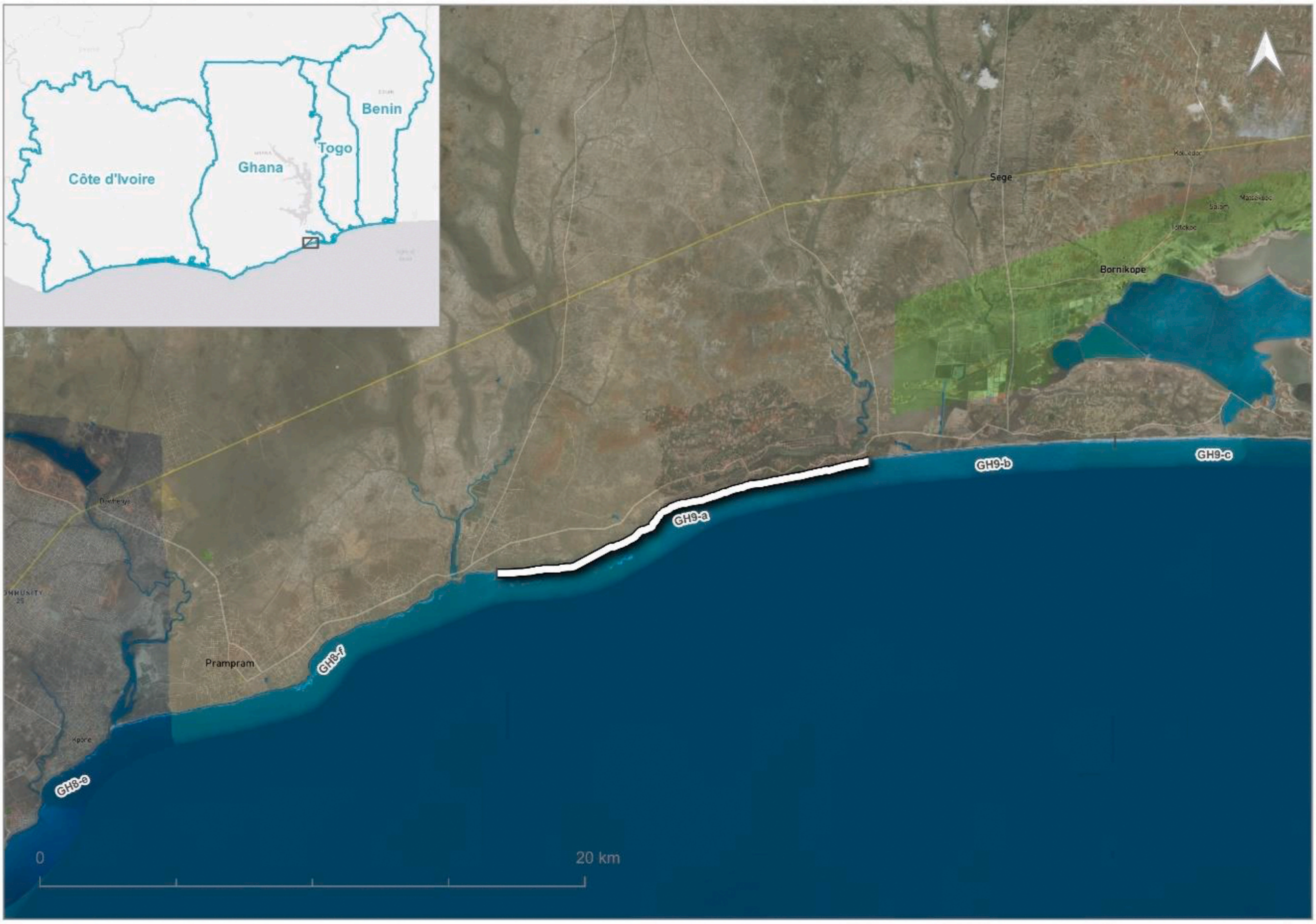


Fig. 10. Pilot-site in Ghana 'New Ningo – Lekpoguno', GH9-a.

year in 2015 – i.e. 3.7% of the estimated GDP of the pilot-site. With a share of over 65%, coastal flood is the most important hazard at pilot-site level. At a 6% discount rate, the total material damages between 2015 and 2030 (over a period of 15 years) amounts to amount to US $ 11 million present value (Table 6). In addition, some risk for human health is expected but difficult to monetise accurately. Data suggests that fatalities from flooding are fairly limited, thus loss of human life could add a few percentual points to material damages – estimated at no higher than 4.2%.

3.2.3. Togo

Coastal erosion in Togo is estimated to increase considerably during this century (Fig. 16). By 2100, 1600 ha (1.12% of the coastal zone) of Togo's coastal areas are expected to be eroded. The number of people affected will increase from 400 in 2015 to more than 40,000 in 2100. In addition, erosion affects land-use categories that are on average more valuable (by 3–4 times) than the average of the coastal zone. Although rural areas are the most affected in terms of area (ha), urban areas are the largest in terms of people affected and economic land-use categories (industry and services) dominate the damage caused by erosion. The share of natural areas in total land-use eroded is low.

In 2015, 1300 ha – nearly 1% of the coastal zone – are exposed to the risk of coastal flooding. Due to rising sea levels, it is expected that in 2050 a 100-year return period flood (T100) will affect a much larger area. However, as part of the flooded area is eroded in 2050, the area affected in 2050 is more or less similar to that of 2015. By 2100, however, the impact of sea-level-rise dominates and the area which is exposed to coastal flood risks enlarges to 6% of the total coastal area.

The total risks are estimated to amount to US $ 3.6 million per year in 2015 – i.e. 0.3% of the estimated GDP of the coastal zone and 0.04% of Togo's GDP. The multi-hazard risk increases over time and will be affected by demographic and economic growth; as the multi-hazard risk will grow faster than economic growth, the total risks can rise up to 1% of the coastal zone's GDP by 2100.

Results in Table 7 indicate that, at 6% discount rate, the present value of the total material damages between 2015 and 2030 is US $ 47 million, of which damage due to flooding has the largest share.

Risk for human health is expected to increase, however, there is much uncertainty in risk quantification and monetisation; a rough estimation based on literature about fatalities from flooding, suggests that the number of fatalities is limited and adds a few percentage points to the material damages, something in order of 1.4%.

The total area impacted by realized erosion and/or coastal flood risks doubles from nearly 700 ha in 2015 to 1400 ha in 2100 – i.e. from 11% to 23% of the surface of the pilot-site area (Fig. 17); in number of people affected it almost triples by 2100 when population growth is taken into account. While coastal floods have the greater share of impact in people, erosion contributes the most to total damage.

As most of the affected areas at pilot-site are rural, the average impact in terms of area for both eroded and flooded land-use is lower than that average at country-level. In terms of damages, economic (industry and services) land-use categories account for the most important share in the total of damages caused by coastal flooding and erosion.

The annual damages due to erosion and flooding amount to US $ 0.3 million in 2015 – i.e. 0.4% of the pilot-site's GDP. Without economic or demographic growth the annual damages due to erosion and flooding

Fig. 11. Pilot-site in Togo 'Togoville – Agbodrafo – Aného', TG1-e, and Benin 'Frontière du Togo – Grand-Popo', BJ1-a.

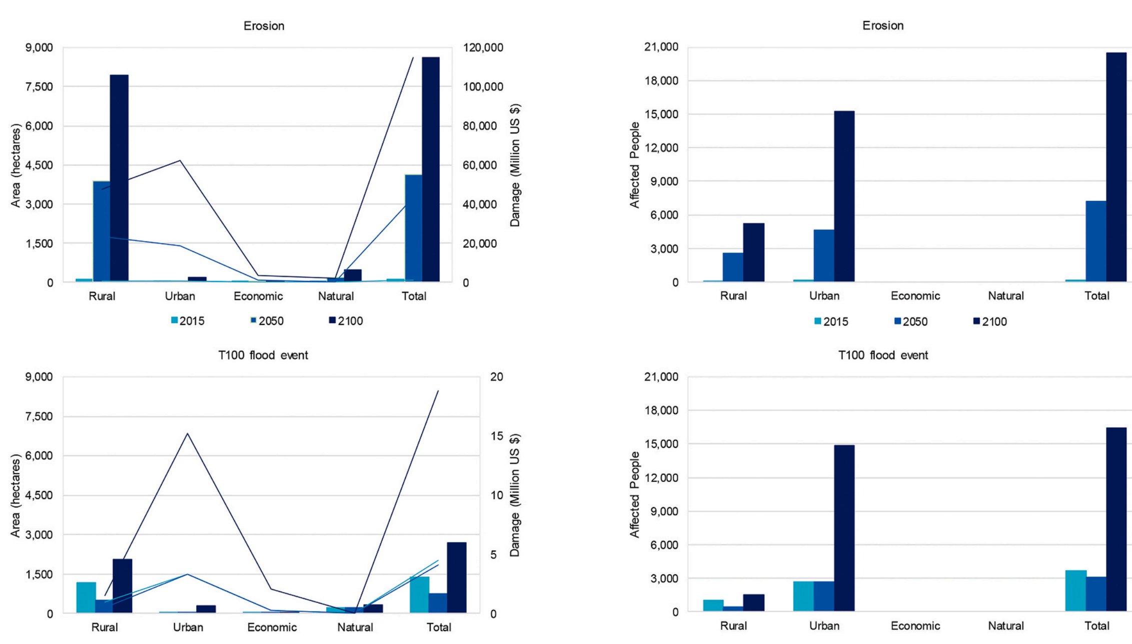


Fig. 12. Impacts from erosion and a T100 flood event in reference years, country level – Côte d'Ivoire.

Table 3
Total aggregated risks, country level – Côte d'Ivoire, in million US $ per period.

Discount rate	Erosion		Flooding		Total	
	4%	6%	4%	6%	4%	6%
2015–2020	6.4	6.2	4.9	4.7	11.3	10.8
2015–2030	20.6	17.7	15.8	13.6	36.4	31.4
2015–2050	45.5	32.9	34.3	24.9	79.7	57.8
2015–2075	69.8	42.2	57.3	33.4	127.1	75.6
2015–2100	83.7	45.4	84.3	39.4	168.0	84.8

would increase slowly through 2100 – however, if the expected population and economic growth is taken into account the annual damages are expected to increase by seven – increasing to about 0.5% of the country's GDP in 2100.

Data in Table 8 indicate that at a 6% discount rate, the present value of the total material damages between 2015 and 2030 (over a period of 15 years) amounts to amount to US $ 7 million of which the highest share is due to erosion. Risks for human health are expected. Though too uncertain to monetise, a rough estimate looking at fatalities from flooding suggests that the total number of expected fatalities is limited and could add up to less than 5% to material damages.

3.2.4. *Benin*

By 2100, almost 4000 ha–1.9% of the coastal zone (herein defined as strip within 20 km inland from the coastline) – of Benin's coastal area is estimated to be eroded (Fig. 18). The number of people affected could increase from a hundred in 2015 to more than 40,000 in 2100. Erosion affects land-use categories that are on average comparable to the rest of the coastal zone in terms of population density and economic value in GDP per hectare. Although rural areas are the most affected in terms of area in hectares, urban areas are the largest in terms of people affected and economic land-use categories (industry and services) dominate the damage caused by erosion. The share of natural areas in the total land-use eroded is low.

In 2015, 18,000 ha – nearly 8.6% of the coastal zone – are exposed to the risk of coastal flooding. Due to rising sea level, by 2050 a 100-year return period flood (T100) will affect a much larger area. However, as part of the flooded area is eroded in 2050, the area affected in 2050 is more or less similar to that of 2015. By 2100, however, the impact of sea-level-rise dominates and the area which is exposed to coastal flood risks enlarges to 14% of the total coastal area.

The land-use categories in affected areas are mixed, which is comparable to the average land-use in the coastal area, and there are no major differences between 2015, 2050 or 2100. The urban area is the largest category in terms of people affected and damage (+80%).

The total risks are estimated to amount to US $ 10 million per year in 2015 – i.e. 0.5% of the estimated GDP of the coastal zone and 0.1% of Benin's GDP. The multi-hazard risks increase over time and will be affected by demographic and economic growth; as these natural hazards will grow faster than economic growth. It is estimated that total risks can rise up to 1% of the coastal zone's GDP by 2100. The risks due to coastal flooding are dominant and represent more than 90% of total risk.

Results in Table 9 indicate that, at 6% discount rate, the present value of the total material damages between 2015 and 2030 is US $ 135 million, of which damage due to flooding has the largest share.

Risk for human health is expected to increase – however there is much uncertainty in their quantification and monetisation; a rough estimation based on literature about fatalities from flooding, suggests that the number of fatalities is limited and adds a few percentage points up to 1.8% to the material damages.

The analysis at pilot-site level (Fig. 19) confirms the analysis at country level – however, it also shows that there are major differences. The total area exposed to risks of erosion and flooding doubles from nearly 500 in hectares in 2015 to 1200 in hectares in 2100, or from 22% to 50% of the surface of the pilot-site (2400 ha). The number of people affected increases from 400 in 2015 to 1200 in 2075 (including the impact of population growth). In the short-term, the area in hectares and

Table 4
Total aggregated risks, pilot-site level – Côte d'Ivoire, in million US $ per period.

Discount rate	Erosion		Flooding		Total	
	4%	6%	4%	6%	4%	6%
2015–2020	2.6	2.5	10.6	10.2	13.2	12.7
2015–2030	8.4	7.3	33.7	29.1	42.1	36.4
2015–2050	18.7	13.5	73.6	53.3	92.2	66.8
2015–2075	28.3	17.2	107.5	66.3	135.8	83.5
2015–2100	33.8	18.4	127.9	71.0	161.7	89.4

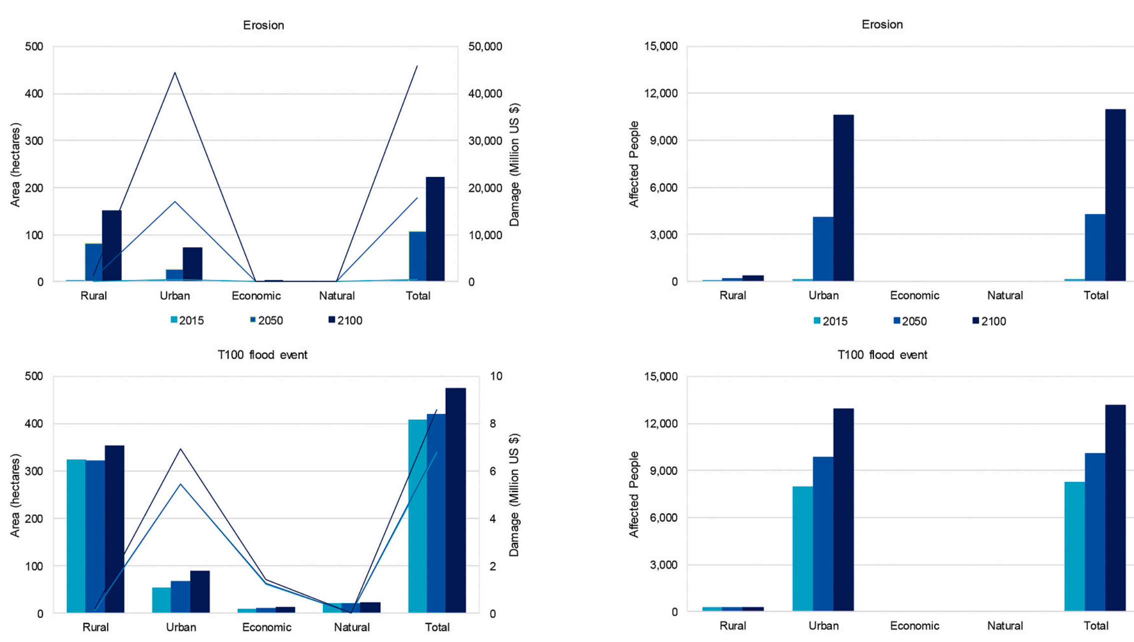


Fig. 13. Impacts from erosion and a T100 flood event in reference years, pilot-site level – Côte d'Ivoire.

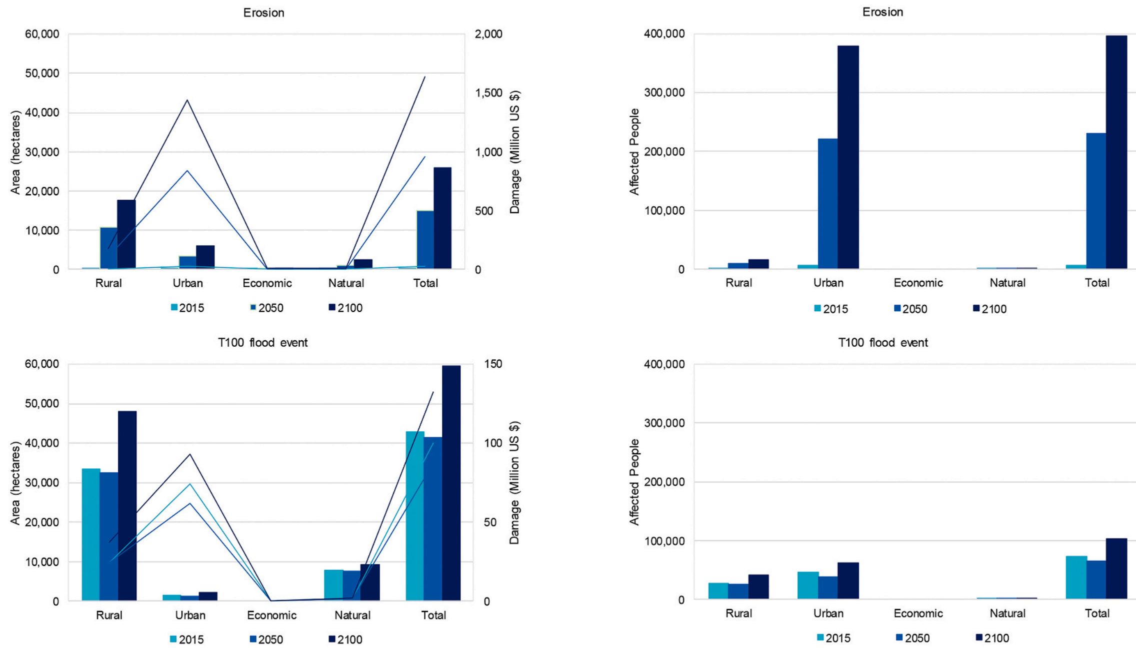


Fig. 14. Impacts from erosion and a T100 flood event in reference years, country level – Ghana.

Table 5
Total aggregated risks, country level – Ghana, in million US $ per period.

Discount rate	Erosion		Flooding		Total	
	4%	6%	4%	6%	4%	6%
2015–2020	137	131	102	98	239	229
2015–2030	413	358	302	262	715	620
2015–2050	851	625	604	447	1455	1072
2015–2075	1027	694	838	536	1865	1230
2015–2100	1109	713	978	568	2088	1281

people at risk of coastal flooding is greater than that for erosion; but in the long-term, the impact of erosion increases sharply, and that of flood decreases because part of the area at risk is eroded. The land-use

Table 6
Total aggregated risks, pilot-site level – Ghana, in million US $ per period.

Discount rate	Erosion		Flooding		Total	
	4%	6%	4%	6%	4%	6%
2015–2020	1.6	1.5	2.9	2.8	4.6	4.4
2015–2030	4.8	4.2	8.1	7.1	12.9	11.3
2015–2050	10.0	7.3	14.1	10.8	24.1	18.1
2015–2075	13.1	8.5	17.3	12.0	30.4	20.6
2015–2100	15.3	9.0	18.4	12.3	33.8	21.3

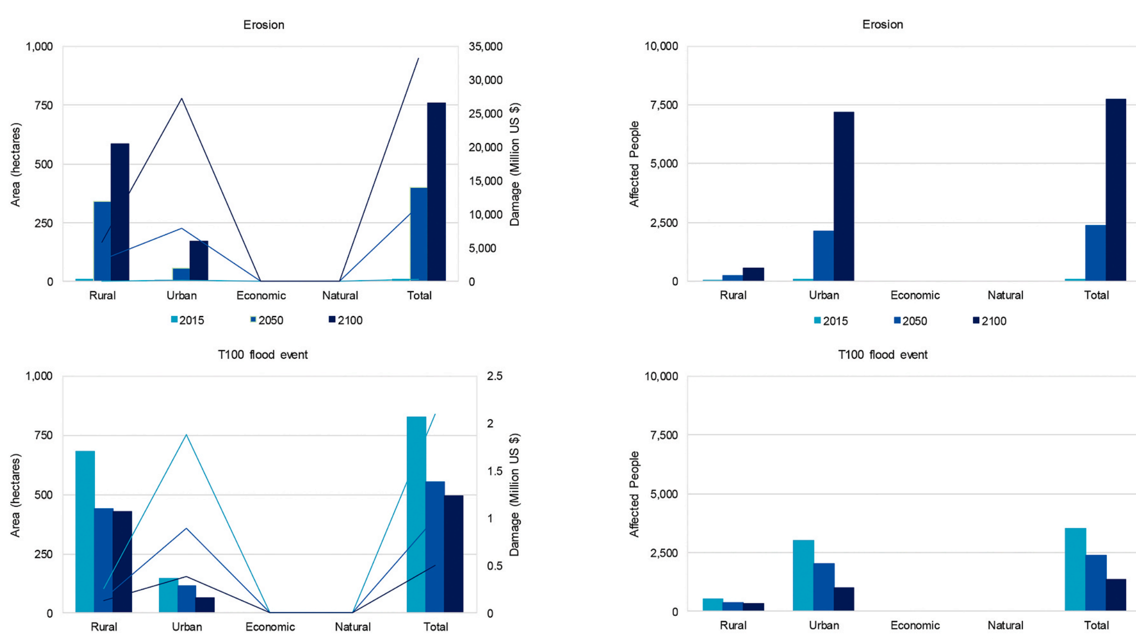


Fig. 15. Impacts from erosion and a T100 flood event in reference years, pilot-site level – Ghana.

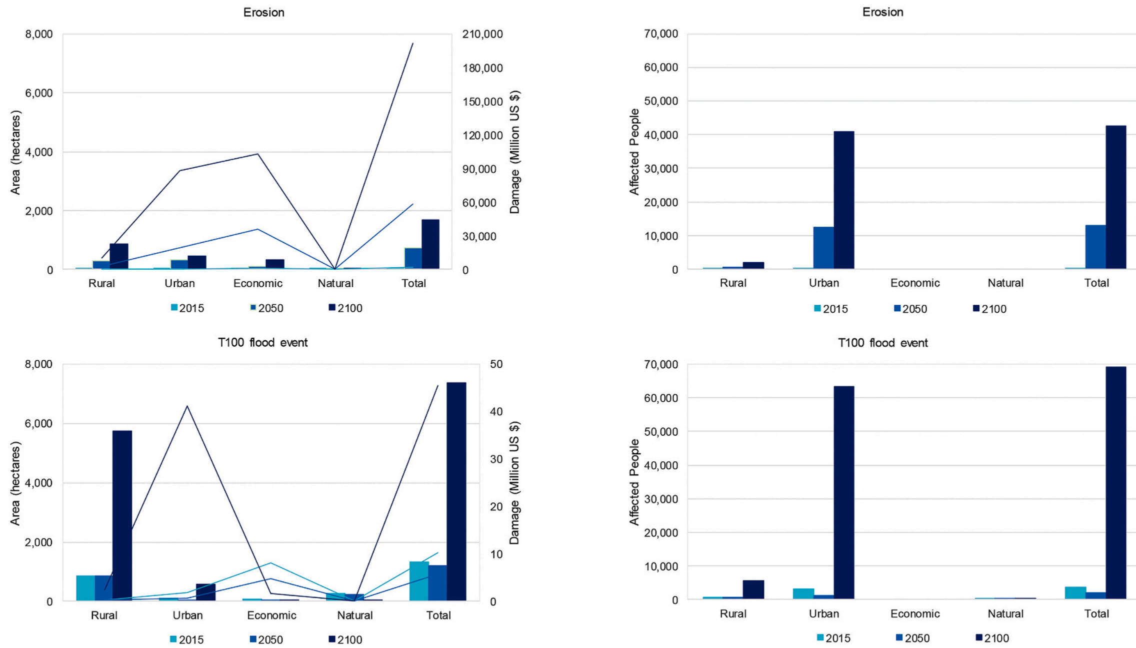


Fig. 16. Impacts from erosion and a T100 flood event in reference years, country level – Togo.

Table 7
Total aggregated risks, country level – Togo, in million US $ per period.

Discount rate	Erosion		Flooding		Total	
	4%	6%	4%	6%	4%	6%
2015–2020	8.2	7.9	10.1	9.7	18.3	17.6
2015–2030	25.0	21.6	28.6	24.9	53.5	46.5
2015–2050	52.8	38.5	53.2	40.0	106.0	78.6
2015–2075	75.1	47.1	88.1	52.7	163.1	99.8
2015–2100	89.1	50.3	132.4	62.6	221.5	112.9

categories affected at the pilot-site-level are similar to those at the country-level and dominated by rural or urban areas.

The annual damages due to erosion and flooding amount to US $ 0.13 million in 2015 – i.e. 1.3% of the pilot-site's GDP – to which erosion risks, representing over 80%, are contributing the most. Annual damages will increase trough the century and could become 2.5% of the

Table 8
Total aggregated risks, pilot-site level – Togo, in million US $ per period.

Discount rate	Erosion		Flooding		Total	
	4%	6%	4%	6%	4%	6%
2015–2020	1.6	1.5	1.1	1.0	2.7	2.6
2015–2030	4.8	4.1	3.1	2.7	7.9	6.8
2015–2050	10.1	7.4	5.8	4.4	15.9	11.7
2015–2075	14.9	9.2	7.5	5.0	22.4	14.2
2015–2100	17.5	9.8	8.3	5.2	25.7	15.0

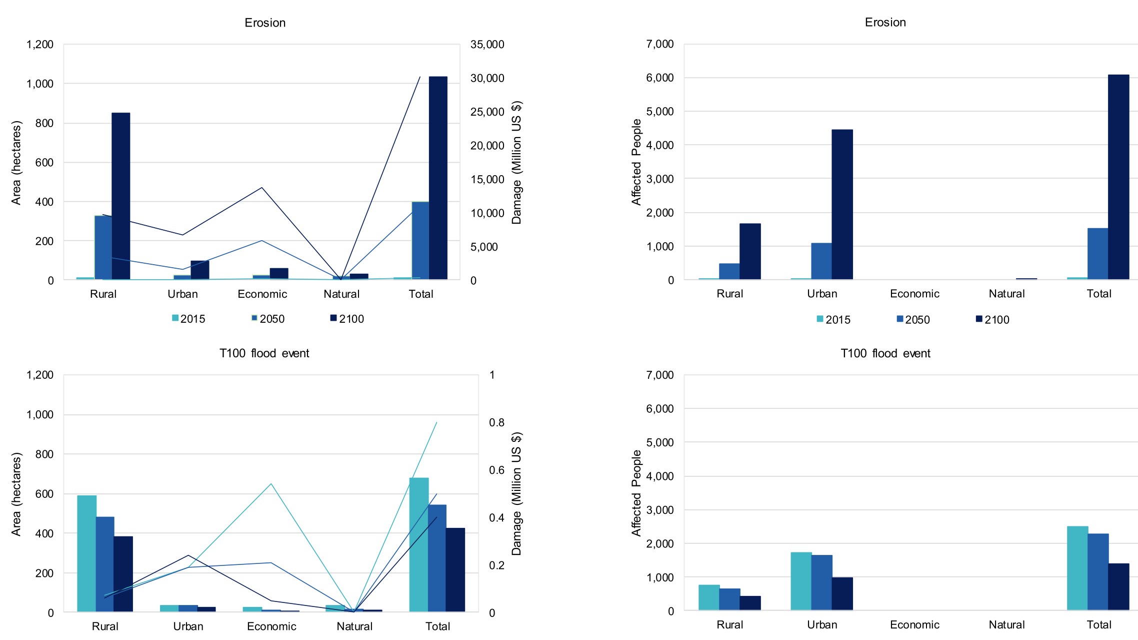


Fig. 17. Impacts from erosion and a T100 flood event in reference years, pilot-site level – Togo.

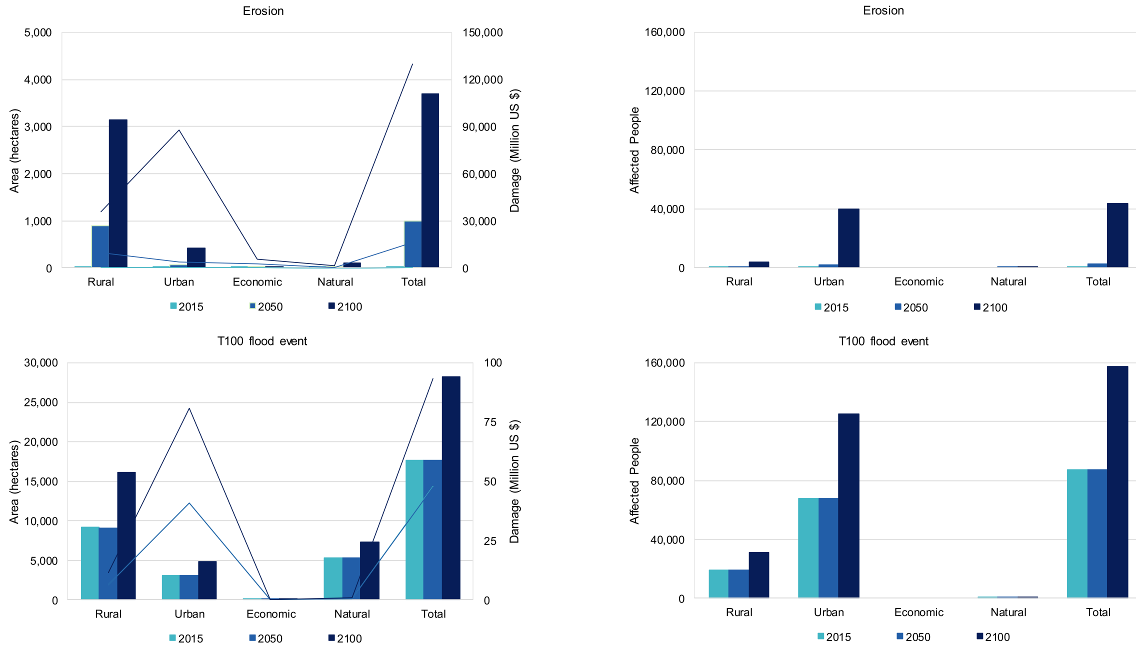


Fig. 18. Impacts from erosion and a T100 flood event in reference years, country level – Benin.

Table 9
Total aggregated risks, country level – Benin, in million US $ per period.

Discount rate	Erosion		Flooding		Total	
	4%	6%	4%	6%	4%	6%
2015–2020	2.3	2.2	48.3	46.3	50.6	48.5
2015–2030	7.0	6.0	149.2	129.0	156.1	135.0
2015–2050	15.2	11.0	325.9	236.4	341.1	247.4
2015–2075	48.4	23.7	493.7	300.1	542.1	323.8
2015–2100	67.3	28.0	620.9	328.8	688.1	356.8

pilot-site's GDP in 2100 mostly due to the increase in erosion risks, which are reinforced by demographic and economic growth.

Natural areas account for a few percentage of impacts in terms of area (in hectares) and damage – however, note here that these figures are bound to greater uncertainty – e.g. the use of locally derived values for ecosystem services could lead to a different conclusion. Comparability with indicators for other land-use categories is limited.

Data in Table 10 indicate that at a 6% discount rate, the present value of the total material damages between 2015 and 2030 (over a period of 15 years) amounts to amount to US $ 1.8 million. Risks for human health are expected. Although too uncertain to monetise, a rough estimate looking at fatalities from flooding suggests that the total number of expected fatalities is limited (<1) and, if monetised using the statistical value of a human life for Benin, could add up to 6–11% to material damages.

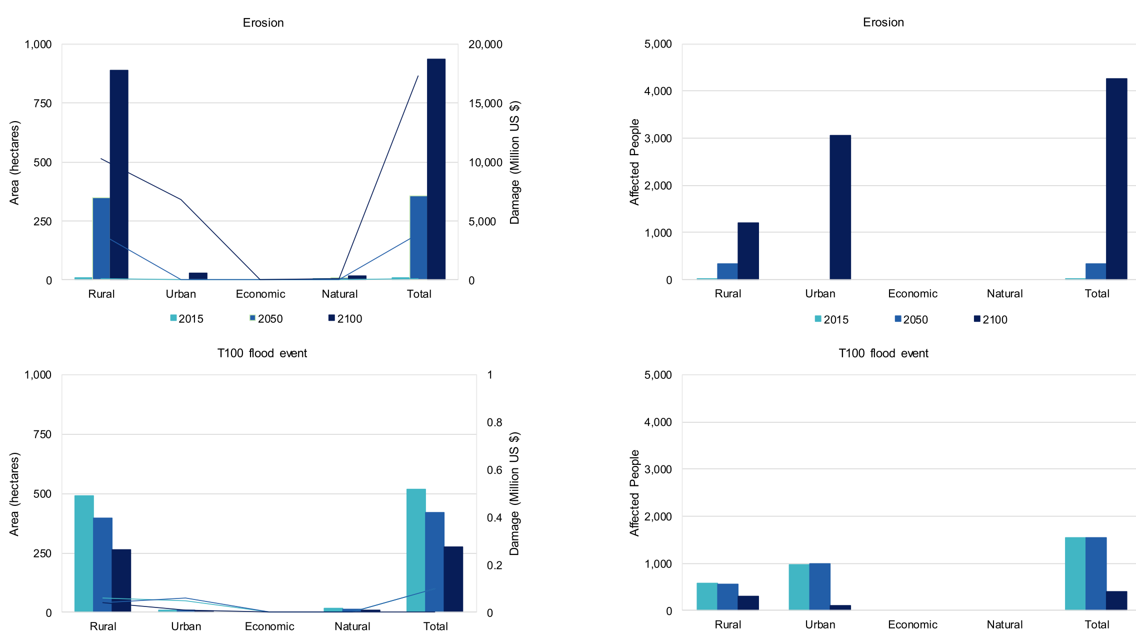


Fig. 19. Impacts from erosion and a T100 flood event in reference years, pilot-site level – Benin.

Table 10
Total aggregated risks, pilot-site level – Benin, in million US $ per period.

Discount rate	Erosion		Flooding		Total	
	4%	6%	4%	6%	4%	6%
2015–2020	0.5	0.5	0.1	0.1	0.7	0.6
2015–2030	1.7	1.5	0.4	0.3	2.1	1.8
2015–2050	3.7	2.7	0.8	0.6	4.5	3.3
2015–2075	7.7	4.2	1.2	0.7	8.8	4.9
2015–2100	9.9	4.7	1.3	0.8	11.1	5.5

4. Discussion and conclusions

An index-based risk assessment has been conducted to screen the entire coastline of the four countries in this study, segment by segment, rank the segments on their level of vulnerability to climate variability and change, and sort out the hotspots from the less vulnerable areas. The Coastal Index scoring was benchmarked against the UEMOA/IUCN studies [39,40], presented in Table 11, which classification is backed up in anecdotal evidence of past erosion and flooding events and damages.

All segments identified in the UEMOA/IUCN studies [39,40] as high to very-high priority coincide with the highest computed Coastal Index (blueish on the used colour scale). This result not only confirms the high-level risk assessment done earlier, but also gives confidence to the methodology developed within the present study which has the advantage of giving more granular insight to compare the hotspots.

Notwithstanding, some differences can be observed too. For instance, a couple of segments are identified as having a high priority (corresponding to a ranking of 4 or more) in the UEMOA/IUCN studies [39,40], whereas, based on the Coastal Index, they are ranked as only moderate (corresponding to a ranking between 2.5 and 3).

This is for example the case for segments that rank higher in the exposure indicator but lower on the hazard indicators – e.g. 'GH2-b: *Cap des Trois-Pointes*' in Ghana with a very-high NSI (see Table 2) – or, otherwise, high on the hazard indicators but low on the Exposure Indicator – e.g. 'CI6-b: *Zone périurbaine est Abidjan – Grand Bassam*' in Côte d'Ivoire. This is as well as the case for segments ranking as moderate on both the hazard and the exposure indicators and showing no clear effect of sea-level-rise – e.g. 'GH3-b: '*Secteur urbain et extension periurbaine de Sekondi – Takoradi*' in Ghana.

In the opposite direction – that is segments that were identified as being slightly more important on the basis of the index-based risk assessment approach in comparison with the ranking of low/average priority in the UEMOA/IUCN studies [39,40] – are a number of segments at mid-rank with respect to the hazard indicators and ranking high or very-high on exposure in one or several receptor types – e.g. 'GH6-b: *Hinterland rural des zones urbaines de Cape Coast et Accra*' with very-high NSI (see Table 2) and 'GH5-a and GH5-b: *Zones urbaines et extensions Elmina – Cape Coast - Saltpond*' scoring very-high on the variable population density, both in Ghana.

Table 11
Summary of hotspot segments in the four countries, as determined in the present research – based on the Coastal Index for erosion and/or inundation – benchmarked against the UEMOA/IUCN studies [39,40].

Country	Segment	Name	CI	Ref. [39]	Ref. [40]
Benin	BJ1-b	*Grand Popo – Ouest Cotonou*			
	BJ1-a	*Frontière du Togo – Grand-Popo*			
	BJ2-d	*Cotonou*			
Côte d'Ivoire	CI6-b	*Zone périurbaine est Abidjan – Grand Bassam*			
	CI7-b	*Terrasse sableuse et cocoteraie de l'est Ivoirien*			
	CI3-c	*Fresco – Assigny*			
	CI5-a	*Abidjan – Port Bouët Ouest*			
	CI5-b	*Abidjan – Port Bouët Est*			
Ghana	GH10-b	*Delta de la Volta rive gauche*			
	GH9-a	*New Ningo – Lekpoguno*			
	GH10-a	*Delta de la Volta rive gauche*			
	GH9-b	*Delta de la volta rive droite Ada Foah – Ningo*			
	GH8-a	*Accra zone urbaine et périphérie Est*			
Togo	TG1-c	*Togo*			
	TG1-d	*Togo*			
	TG1-e	*Togoville – Agbodrafo – Aného*			

Very low (up to 1) | | High to very high (4.5 to 5)

When considering future projected climate conditions, more specifically, when considering sea-level-rise, a number of segments increase in risk priority – e.g. 'GH3-a and GH3-d: *Secteur urbain et extension periurbaine de Sekondi – Takoradi*' in Ghana scoring very-high on the variable population density of SVI and by and large high on the Exposure Indicator, as well as 'CI3-a: *Fresco – Assigny*' scoring high/very-high on the variable population density of SVI and on the NSI. For the remainder of the segments future projected sea-level-rise reinforces the risk profile in areas threatened by coastal inundation.

The index-based risk assessment approach clearly shows that several combinations of exposure and hazard indicators, higher or lower, are possible when it comes to priority segments; therefore, the segment prioritisation with respect to risk is directly linked to the choice of variables that compose the Exposure Indicator and to the resolution and quality of the variables data. In the present study the overall Exposure Indicator is based on existing data for the year of reference – however, as it very much depends on how the elements of vulnerability may change from now through 2100 the computed Exposure Indicator carries much uncertainty. Furthermore, the different individual exposure indicators including the selection of variables to compute the individual exposure indicators – e.g. SVI or ESI – when updated to include more or different ones – e.g. household vulnerability and recovery in the SVI or GDP, houses, road and rail in the ESI – can have an impact on the segment prioritisation. Data gaps – particularly, the availability of quantitative data on exposure, hydro- and morpho-dynamic data to validate/calibrate the numerical models used to estimate hazards' extension and intensity, information on coastal assets and valuation, as well as on aspects of income distribution and social welfare – will disseminate throughout the study and affect the (multi-)hazard risk assessment, as well as limit the subsequent analysis on the cost of coastal environmental degradation and climate adaptation options at pilot-site level.

The natural environment that forms the physical and resource base of West African coastal areas is in general highly vulnerable and subject to many pressures occurring simultaneously. Those pressures risk to degrade the coastal environment, which will undeniably have consequences on economic growth and human wellbeing in the study area. The CoCED analysis framework is aimed at estimating in monetary terms the cost of coastal environmental degradation. The research focused on the current vulnerability to erosion and coastal flooding and to their acceleration and deterioration under future projected sea-level-rise. The CoCED analysis framework has been applied at short-, medium- and long-term to coastal areas of the West African countries of Côte d'Ivoire, Ghana, Togo and Benin, at both country and pilot-site levels. The related damages and risks have been quantified accounting for the current land-use categories (rural, urban, economic) and future demographic and economic growth.

The risk assessment confirms the current threat posed by coastal erosion and flooding to sustainable coastal development in all four countries and in each of the pilot-site areas in study. The numerical modelling of erosion and flooding shows that a substantial part of the coastal areas are at risk of erosion and/or flooding, ranging from 6% – in Côte d'Ivoire – to 22% – in Benin – of the coastal area. In all pilot-site areas, the size of the affected area will substantially increase – from +50% to +300% – throughout this century; furthermore, all four pilot-site areas face coastal flooding for events with a 10-year return period. In addition, the exposure assessment on the affected land-use categories that – on average – the affected areas are as valuable as the average for the countries' coastal zones or pilot-site areas in terms of number of inhabitants per hectare and GDP per hectare. Consequently, the risks can amount to several points percentage of the local GDP.

The CoCED analysis framework shows that risks are country and location specific, and that it is possible to account for these specificities. Firstly, it is seen that some of these differences are driven by physical factors, which explain the vulnerability of the coastal areas of the countries in study to coastal erosion and flooding, and how these threats will develop over time taking an even more important toll on people's health and quality of life. Secondly, affected land-use categories differ between the countries. The total damages are mainly driven by the share of urban and economic land-use categories within the affected areas. Logically, risks expressed in US $ per hectare are higher for the countries that are richer with respect to GDP per capita.

The CoCED analysis offers an accounting framework that integrates different types of information – e.g. risk profiles – and combines generic steps – e.g. damage functions – with country-specific data and information. The CoCED analysis framework shows that it is possible to assess coastal erosion and flooding risks and damages on people and the economy, as well as on natural areas – although, bound to greater uncertainty. The information and data available make it possible to test the implementation of the CoCED analysis framework to estimate material damages to buildings and urban infrastructure, as well as – to a lesser extent – economic activities – i.e. industry, services, port and agriculture – and transport. Very little information is available on the impacts of floods on human health and natural areas. A methodology has been developed to test to what extent these impacts are likely to be significant, using a simplified dose-response function for fatalities together with country-specific data from literature on valuation of fatalities – i.e. value of a statistical life. The CoCED analysis does not yet include the impacts on cultural heritage – e.g. historic buildings – however, the methodology is suitable to be expanded to do so.

On the basis of the present research, the relationship between human activities, environmental degradation and associated costs on human health and economy are well understood qualitatively but more difficult to assess quantitatively, let alone in monetary terms. The lack of data with sufficient quality and resolution exacerbates this fact.

The CoCED analysis framework tested in Côte d'Ivoire, Ghana, Togo and Benin, could be further improved by integrating more of the following elements:

- Mapping of current land-use categories: the current analysis builds on a detailed – 1 ha grid – desktop analysis of land-use categories, combining generic economic indicators with generally available detailed maps of population density. For three out of the four pilot-sites an initial reality check of available land-use maps has been made, but the analysis could improve by a further, more detailed checking, focusing on the affected areas, namely in what relates to economic land-use categories and transport infrastructure.
- Mapping of future land-use categories: an important element of the risk assessment is how the elements of exposure will change over time – e.g. to account for future demographic and economic growth, and how this is likely to affect future land-use categories; this essential aspect has been addressed within the present research using a generic and simplified approach. As such, the quality of the analysis would improve if maps for future land-use categories – which are being developed – could have been integrated in the present research study.
- Site-specific damage functions for impacts on economic land-use categories and transport infrastructure, as well as finer resolution data on assets at risk.
- Site-specific damage functions for impacts on human health, including fatalities due to coastal flooding.
- Site-specific damage functions for erosion: an first estimation of the cost of the 'coastal setbacks' measure – i.e. costs for relocating people and assets inland has been made – however, this could be further developed building on region specific information and/or similar relocation case-studies.
- Impacts on natural areas: the ecosystem services delivered by natural areas have been integrated based on generic data, but do not cover any of the specificities of the interaction between nature, people and the economy; the concept of ecosystem services offers a framework to document and assess this interaction, as well as the consequences from coastal erosion and flooding.

- Impacts of land-use policies and governance on coastal erosion and flooding risks.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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