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EMODnet Geology: pan-European assessment of coastal resilience and vulnerability

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Abstract: Coastal resilience and vulnerability, to marine erosion and flooding, are strongly influenced by geology, geomorphology and the presence or absence of engineering structures. Many studies, using a range of methodologies, have been conducted around the coastline of Europe to assess both resilience and vulnerability. A new EMODnet Geology data product provides a pan-European map visualization, at a range of scales, indicating lower, intermediate and higher levels of coastline vulnerability to erosion and flooding. The shorelines of the Mediterranean and Baltic Seas appear to be less resilient than those of the Atlantic Ocean, Greater North Sea and Black Sea. Estuarine, deltaic and other lowland shorelines with coastal barriers show lower resilience, except where they are managed through nourishments. The map, and associated metadata, provides a tool for users who are interested not only in the pan-European distribution of coastal resilience and vulnerability, but also in the wide range of methodological approaches used in their assessment.

Supplementary material: Guidance for accessing the new EMODnet Geology coastal resilience and vulnerability data tool is available at https://doi.org/10.6084/m9.figshare.c.7646833

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EMODnet Geology data products

The European Marine Observation and Data Network (EMODnet) provides a single-entry point for accessing and retrieving marine data and information derived from direct observations and remote sensing. Its portal hosts numerical and categorical results from field experiments and surveys, descriptions and laboratory analyses of physical samples, database analyses, and measurements made by various types of passive and active sensors from the hundreds of public databases maintained on behalf of agencies, national to local authorities, research institutions and universities throughout the EU. Across seven discipline-based themes – geology, bathymetry, seabed habitats, chemistry, biology, physics and human activities – digital map layers of harmonized or integrated data are delivered for entire sea basins around and even beyond Europe (https://www.emodnet.eu/).

EMODnet Geology delivers integrated geological map products, at various resolutions, for seabed-substrate composition, sedimentation rates, pre-Quaternary and Quaternary geology, geomorphology, coastal behaviour, submerged landscapes of the European continental shelf, geological events such as submarine landslides and earthquakes, and marine mineral occurrences (Moses and Vallius 2021; Asch *et al.* 2022; Hollis *et al.* 2022, 2024). It is important to note that the EMODnet Geology project does not create new data but, by implementing the Shared Environmental Information System (SEIS) approach, makes available existing data and information, enabling end-users to make comparisons at a range of geographical scales. Data integration, harmonization, interoperability and public access facilitate direct benefits, reducing operational costs of data acquisition and delivering a better information base for policy development and implementation (EC 2013; Meiner and Reker 2013; Hollis *et al.* 2022, 2024).

This Case study reports the development of a new data product on coastal resilience and vulnerability, delivered to the EMODnet Central Portal (www.emodnetgeology.eu/) and also accessible through the portal of the European Geological Data Infrastructure (EGDI: www.europe-geology.eu/). It is complementary to existing EMODnet Geology data products on coastline migration and coastal type, each underpinned by data on rates of landward or seaward coastal change, geology and geomorphology.

Coastal resilience and vulnerability

The resilience of a system is defined as its ability to withstand, and recover from, a major disruption. It is an indication of the robustness of the system and its sensitivity to change (Aven 2011). In coastal environments major disruptions, or changes, to the system are often associated with external drivers such as wave impact and marine flooding, usually linked with storms and sea-level rise. But internal drivers, including the strength properties of coastal materials (geology) and the shape or morphology of the coastal ribbon (geomorphology), also determine the sensitivity of the coastline to change, thus influencing its resilience. Coastal resilience can be considered as the ability of a coastline to absorb and recover from erosion before a critical state is reached.

Vulnerability is a measure of the susceptibility of a system to change. Higher resilience reduces susceptibility and thus vulnerability to change. Coastal resilience is typically considered in the context of the vulnerability of the coastline to the potential erosion and flooding events associated with climate change (e.g. Gornitz *et al.* 1994; Klein and Nicholls 1999; McLaughlin *et al.* 2002; Abuodha and Woodroffe 2006; Hinkel and Klein 2009; McLaughlin and Cooper 2010; Ramieri *et al.* 2011; Schultz *et al.* 2012; Bridges *et al.* 2015; Torresan *et al.* 2016; Roukounis and Tsihrintzis 2022). Coastal vulnerability is a function of the geological characteristics of resilience and susceptibility together with the magnitude of coastal forcing and of socio-economic factors. It is generally expressed as an equation in which individual factors are parameterized: Coastal Vulnerability Index (CVI) = *f*(coastal characteristics(resilience and susceptibility) + coastal forcing + socio-economic factors) (McLaughlin and Cooper 2010). CVIs can be mapped at a range of scales. Resilience, and especially its recovery component, is more strongly linked to the timeframe considered than vulnerability. Coastlines with long-term natural resilience may still be highly susceptible to short-term impact of extreme events, especially from an economic point of view. Their return to an earlier state over years or decades does not compensate for any damage suffered during erosion and flooding events in the intervening period.

Method

With input from all EMODnet Geology partners, we have developed the most complete inventory to date of case studies on coastal vulnerability, including studies that focus on related issues: coastal hazard, risk and resilience. Throughout the development of the data product, the methodological approach and progress have been shared with user groups for feedback and input (Moses *et al.* 2022, 2023; Van Heteren *et al.* 2024). The literature database includes scientific journal articles as well as national databases and reports for the EMODnet Geology coastline. Many studies place emphasis on physical and marine characteristics, others also incorporate socio-economic factors (Table 1). The literature database is continually updated as new studies are published, made available by EMODnet Geology partners or found in new internet queries. From a total of 919 sources, those that made direct reference in the title to coastal vulnerability (179), erosion (122), sea-level rise (98), risk (78), hazard (53), flood (40) and resilience (8) were scrutinized for data suitable for collation into a single GIS database.

The aim was to create a GIS base map from which data would be integrated into a common legend indicating lower, intermediate and higher levels of coastal resilience/vulnerability. This step involved geolocating suitable maps from the literature to the standardized EMODnet coastline (the coastline used across EMODnet Geology data products is the Mean Sea Level line available from EMODnet Bathymetry). In total, 565 maps were geolocated. To aid the data-integration process, two GIS layers were produced: one containing only geolocated maps for which a CVI was calculated and visualized, and the other containing geolocated maps that did not fit the standard CVI. Non-CVI indicators included levels of erosion/flood risk, hazard or resilience. Because multiple studies were used this meant that some stretches of coastline had more than one geolocated map. Where this was the case, either the most recently produced map or the map from the most thoroughly peer-reviewed article was selected for data integration, ensuring that the most up-to-date and highest-quality sources were used. The next step assessed the geolocated maps for geographical coverage. Maps for individual beaches or short sections of coastline, judged not to be representative of regional trends, were not used and only those covering several kilometres or more were retained. In total 56 geolocated maps formed the CVI base-map layer and 37 provided information for other vulnerability-related types. Following this quality-assurance process, the two layers, incorporating 93 geolocated maps derived from 59 different studies, were combined for data integration.

From the two base layers, a single map was produced indicating lower, intermediate and higher levels of coastal resilience/vulnerability. Three levels were used so that the data product is informative while still reflecting uncertainties associated with the diversity of the individual source maps. This involved several steps because these maps were produced using a range of methodologies. Using three levels along with zoom functionality ensured clarity in the final data product. Although the majority of studies indicated three levels, some included two additional categories of ‘very low’ and ‘very high’. Where this was the case, these two categories were included in ‘lower’ and ‘higher’, respectively, to retain three levels for the final visualization product. Using this approach, vulnerability levels were traced from the geo-referenced maps in ArcGIS Pro using the Line Notes tool. A legend was devised showing higher levels of resilience/lower levels of vulnerability in light blue, intermediate levels in mid-blue and lower levels of resilience/higher levels of vulnerability in dark blue, following good practice guidance (Martini and Loat 2007; Fig. 1). For CVI studies, lower, intermediate and higher vulnerability levels were recorded as such. For non-CVI maps: higher levels of erosion, flood risk or hazard were recorded as higher vulnerability and vice versa; higher levels of resilience were recorded as lower vulnerability and vice versa. After tracing, metadata were added to the vulnerability lines through the attribute table. In the final product, users are able to view the metadata, including source information and key parameters/criteria used to derive CVI or resilience for corresponding parts of the classified coastline, simply by clicking on the line. For more detailed information, e.g. on spatial scale, coordinate systems and vertical datums used in individual studies, the metadata provide sufficient information for users to access the original source study. Areas for which data have not been found in internet searches, are

Table 1. Typical physical and socio-economic parameters used to measure coastal resilience/vulnerability in the studies underpinning the EMODnet Geology coastal resilience/vulnerability data product

Parameters	Studies used to create base map
Physical: geomorphology, coastal slope, regional elevation, rate of sea-level rise, rates of shoreline erosion/accretion, tidal range, significant wave height	Aitali *et al.* (2020), Anfuso and Del Pozo (2009), Berre *et al.* (2022), Corbau *et al.* (2022), Djouder and Boutiba, (2017), Furlan *et al.* (2021), Harik *et al.* (2017), Hinkel *et al.* (2015), Hzami *et al.* (2021), Idllanène and Van Cauwenbergh (2016), Kont *et al.* (2003), Kovaleva *et al.* (2022), Lincke *et al.* (2020), Maanan *et al.* (2018), Martínez-Graña *et al.* (2016), Martins *et al.* (2012), McLaughlin *et al.* (2002), Mihoubi *et al.* (2014), O’Brien *et al.* (2004), Oxford Analytica (2021), Paprotny and Terefenko (2017), Pruszak and Zawadzka (2005), Rizzo *et al.* (2020), Robin (2002), Ros Montaña (2014), Ružić *et al.* (2019), Satta (2014), Satta *et al.* (2017), Snoussi *et al.* (2008), Stancheva (2010), Valchev *et al.* (2016).
Combined physical (as above) and socio-economic: settlement, cultural heritage, roads, railways, land use, conservation designation	Aernouts and Héquette (2006), Alexandrakis and Poulos (2014), Alexandrakis *et al.* (2010), Bagdanavičiūtė *et al.* (2015), Balounin *et al.* (2013), British Geological Survey (2022), Caloca-Casado (2018), Davies (2012), De Leo *et al.* (2019), Eberhards *et al.* (2006), Farrugia (2008), Fitton *et al.* (2016), Hirschhäuser and Hofstede (2020), Jaskólski *et al.* (2018), Kantamaneni *et al.* (2017, 2018, 2022), Mateescu *et al.* (2018), Mavromatidi *et al.* (2018), Narra *et al.* (2019), Ng *et al.* (2019), Pantusa *et al.* (2022), Poklar and Valentina (2023), Šegina *et al.* (2012), Simav *et al.* (2014), Sterr (2008), Tano *et al.* (2018), Vergouwe (2016), Zújar and Francoso (2009).

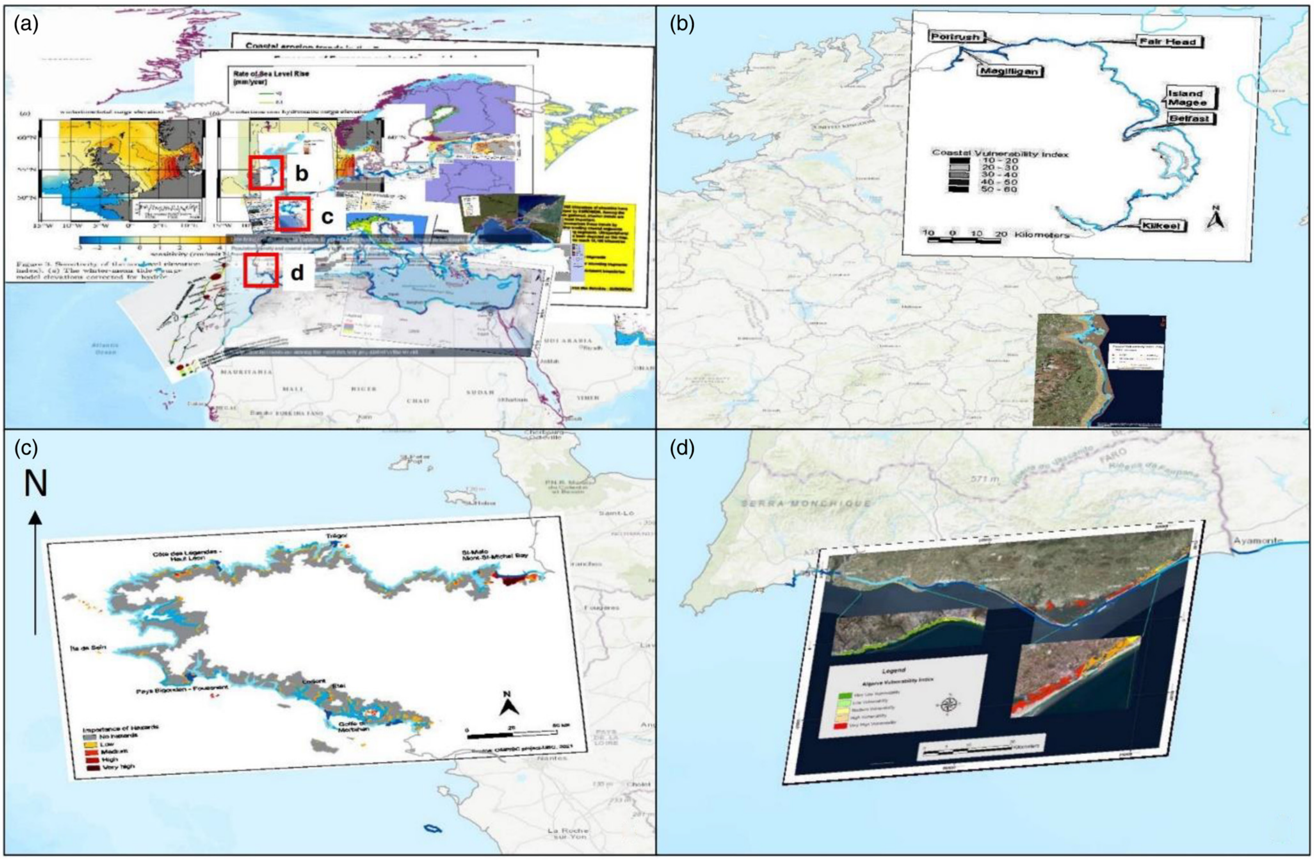

Fig. 1. The final data product, showing higher resilience/lower vulnerability (light blue), intermediate vulnerability/resilience (mid-blue) and lower resilience/higher vulnerability (dark blue) levels, integrates data from a large number of studies. (**a**) The map is underpinned by georeferenced maps from individual studies. Detailed examples of line tracing are shown for (**b**) Ireland, (**c**) northwestern France and (**d**) southern Portugal. The georeferenced maps are not visible on the data product in light of copyright. Source:(b) upper map McLaughlin *et al.* (2002), lower map Caloca-Casado (2018); (c) Berre *et al.* (2022); (d) Martínez-Graña *et al.* (2016).

demonstrably not available or are under development are indicated by a grey line. The associated metadata indicate where this is the case.

The final step in producing the data product was to visualize the data at different zoom levels (Fig. 2), enabling the user to view and download the map and metadata at a range of scales. Current EMODnet coastal data products consist of a zoomed-in base map (polylines for coastal type and coastline migration derived from field data, points for coastline migration based on satellite data) and a series of clearly identifiable points at different zoom levels. These summarize the underlying data by averaging attribute characteristics over increasingly long stretches of shoreline. The wish for the new data product was to portray zoomed-out data as a line rather than separate points. This has been achieved by increasing the point density, minimizing gaps between points and optimzing point density to create the impression of a line.

The zoom levels are correlated to those of the OpenStreetMap viewer basemaps. OpenStreetMap has set zoom levels with accompanying scales (https://wiki.openstreetmap.org/wiki/Zoom_levels). Following visual inspection of those scales, its zoom levels 5 to 12 were selected to create the new data product. At the minimum scale of each zoom level, the density was calculated to be the zoom level divided by 100 million. The tolerance of each point in decimal degrees, established in this step (Table 2), was used to determine the distance between the created points along the original lines.

The original line was processed for each tolerance level using a Feature Manipulation Engine (FME) workbench. FME statistically derived the most common resilience/vulnerability category along the base-level polyline in the tolerance area around the created point, assigning that category to the point. The final step assigned a summary of metadata to each point, via a spatial join to the closest coastline location. Although this creates mismatches between the metadata of the point and those of the underlying base-level data in some places, correspondence of visualized metadata to the colour of associated zoomed-out points took precedence.

Trends identified

Pan-European trends show best at the fully zoomed-out level (Fig. 2a). Keeping in mind the large stretches of non-classified coastline, the shores of the Mediterranean and Baltic Seas appear to be less resilient than those of the Atlantic Ocean, Greater North Sea and Black Sea. When zooming in, estuarine, deltaic and other lowland shorelines with coastal barriers show lower resilience, except where they are managed through nourishments. More detailed trends and causes, made possible with this new data product, need to be derived from future analyses.

Discussion and conclusion

The new EMODnet Geology data product on coastal resilience/vulnerability provides a pan-European visualization indicating lower, intermediate and higher levels of coastline vulnerability to erosion and flooding. It also indicates where there are gaps in knowledge for areas of the coastline where vulnerability data are still lacking or have not been found. The underpinning literature database is regularly reviewed and updated. In time, this will enable many of these gaps to be filled.

It is important to note that the downloadable maps represent integrated data from many studies, covering a wide geographical area and using a range of methodological approaches (Table 1). The

Fig. 2. Maps on coastal vulnerability/resilience at different zoom levels as visualized on the EMODnet Central Portal. (**a**) Fully zoomed-out map. (**b**–**f**) Zooms into the previous map ((b) zoomed into the area of the box in (a) and so on). Higher levels of resilience/lower levels of vulnerability shown in light blue, intermediate levels in mid-blue and lower levels of resilience/higher levels of vulnerability in dark blue. All maps show calculated point classes, except for the base map (f). For the moment, the diversity of the methods used to derive the source maps does not warrant more than three classes to be visualized in one meaningful map. It would suggest higher precision than we can deliver. Further information on source maps with more than three vulnerability classes is available in the attribute table.

Table 2. Determination of tolerance and associated number of points per zoom level

Tolerance (dec. deg.)	Min. scale	Max. scale	Number of points created
0.20000	20 000 000	15 000 001	3090
0.15000	15 000 000	10 000 001	4372
0.10000	10 000 000	4 000 001	7242
0.04000	4 000 000	2 000 001	21 489
0.02000	2 000 000	1 000 001	48 362
0.01000	1 000 000	500 001	106 609
0.00500	500 000	250 001	230 263
0.00250	250 000	150 001	493 467
original	150 000	-	-

data product is a tool that provides an overview visualization and enables users to access more detailed information by directing them, via the metadata, to the original studies. It is not produced from the uniform application of a single methodology for calculating coastal vulnerability as is the case with some other large-scale assessments (e.g. Bridges *et al.* 2015 for America; Abuodha and Woodroffe 2006 for Australia; Hinkel and Klein 2009 for the world). It also differs from the EUROSION's (2004) 'risk of coastal erosion map', which rates exposure to coastal erosion and continues to inform policy development for building coastal resilience in Europe (Villasante *et al.* 2023). Rather, it achieves uniformity of legend and balance in representation of the three defined levels of coastal resilience/vulnerability.

This new EMODnet product is intended to be a complementary and up-to-date visualization of coastal resilience and vulnerability, developed from a large number of individual studies conducted at regional and national level. The downloadable product lends itself to overarching analyses of resilience/vulnerability in function of both geology and other aspects. As such, it provides a useful resource for users who are interested not only in the pan-European distribution of coastal resilience and vulnerability, but also in the wide range of methodological approaches used in their assessment.

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Competing interests 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.

Data availability The datasets generated during and/or analysed during the current study are available in the EMODnet Geology repository, www.emodnet geology.eu/

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