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A geospatial database of coastal characteristics for erosion assessment of Europe's coastal floodplains

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Abstract. Coastal erosion and flooding are known to be linked, with erosion potentially exacerbating flood extents and risk, but analysis of the combined hazards is limited. This paper describes the CoasTER geographic database designed as a first step in integrating existing information on erosion and other relevant characteristics for Europe's coastal floodplains to support flood assessment and climate services. The CoasTER database updates and builds on earlier erosion research and data sources. It also includes a coastal geomorphological typology which incorporates human modification in the form of hard engineering and infrastructure.

Almost 80% (25,000 km) of shorelines associated with coastal floodplains are composed of erodible sediments, with coastal wetlands being the most prevalent geomorphological type. While accretion is the dominant historical trend for these shorelines, approximately 27% are currently classed as eroding over the last 40 years. The majority of floodplain shorelines are associated with either developed or agricultural areas and human structures are visible along almost 8,000 km of shoreline, restricting morphodynamic response to sea level rise. If the erosive trend continues for developed areas, over 2,500 km of shoreline will require further management to maintain current protection levels and nearly 1,000 km will require new management. The CoasTER database reveals the potential magnitude of erosion-flood interactions in the future defining where mobile sediments and coastal floodplains are co-located. It demonstrates that episodic and/or long-term erosion and coastal flooding is a Europe-wide issue that deserves the attention of local to European decision-makers in order to define a coherent management strategy.

1 Introduction

It is well known that the hazards of coastal erosion and flooding are strongly linked (e.g., Grases et al., 2020; Leaman et al., 2021; Pollard, 2019; Toimil et al., 2023): Figure 1, for example, illustrates how erosion and the removal of sediments during a major storm can create flood pathways and exacerbate flooding among other effects. However, quantitative analysis of these two hazards and coastal structures is uncommon due to the complexity of these processes, especially at broad-scales (Baart et al., 2024). With growing interest in climate services to support adaptation (Le Cozannet et al., 2017; McInnes et al.,

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2024) this deficiency is an important issue to address. The Coastal Climate Services (CoCliCo) project is developing tools to plan and manage our response to sea-level rise and climate change concerning coastal flooding around Europe. This includes mapping of the extent of coastal flooding both today and projecting it into the future under climate scenarios.

Figure 1 Aerial photograph (28 February 2010) illustrating how the erosion of Belle Henriette created an additional path for floodwaters into La Faute-sur-Mer, France during Storm Xynthia 2010 (Photo J-P Bichon, interpretation M. Garcin, BRGM; see also Pedreros et al., 2010)

To support this effort in terms of a better understanding of erosion, this paper presents the CoCliCo '*Coastal Typologies and Erosion for Risk database*', which is henceforth abbreviated to the 'CoasTER database'. This database incorporates an earlier Europe-wide erosion study (Eurosion, 2004) on a more recent shoreline (EEA, 2017) with additional relevant coastal characteristics built within a GIS environment. The paper describes how the database was developed and presents an analysis of the insights that emerge in relation to coastal floodplain extents and the scale of linkages between coastal erosion and flooding. The CoasTER database is a step towards inclusion of erosion in broad-scale climate services for Europe and its simple structure allows new or additional content to be incorporated. Possible developments are also considered.

2 Background

Coastal geomorphology reflects geological inheritance and the production, storage and movement of sediments in response to natural and human influences (Woodroffe, 2002). The resultant processes of erosion, transport and deposition produce

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both desirable coastal landforms such as beaches, but also result in erosion and flood hazards which affect people and their assets. These are longstanding issues around Europe's coasts with far-reaching implications for coastal communities, ecosystems, and economies (e.g., Pranzini et al., 2015; van de Wal et al., 2023). As coastal areas continue to develop both in demographic and economic terms, and the consequences of long-term coastal dynamics and climate change, especially sea level rise, become more apparent, understanding and managing erosion and its link with flooding is essential (e.g., Georgic & Klaiber, 2022).

Erosion is often regarded as a permanent loss of coastal land that is associated with direct or indirect impacts for both developed areas and the natural environment. While this is the case for some coastal features such as cliffs, for low-lying areas it is often part of an on-going evolutionary cycle of accretion and erosion (e.g., Bateman et al., 2020; Kennedy et al., 2019; Pollard et al. , 2019; Stive et al., 2002). Classification of these distinct types of coast and their characteristics is recognised as a practical evidence-based tool for coastal analysis (e.g., Athanasiou et al., 2024; Finkl, 2004; Morales, 2022) and has previously been undertaken for erosion around Europe's shoreline based on sediment types (Eurosion, 2004).

The utility of this existing erosion dataset within a broad-scale analysis of coastal erosion and flooding (Le Cozannet et al., 2025) can initially be increased by the use of a recent shoreline which is more representative and potentially usable within other coastal analyses. Building on this, other flood-relevant coastal characteristics such floodplain extents, geomorphological type and shoreline movement further increases the database utility. In addition, as the adaptability of the coastal system to changing water levels is strongly influenced by human actions which have progressively modified and restricted the active coastal system with a growing footprint to reduce the risks and impacts of erosion and flooding. Where present, coastal infrastructure, particularly defences, represent a static 'line in the sand' which constrains morphodynamic evolution and often requires continual maintenance as coastal evolution continues under the influence of wave, tides and changing sea levels.

To capture the historical context and the current ability of the coastal system to respond to changing water levels, a European-scale database of the open coast and its natural and human characteristics was built within a GIS environment using a mixed approach to integrating existing data sources. At the core of the database is a generic, qualitative geomorphologically-based typology built around the premises that; (1) in response to sea level rise, the coastal geomorphological profile will tend to migrate landward over the long-term (e.g., Hanson et al., 2010; Masselink et al., 2020; Mentaschi et al., 2018; Oppenheimer et al., 2019; Wen et al., 2023) and (2) any hard engineered structures will constrain the coastal profile and may become increasingly exposed to coastal processes and forces over time (Enwright et al., 2016; van Rijn, 2011). Building on the core typology, other erosion-related characteristics (sediment type, land cover, historical movement trend and coastal structure types) are combined with coastal floodplain extents to allow identification of sites where flood and erosion could interact resulting in greater flood impacts or disruptions.

This paper explains the development of the coastal typology and the datasets that are used to populate it. It also provides an analysis of the erosion characteristics of coastal floodplains and the scale of linkages between coastal erosion and flooding at the European scale. Lastly future developments are briefly discussed.

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3 The CoCliCo *Coastal Typologies and Erosion for Risk (CoasTER)* database

Coastal environments are characterised by various key factors including sediment supply, beach materials, underlying geology and human activity, which all influence the dynamic nature of the coastal zone. The CoasTER database collates information for a broad-scale flood and erosion analysis of the European coast considering the distribution and evolution of mobile geomorphological features and their attributes.

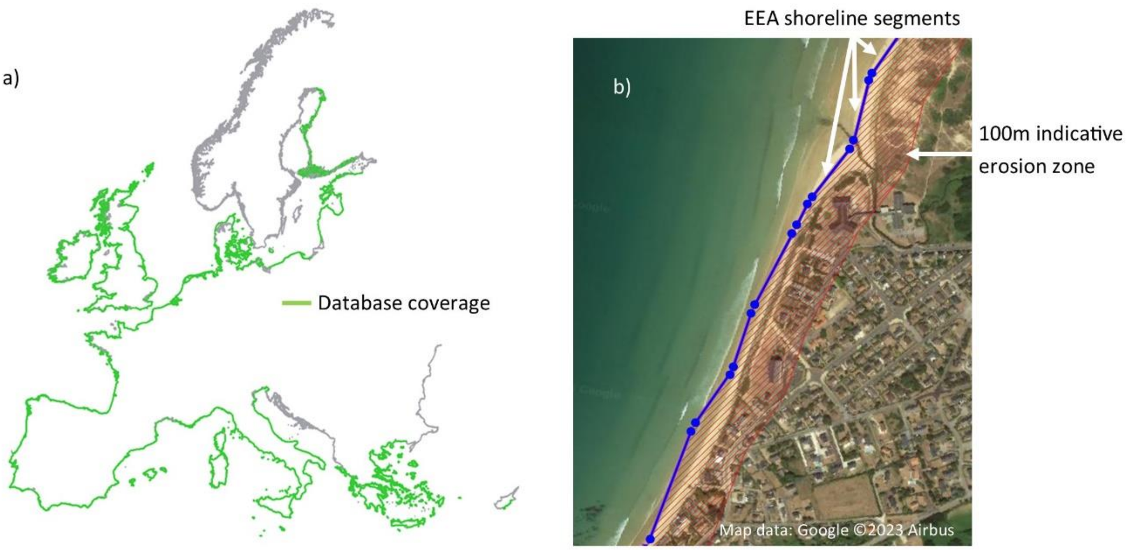

Figure 2 The EEA shoreline showing the database coverage (a) and example of coastal segments with indicative erosion zone (b)

3.1 Reference shoreline

The shoreline dataset selected for the analysis is that provided by the European Environment Agency (EEA, 2017). After cleaning, the coastline covers nearly 128,500 km of shoreline of which 81,000 km is covered by data within the CoasTER database (see Fig. 2a). This covered the majority (73%) of shoreline for 18 EU countries plus the UK and Monaco. Non- and new (post 2005) EU countries, estuaries and inlets, some complex coasts and most small islands (typically less than 1 km^2) were omitted due to lack of information in underlying source data.

The shoreline is composed of a series of segments which have an average length of approx. 100 m with a maximum of 4 km length located along homogenous shorelines. These segments are used as the basis for the CoasTER database (see Fig. 2b) to which flood and erosion-related attributes (characteristics) are appended using spatial joins within a GIS environment. Importantly, coastal characteristics were attributed considering a coastal zone extending approximately 100 m landward of the EEA shoreline (coastal erosion zone). This indicative erosion zone (Fig. 2b) is to consider potential migration or erosion over this century and identify what coastal assets may be exposed over time (e.g., see Marine Scotland, 2020). Note that erosion could exceed this indicative distance in some locations, but in most cases it is likely to be less over this century.

3.2 Key coastal characteristics

The sources for the coastal characteristics and reclassification included in the database are shown in Table 1 and listed in Appendix Tables A1 and A2. with the derived attributes listed in Appendix Table B1. These characteristics, combined with a coastal geomorphic typology, provide a baseline for assessing the tendency for erosion along the shoreline and where this coincides with the potential for flooding.

Table 1 Data sources included in the database and used in the generation of the coastal geomorphic typology

Coastal characteristic	Source
Geomorphology and sediment type	EEA/Eurosion; World Imagery /Google Earth (EEA, 2004; Esri, 2024; Google Earth, 2024)
Land cover/use	Corine Land Cover 2018 (CLC, 2020)
Coastal floodplain extent due to extreme tides and storms	CoCliCo flood units (Lincke & Hinkel, 2023)
Decadal shoreline movement (1984 to 2021)	ShorelineMonitor+ (based on Luijendijk et al., 2018)
Location of coastal structures (hard defences and other human infrastructure that constrain shoreline evolution)	EEEA/Eurosion ; World Imagery/Google Earth (EEA, 2004; Esri, 2024; Google Earth, 2024)

3.2.1 Sediment type

Coastal sediment type is an important characteristic indicative of coastal change and erosion; rocky coasts and foreshores tend to have different erosional dynamics than sandy coasts for example. Each coastal segment therefore has simplified sediment information based on the Eurosion dataset (see Table A1 and Eurosion, 2003) validated by visual interpretation. Four sediment types were defined (Table 2) and applied according to the sediment present at the shoreline. An additional fifth class of 'no mobile sediment' was needed to describe segments where no mobile geomorphology was present, mostly found associated with ports and harbours (human infrastructure) and some erosion-resistant coasts. Where two sediment types are present (e.g., a sandy beach at the edge of a muddy estuary), this was also recorded.

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Table 2 Description of coastal sediment types recorded in the CoasTER database

Sediment type	Description
Mud	Predominantly muddy and/or fine sand sediments, may have sand as upper foreshore
Sand	Predominantly sand
Sand/Gravel	Mixture of sand and coarser grains (pebbles, gravel, shingle)
Rock	Mainly rock or rocky platform with some mobile sediments from sand to boulders. May include small beaches
No mobile sediment	No mobile geomorphology exists (i.e., permanent water presence). Applied to man-made structures and some cliffed coasts

3.2.2 Land cover

As the potential impact of erosion or landward migration is mainly determined by the value and use of any land affected, the Corine 2018 land cover dataset (CLC, 2020) was re-classified to recognise developed, agricultural and natural areas (see Table A2). Each segment was allocated the simplified code according to the land cover within the 100 m coastal zone.

3.2.3 Coastal structures

Coastal segments that are associated with visible human structures, both onshore and offshore, are identified. In this analysis, all engineered structures are considered as potential constraints on geomorphic response (i.e., constrained in Table 3). This extends beyond coastal defences to include infrastructure such as roads and railways as well as buildings that are within the 100 m coastal erosion zone. While these structures may not be defences, they are likely to perform a similar role in restricting the natural evolution of the coastal system either directly or indirectly by triggering a defence response. This allows for the consideration of structures that may, over time and on an erosive coast, require coastal defences to prevent their damage or loss.

Ports and harbours are considered onshore structures but are also identified separately as they can generally be regarded as fixed sections of the shoreline with no geomorphic component of the response. Offshore structures are also recorded separately and are considered to limit rather than constrain geomorphological response unless found in conjunction with onshore structures, where the latter are considered to have the dominant influence. The presence of structures is taken from the incorporated datasets supplemented with new or extended lengths following application of the criteria and verified by visual inspection using World Imagery (Esri, 2024) and Google Earth (Google Earth, 2024).

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Corine 2018 codes were also combined with coastal structure information to differentiate between major ports and minor ports and harbours. Where harbour segments in the database and the Corine 2018 port code coincide, a major port was identified. Ports and harbours associated with other land cover types are then considered to be either minor ports or recreational harbours.

3.2.4 Coastal floodplain extents

Each coastal segment is connected, where appropriate, to a 1 in 100 year coastal floodplain, including an allowance for sea level rise. These extended floodplains use a 2m rise in sea level assuming no human intervention (Lincke & Hinkel, 2023) in line with recent guidance (e.g., Le Cozannet et al., 2023), which argues that 2m of sea level rise is inevitable over the coming centuries and should be considered in planning strategies. The majority of floodplains are directly linked to the open coast and, where they coincide with coastal segments, a local floodplain identification number is assigned. However, erosion can also have non-local, more indirect implications for floodplains behind barrier coast features (e.g., Bateman et al., 2020; Scott et al., 2020; Stéphan et al., 2024). To capture these potential effects, protective barrier features such as barrier islands and spits and their associated 'remote' landward floodplains are also identified in the database. This highlights where erosion may have wider and more extensive consequences.

3.2.5 Historical shoreline movement

Although the general premise is that the coastal profile will migrate landward over the long-term with rising water levels, short-term profile fluctuations are expected to occur as a result of variations in waves, tides, storms and sediment availability and movement, particularly for low-lying geomorphologies. While the Eurosion database includes information about observed shoreline changes over the 1980s and the 1990s, this was obtained by a bottom-up approach whereby local, regional and national observatories reported about their local observations (Le Cozannet et al., 2020). This data was not included here as (1) the observation timeframe is shorter than those based on remote sensing data currently available, and (2) the reporting process was prone to errors due to variable interpretation of the guidance (Le Cozannet et al., 2016).

A dataset of historical spatially-consistent shoreline movement based on satellite measurements covering the period 1984 to 2021 (37 years) was therefore used to consistently describe long-term shoreline movement trends. This is an extension to the data analysed in Luijendijk et al. (2018) and the same definitions based on data limitations were used to identify three movement trends; (1) moving landward (erosion or migration <−0.5 m/yr), (2) moving seaward (accretion >0.5 m/yr) and (3) remaining in the same position (stable −0.5 to 0.5 m/yr). These broad classes identify rapidly eroding or accreting shorelines and slower changing and stable coasts as stable. The CoasTER database therefore focuses on where movement trends are most evident rather than providing precise localised rates.

Soft management (e.g., beach nourishment, managed realignment or saltmarsh restoration) can also modify any underlying natural trend and is recently being practised on larger scales (Brand et al., 2022; de Schipper et al., 2021; Foster et al., 2013;

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Hanson et al., 2002; Hudson et al., 2021). The effects of soft management are not identified in the CoasTER database as there is no European dataset and it is not always possible to distinguish these details at the regional scale.

3.3 Coastal geomorphologically based typology

Building on the coastal characteristics, as a first step, a distinction between erodible and erosion-resistant coast largely based on the Eurosion classification codes (Eurosion, 2004; see Table A1) was developed.

Table 3 Coastal classification with description, including consideration of the effect of structures on the ability of geomorphological landforms to migrate and/or erode

Coastal classification	Human influence	Description
Erosion-resistant coast		Hard rock formations (often cliffs), sometimes fronted by mobile sand and coarser sediments or rock. Can include pocket beaches.
Erodible cliffs	None	Steeply rising land of erodible material, fronted by mobile sand and coarser sediments or rock, which are liable to recede
	Limited	Steeply rising land of erodible material fronted by cross or offshore structures only. Erosion of the cliff due to coastal processes is still possible during extreme events
Dune system	None	One or more mobile ridges of blown sand of variable height (including cliffs) and often vegetated, fronted by a sand beach. Capable of overwhelming any structures to the rear. May include some wetland or saltmarsh areas
	Limited	Dune system fronted by cross or offshore structures only. Landward migration or erosion due to coastal processes during extreme events are still possible
Beach	None	Sand and coarser sediments present at high water and backed by gradually rising ground. May be vegetated. Able to migrate landward
	Constrained	Sand or coarser sediments present at high water, prevented from migrating by long-shore and/or cross-shore structures. Often isolated from the natural geomorphology
Coastal wetland	None	Tidally exposed vegetated areas and open flats, mainly associated with fine-grained (muddy) sediments
	Constrained	Largely vegetated wetland areas prevented from migrating landward by engineered structures
Intertidal	None	Not relevant. On unconstrained mainland coasts intertidal areas always have a landward geomorphological landform which defines the geomorphological class
	Constrained	Areas of mud, sand or rock exposed during low tide with a structure located around high water preventing landward migration
Not active		Sections of human structures where no coastal geomorphology exists (i.e., permanent and abrupt transition from land to water). Mainly ports and harbours where the shoreline is considered ‘fixed’
Water		Where the defined shoreline crosses a river or estuary mouth or other body of water

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Erosion-resistant coastal segments follow the Eurosion codes *A* and *C*, described as mainly 'rocks and/or cliffs made of hard rocks (little subject to erosion) or 'mainly rocky, little erodible, with pocket beaches (<200 m long)' respectively. The remaining segments were then considered to be erodible and, as a second step, were classified according to a four class geomorphological typology based on coastal landforms. This typology identifies the dominant mobile geomorphological landform on the natural cross-shore profile, effectively (erodible) cliffs, dunes, beaches and wetlands.

As a third step, where an engineered structure restricts the ability of the coastal profile to migrate landward (or erode), the geomorphological class is redefined to include just the landforms that are still responsive to coastal processes (i.e. seaward of the structure). Structures may constrain or limit coasts as follows: (1) constrained coasts where a shore parallel structure forms a continuous fixed boundary which prevents potential landward movement, for example, a seawall or promenade; and (2) limited coasts where structures may reduce but not prevent landward migration, especially during extreme events, for example, an offshore structure. Where coastal structures define the shoreline and there is no natural coastal geomorphological landform (most commonly found at ports and harbours), the shoreline is considered to be geomorphically 'not active' (Table 3).

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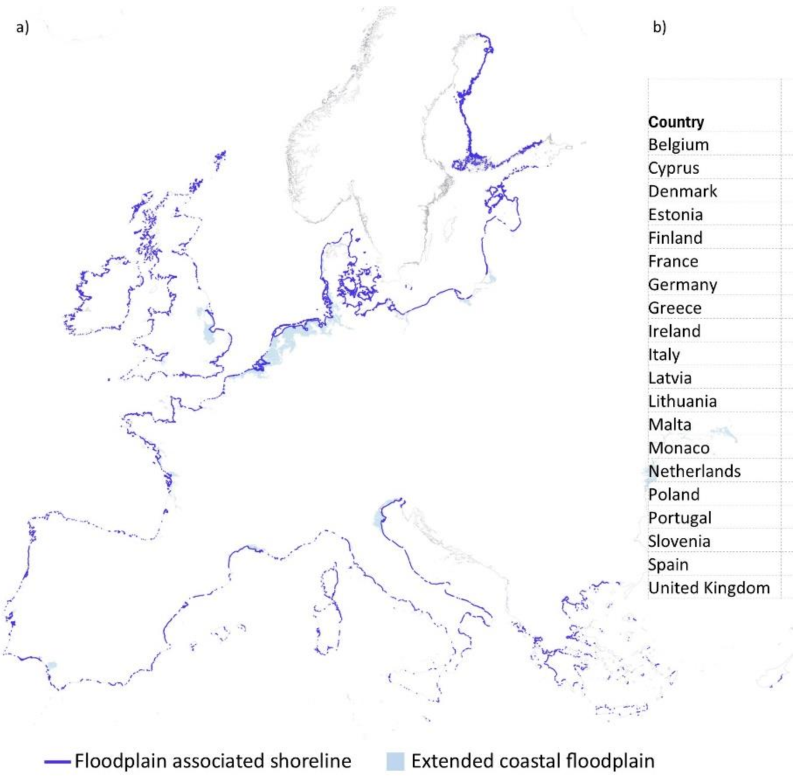
4 Erosion and floodplain interactions around the European coast

The results presented here illustrate the CoasTER database and focus on insights concerning flood and erosion interactions by selecting from the database all the segments associated with an extended coastal floodplain. Over 31,000 km (nearly 40%) of the analysed shoreline have the potential to be flooded when considering the influence of 2 m sea level rise on water levels.. Nineteen of the countries included (Monaco being the exception) have coastal floodplains which range from nationally significant, for example, the Netherlands where 95% of the shoreline is associated with large coastal floodplains (see Fig. 3) to countries where the associated coastal lengths are long, but floodplains cover a relatively small proportion of a country's total area. The latter indicate either the presence of locally significant coastal floodplains (e.g., Portugal, Italy, Poland) or where the floodplains have limited inland incursion but are continuous along the shoreline (e.g., Finland, Estonia).



b)

Country	Floodplain area (km2)	Percentage of shoreline associated with floodplain
Belgium	6,356.7	62
Cyprus	55.8	17
Denmark	8,841.4	71
Estonia	1,330.7	66
Finland	2,931.6	51
France	12,095.6	42
Germany	28,243.8	88
Greece	1,890.9	12
Ireland	1,108.8	38
Italy	7,071.3	30
Latvia	2,067.2	55
Lithuania	838.1	95
Malta	0.1	3
Monaco	0.0	0
Netherlands	28,337.1	95
Poland	3,073.7	75
Portugal	981.5	58
Slovenia	19.2	43
Spain	2,896.5	23
United Kingdom	12,199.5	30

Figure 3 Coastal lengths associated with the extended coastal floodplains (a) and significance for individual countries (b)

Fourteen percent (4,400 km) of the analysed shoreline was identified to be acting as barriers for floodplains, with Germany, Denmark and the UK having the longest length of shoreline so classified. In addition to the local coastal floodplains (directly affected by changes in water levels), another consideration for flood/erosion interactions are natural features such as barrier islands and spits whose evolution can affect local and remote landward floodplains. Just over 2,000 km of barrier shorelines

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are associated with more extensive flooding potential (remote coastal floodplains). Lithuania and Poland have the highest percentage of their shoreline (69% and 51% respectively) identified with this large-scale flooding potential if barrier erosion occurs. However, the historical movement trends, where available, indicate that the majority of these shorelines are currently stable or accreting (66%).

Eroding barrier segments, commonly sandy dune systems, are concentrated in northern Europe along the Dutch and German coasts, although localised eroding examples are also found around the Mediterranean coasts. For local floodplains, although there are some low-lying floodable areas that are considered erosion-resistant due to their rock sediment type (e.g., Greece, the UK, Finland and Ireland), the majority (approx. 25,000 km, 80%) of the extended floodplain shoreline is associated with mobile sediments, almost equal lengths of sand, sand/gravel and fine sediments, and could potentially be subject to erosion. For these erodible coasts, 73% have historical movement trends that include the effects of any coastal management over the past 37 years. In total across all floodplains with shoreline movement data, accretion is the most common trend (46%) with erosion and stability found equally along the remaining shoreline (see Fig. 4). However, erosion, which is most prevalent for sandy shorelines, has more impact on individual country shorelines. France, Belgium and Portugal, for example, have a high prevalence of erosion on their floodable shorelines. This could have implications for Portugal in particular, where the longest erosive lengths are also associated with natural barriers.

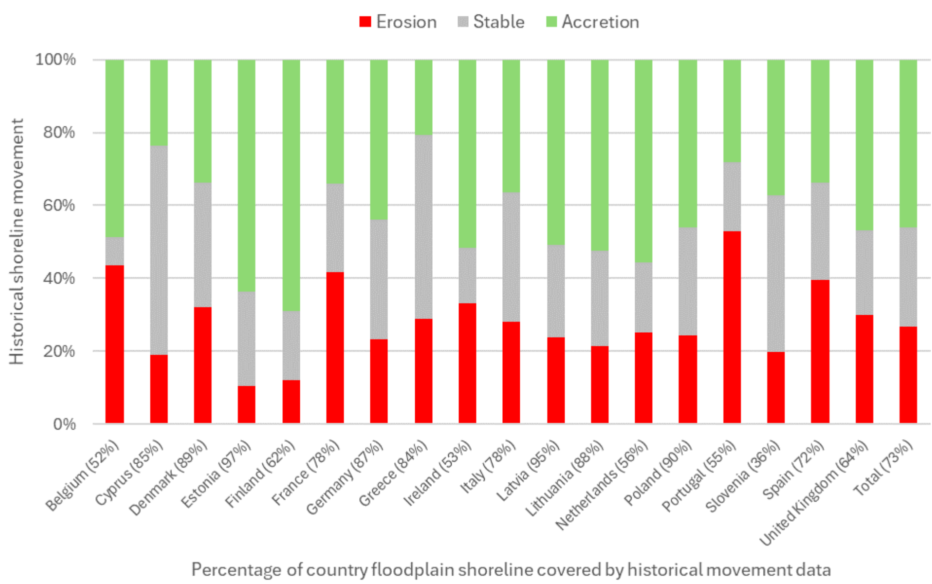

Figure 4 Percentage of erodible coastal floodplain shorelines with historical movement trends, irrespective of human activity and coastal type. Excludes erosion-resistant shorelines, ports and harbours and shorelines with no data.

The current coastal geomorphology along the floodplain shoreline is most frequently natural coastal wetlands and dune systems which are associated with extensive local floodplains (Fig. 5). For these shorelines, landward movement

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(represented as erosion) is found along around 3,500 km (34%) of floodable shoreline and is part of the natural evolution of the coastal system. The majority of these combined geomorphological classes are associated with open scrubland with less than 125 km of the eroding shoreline associated with developed areas and 540 km with agricultural land.

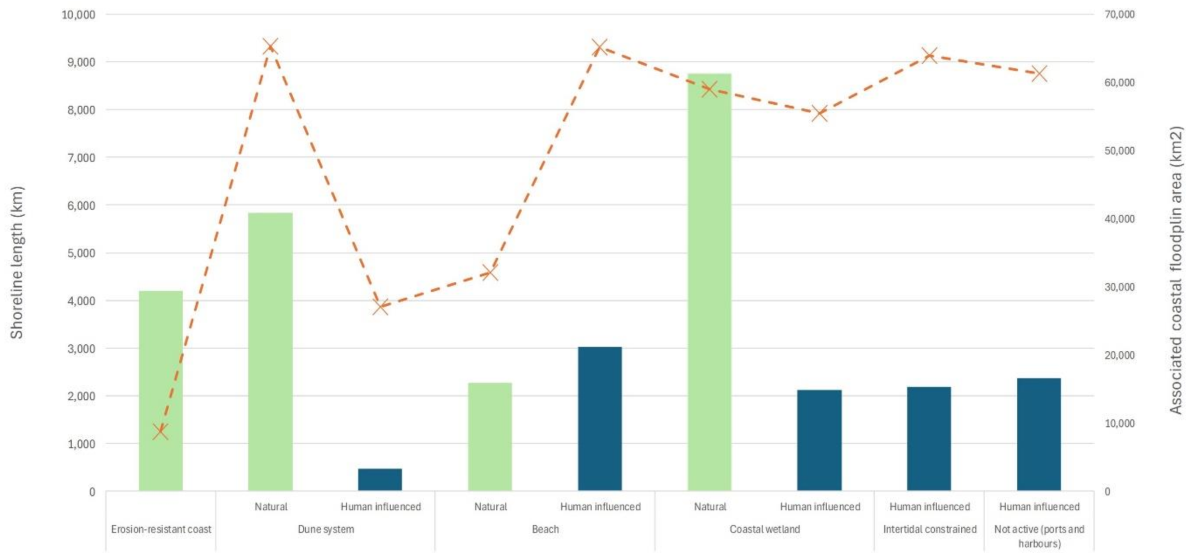

Figure 5 Distribution by length (km) of coastal classification with associated local floodplain areas

Human activity, in the form of human structures within 100 m of the shoreline, extends over approximately 10,000 km (33%) of the total floodable shoreline and is related to almost 211,500 km^2 of coastal floodplain, a significantly larger area than natural areas. The effect of human structures on the natural coastal geomorphology is to reduce the active coastal system to either a beach or wetland that cannot migrate landward ('constrained' classes; see Table 4 for distribution across countries) and would be expected to decline in width (erode) exposing any landward structures to enhanced wave activity under the influence of sea level rise. Where the coastal classification is 'intertidal constrained' or 'fixed' (ports and harbours), tidal and wave processes are already directly affecting the associated structures and the likelihood of increasing overtopping due to sea level rise is high (Almar et al., 2021).

While the percentage of developed coasts geomorphologically constrained by human structures in floodplains is high (commonly 'beach constrained'), the presence of structures for other land cover classes is also significant (Fig. 6). Distribution of the 'coastal wetland constrained' class which is often associated with agricultural landcover, for example, reflects the social and economic importance (e.g., food security) placed on these areas (e.g., Linnér & Messing, 2012). Structures in these cases are generally erosion and/or flood defence structures. For these constrained shorelines, historical shoreline movement over the past 37 years indicates that erosion has occurred along 1,800 km across all land cover types. Where wetland areas are subject to erosion (over 160 km), it suggests that these defences are often removing accommodation space and impacting coastal wetland extents (e.g., Schuerch et al., 2018). The remaining nearly 5,000 km of erodible constrained shorelines have either remained stable or accreted.

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Table 4 Coastal length (km) associated with floodplains by coastal typology and country (see table 3 for details about the various classes)

	Coastal floodplain length (km)								
Coastal type	**Erosion-resistant**	**Erodible**							**Not active (mainly ports and harbours)**
Geomorphological class	**Erosion-resistant**	**Dune system**		**Beach**		**Coastal wetland**		**Intertidal**	
Human influence		**None**	**Limited**	**None**	**Constrained**	**None**	**Constrained**	**Constrained**	
Belgium	0	9	13	0	7	0	0	0	26
Cyprus	0	7	0	6	7	0	0	1	3
Denmark	0	590	64	1,116	209	844	147	222	276
Estonia	0	181	0	76	2	1,263	8	2	19
Finland	1,991	38	0	18	43	3,758	247	192	238
France	79	685	66	121	526	239	239	137	297
Germany	0	535	112	19	130	407	611	271	180
Greece	30	614	11	152	331	280	70	113	80
Ireland	762	435	4	174	76	180	42	64	31
Italy	16	660	51	118	706	220	21	87	369
Latvia	0	240	1	1	11	11	0	3	11
Lithuania	0	105	0	0	0	31	0	6	19
Malta	7	0	0	0	0	0	0	0	1
Netherlands	0	216	75	0	54	158	249	540	175
Poland	0	241	54	4	28	37	10	14	39
Portugal	2	296	0	3	75	316	192	63	88
Slovenia	6	0	0	0	1	0	0	7	13
Spain	27	431	8	29	262	106	67	63	256
United Kingdom	1,285	559	12	440	550	904	223	406	258
Total length	**4,205**	**5,841**	**473**	**2,278**	**3,019**	**8,753**	**2,127**	**2,189**	**2,377**

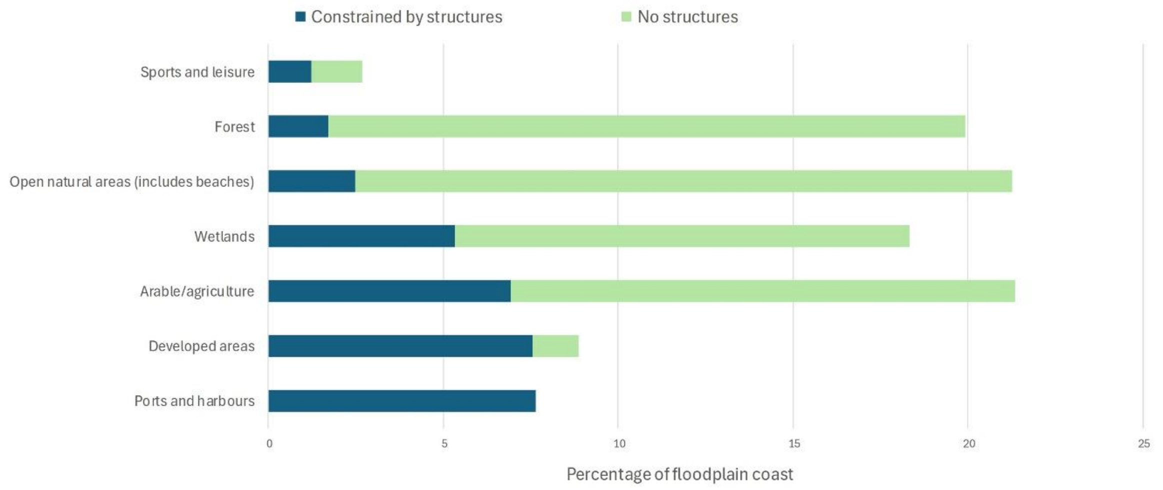

Figure 6 Human structures within 100m of the shoreline across landcover types for extended coastal floodplains

Human structures are a identified as onshore and offshore hard engineering or harbours. The latter representing almost a quarter of the onshore hard engineering by coastal length (see Table 5). As with the length of shoreline associated with the extended floodplains, countries with significant lengths of coastal structures are located in northern Europe (Germany, UK, Netherlands). Italy is an exception with extensive development, ports and defence structures along its mainly open shoreline. Italy also has the most notable length of combined onshore and offshore structures, particularly along its Adriatic coast.

As engineered structures, ports and harbours represent fixed sections along the coast with the necessary infrastructure exposed directly to changing water levels and requiring continual maintenance and upgrade. Major port infrastructure in particular is unlikely to be abandoned even if the port itself is relocated (e.g., Andrade et al., 2024). Figure 7 shows that Italy has the highest commitment to maintaining open coast major port infrastructure in floodplains followed by France, Spain and the UK. Germany, Denmark and Finland, with their large number of islands, have long extents of secondary ports and other harbours. It should be noted that some large ports are not included in the database as a geomorphological landform exists to seaward (e.g., the land reclamation - Maasvlakte-2 - seaward of the Port of Rotterdam is fronted by an artificial beach) and some ports may be over represented by length due to the form of the shoreline.

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Table 5 Length of human structures by country and structure type

Country	Floodplain with structures (%)	Coastal length with associated floodplain (km)				
		Onshore only	Offshore only	Off and onshore	Ports and harbours	Ports with offshore structures
Belgium	83	20	0	0	26	0
Cyprus	45	5	0	3	3	0
Denmark	26	625	0	16	276	0
Estonia	2	12	0	0	19	0
Finland	11	487	0	1	238	0
France	53	959	0	14	288	9
Germany	57	1,122	0	2	180	0
Greece	36	526	0	2	79	0
Ireland	12	186	0	0	31	0
Italy	55	711	1	153	334	34
Latvia	10	17	0	0	11	0
Lithuania	15	6	0	0	19	0
Malta	9	0	0	0	1	0
Netherlands	74	914	0	4	175	0
Poland	34	103	0	3	39	0
Portugal	40	330	0	0	88	0
Slovenia	78	9	0	1	13	0
Spain	52	395	0	4	251	5
UK	31	1,170	0	15	258	0
Floodplain total	**33**	**7,596**	**1**	**219**	**2,327**	**48**

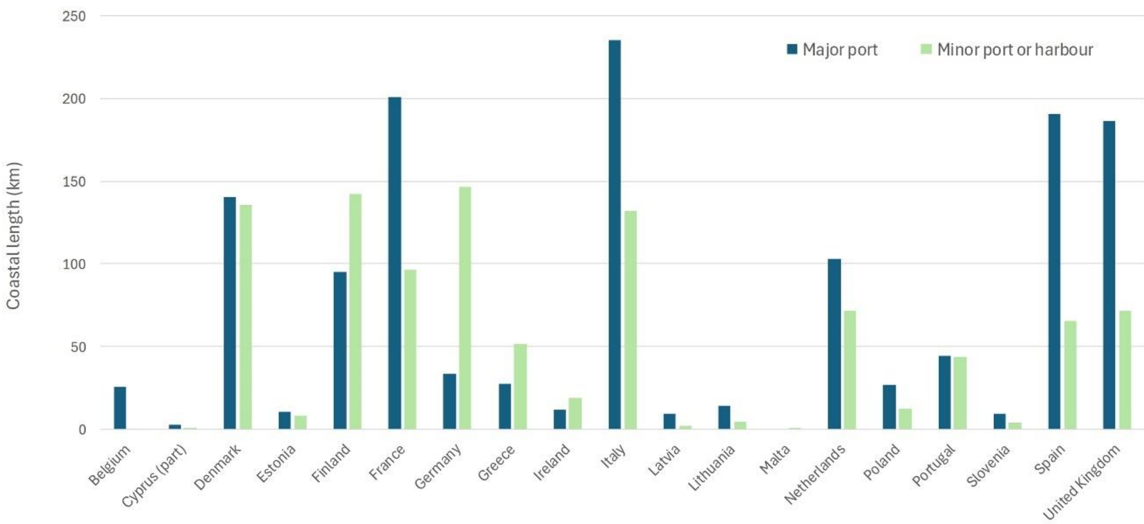

Figure 7 Length of coastal floodplain classified as a major port or minor ports and harbours

In summary, while erosion occurs over significant lengths of shoreline subject to coastal flooding, it is not the dominant historical shoreline tendency even for developed areas where buildings and other infrastructure restrict natural evolution. However, it is important to remember that even where the historical movement trend is stable or accretion, this may not continue into the future under the influence of rising sea levels. Excluding ports and harbours which are assumed to be maintained and/or adapted in place, if erosion is universal along developed coasts, over 2,500 km will require additional defences to maintain current protection levels and nearly 1,000 km are likely to require new defences to be implemented over the short or medium term. Over 5,000 km of other land cover classes are likely to also experience land loss, particularly important for barrier features. The decision on whether to protect these areas or not will depend on the legislative circumstances, the available funds and social value assigned to agricultural areas and the environment among other issues. For lengths of floodplain coast classified as erosion-resistant, protective structures may still be required but focussed on reducing flood risk rather than preventing erosion.

5 Discussion

As coastal areas in Europe are expected to be at a higher risk of flooding and erosion over the coming century due primarily to climate-induced sea level rise, the CoasTER database offers a new overview of hazard interactions and potential implications for developed areas. The analysis presented here indicates that erosion and flood hazards presently interacts over approximately a third of the analysed shoreline, based on 37 years of shoreline movement data. This has not only local implications but could also have consequences for much larger impacts for developed areas by affecting the evolution of natural protective barrier features. At the same time, human activity along the shoreline provides a restriction on the coastal system by curtailing its ability to respond to changing coastal water levels by migrating landward. Largely associated with

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developed and agricultural areas, these constrained shorelines are found along over a third of the floodplain coastline and are related to extensive floodplain areas. There is no direct relationship of these shorelines with historical erosion as two thirds are found to either be stable or accreting. This may be due to natural shoreline variations, the presence of effective defence structures or management using 'soft' engineering such as beach nourishment masking the underlying trend as, for example, in the Netherlands . Also, the assessment of erosion is dependant on the current limitations of remote-sensing based approaches. These are appropriate to detect erosion or accretion rates exceeding 0.5m/year but slower erosion rates which can cause significant risks locally are omitted; erosive shoreline lengths reported here may therefore be underestimated. Hence, it would be useful to add or update the historical shoreline movement e.g. through a bottom-up process involving coastal observatories as in Eurosion, or when suitable data or local knowledge become available. However, based on the assumption of erosion as a future response to sea level rise over this century, significant lengths of urban and other developed shorelines are likely to need new or enhanced management to maintain current levels of risk.

The CoasTER database makes it easier to understand and explore relationships and interactions between various aspects of the coastal system and identify trends which may otherwise be overlooked. These can highlight areas where particular issues arise. The regional scale of the database offers a general assessment of flood and erosion issues encountered around Europe and provides an estimate of the length of coast that will require management to protect valuable assets in the future. In particular, the combination of the geomorphological classification to capture the historical context of human activity in the coastal zone, use of an allowance for sea level rise which captures uncertainty and historical shoreline movement, provides a first assessment at the regional scale for insights into flood and erosion interactions as well as the existing commitment to coastal defence. The classification also illustrates the length of coast which is already 'fixed' or constantly exposed to water levels and unlikely to be abandoned. This is currently focussed on ports and harbours, but could also cover coasts where any structure is at or near hightide (currently 'intertidal constrained'). Also, although generalised results are presented here, the use of coastal segments within the shoreline does offer the opportunity for more detailed analysis. This is particularly the case for historical movement as floodplain evolution is more locally defined and varies both within and between floodplains.

Inevitably, there are limitations associated with the source data. The EEA shoreline data offers a detailed and representative shoreline for analysis but some features, especially land claim, harbours, and other infrastructure contain digitizing artifacts that do not reproduce their general shape. Geomorphically inactive shoreline, mainly ports and harbours, may also appear over represented as a percentage of a country's coast (notably in Belgium, Netherlands); the detailed inclusion of quays, wharves and other structures within the shoreline creating a disproportionate long shoreline length, reflecting the fractal nature of shorelines. There is a similar effect for coastal wetlands (e.g., Portugal) where the detailed shoreline significantly increases lengths and percentages for this geomorphological class. In addition, the shoreline sometimes follows features which are misinterpreted (e.g., following inland cliff lines) or are not visible in satellite imagery (e.g., obscured by vegetation) leading to some subjective inferences being made on the form and composition of the coast. The EEA shoreline also excludes some new developments, e.g., the Port of Rotterdam expansion. Not all of these have been identified and manually corrected. Limitations of coastal characteristic data also need to be recognised. The definition and purpose of the

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other source shorelines mean that sections of the EEA shoreline do not have information. Full coverage of estuaries, inlets and lagoons is notably missing as is the majority of Cyprus' shoreline. The Netherlands for example has sections of shoreline behind artificial coastal barriers which are not covered by the historical movement data and the 'inland' coasts of North Jutland, Denmark are not covered by sediment and geomorphological information. Transference of attribute data from different shorelines also required the use of assumptions which may have led to inaccuracies and inconsistencies. For example, complex coastline such as those found in Finland, Ireland and the UK present challenges for the accurate allocation of data and coverage in the Corine data set does not always correspond with the shoreline.

Despite these limitations, the CoasTER database provides an updated European-scale database that lends itself to development and improvement and is instrumental in allowing investigation of areas of interest for both flooding and erosion, particularly in areas where erosion may ultimately result in increased flood risks. Notably, out of the 31,000km of European coastal floodplain shorelines, 16,700km are made of unconstrained wetlands, dune systems or beaches (Table 5), and may ultimately become pathways for flooding. Adaptation strategies to manage this challenge will include a combination of measures ranging from relocation, ecosystem restoration, accommodation and protection – this goes beyond the scope of this study. However, these results reveal the magnitude of the problem, indicating a Europe-wide issue that deserves the attention of national and European decision-makers in order to define a coherent strategy. For more local studies, CoasTER can inform the locations where both erosion and flooding should be considered in model-based assessments.

6 Conclusions and development for future research

There is international recognition that, for many countries, some of the first and most obvious effects of climate change will be through increased erosion and flood impacts along the shoreline and this attracts stakeholder concern (e.g., Jiménez et al., 2024). Part of coastal risk assessment is a developing an approach which helps to pinpoint and appraise risks that could potentially result in major impacts or disruptions. The CoasTER database also describes what coastal stakeholders perceive or interact with in a real and tangible way. The database shows that erosion and flooding are potentially widely linked with most coastal floodplains being situated on coasts where erosion may occur. While this is European in scale, by drilling into detailed sections it may be possible to engage with coastal stakeholders in more detail and capture more details as demonstrated by French et al. (2016) for relatively detailed case studies.

The CoasTER database represents an advancement over existing European coastal erosion datasets (e.g., Eurosion (EEA, 2004)). It refines earlier work by simplifying and harmonizing classification schemes while integrating more recent datasets, such as land cover classification and historical shoreline movement (see Luijendijk et al., 2018). Additionally, the underlying coastline dataset has been manually corrected to remove digitization artifacts and generalized where possible. A key improvement of this dataset is the inclusion of engineered coastal structures. By systematically mapping sediment type, land

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cover, coastal structures, floodplain identifiers, shoreline movement, and geomorphological classification onto a consistent, corrected coastline, the dataset provides a robust foundation for large-scale coastal erosion and flood analysis.

Compiling this database required significant manual effort, often due to inconsistencies in the underlying data sources, which had to be standardized, mapped, and corrected. While it is a valuable geospatial resource for European-scale and regional coastal analysis, it has limitations. Some regions, such as Norway and the Adriatic Sea, lack coverage in key source datasets, making it difficult to extend the database to those areas. However, additional datasets such as geomorphological information (e.g., regional data EMODnet https://emodnet.ec.europa.eu/en; national data e.g., BGS (2023)), coastal water level data (e.g., LISCOAST, Vousdoukas et al., 2020), or more innovative earth observation datasets such as characterising muddy coasts (Hulskamp et al., 2023), could be incorporated using a similar approach.

Also, the current availability of satellite data, powerful (cloud-) compute infrastructures and machine learning methods (Calkoen et al., 2025) can nowadays enable automated approaches to coastal classification that can update and improve the dataset presented here. Satellite-derived data products offer consistent, global coverage, while machine learning techniques can be trained to extract coastal characteristics using a consistent method. When combined with modern (cloud-) compute infrastructures, such approaches make it possible to conduct high-resolution, broad-scale coastal analysis with far less manual work. The methodology applied here aligns with this direction, demonstrating the potential for future geospatial data products that leverage satellite data, cloud infrastructure and machine learning.

7 Data availability

The CoasTER database is available as a download in cloud-optimized format and described in a STAC collection produced using CoastPy (see Calkoen et al., 2025). It can be found in through the CoCliCo data catalogue https://www.openearth.nl/coclico-workbench/data_catalog/ or directly from https://coclico.blob.core.windows.net/items/coaster.parquet

8 Author contributions

SH developed and constructed the database with conceptual and practical support from RN, FC GL and AL. SH prepared the manuscript with contributions from all co-authors.

9 Competing interests

The authors declare that they have no conflict of interest.

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Appendix A

535 **Table A1 Coastal and sediment type reclassification based on Eurosion (2004) description**

Code	Description	Term
Coasts		
A	Rocks and/or cliffs made of hard rocks (low level of erosion), sometimes with a rock platform	**Erosion-resistant**
B	Conglomerates and/or soft-rock cliffs (e.g. chalk), which are subject to erosion: presence of rock waste and sediments (sand or pebbles) on the strand	**Erodible**
AC	Mainly rocky, low level of erosion, with pocket beaches (<200 m long), not localised on the segment	**Erosion-resistant**
C	Small beaches (200 to 1000 m long) separated by rocky capes (<200m long)	**Erosion-resistant**
L	Coastal embankments	**Intertidal constrained**
Y	Artificial shoreline without sandy strands	**Intertidal constrained**
Sediment type		
A	Rocks and/or cliffs made of hard rocks (low level of erosion), sometimes with a rock platform	**Rock**
B	Conglomerates and/or soft-rock cliffs (e.g. chalk), which are subject to erosion: presence of rock waste and sediments (sand or pebbles) on the strand	**Sand/Gravel**
AC	Mainly rocky, low level of erosion, with pocket beaches (<200 m long), not localised on the segment	**Rock**
C	Small beaches (200 to 1000 m long) separated by rocky capes (<200m long)	**Rock**
D	Extensive beaches (>1 km long) with strands of coarse sediment (gravel or pebbles)	**Sand/Gravel**
E	Extensive beaches (>1 km long) with strands of fine to coarse sand	**Sand**
F	Shorelines of soft non-cohesive sediments (barriers, spits, tombolos)	**Sand**
G	Strands of muddy sediments: "wadden" and intertidal marshes with "slikkes and shorres"	**Mud**
J	Harbour areas	**No mobile sediment**
K	Artificial beaches	Not used

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M	Polders	Not used
N	Very narrow and vegetated strands (pond or lakeshore type)	**Sand/Gravel or Mud**
P	Soft strands with rocky "platforms" (rocky flats) on intertidal strands	**Rock**
R	Soft strands with "beach rock" on intertidal strands	**Sand/Gravel**
S	Soft strands made of mine-waste sediments	**Sand/Gravel**
X	Soft strands of mixed grain-size categories	**Sand**
Z	Soft strands of unknown grain-size category	**Sand/Gravel**

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Table A2 Simplified CoCliCo land cover classification derived from Corine

CoCliCo code	Corine 2018 code	Code description
1. Developed areas	111	Continuous urban fabric
	112	Discontinuous urban fabric
	121	Industrial or commercial units and public facilities
	122	Road and rail networks and associated land
	124	Airports
	131	Mineral extraction sites
	132	Dump sites
	133	Construction sites
2. Sports and leisure	141	Green urban areas
	142	Sport and leisure facilities
3. Agriculture	211	Non-irrigated arable land
	212	Permanently irrigated land
	213	Rice fields
	221	Vineyards
	222	Fruit trees and berry plantations
	223	Olive groves
	231	Pastures
	241	Annual crops associated with permanent crops
	242	Complex cultivation patterns
	243	Land principally occupied by agriculture, with significant areas of natural vegetation
4. Forests	244	Agro-forestry areas
	311	Broad-leaved forest
	312	Coniferous forest
	313	Mixed forest
5. Open natural areas	321	Natural grasslands
	322	Moors and heathland
	323	Sclerophyllous vegetation
	324	Transitional woodland-shrub
	331	Beaches, dunes, sands
	332	Bare rock
	333	Sparsely vegetated areas
	334	Burnt areas
6 . Inland wetlands	411	Inland marshes
	412	Peat bogs
7. Maritime wetlands	421	Saltmarshes
	422	Salines
	423	Intertidal flats
	511	Water courses

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8. Ports and harbours	123	Port areas
9. Water	512	Coastal lagoons
	521	Inland waters
	522	Estuary
	523	Sea and ocean

540 **Appendix B**

Table B1. List of coastal attributes and descriptions in the CoasTER database

Name	Data Type	Description
source	string	Source of coastline data used in analysis.
country	string	ISO 2-letter country code where the segment is located.
covered	string	Indicates if the coastal classification has been applied: 'Y' (Yes), 'N' (No), 'N/A' (Not included).
seg_id	string	Unique segment ID assigned within each country.
seg_length	int	Length of the coastal segment in meters.
associated_floodplain	string	Indicates if the segment is associated with a floodplain ('Y' for Yes, 'N' for No).
local_floodplain	string	ID of the local floodplain adjacent to the coastline segment.
remote_floodplain_1	string	ID of the first remote floodplain associated with the coastline segment.
remote_floodplain_2	string	ID of the second remote floodplain associated with the coastline segment.
onshore_structure	string	Indicates presence of onshore engineered structures affecting coastal evolution ('Y' for Yes, 'N' for No).
offshore_structure	string	Indicates presence of offshore structures like breakwaters affecting coastal evolution ('Y' for Yes, 'N' for No).
harbour	string	Indicates presence of a permanent port or harbour structure ('Y' for Yes, 'N' for No).
geomorphological_class	string	Classification of the coastal geomorphology (e.g., Beach, Dune system,), including the influence of structures
barrier	string	Description of the broad-scale coastal barrier feature, if present (e.g., Spit, Barrier Island, Tombolo).

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primary_sediment_type	string	Primary sediment type of the coastal segment (e.g., Sand, Mud, Rock, Sand/Gravel).
secondary_sediment_type	string	Secondary sediment type, if applicable (e.g., rock platforms in a sandy beach).
historical_shoreline_change_regime	string	Historical trend of shoreline movement from 1984 to 2021: 'Ero' (Erosion), 'Acc' (Accretion), 'Sta' (Stable).
corine_code_18	string	Corine 2018 land cover classification code for the segment.
corine_code_simplified	string	Simplified reclassification of Corine 2018 land cover codes.
Notes	string	Additional notes or comments on the segment.
Local_floodplain_area_km2	float	Total area (km^2) of the associated local floodplain.