Impacts and risks

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This document should be cited as:
Burak, Z.S., Hilmi, N., Jiménez, J.A., Ali, E., Balzan, M.V., Bonazza, A., Dechraoui-Bottein, M.-Y., Demirel, N. Farahmand, S., González, M., Montserrat, S., Pulido-Velázquez, D., Safa, A., Vacchi, M., 2024: Impacts and Risks. In: *Climate and Environmental Coastal Risks in the Mediterranean.* [Djoundourian, S., Lionello, P., Llasat, M.C., Guiot, J., Cramer, W., Driouech, F., Gattacceca, J.C., Marini, K. (eds.)]. MedECC Reports. MedECC Secretariat, Marseille, France, pp. 131-208, doi: 10.5281/zenodo.15096247

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Chapter 3
Impacts and risks

Executive Summary

This chapter gives a comprehensive overview of the main coastal impacts and risks affecting Mediterranean coasts. Due to their importance and potential impact on the Mediterranean coastal system, the main risks covered are erosion, flooding, water-related risks (e.g. saltwater intrusion and pollution), and biological risks. They are analysed at different time scales associated with drivers of different origin, as described in *Chapter 2*. The different risks under current conditions and under the effect of climate change are characterised, providing the respective magnitude for the Mediterranean and identifying coastal hotspots. The main impacts induced by analysed drivers and hazards are characterised by considering their potential effects on the economy (related to main economic sectors in the Mediterranean coastal zone such as tourism, agriculture, and fisheries), ecology (impacts on representative habitats and ecosystems such as deltas, wetlands, and seagrass) and on the human system (cultural heritage and human health).

It is important to bear in mind that some of the economic activities potentially affected by analysed hazards, such as coastal tourism, are also drivers of impacts along the Mediterranean coastal system. The current picture for the Mediterranean Basin is a coastal fringe affected by multiple hazards, with significant exposure due to the socio-economic-cultural setting of the Mediterranean with high population density and concentration of assets and relatively high vulnerability due to the decrease in natural coastal resilience.

***Coastal erosion* {3.2.2}**

The Mediterranean coastline is currently experiencing significant long-term erosion. Based on observed rates, the median projected shoreline retreat by 2100 compared to 2010 is estimated to be 17 m, with *very likely* (5th, 95th percentiles) values between –32 m and –1 m. This trend presents significant spatial variability, with the western Mediterranean concentrating the largest regional erosion hotspots, which are mainly located in river mouth areas and coastal stretches around harbours and other coastal infrastructure.

This erosion will increase under the effect of climate change, as sea level rise (SLR) will induce widespread shoreline retreat *(very high confidence)*. The estimated median value of SLR-induced shoreline retreat for the Mediterranean with respect to 2010, is –17.5 m and –23 m by 2050 under the IPCC AR5 RCP4.5 and RCP8.5 scenarios, respectively, increasing to –40 m and –65 m respectively by the year 2100. Although shoreline retreat is certain, there is significant uncertainty regarding the computed induced rates due to the models used. Nevertheless, this SLR-induced component must be considered in addition to ongoing shoreline evolution rates.

In the absence of adaptation and protection measures, Mediterranean beaches will continuously erode over the next decades. In urbanised areas, where the coast is limited by physical barriers, this will lead to the progressive narrowing and eventual disappearance of beaches. This constitutes a high risk for intensive sun-and-beach tourism areas due to the expected decrease in beach carrying capacity and the associated economic impacts *(very likely)*.

The progressive narrowing of beaches will reduce the degree of protection provided to existing infrastructure along the coast, with the corresponding increase in the risk of storm induced damage. Therefore, even despite the absence of any significant increasing trend in storm intensity and frequency, storm-induced damage will increase *(very likely)* over the next decades along the Mediterranean coast.

***Coastal flooding* {3.2.3}**

In the Mediterranean, coastal flooding from coastal storms is mainly caused by waves, due to the relatively low magnitude of surges. The most exposed areas are waterfronts and the more seaward parts of urban developments. The highest-risk areas show significant spatial variability, depending on local storm climate and the extent and dimensions of existing natural and human defences.

In the future, SLR will *very likely* increase the frequency and magnitude of storm-induced flooding along the Mediterranean coastal zone due to an increase in the total water level at the shoreline, leading to an increase in the existing risk in the absence of adaptation and protection measures. This effect will be more significant in low-lying areas and will be enhanced by the decrease in protection due to beach erosion.

SLR will result in the gradual and permanent inundation of low-lying unprotected areas *(high confidence).* Within the Mediterranean Basin, deltas and coastal plains are particularly vulnerable, as subsidence can locally and significantly increase relative sea level rise. These areas, often home to the highest natural values in the Mediterranean coastal zone, while being also used for agriculture, are at the greatest risk from relative sea level rise (RSLR).

The Mediterranean Basin is one of the areas in Europe where disastrous flash floods caused by intense precipitation events are more frequent, mainly affecting river mouths and coastal areas. This is due to local climate and topographic conditions, and the existing high population and urban settlements in flood-prone areas. In the future, without adaptation measures, the risk is *likely* to increase due to more frequent heavy rainfall episodes linked to climate change and the continuous growth of urban areas along the coast, although showing large spatial variability *(medium confidence).*

The Mediterranean coast is one of the areas in Europe at highest risk to compound flooding due to co-occurrence of heavy rainfall and high-water levels. The expected evolution of these events under climate change shows large spatial variability in their occurrence without a clear trend regarding their intensity *(medium confidence).*

SLR will increase the extreme total water level at the shoreline and the associated flood risk. However, except for certain localised areas like the northern Adriatic, the Mediterranean stands out among European coastlines for experiencing relatively low extreme total water levels under SLR *(high confidence).* The Mediterranean region is particularly vulnerable to coastal flooding, due to the widespread presence of unprotected buildings and activities along the Mediterranean coastline, and the relatively small values of maximum coastal water levels. In the absence of coastal protection or adaptation, climate change will very likely be the main driver of future increase in coastal flood losses.

***Tsunamis and meteotsunamis* {3.2.4}**

Due to the high seismicity of the Mediterranean Basin, the short travel times of tsunami waves to the coast from source areas and the high population density and concentration of assets along the coast, tsunamis are a significant threat for Mediterranean coastal zones despite their low frequency, with the eastern Mediterranean being the most affected area.

Meteotsunamis occur regularly on the Mediterranean coast and show large spatial variability, with their highest intensities in bays and inlets where resonance is favoured. As a result, the greatest damage and, consequently, the areas of highest risk, are concentrated in local hotspots where existing coastal infrastructure and developments are not adapted to accommodate significant changes in sea level. Despite this, hazard assessments are only available for a few areas, while risk assessments are lacking.

***Freshwater resource scarcity* {3.2.5}**

Without appropriate adaptation and protection strategies, the quantity and quality of freshwater resources in coastal areas will decline, reducing the water available for future uses *(very likely).*

Maintaining the socio-economic activities related to the significant urban, agricultural and/or industrial development in Mediterranean coastal areas, which require supplying significant freshwater demands, will be a challenging issue which will be exacerbated due to seawater intrusion in coastal aquifers. In the future, associated risks will be amplified due to the expected reduction in aquifer recharge, sea level rise, the increase in water demands and the frequency and severity of droughts.

The use of unconventional water resources generated by desalination will reduce the risk of water scarcity and their socio-economic implications, but it may increase the risks of environmental impacts, especially on coastal ecosystems (e.g. adverse impact due to brine water discharge) and will increase associated CO_2 emissions.

***Coastal pollution risks* {3.2.6}**

Water pollution along the Mediterranean coast is mainly generated by land-based point and diffuse sources (80%) due to the existing high urbanisation of the coastal zone, with ship-induced and air pollution contributing the remaining part. This puts the coastal zone at risk of impacts on ecological systems and human health due to diverse pollutants generated either on land and discharged into the coastal waters or accidental oil spills.

Along the Mediterranean coast there are numerous sites that present a high risk associated with eutrophication of coastal waters due to nutrient inputs from land. Coastal eutrophication is of medium or important significance in 13 Mediterranean countries. This has adverse impacts on coastal ecosystems and may also have significant local socio-economic impacts due to its impact on aquaculture, fishing and coastal tourism. In the future, it is expected that the risk along the Mediterranean coasts will increase following the expected increase in their occurrence and the increasing pressure on the coastal zone *(high confidence).*

The presence of areas with high concentrations of plastics along the Mediterranean coast has high adverse impacts on marine biodiversity and human health due to the ingestion and accumulation by marine fish.

Synergistic interactions between climate change impacts and emerging pollutants in the coastal environment will become more frequent *(medium confidence)* due to multiple stressors from both natural and anthropogenic sources.

Accumulated pollution from various sources in coastal and bathing waters endangers coastal ecosystems and human health. The magnitude of anthropogenic impacts has been higher in coastal waters compared to offshore waters due to the increasing anthropogenic pressure (e.g. overfishing, land-based pollution) on coastal zones and climate change as prevailing pressures altogether *(medium confidence).*

***Biological risks* {3.2.7}**

The Mediterranean coastal zone is subjected to a high risk associated with invasive non-indigenous species that produce different ecological and socio-economic impacts through their interaction with native species, which significantly affect native biodiversity. In addition, there is strong evidence that most of the services provided by Mediterranean marine ecosystems are affected by invasive non-indigenous species, those related to food provision being the most impacted ones *(high confidence).*

The massive abundance of jellyfish is a threat to anthropogenic coastal activities and human health due to their competitiveness and predatory impacts on marine biodiversity and their multiple direct and indirect consequences. Jellyfish blooms have potential adverse impacts on the marine ecosystem with consequent health risks for marine organisms and humans because they represent vectors of potential bacterial pathogens affecting fish aquaculture, in particular.

Mass mortality events (MMEs) are attributed to the increase in frequency and intensity of marine heat waves (MHWs) and pathogen infections. The frequency and intensity of MMEs will *likely* increase in the future in parallel with rising MHWs *(high confidence).*

The frequency of the mucilage phenomenon has been reported to have increased significantly over the last decades. Mucilage adversely affects seawater and makes it unsuitable for bathing due to the adherence of this mucus-like substance on bathers' skin. Marine mucilage settled on the benthos in the form of large aggregates, coats the sediment, causing hypoxic and/or anoxic conditions resulting in the suffocation of benthic organisms. The mucilage phenomenon can cause serious economic damage to tourism and fisheries *(high confidence).*

***Impacts on the economic system* {3.3}**

Coastal tourism along the Mediterranean is *likely* to be affected by climate change due to a decrease in climate comfort during the summer season and its increase in spring and autumn *(medium confidence).* In addition to this, sun-and-beach tourism will be negatively affected by the decrease in beach carrying capacity due to SLR-induced beach erosion. This will result in the risk of a substantial decrease in revenue for coastal communities and consequently declines in GDPs of countries in the region *(medium confidence).*

Without effective adaptation, agriculture production in Mediterranean coastal zones will be negatively affected by climate change due to the expected decline in water resources, soil degradation, and increase in salinity. This can directly affect food security *(medium level).*

There is a *high agreement* that Mediterranean fisheries are overexploited, and the majority of the commercial stocks are declining. In addition, the risk of traditional fish stocks shrinking in quantity and economic value is further increased by pollution and widespread emergence of non-indigenous species. This represents a financial and technical challenge for many artisanal fishermen, who are the main operators in coastal fisheries *(high confidence).*

Climate change exacerbates challenges related to water and energy security through increasing temperatures, as well as decreasing precipitation and enhanced droughts *(high confidence).*

The risk for coastal infrastructure along the Mediterranean due climate change in general, and SLR in particular is related to the decrease in their functionality, mainly associated with increased coastal flooding and overtopping. For Mediterranean ports, the expected change in risk level by 2100 will be small under low-medium SLR scenarios, but it will significantly increase becoming high or very high under the RCP8.5 scenario *(medium confidence).* Although an increase in risk associated with decreased functionality of coastal protection infrastructure due to SLR is expected at basin scale *(high confidence),* its significance will depend on its specific local configurations.

***Impacts on the human system* {3.4}**

A large part of the existing UNESCO cultural World Heritage Sites (WHS) in the low elevation coastal zone of the Mediterranean are currently at risk to erosion and coastal flooding *(medium confidence),* with an expected increase in flood and erosion risk that will reach 50% and 13% higher values respectively by 2100 under a high-end SLR scenario *(unlikely).* Additionally, the built heritage is *likely* to be affected by climate change through slow cumulative deterioration processes. As a result, the risk of decohesion and fracturing in porous building materials is expected to increase.

The occurrence of natural disasters and environmental degradation linked to pollution have multiple direct and indirect impacts on the health and well-being of coastal populations along the Mediterranean Basin *(high confidence).* In the absence of adaptation, their impacts are expected to increase in the near future due to the expected increase in hazardous conditions due to climate change and rising coastal population *(medium confidence).*

***Impacts on the natural system* {3.5}**

Mediterranean coastal wetlands have significantly declined during the 20th century due to a combination of erosion, extreme events, salt-water intrusion, and mainly human-induced pressures such as the expansion of irrigated agriculture and urban development. They are projected to be significantly affected by future changes in precipitation *(high agreement, medium evidence),* although with high spatial variability. SLR-induced hazards are expected to result in the loss of coastal wetlands *(high agreement, robust evidence),* with locally significant impacts in areas where rigid inland boundaries limit their potential for horizontal migration.

SLR-induced erosion along the Mediterranean coast will induce a decline in ecosystem services provided by coastal habitats, as these areas degrade and, eventually, disappear with ongoing erosion *(high confidence).* For the northern Mediterranean coast, a decline in approximately 5% in services by 2100 relative to current conditions under RCP8.5 has been estimated *(medium confidence),* presenting a high spatial variability; the eastern Mediterranean is expected to experience the largest declines.

Changes in sediment supply, industrial development, and urban processes will enhance the vulnerability of natural coastal ecosystems (e.g. sandy coastal sandy beaches, saltmarshes, coastal lagoons) to sea level rise. In addition, coastal systems are experiencing compound threats from ocean warming, sea level rise, eutrophication, and the expansion of low-oxygen zones as a result of climate change. The risk to these ecosystems is projected to become very high by the end of the century.

3

3.1 Introduction

The Mediterranean Basin is generally characterised by a narrow and highly populated coastal area. In the second half of the 20th century, the Mediterranean population has doubled from 240 million to 480 million (UNEP/MAP 2016) and the human pressure on the coasts is further amplified by increased international tourism. The Mediterranean coastal zone is therefore characterised by an increased pressure from human activities, but also subject to future global environmental change as the Mediterranean area is considered a hotspot of current climate change (Giorgi 2006; Guiot and Cramer 2016; MedECC 2020b; Ali et al. 2022). This may result in high sea-level rise rates compared to global averages, leading to significant losses in the environmental, cultural and economic values of Mediterranean coasts (Vacchi et al. 2021).

Mediterranean sea level rise will lead to more frequent flooding of low-lying coastal areas through storm surges, wave extremes and, in minor terms, through higher tides (See *Chapter 2, Section 2.2.4*).

Robust knowledge on current and future coastal risks enables Mediterranean policymakers to anticipate impacts that could be triggered by the multiple effects of climate change.

The assessment of impact and vulnerability is required in the framework of Integrated Coastal Zone Management (ICZM) Protocol of the Barcelona Convention (UNEP/MAP and PAP/RAC 2008). The integration of information from various fields including physical, ecological and socio-economic disciplines is a prerequisite for any coastal impact assessment and for planning appropriate future interventions along the Mediterranean shores (Wolff et al. 2018).

Due to the high natural, cultural and socio-economic values that might be threatened or lost in Mediterranean coastal areas, several efforts have been made by the scientific community to produce future climate drivers including sea level scenarios (see *Chapter 2*) which may determine the magnitude of problems that different Mediterranean coastal areas may have to face, as well as possible solutions.

3.2 Main risks in coastal areas

3.2.1 Coastal risks – general

The Mediterranean can be considered a region with a high coastal risk due to the combination of multiple hazards such as erosion, flooding, pollution and biological hazards (e.g. Sánchez-Arcilla et al. 2011; Sarkar et al. 2022), a highly sensitive coast and increasing exposure due to urban development (e.g. Wolff et al. 2020), a high concentration of coastal dependent economic sectors such as tourism (Plan Bleu 2022) and valuable ecosystem services (Liquete et al. 2016).

Due to this, multi-hazard risk assessments have become an important tool for understanding and mitigating their potential impacts. However, due to the large diversity in risk components along the Mediterranean coast, most of the existing risk assessments are local (e.g. Torresan et al. 2012; Roukounis and Tsikriktsis 2022), or they analyse single hazards and some consequences (e.g. Reimann et al. 2018a). Therefore, most of studies covering large areas in the Mediterranean evaluated the coastal vulnerability instead of the coastal risk, that is the potential of the coastal system to be harmed by the considered hazards (e.g. Snoussi et al. 2009; Torresan et al. 2012; Hereher 2015; Satta et al. 2017). Satta et al. (2017) developed one of the few multi-risk assessments at the Mediterranean scale using an index approach to characterise hazards, vulnerability and exposure. Their analysis focuses on risks associated with erosion and flooding induced by different drivers and results are given in a 5-class qualitative scale from extremely high to extremely low risk. Obtained results characterise the Mediterranean coast with a heterogeneous spatial distribution of the risk, in the form of hotspots, mostly determined by the diversity in values to exposure and vulnerability (e.g. coastal geomorphology) *(Figure 3.1).*

3.2.2 Coastal erosion risks

One of the most common coastal risks is that induced by shoreline erosion, which currently affects a large extent of the world's sandy coasts (Luijendijk et al. 2018; Mentaschi et al. 2018) and may be exacerbated by climate change (e.g. Nicholls and Cazenave 2010), threatening the survival of many sandy beaches (Vousdoukas et al. 2020) and affecting the functions

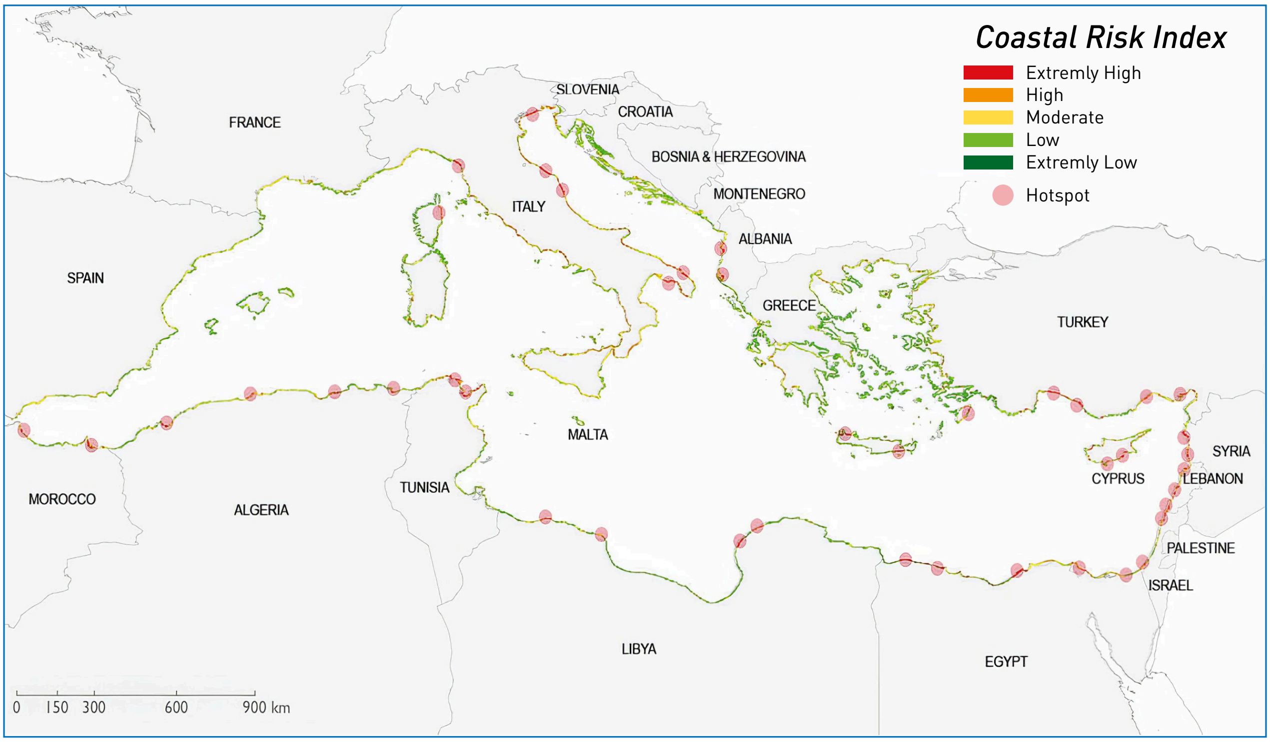

Figure 3.1 | Coastal Risk Index map of the Mediterranean. Source: Satta et al. (2017).

they provide (Defeo et al. 2009; Roebeling et al. 2013; MedECC 2020a). The drivers and factors that control and determine coastal erosion, interact along the coast and operate at different timescales, such that to adequately characterise erosion requires doing so at multiple scales (e.g. Ballesteros et al. 2018; Vousdoukas et al. 2020). Many beaches along the Mediterranean are currently retreating and will significantly narrow and eventually disappear by the end of the 21st century. Vousdoukas et al. (2020) using the data from Luijendik et al. (2018) and Mentaschi et al. (2018) obtained for the entire Mediterranean Basin a median shoreline retreat[32] of –17 m by 2100, with *very likely* values between –32 m and –1 m. These values presented large spatial variability, although existing regional-scale analyses highlight the relevance of shoreline erosion around the Basin. Thus, Jiménez and Valdemoro (2019) estimated that about 67% of the sandy shoreline of the Catalan coast (northwestern Mediterranean, Spain) is eroding at an average erosion rate of –1.6 m yr^{-1}, whereas the regional average shoreline evolution is around –0.4 m yr^{-1}. Similarly, Pranzini (2018), using data from the Italian National Table on Coastal Erosion 'Tavolo Nazionale sull'Erosione Costiera' (MATTM-Regioni 2018) reported that about 50% of Italian sandy beaches are currently experiencing erosion despite the implementation of coastal protection projects. Along the southern Mediterranean coast, (Amrouni et al. 2019) estimated that about 70% of sandy beaches along the Hammamet Gulf (Tunisia) are persistently eroding at an average rate exceeding –0.5 m yr^{-1}.

Current erosion hotspots[33] are mainly located in river mouth areas and coastal stretches around harbours and other coastal infrastructure. In the first case, river mouth areas are a direct consequence of one of the main terrestrial drivers affecting coastal stability, the decrease in river sediment supplies as a result of human-induced modifications to river basins (e.g. Syvitski et al. 2005). Therefore, about 75% of the deltaic coastlines in the Mediterranean are retreating (Besset et al. 2019), and they comprise areas with the largest local erosion rates along the Mediterranean coastline such as Cap Tortosa at the Ebro delta, Spain (35 m yr^{-1} from 1957 to 2013; Ramírez-Cuesta et al. 2016); areas near the mouth of the Petit Rhône, France (10 m yr^{-1} from 1960 to 2000; Sabatier and Suanez 2003); the Medjerda delta, Tunisia (up to 42 m yr^{-1}, from 1972 to 2013; Louati et al. 2015); Moulouya delta, Morocco (up to 10 m yr^{-1}, from 1958 to 2006; Mouzouri and Irzi 2011); Ombrone delta, Italy (10 m yr^{-1} up to 2013–16; Mammì et al. 2019), and Damietta promontory at the Nile delta, Egypt (42 m yr^{-1}, 1972–1990; Dewidar and Frihy 2007); before the implementation of coastal stabilisation works. In the second case, stretches surrounding harbours and marinas are the result of the modification of coastal dynamics by existing coastal infrastructure. Examples of such hotspots associated with large infrastructure are found at the ports of Tangier, Morocco (Sedrati and Anthony 2007) and Valencia, Spain (Pardo-Pascual and Sanjaume 2019), or with the existence of several marinas along coastal regions such as in Tuscany, Italy (Anfuso et al. 2011); in Catalonia, Spain (Jiménez and Valdemoro 2019); and Greece (Tsoukala et al. 2015).

Future changes in decadal-scale shoreline erosion will be determined by the projected changes in corresponding drivers. With respect to the contribution of waves, as mentioned in *Chapter 2*, existing projections under different scenarios predict a slight decrease in significant wave height and in storminess for the Mediterranean. This would imply that, in the worst case, the magnitude of coastal dynamics along the Mediterranean will tend to decrease slightly. However, there are some regional studies such as Casas-Prat and Sierra (2012) for the Catalan coast, which have estimated more significant changes in wave direction than in wave height. This discrepancy in the contribution of wave drivers will introduce significant uncertainty in the projection of coastal dynamics, as it does not depend on one, but on a set of wave parameters, which may lead to opposite changes in sediment transport. In this sense, the expected changes in wave height and wave direction may lead to opposite changes in longshore sediment transport and have to be estimated locally (Casas-Prat et al. 2016).

32 These values were estimated by extrapolating obtained shoreline evolution rates from satellite images over two decades to the end of the century without including SLR or any additional changes in drivers.

33 Erosion hotspots are coastal locations where erosion rates are significantly higher than in surrounding areas.

With respect to the contribution of river sediment supplies, existing estimations of average sediment delivery for 21st century climate warming scenarios predict an 11–16% increase (Moragoda and Cohen 2020), while for deltas, projected changes predict mean and maximum declines of 38% and 83% respectively between 1990–2019 and 2070–2099 (Dunn et al. 2019). The final contribution will be the result of the balance between climate-induced changes and human-modifications in river basins (Syvitski et al. 2022).

Finally, the estimated increase of human occupation and use of coastal areas along the Mediterranean for the next decades (e.g. see *Chapter 2, Section 2.6*) will *likely* contribute to altering coastal dynamics patterns and reducing the existing accommodation space along the coast due to the construction of coastal infrastructure. However, this will depend on the level of existing artificialisation along the coast, as the already highly developed areas have shown attenuation in the increase of armouring as observed in the Mediterranean coast of Andalusia (Spain) (Manno et al. 2016).

Superimposed on current evolution rates, sandy shorelines will be directly affected by relative sea level rise (RSLR), inducing additional shoreline retreat. Unlike current conditions, this general retreat will vary spatially, depending on local RSLR values, existing geomorphology, and local sediment balance (Nicholls and Cazenave 2010; Ranasinghe 2016). Although RSLR-induced erosion is a well-established hazard, quantitative assessments remain subject to uncertainty due to limitations in process understanding and model validation. Although the equilibrium-based Bruun's rule is the most used method (e.g. Le Cozannet et al. 2014), there is disagreement about its validity (e.g. Cooper and Pilkey 2004) and alternative models have been proposed (e.g. Ranasinghe et al. 2012), though all models exhibit inherent uncertainty and have been hardly validated (e.g. Le Cozannet et al. 2016). Their application also involves different sources of uncertainties (Toimil et al. 2020) and, as a consequence, no universally accepted model exists.

At the Mediterranean Basin scale, long-term shoreline retreat due to sea level rise (SLR) has been estimated using a modified version of the Bruun's rule. Median retreat projections by 2050 are –17.5 m [–27.7 to –8.8 m][34] and –23 m [–36.3 to –11.1 m] under the Representative Concentration Pathways (RCP)[35] RCP4.5 and RCP8.5 respectively *(very likely)*, increasing to –40 m [–65.1 to –20.1 m] and –65 m [–115.0 to –31.3 m] by 2100, respectively *(very likely)*. Expected RSLR-induced retreats present a spatial variability driven by local increases in RSLR, with expected larger values in subsiding areas such as major deltas, and areas with milder slope shore faces. As an example, Sharaan and Udo (2020) estimated a 66% increase in SLR-induced shoreline retreats along the Nile delta when compared to those calculated for RCP8.5. In addition to this global and consistent assessment, there are numerous local and regional assessments using different RSLR scenarios and erosion models. Among them, it is worth highlighting there are few for high-end scenarios that are relevant from a risk management perspective (Hinkel et al. 2015), such as that of Jiménez et al. (2017) for Catalonia (Spain) and that of Thiéblemont et al. (2019) for the entire European coastline. These assessments predict much larger shoreline retreats, proportional to the increase in SLR considered in such scenarios.

The combination of beach evolution rates at the different scales and their projection for the next century will result in a progressive and cumulative shoreline retreat along the entire Mediterranean coastline, with the exception of areas where local sediment budget determines the accumulation of sediment to compensate for such erosion. This, combined with current high rates of urbanisation along the Mediterranean coastline and projected urban development (Wolff et al. 2020), results in limited accommodation space along the coast. This situation favors the appearance of coastal squeeze, leading to generalised beach narrowing and, consequently, an increased likelihood of beach disappearance in the

34 In the report, unless stated otherwise, square brackets [x to y] are used to provide the assessed very *likely* range, or 90% interval.

35 Representative Concentration Pathways (RCP), as defined in IPCC AR5 are greenhouse gas concentration (not emissions) trajectories labelled by the associated radiative forcing values in the year 2100 (2.6, 4.5, 6, and 8.5 W m^{-2}), respectively and corresponding to one stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0) and one scenario with very high GHG emissions (RCP8.5). See also: https://apps.ipcc.ch/glossary/

absence of adaptation measures (e.g., Jiménez et al. 2017; Vousdoukas et al. 2020).

One of the direct consequences of coastal erosion is the loss of ecosystem services (ES) provided by beaches, since habitats in coastal areas may be affected, degraded and, eventually, disappear as erosion progresses, especially due to coastal squeeze. In the Mediterranean Basin, the most comprehensive existing study is that of Paprotny et al (2021) who evaluated the effect of coastal erosion for ecosystem services on the European coast (just the northern Mediterranean coast) for RCP4.5 and RCP8.5 scenarios. They estimated a roughly 5% decline in services with respect to current conditions by 2100 under RCP8.5. The estimated risk presented high spatial variability reflecting the variability on habitat distribution and magnitude of induced erosion, the eastern Mediterranean, being the area concentrating the largest estimated declines in ecosystem services along the European Mediterranean coast.

In addition to these chronic erosion processes, the impact of storms on Mediterranean sedimentary coasts can cause major episodic erosional events, with shoreline retreats of the order of several tens of metres occurring over the duration of the event (up to a few days) (e.g. Adriatic coast: Ferrarin et al. 2020; Algier: Amarouche et al. 2020; northwestern Mediterranean: Jiménez et al. 2018). The magnitude of the induced erosion will depend on the incident storm properties (waves and surge). Since the most severe wave storm conditions are generally found in the western Mediterranean (e.g. Sartini et al. 2017), this would be the area most susceptible to experiencing larger storm-induced impacts. However, the real beach erosion will not only depend on the storm magnitude but also on the protection capacity provided by beaches and dunes (i.e. local geomorphology) in such a way that storms need to exceed a given threshold to produce a significant impact on the coast (e.g. Armaroli et al. 2012 for critical thresholds in the North Adriatic Italian coast; Gervais et al. 2012 in the Gulf of Lion French coast). The stochastic nature of storms and their large spatial variability along the Mediterranean Basin, the dependence on the geomorphology of the coast at the moment of impact, and the variety of existing models with different predictive capabilities contribute to a limited number of comprehensive storm impact assessments at the Mediterranean Basin scale. Vousdoukas et al (2020) estimated a basin-averaged storm-induced shoreline retreat of about 4 m for a 100-year return period event, with no significant climate change-induced variation by the end of the century. This estimate was derived using a simplified approach to optimise calculations along the entire world coastline and, as average value, it underestimates registered retreat recorded along the Mediterranean coastline, where observed and locally modelled values for similar return periods amounts to about 20 m or even greater (e.g. Armaroli and Duo 2018; Jiménez et al. 2018).

Future changes in the magnitude of storm-induced erosion will be determined by projected changes in wave storms along the Mediterranean. Although, as mentioned in *Chapter 2*, existing projections for different scenarios do not predict any significant increase in wave height, some new analysis of wave buoy records and hindcasts have detected an increasing trend of recorded maximum significant wave height over the last 40 years in the western Mediterranean, with some records over recent years (Amarouche et al. 2022). Also, potential changes in medicanes will modulate future risks at this scale according to the potential changes in their frequency and intensity (see *Chapter 2, Section 2.2.3*). Finally, it is important to consider that the impacts associated with coastal erosion are largely determined by existing geomorphology. As described above, medium- and long-term erosion processes will largely dominate future coastline evolution around the Mediterranean Basin. Therefore, even in the absence of changes in storm climate over the next decades, decreasing beach widths (increasing geomorphic vulnerability) and increasing development of coastal areas (increasing exposure) will lead to increased erosion risks around the Mediterranean Basin. Evidence of this trend has already been observed in the northwestern Mediterranean during the last decades of the 20th century and early 21st century in the northwestern Mediterranean (Jiménez et al. 2012).

3.2.3 Flood risks in coastal zones

Flooding in coastal zones can be simply defined as the situation in which dry land is submerged by water. Like the case of erosion, the drivers and factors that control and determine flooding are of different origin and operate at different time scales and spatial scales which leads to it being possible to identify different types of flooding. In the case of the Mediterranean coast, the most common types are floods associated with maritime storms, river floods, flash floods, pluvial floods, and those due to breakage of hydraulic infrastructure. On numerous occasions, events combining more than one type of flood occur. Given that a majority of coastal cities and towns are in flood-prone areas, and that intense rainfall is very frequent in the region, urban flooding is a problem aggravated by the growing shift of the population towards coastal locations. Often a combination of these factors worsens the situation.

3.2.3.1 Flash floods and fluvial floods

As mentioned in *Chapter 2*, the most frequent drivers of flooding in the Mediterranean coastal zone are short but heavy precipitation events usually associated with cyclonic activity. The Mediterranean coast is characterised by a marked orography that has led to the existence of numerous torrents and small basins with high slopes, in which flash floods frequently occur because of this heavy rainfall (Llasat et al. 2010; Gaume et al. 2016). In coastal towns that have grown around these torrents, the damage caused by flash floods can be very significant. In some towns the torrents are totally or partially covered, but if the drainage network is not sufficient, they can still flood. Many times, floods caused directly by rain are combined with flash floods. Consequently, disastrous flash floods are more frequent in Mediterranean coastal areas than other European regions due to local climate and topographic conditions, and the high population and urban settlements in flood-prone coastal areas (Gaume et al. 2016). Flash floods particularly impact the northwestern, eastern and southeastern coasts of the Mediterranean, but also remote areas (Gaume et al. 2016; Gohar and Kondolf 2017; Petrucci et al. 2019; del Moral et al. 2020; Faccini et al. 2021; Diakakis et al. 2023). Fluvial floods occur less frequently on the Mediterranean coast because they require more sustained heavy precipitation events, and in some regions, structural measures, such as dams have been used to reduce the potential hazard (Ward et al. 2020).

The analysis of river flooding trends can be carried out from gauging stations. The analysis by Blöschl et al. (2019) shows a decreasing trend for the Mediterranean region in medium and large basins for the period 1960–2010, mainly due to a decrease in precipitation and increased evaporation (see also *Chapter 2, Section 2.2.2*). This trend is consistent with the climate projections shown by Alfieri et al. (2015), that agree on a 30% reduction in annual precipitation in southern European countries, particularly in the Iberian Peninsula, Greece, and southern Italy, with the consequential decrease in average streamflow. In some basins, the increase in forest mass must be added to the previous explanation, mainly due to the abandonment of agricultural activity (Fader et al. 2020). Tramblay et al. (2019) shows that most trends point towards fewer annual flood occurrences above both the 95th and 99th percentiles for the majority of basins of the south of France, and particularly, on the Mediterranean French coast. These results imply that the observed flood risk increase in recent decades is mostly caused by human factors such as increased urbanisation and population growth rather than climate factors. Since most flash floods occur in ungauged catchments, trend analysis is more difficult, and is usually carried out from the episodes produced and identified by the damage they have caused. Flash flood events have increased since 1981 in coastal Mediterranean regions of Italy, France, and Spain (Llasat et al. 2013). This positive and significant trend of 2.5 floods per decade would also be justified by the increase in vulnerability and exposure in coastal areas close to the torrent or stream, despite improved coping capacities (Llasat et al. 2021a). However, some studies already show an increase in rainfall intensity on a sub-daily scale, and even on a sub-hourly scale, as well as the increase of convective precipitation in some Mediterranean regions (Llasat et al. 2021b; Treppiedi et al. 2023). The frequency of flash floods has been increasing over recent decades *(medium confidence)* for the combined effect of urban expansion in areas of fluvial pertinence and climate change, namely the interaction between anthropogenic landforms and hydro-geomorphological dynamics (Faccini et al. 2021). Land or urban mismanagement is a third concurrent factor affecting flood vulnerability (Saber et al. 2020). Added to this increase in vulnerability and exposure, heavy precipitation on a sub-daily scale shows a positive trend in recent decades *(medium confidence).* Therefore, in some regions of the northern Mediterranean, an increase in convective precipitation has already been detected (Llasat et al. 2021b; Treppiedi et al. 2023).

In the future, disastrous flash floods will *likely* become more frequent and/or intense due to climate change and the growth of urban areas *(medium* *confidence).* This fact is aligned with the increase in heavy precipitation projected by Tramblay and Somot (2018) in the northern Mediterranean for the middle of the century, and by Cortès et al. (2019) for the eastern Iberian Peninsula. These authors have projected an increase in the precipitation recorded for events exceeding 40 mm per day, which is the threshold associated with potential flash floods. If this increase in precipitation is combined with different socioeconomic scenarios, it is *likely* to raise the probability of an event causing significant economic damage.

3.2.3.2 Coastal floods

At the same scale but of marine origin, the impact of coastal storms with high waves and/or storm surges will cause the temporary inundation of the coastal zone when water levels at the shoreline exceed the elevation of the coast. This hazard, usually accompanied and exacerbated by beach and dune erosion in sedimentary coasts, is frequent along the entire Mediterranean coastline, with their magnitude depending on the local values of the total water level, the local level of protection (provided by the beach or dune in natural areas and structures on urbanised coasts) and the extension of the flood plains. Consequently, although there are different studies providing global or continental-scale extreme sea levels for both present and future climate change, existing attempts for mapping flood-prone areas at such scale have not been validated (Paprotny et al. 2019), and they need to be done at local level to have a reliable estimation of the risk (e.g. Perini et al. 2016). It should also be noted that under the European Directive on Floods, most European Mediterranean countries have produced risk maps for coastal inundation associated with different return periods.[36]

Scicchitano et al. (2021) analysed coastal flooding in Sicily under both common storms and medicanes. They found that, although they are apparently similar drivers, the risk of flooding associated with medicanes was significantly greater than that estimated for common seasonal storms, due to the higher induced storm surge. Toomey et al. (2022) characterised coastal hazards associated with medicanes and found that the highest induced waves are generated in the central and the southwest part of the western Mediterranean, while the highest surges are predominantly observed in the Adriatic Sea.

3.2.3.3 Compound events

One intrinsic characteristics of flooding in coastal areas is that it can be induced by different climate drivers, such as storm surge, run-up, rainfall, and river flow, which are often interconnected (Berghuijs et al. 2019), and may produce what is commonly referred to as compound flooding. Depending on their type, these events can amplify impacts relative to those from the same events occurring separately, or accumulate impacts at spatially distant locations (Zscheischler et al. 2020). Compound flooding has been identified in historical records of past damaging floods in Europe, especially in Italy and France (Paprotny et al. 2018). The very extreme impact of Storm Gloria in January 2020 along the Spanish Mediterranean coast drastically demonstrated their integrated impact (e.g., Amores et al. 2020; Canals Artigas and Miranda Canals 2020). From a risk perspective, these events are highly relevant, as they can significantly increase the intensity and/or the spatial and temporal extent of the impact (and associated damage). They may overwhelm the capability of emergency response services, which would be required to address a large number of simultaneous emergency situations throughout the region and/or sustain response efforts over a relatively long period.

In the analysis of these events, different drivers can be considered to contribute to compound flooding. Bevacqua et al (2019) analysed compound flooding by considering events compounded by heavy rainfall rates and high-water levels due to surge and astronomical tides. They found that the highest probability under present climate conditions is mainly concentrated along the Mediterranean coast, with the regions of the Gulf of Valencia (Spain), northwestern Algeria, the Gulf of Lion (France), southeastern Italy, the northwestern Aegean coast, southern Türkiye, and the Levante region having return periods shorter than 6 years for

36 https://ec.europa.eu/environment/water/flood_risk/links.htm

compound flooding. A similar result was obtained by Camus et al. (2021), who analysed compound events involving pluvial, fluvial, and oceanographic drivers along European coasts, identifying the northern Mediterranean as a hotspot for compound flooding potential *(medium confidence).* In contrast, Couasnon et al. (2020) analysed compound flooding by combining river discharges and storm surges and found that the Mediterranean Sea did not exhibit a clear pattern in the co-occurrence of these drivers.

As an example, at a smaller scale, Sanuy et al (2021) analysed the occurrence of compound events involving heavy rainfall and storm waves on the northwestern Mediterranean coast (Catalonia, Spain). They found that the area has a high probability of experiencing compound extreme events, with an average of three events per year. However, significant variations in event characteristics were observed along the territory, despite its relatively small size (about 500 km of coastline).

Regarding the future evolution of these events, existing analyses do not provide conclusive results. According to Bevacqua et al. (2019), climate models show disagreement on the direction of future changes in the probability of compound flooding along much of the Mediterranean coast. In this context, Paprotny et al. (2020) analysed the performance of different models in predicting these events in Europe and found considerable regional differences in the strength of the dependence on surge-precipitation and surge-discharge pairs. While the models reproduce these dependencies reasonably well in northwestern Europe, their performance is less successful in the in the southern part.

3.2.3.4 SLR-induced inundation

At long-term scale, flooding in coastal zones will be driven by climate change, which can cause gradual permanent inundation due to sea level rise, and may also exacerbate storm-induced flooding events. To assess the extent and risk associated with SLR-induced inundation, the first element to be characterised is the local magnitude of RSLR along the coastal zone. In the Mediterranean, there is an increasing availability of SLR flooding scenarios, notably for sites which are particularly prone to the coupled effects of sea-level rise and negative vertical land motions such as deltas and coastal plains, which concentrate the highest risks of permanent inundation (e.g. Snoussi et al. 2008; Antonioli et al. 2017; Aucelli et al. 2017; Vecchio et al. 2019; López-Dóriga and Jiménez 2020). These studies have employer various methodologies, mainly based on the use on projections of future global sea-level rise based on various IPCC greenhouse gas emission scenarios, corrected for the local glacial isostatic adjustment (GIA) contributions. These projections are coupled with the assessment of local subsidence which can be derived from Holocene data (e.g. millennial scale), from long tidal gauges (e.g. centennial scale), GPS, or Interferometric Synthetic Aperture Radar (InSAR) data (e.g. decadal scale).

Furthermore, for future sea-level rise scenarios to be considered reliable, they must be based on high-resolution topography data, specifically Digital Elevation Models (DEMs) derived from Light Detection and Ranging (LiDAR) surveys. These LiDAR-baseed DEMs are now available for a large portion of the Mediterranean coasts and are often provided with 1 x 1 or 2 x 2 m cell width. These data have a general mean vertical resolution of about 10 to 20 cm (Anzidei et al. 2021; Rizzo et al. 2022). In contrast, scenarios based on topographic data with lower vertical accuracy should be disregarded, as the associated topographic error may represent more than 30% and more than 50% of the expected flooding under the RCP8.5 and RCP2.5 sea-level rise scenarios for the year 2100, respectively.

With respect to the flooding technique used, most of the Mediterranean Sea-level scenarios are based on a classic 'bathtub' approach in which areas below the expected sea-level elevation and hydraulically connected to the sea are delineated as being flooded (e.g. Di Paola et al. 2021). This methodology is considered suitable for urban, armoured, rocky, and passive coasts characterised by moderate wave action and reduced sediment supply. However, the 'bathtub' flooding scenarios approach may be less accurate for active sedimentary coastal areas where future sea-level rise has more dynamic effects than inundation alone (FitzGerald et al. 2008; López-Dóriga and Jiménez 2020). In this morphological context, a wide range of processes driving coastal evolution is expected to occur, which may counteract the incoming sea-level rise. To date, the dynamic responses of shorelines have rarely been included in most of the Mediterranean assessments of future sea-level scenarios.

Another important challenge in the definition of future flooding scenarios is to define a clear relationship between the inundated area and the resulting damage (López-Dóriga and Jiménez 2020). A typical approach is to consider the loss of function/habitat in the inundated area even if this often overestimates damage, especially from an environmental standpoint, as the resilience of natural areas is not always considered (Lentz et al. 2016). Presently, determining the physical and ecological responses of coastal habitats to future change remains a difficult task (López-Dóriga and Jiménez 2020). There is thus a growing need to integrate dynamic interactions between physical and ecological factors to better predict the impact scenarios of sea-level rise on low-lying coasts.

3.2.3.5 SLR-enhanced floods

It is expected that climate change and, SLR in particular, will increase extreme total water level at the shoreline (including wave runup and storm surge) and the associated flood risk (e.g. Vousdoukas et al. 2018; Kirezci et al. 2020; Almar et al. 2021). Practically, SLR will cause a decrease in return periods for given total water levels, which implies an increase in the likelihood of flood events (i.e. they will be more frequent). Alternatively, the total water level associated with a given likelihood of occurrence will be higher.

Almar et al. (2021) estimated the current variation in temporary coastal flooding by assessing the annual number of overtopping hours[37] from 1993 to 2015. They identified an increasing trend along most of the world's coastlines, with the southern Mediterranean being one of the areas experiencing the largest increase. This trend was associated with the region's small variability in extreme coastal water levels, meaning that even small increases in regional sea level can have a significant impact on overtopping. Under the RCP8.5 scenario, these authors estimated that by the end of the 21st century, the globally aggregated annual overtopping hours were projected to be up to 50 times greater than present-day levels, with more regions projected to become exposed to coastal overtopping.

In an independent study, Kirezci et al (2020) estimated that, in the absence of coastal protection or adaptation, and assuming a mean RCP8.5 SLR scenario, there will be a 48% increase of the world's land area, 52% of the global population and 46% of global assets being at risk of flooding by 2100 with respect to the current situation. The estimated increase in flood risk along the European coast has been associated with rising extreme water levels and increasing socioeconomic development of the coastal zone (Vousdoukas et al. 2018), with climate change being the main driver of the future rise in coastal flood losses. Regarding the magnitude of estimated extreme total water levels under SLR by 2100, the Mediterranean Basin is the area with the lowest predicted total water level, with the North Adriatic in Italy and the Gulf of Gabes in Tunisia being the areas with the highest water levels.

3.2.4 Tsunamis and meteotsunamis

3.2.4.1 Tsunamis

Tsunamis are unpredictable and infrequent but potentially large-impact natural disasters (see *Chapter 2, Section 2.2.9.4*). They are generated by underwater and/or coastal earthquakes, volcanic eruptions, as well as landslide processes (Papadopoulos et al. 2014). Tsunami activity, although infrequent, seriously threatens the communities along the coastal zones of the Mediterranean Basin (e.g. CIESM 2011). Tsunami sources in the Mediterranean Sea are situated in the near-field domain, meaning that the travel times of first tsunami wave arrivals do not exceed half an hour or so. This feature is extremely critical from a tsunami risk mitigation perspective.

Tsunamis in the Mediterranean Sea have often caused severe damage and loss of lives. Although they are less frequent than those of the Pacific or Indian oceans, some of them are well documented historical records, such as the M[38] > 8 earthquakes in 365 CE and 1303 near Crete, and the M > 7 earthquake in 1222 near Cyprus in the eastern Mediterranean. In the eastern Mediterranean, a devastating tsunami hit the coasts of Sicily and

37 Defined as the number of hours during which the extreme coastal water level exceeds the maximum coastal elevation.

38 Where M is the moment magnitude scale of the earthquake generating the tsunami.

Calabria in 1908 following a M > 7 earthquake in the Messina Straits (Lorito et al. 2008). More recent examples include the M6.8 Boumerdès earthquake in 2003 (Algeria), which affected the Balearic Islands, the M6.7 Kos-Bodrum earthquake in 2017 (Greece-Türkiye) in the Aegean Sea, and the M7.0 Samos earthquake in 2020 (Greece-Türkiye) in the Aegean Sea. According to Papadopoulos (2014), most of the events, and the most intense ones, in the Mediterranean have occurred in the eastern Mediterranean, resulting in a tsunami recurrence of 93 years. The Hellenic Arc is a major geotectonic structure dominating the eastern Mediterranean which produce large earthquakes and tsunamis. Respective rates in the western Mediterranean are 227 years; the Marmara Sea and the Black Sea are 500 and 1250 years.

A great deal of effort has been put into data collection in the Mediterranean for tsunami monitoring operations, utilising new observational techniques and sensors. These include deep-sea sensors including ocean bottom seismometers, tidal gauges, tsunameters, smart cables, and possibly DAS (Distributed Acoustic Sensing) technology, and high-precision coastal real-time GNSS (Global Navigation Satellite Systems) for better characterisation of the tsunami source (see Babeyko et al. 2022). These instruments have been essential to reducing the uncertainty associated with both the tsunami events themselves and their sources, in addition to the uncertainty exploration that has been achieved by tsunami simulations.

Although climate change will not alter the probability of occurrence of a tectonically-induced hazard, such as tsunamis, it will indirectly increase their potential impact and risk due to higher water levels associated with SLR, which would potentially increase the inundated surface (e.g. Li et al. 2018). Preliminary assessments of these effects in the eastern Mediterranean have indicated that risks would increase due to SLR and that this driver needs to be incorporated into future tsunami risk assessments (Yavuz et al. 2020).

3.2.4.2 Meteotsunamis

Meteotsunamis are those tsunamis induced by atmospheric processes (see *Chapter 2, Section 2.4.2.3*).

Hotspots in the Mediterranean where meteotsunamis are observed to occur regularly and where severe damage has been reported mainly include the Balearic Islands (more particularly Ciutadella harbour in Menorca Island) (Monserrat et al. 1991; Ličer et al. 2017) and the Adriatic Sea (e.g. Vela Luka, Stari Grad in Croatia: Hodžić 1979; Maramai et al. 2022), but also the Strait of Sicily (Šepić et al. 2018b), the Maltese Islands (Drago 2009), and some sites in the Black Sea (Šepić et al. 2018a; Vilibić et al. 2020). A comprehensive review of the meteotsunamis occurred on the Mediterranean and the Black Sea has been made by Vilibić et al. (2021).

Despite their undoubted risk for Mediterranean coasts, the meteotsunami hazard has only been assessed in the Mediterranean for the Adriatic and Balearic sites (e.g. Vilibić et al. 2008; Orlić et al. 2010; Šepić et al. 2016; Ličer et al. 2017), and not for other regions. No formal risk assessment has been carried out for any of the Mediterranean hotspots, even for those that are periodically affected by meteotsunamis.

In spite of the great efforts invested in the development of the meteotsunami warning systems, the results are still not satisfactory, leading to a loss of trust in the early warning systems. The forecasts are known to be wrong, especially when it comes to estimating the strength and destructiveness of the event *(very low confidence)* (Jansà and Ramis 2021).

3.2.5 Scarcity of suitable water resources

3.2.5.1 Freshwater resources risks; saltwater intrusion

The magnitude of the risk for coastal water resources is the result of the balance between water demands and existing resources. The recent historical climatology in the Mediterranean coastal areas explains the existence of important water demands in these areas, which tend to have a high seasonality (Niavis and Kallioras 2021). These demands are due to the existence of large populations, as well as intensive and highly productive agricultural and/or major industrial activities (Renau-Pruñonosa et al. 2016). The very important Mediterranean tourism sector (the Mediterranean zone is the top tourist destination in the world; World Tourism Organization 2018) and irrigated agriculture produce clear demand peaks during summer and will grow even more in the future, stressing water availability during these periods (Toth et al. 2018). Therefore, supplying water demand in these coastal areas with significant urban, agricultural and/or industrial development, and scarce water resources is a challenging issue (Zouahri et al. 2015), especially during droughts and, even more critically, during the summer due to tourism demand, which might be exacerbated in the future due to climate change (Tramblay et al. 2020). Global warming scenarios predict an increase in irrigation demands alongside population growth, especially in the coastal areas of eastern and southern Mediterranean countries, leading to higher water demands and further deterioration of water quality (Cramer et al. 2018).

In many areas along the Mediterranean coast, surface water resources are scarce or intermittent, which forces demand to be partially or fully supplied using groundwater resources (Sola et al. 2013). Preserving water quality in these water bodies, which also influence water availability for different water uses, is a challenging issue. In addition to the traditional water quality risks that exist in inland systems (e.g. nitrate and pesticide pollution, urban and industrial discharges, emerging contaminants, etc.) the issue of salinity from seawater intrusion also needs to be addressed (Custodio 2017). Considering that aquifers are the main source of water supply in many Mediterranean countries (Leduc et al. 2017), there has been a certain degree of over-pumping, especially during summer and drought periods. It has led to salinisation processes with seawater progressing into coastal aquifers (Rosenthal et al. 1992). In general, the Mediterranean areas with higher risks from extreme hydrological events (droughts and floods) are located in coastal areas (Fader et al. 2020). The most frequent and severe droughts are usually observed near the coast (Gomez-Gomez et al. 2022). Many aquifers of the EU Mediterranean coastline in Italy, Spain and Türkiye have suffered historically from saltwater intrusion *(Figure 3.2a)* (EEA 2009). For example, in Spain, 56 of the 95 identified coastal groundwater bodies have been affected by seawater intrusion processes (Custodio 2017). Intrusion is also very relevant across Greece, where it is estimated that the total surface area of aquifers impacted by seawater intrusion is about 1500 km² (Daskalaki and Voudouris 2008). The North African coast of the Mediterranean is also extensively affected by seawater intrusion *(Figure 3.2b).* Significant saltwater intrusion is observed in the Nile Delta in Egypt (Sefelnasr and Sherif 2014), in Morocco coastal areas (Khouakhi et al. 2015), Tunisia (Agoubi 2021) and in Jeffara plain, Libya (CEDARE 2014).

Regarding the future evolution of freshwater resources, the availability of conventional freshwater resources for the different uses is expected to decrease and be degraded, especially in the southern and eastern Mediterranean *(high confidence).* The increase in water demand and in the frequency and severity of droughts, the reduction of freshwater recharge, and the effect of sea level rise will lead to an increase in seawater intrusion in coastal aquifers (Pulido-Velazquez et al. 2018; Tramblay et al. 2020).

The unconventional water resources generated by desalination in the Middle East and North Africa will reduce the risk of water scarcity, but it will increase the risks of environmental impacts, especially on near-coastal marine ecosystems, energy requirements and associated CO_2 emissions *(high confidence).*

3.2.6 Coastal pollution risks

In the Mediterranean Basin, coastal and estuarine waters and their ecosystems have long been under the pressure of land-based pollution, which is increasingly exacerbated by climate change impacts at present. Combined effects of pollution and climate change influence coastal water quality and

A

B

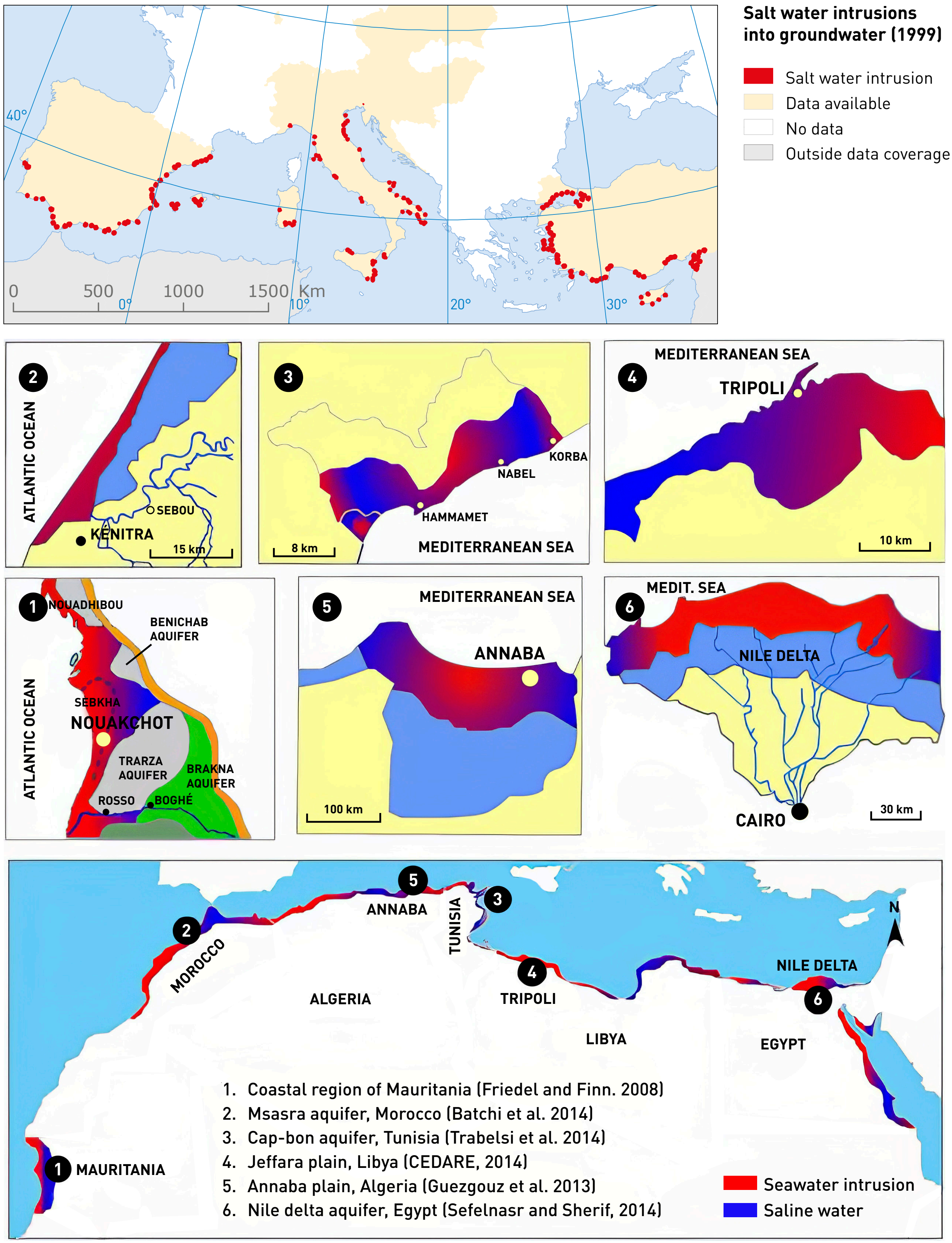

Figure 3.2 | Historical and current saltwater intrusions into groundwater in Europe and North Africa. A) Map of historical saltwater intrusions into groundwater in Europe in 1999 as a result of groundwater over-exploitation. Source: EEA (2009). B) Maps of seawater intrusion in North Africa. Source: Agoubi (2021).

ecosystem health, and trigger habitat changes and losses. Furthermore, pollution build-up on coastal ecosystems affects human health via the food chain. Coastal water pollution may be of various physical, chemical or biological origin whilst others are toxic, persistent, and emerging and may also have transboundary impacts. The combined effect of human-induced pollution and climate change pose severe risks on ecosystems and human health *(high confidence).*

Littoralisation[39] together with heavy urbanisation in Mediterranean coastal areas have increased water quality risks. Consequently, coastal waters suffer from pollution risks generated by diverse pollutants. Marine pollution stems from a wide diversity source comprising physical, chemical and biological origins that create harmful effects on ecological systems. These adverse impacts on natural systems might be generated due to various anthropogenic activities that bring several substances/materials into coastal waters. If they exceed certain threshold values, these substances are *very likely* to become harmful and have detrimental effects on the biological components of coastal ecosystems (Beiras 2018). In addition to organic pollution, other pollutants of various origins exist, some of which are toxic and persistent, such as POPs, whose origins can now be identified. Their threshold values are regulated by the Stockholm Convention[40]. Others are micro-pollutants whose components are also of various origins (e.g. pharmaceuticals and personal care products (PPCPs), microplastics), which are emerging.

Accumulated pollution from various sources in coastal and bathing waters endangers human health as well as the health of coastal ecosystems because the magnitude of anthropogenic impacts has been higher in coastal waters compared to offshore waters with increasing pressure due to climate change, overfishing and pollution as prevailing pressures (Halpern et al. 2008; Díaz et al. 2019).

An overview of nutrients, metals, emerging pollutants, persistent organic pollutants, and major environmental changes due to climate change and their impacts on coastal ecosystems will help understand the synergistic effects of climate change and marine pollution. Researchers have revealed that the interplay between environmental effects and impact caused by multiple stressors both from natural and anthropogenic sources result in synergistic effects. However, interactions among multiple stressors in marine environments may be synergistic or antagonistic. These interactions among multiple stressors vary with stressor intensity, exposure duration and biological response. Recent findings suggest that synergisms are predominant under multiple stressors because increased stressor intensity is *likely* to overcome compensatory mechanisms (Harley et al. 2006; Crain et al. 2008; Park et al. 2014; Przeslawski et al. 2015; Gunderson et al. 2016; R. Lange and Marshall 2017).

3.2.6.1 Nutrients

Eutrophication caused by excessive land-based nutrient inputs has affected many areas in the coastal zone (see *Chapter 2, Section 2.4*). Coastal eutrophication, which is caused by seawater being enriched with mainly nitrogen and phosphorus, has significantly increased within recent decades in the semi-enclosed parts of the Mediterranean in particular (Danovaro et al. 2009; Cabral et al. 2019; UNEP/MAP 2023). This phenomenon has a widespread impact on ecosystems by promoting various negative effects including hypoxia or anoxia, episodes of massive mucilage formation, harmful algal blooms (HABs), and acidification.

The most detrimental negative effect is usually hypoxia, which represents concentrations of dissolved oxygen lower than 2 mg L^{-1}, the threshold value for living organisms (Crain et al. 2008; Howarth 2008). Similarly, another harmful effect may be generated by toxic HABs which may cause human illness and even mortality. They also have socio-economic impacts related to toxicity of harvested fish and shellfish, loss of aesthetic value of coastal zones, and reduced bathing water quality impacting the tourism activities of coastal areas around the Mediterranean Basin.

39 Littoralisation is defined by the United Nations in CCD Annex IV for the Northern Mediterranean as the process of concentration of population, settlements along with economic activities in coastal areas: https://www.unccd.int/convention/regions/annex-iv-northern-mediterranean

40 https://chm.pops.int/TheConvention/Overview/TextoftheConvention/tabid/2232/Default.aspx

Coastal eutrophication is of medium or important significance in 13 Mediterranean countries (Table 3.4 in Fader et al. 2020).

3.2.6.2 Metal pollution

Estuaries function as long-term repositories and sinks for historical metal contamination, driven by the strong particle reactivity of metals with sediments (e.g. Golden Horn estuary in Istanbul, Türkiye, Acheloos River estuary, Greece) (Ridgway and Shimmield 2002; El-Amier et al. 2021; Zeki et al. 2021). Although biological processes require certain metals that are essential for biochemical reactions, some metals are not metabolised, but in both cases, high toxicity may occur even at low concentrations. The toxic effects of metal exposure include increased energy demand, which impacts the metabolic structure and growth of marine ecosystems (Richir and Gobert 2016; Yilmaz et al. 2017 2018). The toxic effect of metals may also cause significant immunosuppression or cause impaired reproduction and/or development (Rainbow 2002).

Benthic fish are prone to bioaccumulate heavy metals like cadmium and mercury, reflecting the contamination status of the marine environment by heavy caused mainly by industrial pollution. Heavy metals and pesticides cause toxicity and various diseases in fish due to aquatic pollution (Islam et al. 2018; Rani et al. 2022). Environmental assessment studies have been largely conducted in polluted areas affected by industries and ports activities. For example, several research studies conducted in Portman Bay (Spain) have shown that metal pollution from industrial and urban dumping has impacted the marine ecosystem. In this context, fish accumulate metals through ingestion of particulate material suspended in the water, food ingestion, ion-exchange with dissolved metals, and adsorption by tissue and membrane surfaces (Ben Hamed et al. 2017).

Since trace metals are not degradable, they accumulate in marine organisms throughout food webs (Vareda et al. 2019). Mercury bioaccumulation in marine food webs is a representative example of this issue (Fonseca et al. 2019), as mercury exposure has been shown to causes severe neurotoxic effects in marine fauna and humans (Depew et al. 2012; Karagas et al. 2012). Although trace metal abatement measures in the marine environment have improved in recent decades in parallel with the enforcement of the EU Directives, mercury pollution remains a global issue due to its persistence and, most importantly its capacity for long-distance transport in the environment, which can lead to transboundary pollution.

3.2.6.3 Persistent Organic Pollutants (POPs)

POPs can travel long distances in the aquatic environment and tend to accumulate in sediments due to their strong particle association associated with their hydrophobic properties. Contaminated sediments represent a significant threat to associated biota and to other organisms via the marine food web (e.g. demersal fish and marine birds). Furthermore, sea level rise and seawater intrusion in coastal aquifers may cause POPs present in coastal waters to contaminate these aquifers, compromising the quality of freshwater resources.

Across the Mediterranean Basin, pollution is transboundary, ubiquitous, diverse and increasing in both quantity and variety of pollutants, due to intensified domestic, industrial, and agricultural activities, as well as climate change *(high confidence)* (see Cherif et al. 2020, *Section 2.3.1*).

Persistent organic pollutants (POPs) pose a serious concern for transboundary pollution as their transmission can be long distances away from their sources, since they are not biodegradable in water but in fatty acids of living organisms and can enter the marine food web (Fader et al. 2020). Therefore, the synergistic effects of climate change and coastal water pollution may result in transboundary water pollution affecting even terrestrial coastal systems such as coastal aquifers and coastal ecosystems located at long range from the source of pollution.

The synergistic effects of climate change and coastal pollution are shown on *Figure 3.3* (Cabral et al. 2019).

Furthermore, interactions among multiple stressors in marine environments may be synergistic or antagonistic. These interactions among multiple stressors vary with stressor intensity, exposure duration and biological response. For instance, recent research shows that the individual and combined effect of three common water quality stressors on marine diatoms depend on additive, antagonistic or synergistic interactions (King et al. 2022).

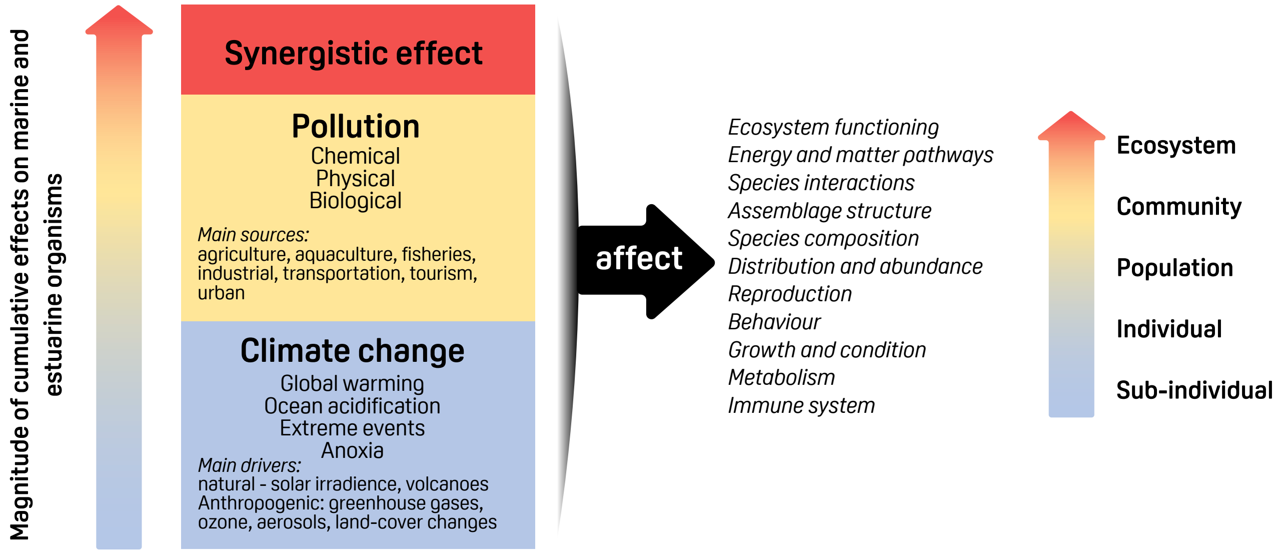

Figure 3.3 | Synergistic effect of climate change and coastal pollution. Source: Cabral et al. (2019).

POPs may create increased impact on the marine organisms, if microplastic pollution (MPs) exists in the same environment, because MPs, due to their high sorption ability for POPs (e.g. polychlorinated biphenyls (PCBs) and organochlorine pesticides (OCPs)), generate direct or indirect toxicity in marine organisms, ecosystems, as well as humans. Beaches are considered as the ecosystems most affected by MP pollution, therefore, indirectly by POPs since the ubiquitous feature of POPs on the one hand, and the pervasiveness of the MPs on the other, generate combined toxicity impacts on the marine environment (Barhoumi et al. 2023).

3.2.6.4 Microplastics

Field surveys have been conducted to evaluate the threat posed by plastic pollution to the coastal and marine ecosystems of the Mediterranean (Jambeck et al. 2015; Geyer et al. 2017; Compa et al. 2019).

With the high production and consumption of plastics worldwide, the marine environment has been suffering from plastic dispersion and deposition at all levels (i.e. coastal waters, offshore, sediment). Similarly, Mediterranean marine biodiversity is at high risk of plastic exposure (Compa et al. 2019). In addition to their continuous release into the environment, plastics disintegrate into smaller pieces and disperse into nature, undergoing various physical and chemical processes. Some of the principal sources of plastics include marine litter, which is brought into coastal zones primarily by river discharge and ships (Löhr et al. 2017). High concentrations of plastics, including tiny plastic items, could have considerable environmental, health, and economic impacts (Pedrotti et al. 2016). The worst impacted regions are coastal areas, which are hotspots for plastic ingestion, and the Mediterranean coastal area is no exception (Compa et al. 2019). Plastic ingestion affects the gastrointestinal system of marine species, from invertebrates to mammals, across both demersal and pelagic ecosystems (M. L. Taylor et al. 2016). Analyses of plastic exposure show that marine species with larger home ranges are more at risk of exposure due to covering longer distances, while local species are more *likely* to be exposed to plastic closer to their home range areas (Compa et al. 2019).

Fossi et al. (2017) suggested that a risk assessment of plastic pollution across the entire Mediterranean Basin will help gather data sets to better understand the species under exposure and/or threat, as well as identify hotspot risk locations. It should be noted that the existing threat is quite difficult to assess due to the varying ecological requirements of multiple species. Compa et al. (2019) identified hotspots at risk of plastic ingestion across multiple taxa in the Mediterranean Sea, highlighting that coastal species

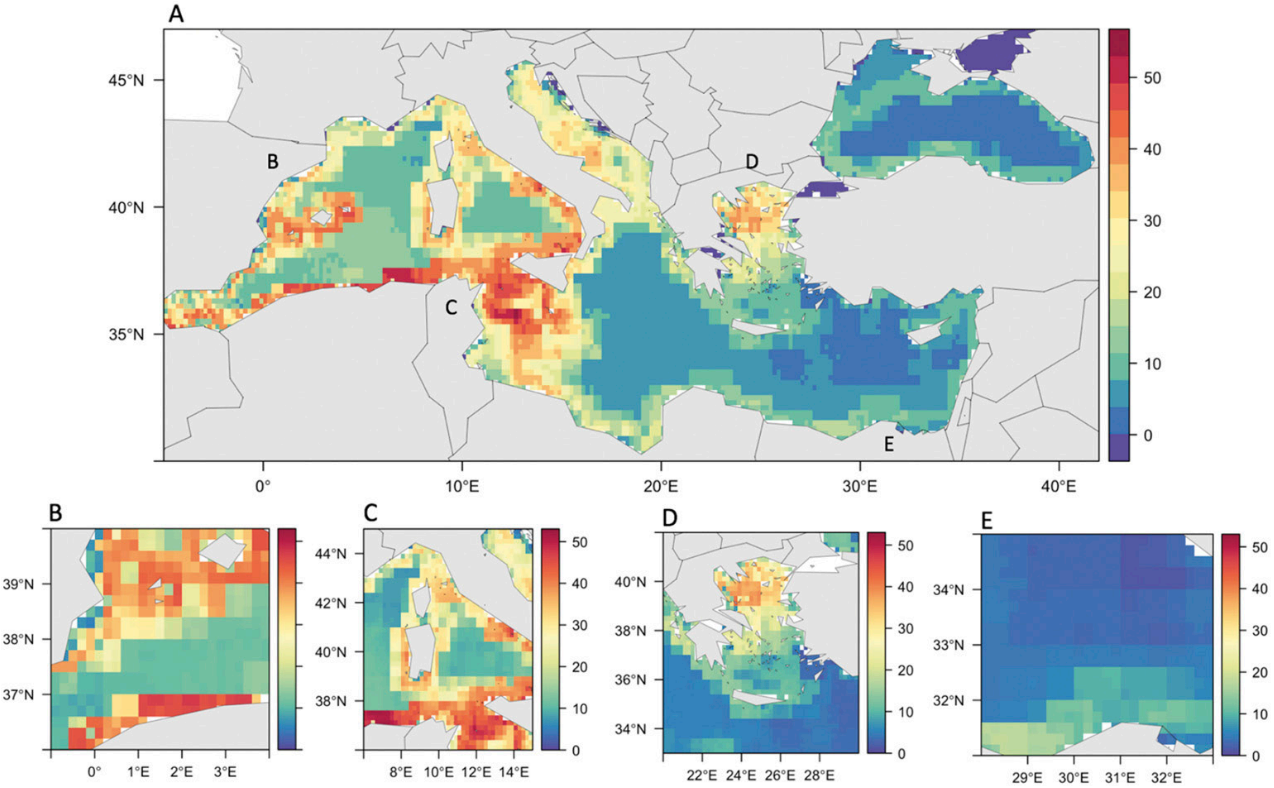

Figure 3.4 | Plastic ingestion risk across the Mediterranean Sea. A) Overall risk of predicted plastic ingestion for the 84 species modeled based on the best-fit GAM model incorporating motility, habitat, body size, and class. Red indicates high-risk areas and blue areas of low-risk of plastic ingestion in the marine diversity. Hotspot areas of plastic ingestion risk of the marine diversity for: B) coastal areas of the Strait of Gibraltar and surrounding countries, C) the Pelagos Sanctuary and the northern coast of Africa, D) Aegean Sea and E) the northern coastal areas of the south-eastern Mediterranean Sea. Source: Compa et al. (2019).

are at higher risk of ingesting plastic in the marine environment than open-sea species, as shown on *Figure 3.4.* However, the impact of plastic pollution on different seabirds and sea turtles suggests that the risks are not limited to coastal areas but may expand further to the high sea locations (Schuyler et al. 2016). The cumulative quantity of plastic waste to enter the Mediterranean Sea from land is predicted to increase by an order of magnitude by 2025 (Jambeck et al. 2015) *(high confidence)* if appropriate waste management infrastructure is not made operational.

3.2.6.5 Emerging Pollutants, pharmaceuticals, and personal care products (PPCPs)

Pharmaceutical residuals can be found in surface waters, coastal waters of heavily populated settlements, and in drinking water samples in Europe (López-Serna et al. 2013; H. Chen et al. 2018; L. Yang et al. 2020). These substances may present acute or chronic toxicity risks for aquatic organisms in coastal waters. In addition to their toxic effect, some of them are endocrine disruptors (EDCs) (Esplugas et al. 2007). Therefore, PPCPs exhibit hazardous effects due to their continuous discharge (treated or untreated) into coastal waters via wastewater treatment plants which are unable to treat them through conventional processes. Environmental health concerns stem mainly from long-term exposure to these substances, whether they are persistent or not because long-term exposure should also be considered as pseudo-persistence (Daughton and Ternes 1999; Korkmaz et al. 2022).

Several recent studies have investigated the environmental risk assessment of pharmaceuticals in coastal waters (Corcoll et al. 2014; Chaves et al. 2020; L. Yang et al. 2020; Navon et al. 2020; Dehm et al. 2021; Sadutto et al. 2021; Korkmaz et al. 2022). Based on the risk assessment results carried out in the marine environment, the following pharmaceuticals namely naproxen, diclofenac,

clofibric acid, gemfibrozil, 17β-estradiol, and 17α-ethynylestradiol have been identified as posing high risks to aquatic organisms, and consequently to human health via the food chain. These findings emphasise the critical importance of monitoring these contaminants in the marine environment to protect the ecosystem and therefore human health (Korkmaz et al. 2022).

In addition, organic waste and antibiotics input into the marine environment via aquaculture is another pollution risk on coastal waters since feed waste excess and antibiotics that are partly metabolised by fish accumulate on the bottom of the sea floor. Feed waste and antibiotics deposition in the sediment and their accumulation in the wild fauna threatens the health of marine ecosystems due to the change in the chemical conditions of the sediment, thus affecting marine biodiversity. Studies identified that feed waste and antibiotics significantly reduce the biodiversity and abundance of benthic invertebrates (Björklund et al. 1990; Grigorakis and Rigos 2011; Liu et al. 2017; Neofitou et al. 2020; González-Gaya et al. 2022). In Murcia, Spain, it has been identified that fish feed waste from aquaculture alters the habitat and biodiversity of the benthic ecosystems in the Mediterranean Sea, whilst antibiotic residuals have additive effects to the enrichment of bacterial genes (González-Gaya et al. 2022). In addition, antibiotics may create antibiotic resistance genes in the marine environment neighbouring fish cage farms, thus threatening the effectiveness of antibiotic classes of high relevance for human medicine (H. Chen et al. 2018; Higuera-Llantén et al. 2018).

Similarly, researchers pointed out that among the emerging pollutants, caffeine poses a considerable risk whereas tramadol may also have adverse effects at high concentrations. However, results indicated that the mixture of contaminants represents a potential risk for most sensitive organisms. Researchers advise the importance of examining the mixture of contaminants to carry out proper environmental risk assessments (Sadutto et al. 2021).

3.2.6.6 Atmospheric pollution

Atmospheric pollution poses a significant risk to human health and marine ecosystems (Linares et al. 2020b; MedECC 2020b; UNEP/MAP and Plan Bleu 2020; Carreño and Lloret 2021).

Atmospheric deposition settling at sea is a source of pollution that contribute to ocean acidification, which has severe impacts on a wide diversity of marine organisms including corals, planktonic organisms, and calcifying organism structures, resulting in their degradation and mortality. Several studies in the Mediterranean have been initiated by research institutions, particularly in the eastern Mediterranean (the Levant Sea), to monitor the evolution of acidification and assess its impact on marine food webs (Lacoue-Labarthe et al. 2016).

Atmospheric pollution in coastal areas elevates the risk of respiratory and other health issues for a large number of the Mediterranean coastal population due to exposure to concentrations higher than WHO Air Quality Guideline (AGQ, WHO 2021). Although regulations are projected to reduce premature mortality from $PM_{2.5}$ by up to 55% in the EU-27 by 2030[41] (compared to 2005 levels between 340,000 and 480,000), significant portions of the Mediterranean population remain exposed to harmful pollution levels (e.g. Gómez-Losada and Pires 2020; Rovira et al. 2020; Osipov et al. 2022).

In addition, atmospheric poses a risk cultural heritage, as many UNESCO World Heritage sites in the region remain vulnerable to material degradation due to continued exposure to harmful pollutants (Spezzano 2021).

3.2.6.7 Oil spill pollution

Oil spills from refinery and maritime accidents can be the source of very serious oil pollution which affects the marine and coastal ecosystem for several years and has severe impacts on human and environmental health which translates into significant economic losses (Ülker and Baltaoğlu 2018; Ülker et al. 2022). In addition, offshore oil drilling, extraction and exploration enhances the potential of oil spills which damage marine ecosystems with hydrocarbon toxicity (El-Magd et al. 2021). Beaches and recreational areas may be destroyed or degraded by oil pollution and may further cause alterations of the ecosystem by affecting and modifying the marine habitat. The impact of petroleum toxicity causes marine organisms to be injured or killed by being covered with insoluble petroleum compounds, sublittoral organisms to be poisoned, beach flora to be destroyed by oil, and benzene, toluene, and naphthalene to bioaccumulate in marine flora, fauna, and marine life in general, causing hazardous effects on human consumption (Doğan and Burak 2007).

3.2.6.8 Final remarks and research gaps

Coastal pollution presents increasing risks for coastal ecosystem health and consequently environmental health due to the build-up effects of pollution load which is exceeding the assimilation capacity of the receiving media and due to emerging pollutants, with some of the compounds still difficult to detect and monitor. Moreover, all emerging compounds in these pollutants (e.g. PPCPs) and/or micro-pollutants (e.g. micro-plastics) can be ingested by marine species and can be home to various harmful microorganisms including pathogenic species (e.g. bacteria and viruses).

Recent research has identified that interactions among multiple stressors in marine environments may be synergistic or antagonistic. Findings suggest that an overview of pollutants of various origin and major environmental changes due to climate change and their impacts on coastal ecosystems will help understand the synergistic effects of climate change and marine pollution.

Similarly, risk assessment of plastic pollution across the Mediterranean Basin can generate valuable datasets to better understand the species at risk and pinpoint hotspots. In addition, monitoring the fate of emerging pollutants and their impact on coastal ecosystems and human health will help raise awareness, so that relevant standards to preserve both natural and human health can be monitored and enforced.

3.2.7 Risks of biological origin

3.2.7.1 Non-indigenous species

Non-indigenous species, regardless of their origin, are producing a variety of ecological and socio-economic impacts on the Mediterranean (Katsanevakis et al.

41 https://environment.ec.europa.eu/topics/air_en

2014; Azzurro et al. 2022). Most of these species have been reported to affect multiple native species through a variety of mechanisms, such as predation (Gueroun et al. 2020; Prado et al. 2022), competition for resources (Caiola and Sostoa 2005; Marras et al. 2015), food web shifts (Finenko et al. 2003; Piscart et al. 2011), and vectors of pathogens or parasites (Roy et al. 2017; Peyton et al. 2019). In many cases, they also impact keystone species or species of high conservation value (Caiola and Sostoa 2005; Prado et al. 2022). However, both native and non-native (non-indigenous) species can affect species extinction and lead to serious threats to the continued health of ecosystems (Blackburn et al. 2019).

There are many examples of non-indigenous species that modify ecosystem processes or wider ecosystem functions in the Mediterranean region (Pancucci-Papadopoulou et al. 2012; Rilov et al. 2019). Extreme examples are species that behave as ecosystem engineers, that is to say that modify, create or define habitats by altering physical or chemical properties of the habitat(s) (Wallentinus and Nyberg 2007; Berke 2010). Furthermore, the lack of certain predator species can be a cause for 'eruptions' of non-indigenous species. For example, 77 species of fish are known to be predators of certain mussels (Dreissena species). However, as these fish are reduced in number and dispersion, predation of this invasive species decreases as well. The relative absence of a diverse range of native enemies (mainly predators and parasites) in newly invaded regions contributes to the rapid population growth of the invasive species (Karatayev et al. 2015).

In addition to the mentioned impacts on native biodiversity, invasive non-indigenous species negatively affect coastal ecosystem services

Table 3.1 | List, type, and description of marine ecosystem services. Adapted from Liquete et al. (2013).

PROVISIONAL SERVICES
Food: Provision of biomass (fishery and aquaculture) from the marine environment for human consumption
REGULATING AND MAINTENANCE SERVICES
Water purification: Biochemical and physicochemical processes involved in the removal of waste and pollutants from the aquatic environment
Air quality: Regulation of air pollutant concentrations in the lower atmosphere
Coastal protection: Natural protection of the coastal zone against inundation and erosion from waves, storms or sea level rise
Climate regulation: Carbon sequestration
Weather regulation: Influence on local weather conditions (e.g. influence of coastal vegetation on air moisture and temperature)
Ocean nourishment: Natural cycling processes leading to the availability of nutrients and organic matter
Lifecycle maintenance: Maintenance of key habitats that act as nurseries, spawning areas or migratory routes.
Biological regulation: Biological control of pests and invasive species
REGULATING AND MAINTENANCE SERVICES
Symbolic and aesthetic values: Senses and emotions heightened by seascapes, habitats or species
Recreation and tourism: Opportunities for relaxation and entertainment (e.g. bathing, sunbathing, snorkelling, scuba diving, sailing, recreational fishing, whale watching).
Cognitive effects: Inspiration for arts and applications, material for research and education, information and awareness

(Katsanevakis et al. 2014; Galil et al. 2017). There is strong evidence that most of the services provided by Mediterranean marine ecosystems are affected by them (Balzan et al. 2020; Dimitriadis et al. 2021; Kleitou et al. 2022; Tsirintanis et al. 2022). The most affected services are those related to food provision, but regulating and maintenance and cultural benefits are also impacted *(Table 3.1).*

As already mentioned, and according to Katsanevakis et al. (2014), food provision is the ecosystem service that has been impacted by the highest number of invasive non-indigenous species. The most cited examples of this impact are the negative effect on fisheries resources (Prado et al. 2020; Kleitou et al. 2022). Following food provision, the ecosystem services that have been most negatively affected by species are ocean nourishment, cultural services in general, and lifecycle maintenance (Katsanevakis et al. 2016, 2023).

Harmful algal blooms caused by non-native species negatively impact food and water provision (Marampouti et al. 2021). Furthermore, their impact on water resources can be exacerbated by climate change effects that will cause water shortages in some Mediterranean regions; blooms may even affect desalination, or at least increase the cost of it. There is also evidence of invasive non-indigenous species' impacts on water purification (see Salomidi et al. 2012).

Native phanerogam species and some bivalves potentially deliver coastal protection services, which are quite important under climate change scenarios with significant sea level rise and the increase in magnitude and frequency of storm surges (Ibáñez and Caiola 2021). Invasive non-indigenous species affecting these indigenous species (Prado et al. 2020, 2022; Houngnandan et al. 2022) will potentially impact coastal protection services.

Mediterranean seagrasses are potential carbon sinks and therefore provide weather regulation services. Thus, invasive aquatic vegetation that competes with native seagrasses can potentially negatively impact this ecosystem service (Silva et al. 2009). No or negligible impacts has been documented for air quality regulation and biological regulation services (Katsanevakis et al. 2014).

3.2.7.2 Mass mortalities

Mass mortality events (MMEs) have progressively increased in the Mediterranean Sea, and they have been attributed to the increase in frequency and intensity of marine heat waves (MHWs) (Diaz-Almela et al. 2007; Rivetti et al. 2014; Garrabou et al. 2022; Estaque et al. 2023) and pathogen infections *(high confidence)* (Vezzulli et al. 2010; Vázquez-Luis et al. 2017), *(Figure 3.5).* MMEs have been reported for organisms with reduced mobility, such as gorgonian corals (Estaque et al. 2023), sea grass (Diaz-Almela et al. 2007), and pen shells (Vázquez-Luis et al. 2017). In decreasing order, cnidaria, porifera, mollusca, bryozoa and echinodermata are the most affected phylums from MMEs *(high confidence)* on Mediterranean coasts (Garrabou et al. 2019, 2022).

Although the eastern Mediterranean is warming faster (Garrabou et al. 2019) and has many species living to their thermal tolerance limits, MMEs were mainly documented on the western Mediterranean coasts due to the extensive and long-term sampling efforts in favour of the west *(high confidence)* (Garrabou et al. 2019, 2022). The frequency and intensity of MMEs will *likely* increase in the future in parallel with rising MHWs *(high confidence).*

3.2.7.3 Jellyfish blooms

Jellyfish blooms, particularly those of the species *Pelagia noctiluca*, became increasingly evident in the 1980s. Not only these outbreaks were ecologically concerning but also presented immediate socio-economic repercussions (UNEP/MAP 1991; CIESM 2011). For tourists and local fishers, the presence of these jellyfish was more than just an inconvenience. Their stinging tentacles caused painful injuries, leading to direct implications for tourism, a significant industry for many Mediterranean nations. Beach tourists were often hesitant to swim in infested waters, and fishers found their catches compromised either by stings or by the presence of jellyfish in their nets (De Donno et al. 2014). Chelsky et al. (2016) emphasise that the massive abundance of jellyfish is not just an ecological concern but a substantial threat to coastal activities. This goes beyond the direct injuries caused to humans. Jellyfish blooms can impact power plants by clogging cooling water intakes, thereby causing operational challenges and monetary losses. Additionally, the post-mortem accumulation of jellyfish on shores results in beach fouling, leading to clean-up costs and a decline in beach aesthetics, further affecting tourism (Ghermandi et al. 2015).

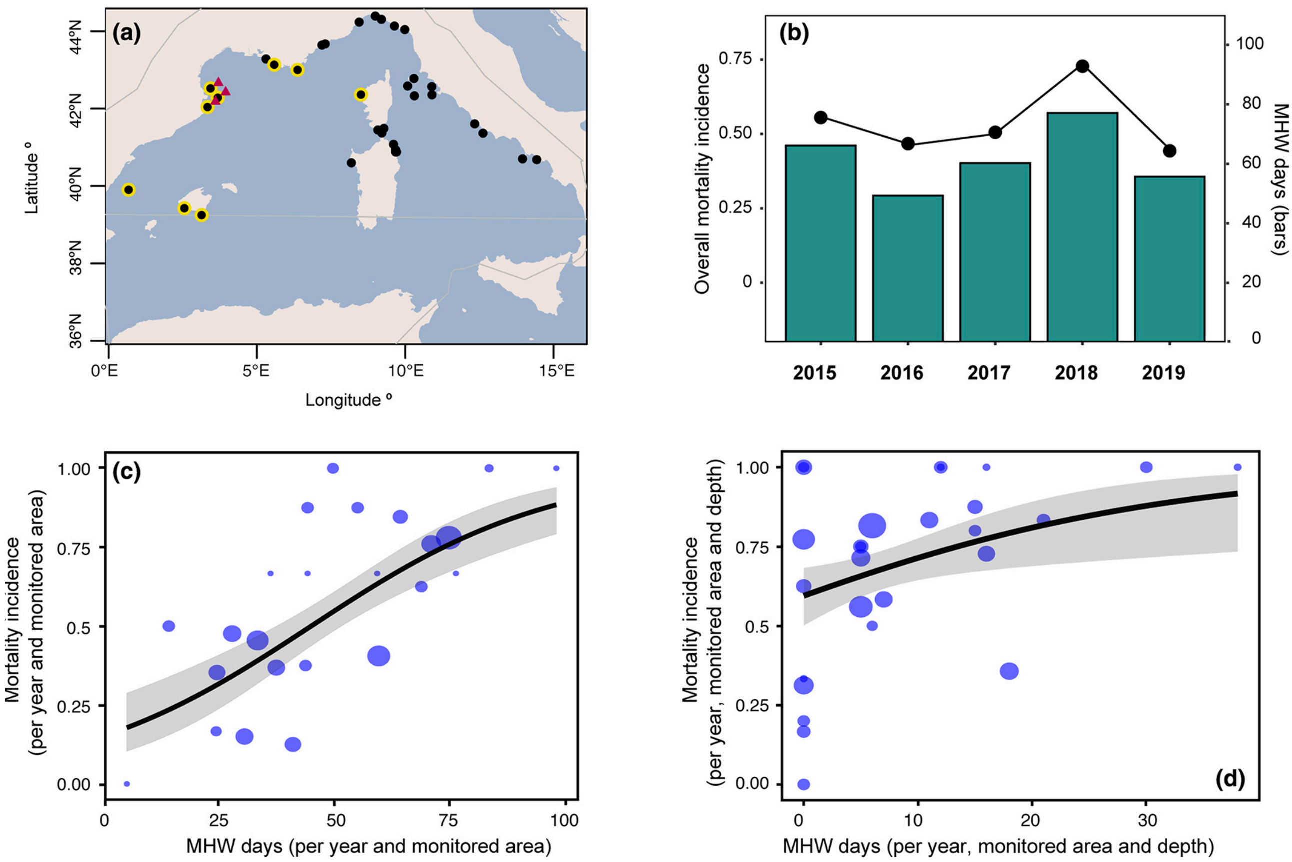

Figure 3.5 | Relationship between heat exposure (marine heatwave [MHW] days) and mortality incidence in the Northwestern Mediterranean ecoregion during 2015–2019. (a) Map of the northwestern Mediterranean ecoregion showing the location of the monitored areas included in the analysis; black dots: monitored areas used in the regional analysis shown in panel b), yellow dots : the monitoring areas considered for the analysis shown in panel c), red triangles: areas with long-term, in situ temperature monitoring used for the in-depth analysis shown in panel d); (b) Bars and points show, respectively, the yearly mean number of MHW days and mortality incidence (proportion of records showing mortality) observed across the northwestern Mediterranean basin. Panels c and d show respectively the relationship between heat exposure (yearly average of MHW days during the JJASON period) at the surface (sea surface temperature) or across depth (from 5 to 40 m) and the corresponding mortality incidence in the studied monitored areas, years, and/or depths. The lines show the predicted values of the generalized linear models and their confidence interval (95%). The size of the points is proportional to the sampling size. The map lines in panel (a) delineate study areas and do not necessarily depict accepted national boundaries. Source: Garrabou et al. (2022).

A more insidious concern associated with jellyfish blooms is the potential public health risk they pose. Jellyfish can act as vectors for bacterial pathogens, which can severely impact fish aquaculture. These pathogens, when introduced into aquaculture settings, can cause diseases among farmed fish, leading to economic losses and potential health risks if contaminated fish are consumed (Delannoy et al. 2011). Basso et al. (2019) further highlights the risks associated with jellyfish and bacterial pathogens, emphasising the need for comprehensive strategies to monitor and manage jellyfish blooms in order to safeguard both marine ecosystems and human health.

From an ecological standpoint, the proliferation of jellyfish poses significant challenges to marine biodiversity. Jellyfish are highly effective predators and compete aggressively for resources. Their burgeoning populations can deplete the availability of zooplankton, which has cascading impacts on the food web. Predatory fish that rely on smaller organisms for food can face scarcity, leading to overall reduced fish stocks (Purcell 2012; Báez et al. 2022). This not only affects the marine ecosystem but also the fishing industry, which is pivotal to many Mediterranean economies.

3.2.7.4 Mucilage

Mucilage is a dense and highly viscous substance made up of extracellular polysaccharides produced and secreted by the overgrowth of various aquatic species. Rising ocean temperatures, as well as human-induced stressors such as insufficient treatment levels and overfishing, are common causes of such algal blooms. Although mucilage is a harmless organic material structurally, studies have indicated that mucilage is home to various harmful microorganisms including pathogenic species (e.g. bacteria and viruses) (Del Negro et al. 2005; Precali et al. 2005; Danovaro et al. 2009).

The highly productive and shallow Adriatic Sea within the Mediterranean Sea is reported as the area most severely affected by massive marine mucilage (Danovaro et al. 2009). The frequency of the mucilage phenomenon is indicated to have increased significantly in recent decades. Mucilage adversely affects seawater and makes it unsuitable for bathing due to the adherence of this mucus-like product on bathers' skin. Marine mucilage may float on the sea surface and then in the water column for a long-life span of two to three months and once settled on the benthos in the form of large aggregates, it coats the sediment, causing hypoxic and/or anoxic conditions (Precali et al. 2005). Consequently, suffocation of benthic organisms causes serious economic damage to tourism and fisheries (Rinaldi et al. 1995).

As an example, the semi-enclosed Marmara Sea was severely threatened by a mucilage outbreak in May 2021. The Marmara Sea is a semi-enclosed water body connecting the Mediterranean and the Black Sea via the Çanakkale (Dardanelles) and Istanbul Strait (Bosphorus). This system is formed by a two-layer current driven by a salinity gradient between the more saline (38 psu) and dense waters of the Mediterranean, flowing towards the Black Sea in the lower layer, while the less saline (18 psu) waters of the Black Sea move in the opposite direction. The strong and permanent stratification because of salinity, density and temperature gradient exacerbate the risks of pollution of biological or anthropogenic origin. Sea surface was covered with thick layers of foam on beaches and harbours, threatening marine life, tourism, fisheries, maritime traffic, and the economy. Fishing activities were temporarily halted to prevent potential sea-borne diseases and due to consumer reluctance. Although mucilage events in the Marmara Sea are not new or region specific, this instance was the most severe on record. The phenomenon has drawn increasing attention as it severely impacts overall ecology, particularly benthic organisms (Savun-HekiMoğlu et al. 2021).

3.3 Impacts on the socio-economic system

Some regions of the world are expected to be affected by climate change, which will act in most cases as a catalyst for already deteriorating socioeconomic and environmental conditions including low average per capita income, fast demographic growth, and conflicts in many countries in the MENA region and Africa (Ali et al. 2022). This is expected to cause distressed movements as a coping strategy, either within the region or toward Europe. Anticipated trends suggest that the Mediterranean region will experience climate-induced migration due to extreme weather events in the affected nations since it is expected to confront the gradual and incremental impacts of climate change (Moatti and Thiébault 2016). Importantly, it is challenging to determine the precise number of individuals currently displaced by climate change effects within the region (Moatti and Thiébault 2016).

3.3.1 Impacts on tourism

The impact of climate change on the tourism industry in the Mediterranean, a region that draws nearly 200 million tourists annually, illustrates a critical challenge. Increasing heatwaves, reduced rainfall, and rising sea levels threaten its tourism-driven economy, necessitating urgent examination and adaptation strategies.

There is *high agreement* with *robust evidence* that climate change and its induced hazards impact tourism (Perch-Nielsen et al. 2010; Seetanah and Fauzel 2019; Arabadzhyan et al. 2021) *(high confidence).* The Mediterranean region, the destination for almost 200 million tourists, is known as one of the most vulnerable regions to climate change (Stratigea et al. 2017; Cannas 2018; Rick et al. 2020). The region is expected to face more intense and frequent heatwaves, a significant decrease in rainfall, an increase in periods of drought, and an increase in sea levels (Galeotti 2020), all of which will *likely* influence the tourism industry in the region (Perry 2000; World Tourism Organization 2008; Anfuso and Nachite 2011; Dogru et al. 2016; Rizzetto 2020). It has been predicted that the Mediterranean region will become excessively hot for tourists' comfort in the summer months (Amelung and Viner 2006; World Tourism Organization 2008; Rutty and Scott 2010; Arabadzhyan et al. 2021). For instance, the suitability of southern Europe to appeal to tourists will decrease during the summer holiday months but improve between October and April (Perch-Nielsen et al. 2010). Climate change *likely* changes the destinations and seasonal distribution of tourism (Ciscar et al. 2011; Amengual et al. 2014; Koutroulis et al. 2018), tourist activities (Caldeira and Kastenholz 2018), and alter tourism flows as well (World Tourism Organization 2008; Magnan et al. 2013).

Moreno (2010) found that while climate is a significant consideration for Mediterranean tourists, heat waves are considered the least consequential factor. However, projections by Amelung and Viner (2006) indicated spatial and temporal changes in climate attractiveness, which would affect the sustainability of tourism development, making spring and autumn more desirable *(high confidence).*

There are various case studies on the impacts of climate change on tourism in the Mediterranean region. El-Masry et al. (2022) argued that climate change will cause devaluation of coastal tourist destinations and thus a decline in revenues for the El Hammam–EL Alamein region in Egypt. They predict a downward shift in the region in terms of tourism climate suitability in the future. Abo El Nile (2017), through survey research for MENA countries, showed the impact of climate change on beach tourism in the region and discussed the need to anticipate changes and to adapt. Katircioglu, et. al. (2019) presented positive climate change influences on foreign tourist flows to Cyprus and Malta. Enríquez and Bujosa Bestard (2020) found the negative impact of climate-induced environmental change on tourist attractions by measuring economic impacts on the coast of Mallorca (Spain). Vrontisi et al. (2022) also found harmful impacts of climate change on the tourism sector in the southern European islands (Baleares, Crete, Cyprus, Malta, Sardinia, and Sicily). Hall and Ram (2018) analysed the negative influences of climate change on coastal tourism in Israel. In summary, there is *high confidence* that climate change influences tourism and consequently affects Mediterranean economies. While increasing temperatures might conceivably diminish the suitability of the Mediterranean climate for summer tourism, one could argue that there might be a rise in tourist visits during alternative seasons like winter, autumn, and spring. Therefore, the potential negative impact on Mediterranean economies is debatable, as it could result in an

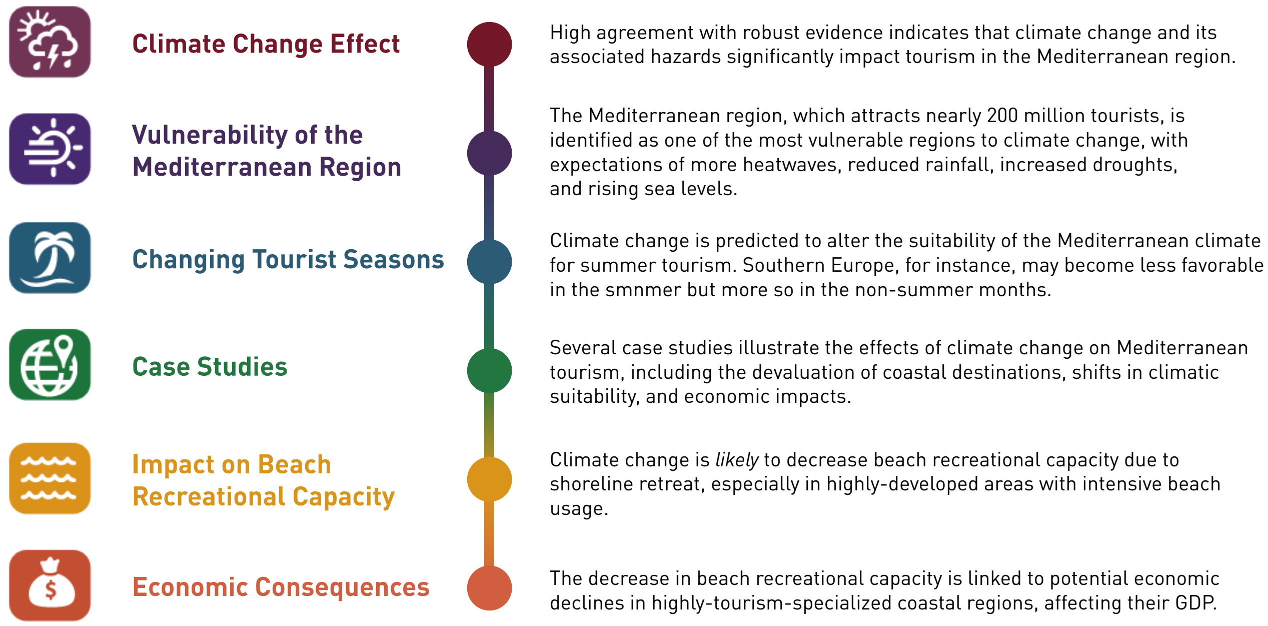

Figure 3.6 | Key points on climate change impact on Mediterranean tourism.

overall increase in tourism spread across seasons rather than being concentrated solely in the summer.

One of the most direct impacts of climate change on coastal tourism along the Mediterranean Basin is *likely* the decrease in the recreational beach carrying capacity (BCC) as a consequence of the projected increase in shoreline retreat (see *Chapter 3, Section 3.2.2*). This is due to the decrease of available beach surface for recreational purposes due to beach narrowing (in areas with a rigid landward boundary limiting the accommodation space as tourist beach areas used to be) with the corresponding increase in density of users during the first stages, which will be followed by the decrease in beach users as density exceeds beach saturation values (Valdemoro and Jiménez 2006; Rodella et al. 2017). This risk is *very likely* to occur in highly developed areas with beaches of intensive use such as the Spanish, Italian, French and Greek coasts. López-Doriga et al. (2019) therefore estimated that by 2050, without adaptation, the beaches along the Catalan coast (Spain, north-western Mediterranean) will potentially experience an overall 19% decrease in BCC under current conditions, increasing to 36% under RCP8.5. For coastal counties highly specialised in tourism, this represented a potential decline in their GDP of between 18% and 26% under RCP8.5 by the end of the century (Garola et al. 2022). *Figure 3.6* provides a concise summary of the impacts of climate change on Mediterranean tourism.

As a final conclusion, existing research reveals climate change's multifaceted effects on Mediterranean tourism, suggesting a shift towards alternative seasonal tourism as a potential mitigation strategy. Adaptive measures are essential to harnessing opportunities and mitigating economic impacts, ensuring the region's tourism sustainability in the face of climate change.

3.3.2 Impacts on food security and agriculture

Climate change is one of the critical environmental challenges for production systems in the Mediterranean area (Capone et al. 2020; Hossain et al. 2020) and is expected to threaten agriculture (Aguilera et al. 2020; Kavadia et al. 2020). It is expected to reduce food production in the region (Grasso and Feola 2012; Galeotti 2020) and negatively impact the biodiversity of agriculture (Palatnik and Lourenço Dias Nunes 2015; Galeotti 2020), fisheries and aquaculture (see *Section 3.3.3*). Crop yields for winter and spring are expected to decline because of climate change, especially in the southern Mediterranean (Galeotti, 2020). In addition, climate change will influence the growth cycles of crops and could

result in significant limitations in this regard (Funes et al. 2021). On a sub-regional scale, North African countries, due to their limited adaptive capacity, face higher vulnerability to climate change's impact on agriculture compared to northern Mediterranean countries (Atay 2015).

As introduced before, climate change is presently exerting adverse effects on regional water availability, and climate change is intensifying the ongoing trend of reduced water availability (see *Section 3.2.4*). Since agriculture is the leading water consumer in the Mediterranean region (Daccache et al. 2014; Pool et al. 2021), this expected decrease in water resources will affect agriculture (García-Garizábal et al. 2014; Papadopoulou et al. 2016), with significant detrimental ramifications on the productivity of crops, including orchards and vineyards (Del Pozo et al. 2019). Due to climate change, the Mediterranean area may need between 4 and 18% more water for irrigation (Fader et al. 2016; MedECC 2020b). Brouziyne et al. (2018) predicted a 26.4% decrease in Mediterranean water yield and a 44.7% decrease in crops produced by rainfall (winter wheat, and sunflower) by 2050. Decreased spring rainfall due to climate change would therefore result in a decrease of rain-fed crop production. In addition, climate change could harmfully impact intensive dairy farming in terms of milk production and quality, and cattle mortality (Dono et al. 2016).

Another impact of climate change on agriculture is soil degradation as climate change threatens the natural capital of soils (Ferreira et al. 2022). Kourgialas et al. (2016) predicted considerable soil erosion with a mean annual loss of 4.85 t ha^{-1} yr^{-1}. This study highlighted that soil loss would increase by 32.44% and 50.77% in 2030 and 2050, respectively, compared to current conditions (Kourgialas et al. 2016).

Various case studies focus on the impacts of climate change on agriculture and food production. In Egypt, according to projections by Fawaz and Soliman (2016), by 2030, the cultivated area is anticipated to decrease to approximately 0.949 million acres, and the crop area will decrease to about 1.406 million acres. These figures represent approximately 8.22% and 6.25% of the current area, respectively. Consequently, the value of Egyptian agriculture production would decrease by about 6.19 billion US dollars (Fawaz and Soliman 2016). Salinity in the soil in the Nile Delta coast would rapidly increase and organic matter content will decrease, especially during the summer season (El-Nahry and Doluschitz 2010). In Türkiye, the yield of crops would decrease at a growing rate due to climate change (Bozoglu et al. 2019). In Andalucia (southern Spain), climate change could cause a 95% reduction in sunflower crops by 2100 in addition to a decline in wheat production (Abd-Elmabod et al. 2020). Bosello et al. (2013) predicted an average production loss of 0.5% for the agricultural sector of southern and eastern Mediterranean countries.

In addition, there are studies focused on the detrimental impact of climate change on particular products in parts of the region, including orchards (Del Pozo et al. 2019), grapevines (Ferrise et al. 2016; Del Pozo et al. 2019), viticulture (Santillán et al. 2020), wheat (Ferrise et al. 2016; Dixit et al. 2018; Zampieri et al. 2020; Reyes et al. 2021), durum wheat (Ferrise et al. 2011), barley yield (Cammarano et al. 2019), olives (Ponti et al. 2014; Fraga et al. 2020a, 2020b; Rodrigo-Comino et al. 2021), and rice (Bregaglio et al. 2017) in the eastern Mediterranean and the Middle East (Constantinidou et al. 2016). For mushrooms, unlike the results for the other products, Karavani et al. (2018) predicted higher fungal productivity for 2016–2100 compared to current mushroom yields. Moreover, Atay (2015) anticipated a 1.1% rise in wheat yields, 0.36%, and 0.67% decline in maize yields, and 2.0% and 2.8% increase in potato yields due to a 1% increase in temperature in two groups of countries in the Mediterranean region.

Reduced crop yields, combined with population growth and urbanisation, increasing competition for water, and changing lifestyles, including diets, are also expected to impact food security in the Middle East and North Africa (MENA) region (Jobbins and Henley 2015). A typology of the impacts of coastal risks, mostly driven by climate change, on agriculture and food security can be proposed. First, the direct impact of coastal risks (from climate change) on agriculture: loss of agricultural productivity in coastal areas (but not necessarily due to the location of crops and livestock near coasts); loss of ecosystem services associated with food provision (Mehvar et al. 2018), depletion of natural resources, especially nutrients and water. The latter is due to salt intrusion linked to sea level rise and over-pumping from groundwater resources (Mastrocicco and Colombani 2021). For agroecosystems, salinisation of soils may cause changes to the distribution of plants and animals, while seawater intrusion is expected to cause additional risks in coastal aquifers, with severe impacts on agricultural productivity (Ali et al. 2022).

Secondly, a direct impact on total agricultural output is due to land loss because of coastal erosion, and loss of some farm infrastructure (access roads, agricultural buildings, irrigation networks, etc.). For example, farmland may be converted to tourism-related areas because of coastal erosion (Luisetti et al. 2008), while in some cases farmland is lost ('coastal squeeze') to wetlands that 'retreat' onto agricultural land that cannot no longer be cultivated because of submersion (Kuhfuss et al. 2016). Erosion and salinisation are already harming soil contents and production capacity in the Mediterranean region, with previously fertile soil prone to desertification, and these factors of reduced agricultural land are exacerbated by climate change (ARLEM 2021). As pointed out by FAO (2015), reduced livelihood options in coastal regions will force occupational changes and may increase social pressures, because livelihood diversification as a means of risk transfer will be reduced (e.g. between farming and fisheries).

Thirdly, indirect impacts due to land use change because global trends connected or not to climate change will also affect agricultural activities in coastal areas. Moreover, water availability and quality in coastal areas will probably diminish due to saltwater intrusion driven by enhanced extraction and SLR, also because of increased water pollution from urban sprawl, tourism development and population growth (Hinkel et al. 2014). Population growth in coastal areas will mechanically increase demand for local food, with increased demand for irrigation water as a corollary, particularly in the coastal areas of eastern and southern Mediterranean countries (Cramer et al. 2018).

Local ecosystem-based and nature-based solutions (e.g. conservation and revegetation projects, Integrated Coastal Area and River Basin Management) that may reduce the impacts of coastal risks on agriculture in the Mediterranean have been proposed in UNEP/MAP and Plan Bleu (2020). Joshi et al. (2016) estimate the economic impacts of SLR on regions including Africa and the Middle East, to conclude that economic impacts due to loss in cropland without protection are low (compared with loss of capital, change in labour supply and government

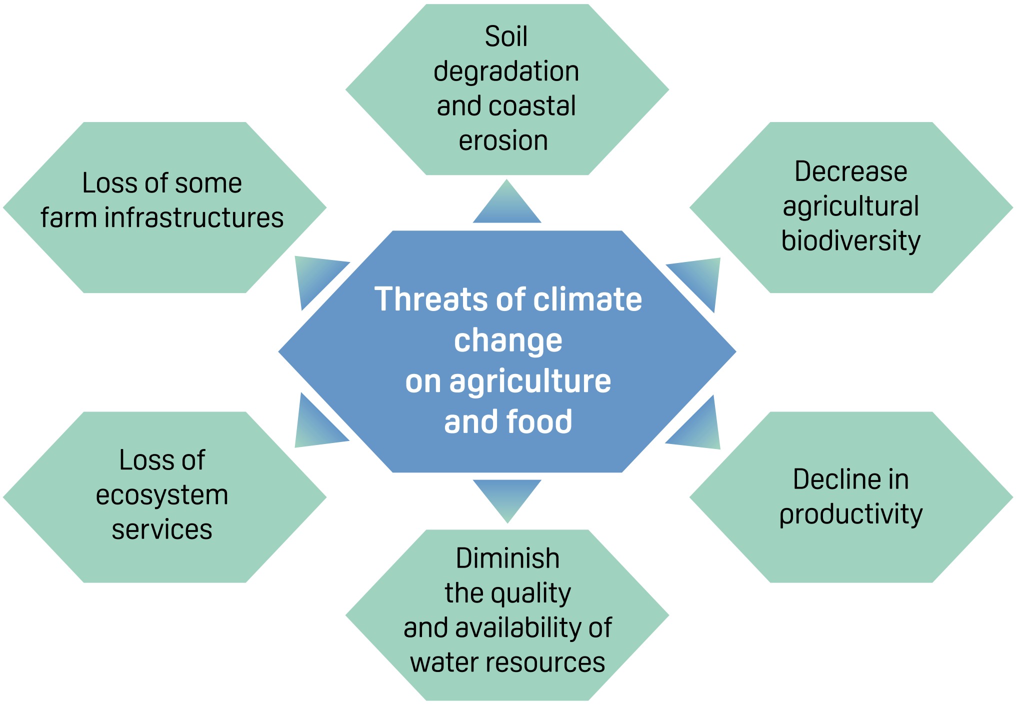

Figure 3.7 | Key climate change threats to agriculture and food security at a glance.

expenditure on migration), and that the economic impact of SLR is affecting South-East Asia, Australia and New Zealand potentially the most. Note also that, given the limited share of total agricultural output of MENA countries (except for Türkiye), coastal risks due to climate change in the MENA region are not *likely* to have a strong impact on global markets for agricultural commodities (C.-C. Chen et al. 2012). *Figure 3.7* shows an overview of the pivotal climate change threats to agriculture and food security.

As a final conclusion, the diverse studies on climate change's impact on Mediterranean agriculture reveal a sad picture: declining crop yields, exacerbated soil degradation, and increased water demands for irrigation. This situation underscores a move toward more adaptive measures and enhanced research focusing on underrepresented crops and the indirect effects of land use change. Dealing with these challenges through comprehensive policy design and informed decision-making is essential for securing the region's food security in the face of climate change.

Confidence level and knowledge gaps

There is a particular need for research into various aspects of climate change in relation to agriculture and food security. First, more research is necessary on the impact of climate change for crops and products less present in the agricultural literature than orchards, grapevines, viticulture, wheat, barley, olives, and rice in particular. Secondly, several issues could not be addressed due to a lack of data, in particular the expected decrease in local water resources that will affect agriculture at the landscape (or small river basin) level. Uncertainty about the extent to which the Mediterranean area may need more water for irrigation may be reduced by collecting more comprehensive data on the extent of soil degradation (as climate change threatens the natural capital of soils). Moreover, uncertainty remains on the indirect impacts on coastal areas due to land use change, because changes at the global level (associated or not with climate change), will impact agriculture in these areas. Water availability, and water quality, will probably be reduced because of saltwater intrusion due to excess resource extraction and SLR, but also because of increased water pollution from urban expansion and population growth. However, more case studies on a larger set of contrasted settings in the Mediterranean region are necessary to obtain a more representative vision, which could provide guidance for policymaking and decision makers.

Finally, better knowledge of local expected impacts and data collection efforts, especially in the southern and eastern Mediterranean, are needed to provide a more effective plan for action, as the majority of scientific literature addresses coastal risks and agriculture in South Asian countries, the United States and Pacific Islands (Kumar et al. 2022) or for large world regions excluding the MENA region (Bosello et al. 2007).

3.3.3 Impacts on fisheries and aquaculture

When considering Mediterranean fisheries and aquaculture, climate change significantly affects species diversity, distribution, and productivity. The region's fisheries, renowned for their rich biodiversity and intricate socio-economic dynamics, face increasing pressure from overexploitation and environmental shifts. These challenges intensify the vulnerability of marine ecosystems and the communities reliant upon them.

Mediterranean fisheries are extremely diverse because of the heterogeneity of the sea with respect to the number of species harvested, variety of fleets, hydrography, bathymetry, and productivity (Barange et al. 2018), but also to the varying cultural, social and economic conditions across the Mediterranean coastline (Stergiou et al. 2016). Nearly 400 species of fish, crustacean, and molluscs are being fished by numerous types of fishing gear and methods in the Mediterranean Sea, yielding over one million tonnes of catches per year according to official statistics. (FAO 2022) Recent studies based on scientific surveys, stock assessments and catch data, generally agree that the Mediterranean fisheries are overexploited, with the majority of fish stocks experiencing a decline in biomass (Cardinale and Scarcella 2017; Colloca et al. 2017). The cumulative percentage of collapsed and overexploited stocks was reported to exceed 60% (Tsikliras et al. 2013) with the exploitation pattern differing among the Mediterranean subareas (Tsikliras et al. 2015). Local reports also confirm the overexploitation of Mediterranean fisheries (e.g. Greek seas: Tsikliras et al. 2013; Ligurian Sea: Abella et al. 2010; Turkish seas: N. Demirel et al. 2020), which is often attributed to poor or inadequate management practices (Tsikliras and Stergiou 2014; Cardinale and Scarcella 2017). Finally, there is *high confidence* that the exploitation rate in the Mediterranean is steadily increasing and gear selectivity deteriorating; both conditions are *likely* leading to shrinking fish stocks (Vasilakopoulos et al. 2014).

Climate change is adversely affecting the range and quantity of species available (*high confidence*; Costello et al. 2022) and is leading to changes in fisheries (Brander 2007) and the emergence of non-indigenous species (*high confidence*; Costello et al. 2022). The progressive occurrence and establishment of warm-water species (Lloret et al. 2015) *likely* generates both positive and negative effects on fisheries (Hidalgo et al. 2018), especially on small-scale fisheries because of their socio-economic and ecological sensitivity. These generalised effects can be listed as (1) increase of warm water species such as bluefish *(Pomatomus saltatrix)* and barracuda (*Sphyraena viridensis*) as examples of 'Meridionalisation' in northern Mediterranean areas *(medium confidence)*; (2) presence of Indo-Pacific species (Lessepsian migrants) in the eastern Mediterranean (Boero et al. 2008) as evidence of 'Tropicalisation' *(high confidence)*, and (3) extension of the distribution ranges of Mediterranean species and detection of non-indigenous species in the Black Sea, called as 'Mediterranisation' *(low confidence).* There is *high confidence* that non-indigenous species compete with native species (e.g. rapa whelk – *Rapana venosa*; N. Demirel et al. 2021) or include highly damaging toxic species such as pufferfish (e.g. silvercheeked toadfish – *Lagocephalus sceleratus*; (Ünal and Göncüoğlu Bodur 2017). Some studies have considered the impacts of climate change on species and stocks, including trout (climate change influences the largest, oldest trout through increased metabolic costs) (Ayllón et al. 2019); finfish aquaculture in Greece (Stavrakidis-Zachou et al. 2021; Aragão et al. 2022); demersal fisheries (Aragão et al. 2022); shellfish (Martinez et al. 2018; Carosi et al. 2019); endemic freshwater fishes (*Padogobius nigricans, Squalius lucumonis* and *Telestes muticellus*) in the Tiber River basin (Italy) (Carosi et al. 2019).

Future projections show that regional changes in fish abundance and their distribution will *likely* alter species diversity, with an expected increase in overall diversity by the mid-21st century in the eastern Mediterranean, and a decrease in the western region (Sinclair and Valdimarsson 2001; Albouy et al. 2013). A *likely* decrease in connectivity between neighbouring ecosystems within the Mediterranean is expected due to a decrease in the size of the spawning areas and an increase in larval retention on smaller areas of the continental shelf. Fish often move between marine ecosystems, making them difficult to track, count and assess (Sinclair and Valdimarsson 2001). Each species has a unique reproductive strategy and behavioural, physiological, and energetic adaptations, which comprise their ecological niche. Healthy fish populations therefore ultimately depend on the collaborative success of their spawning *(very likely)* and reproductive seasons, as well as prey availability *(very likely)*, especially in changing environments under climate change.

Aquaculture plays an important role in the Mediterranean economy (Cubillo et al. 2021). The average per capita consumption of seafood in the Mediterranean region is 16.5 kg per year, and aquaculture activities provide almost 25% of it (Rosa et al. 2012, 2014). Climate change is *likely* expected to have direct and indirect effects on the aquaculture sector (FAO 2020). There is a virtually certain connection between the temperature preferences of aquatic species, and their oxygen demands (Barange et al. 2018; Pauly 2019). Specifically, the oxygen concentrations required to meet the maximum oxygen demand for organisms determines their temperature preference. Exposure of fish to temperatures beyond their adaptive range to leads to changes in their physiological responses and increases in stress levels (Bell et al. 2018). In the short term, although rising water temperatures *likely* increase the forage availability and growth rates of organisms, these rates will decrease as temperatures continue to rise, as cultivated species have limited space to move (Crozier et al. 2008). Optimal areas for aquaculture are therefore expected to shift towards the poles. As a result of climate change, extreme weather events such as strong winds and waves will *likely* damage facilities such as cages and platforms used in shell and fin aquaculture and cause negative consequences such as losses of brood stocks and significant damage to facilities. Possible flooding in flat coastal areas at sea level suitable for breeding brackish water species is also predicted (FAO 2020).

Final remarks

The socio-economic importance of fisheries and aquaculture in food security and economic development, as well as in generating employment and income, requires a proactive approach in the development of adaptation and mitigation policies regarding climate change and aquaculture interactions. Raising awareness and understanding the perceptions of stakeholders about the impact of climate change on fisheries is an important pillar of the adaptation and/or mitigation policy development process.

Sustainable fishery management is needed to ensure long-term optimal resource use. To effectively manage fish stocks, various control measures exist that directly or indirectly limit catches. However, the diversity of multiple types of fishing gear and target species makes fisheries management applications even more complex. In the Mediterranean Basin, which is more heavily affected by climate change and human-induced pressures than the global seas, intensive efforts are necessary to develop responsive fisheries management. This, for example, includes timely restriction on fishing and protection of spawning stocks by way of fishery closure to minimise the amplified impacts of excessive fishing and environmental change. Continued expansion of the fishing capacity in the absence of effective and restrictive management actions may exacerbate the risk of overexploitation. While considering the social, legal, and economic drivers fostering fleet growth, a bottom-up governance approach for the well-being of small-scale fishers is greatly needed.

As a final remark, addressing climate-induced impacts on the fishing and aquaculture sectors, while safeguarding their sustainability and contributions to regional food security and economic stability, can be advanced through stakeholder collaboration, research-driven insights and ecosystem-based approaches.

3.3.4 Impacts on water and energy security

As the impacts of climate change intensify, the Mediterranean region is facing growing threats to its water and energy supplies. Decreased rainfall and more frequent heatwaves are already straining the region's natural resources, underscoring the pressing need for strategic planning to address these vulnerabilities.

Climate change affects water security adversely (Al-Jawaldeh et al. 2022; Daoudy et al. 2022; Marangoz and Daloglu 2022). It can substantially

decrease water yield, surface runoff, groundwater recharge, and baseflow in the Mediterranean region (Pulighe et al. 2021). Some studies have emphasised this effect for Mediterranean countries such as Algeria (Bouregaa 2022), Cyprus (Gökçekuş et al. 2021), Egypt (Alkhawaga et al. 2022), Morocco (Hadri et al. 2022), Palestine (Sarsour and Nagabhatla 2022) and Türkiye (Gümrükçüoğlu Yiğit 2022). In addition, Iglesias et al. (2011) highlighted challenges to water resources in Mediterranean countries and outlined the risks and opportunities for water under climate change. Chenoweth et al. (2011) predicted that precipitation would decline by 10% in the region by both the middle and the end of the century. It will not significantly change per capita water resources in the North, while it will significantly reduce per capita water resources in the eastern Mediterranean.

Likewise, it is expected that climate change will exacerbate challenges related to energy security in the Mediterranean region (M. A. Lange 2019; Drobinski et al. 2020). In urban areas, there is an expected increase in heat waves and droughts due to the major climate impacts such as rising temperatures and reduced precipitation, resulting in shortages of both water and energy (M. A. Lange 2019, 2022). To tackle climate change and its effects on energy security, Mediterranean economies need mitigation and adaptation strategies including enhanced efficiency of resource use, integrated technology assessments regarding electricity generation, and a stronger reliance on renewable/ solar technologies (M. A. Lange 2019). They are required in order to adopt accelerated energy transition policy and diversify the energy mix (Drobinski et al. 2020). It should be mentioned that climate change affects the pace of the energy transition (Flouros 2022). Baglivo et al. (2022) suggested zero-energy buildings for energy security and to combat climate change.

To cope with energy and water scarcities, Drobinski (2020) proposed integration of a regional energy market and cooperation as a mitigating strategy. Furthermore, M. A. Lange (2019) recommended an integrated water–energy nexus concept. Some studies have also focused on the Water–Energy–Food (WEF) nexus to address water, energy, and food security under climate change, including Riccaboni et al. (2022), Zebakh et al. (2022), and Bazzana et al. (2023).

3.3.5 Impacts on coastal infrastructure

Mediterranean coastal infrastructure faces escalating threats from climate change. Ports, airports, and transport networks are increasingly vulnerable to SLR, coastal flooding, and erosion. With approximately 150 million people residing in at-risk areas, the urgent need to strengthen these structures against forthcoming climatic shifts has never been more critical.

Coastal infrastructure in general, and ports in particular, are affected by different risks which can be increased by climate change in terms of stability and, fundamentally, in terms of functionality, mostly associated with increased coastal flooding and overtopping due to SLR (e.g. Sánchez-Arcilla et al. 2016; Arns et al. 2017; Izaguirre et al. 2021).

Around 150 million people live in coastal areas and port cities in the Mediterranean (Galeotti 2020). It is expected that by 2050, for the lower sea-level rise scenarios and current adaptation measures, 10 of the 20 global cities with the highest increase in average annual damage are in the Mediterranean, located in Algeria, Egypt, Libya, Morocco, Palestine, and Syria (Galeotti 2020). Erosion and flooding are two major threats to Mediterranean coasts and will cause damage to human settlements (Rizzetto 2020).

Furthermore, potential consequences of climate change may impact Mediterranean airports, putting them at risk (De Vivo et al. 2022). Therefore, airports located in coastal areas could be at risk of coastal flooding, which could be increased under SLR. Yesudian and Dwason (2021) conducted a global analysis of SLR risk for airports located in the Low Elevation Coastal Zone (LECZ) in terms of expected annual route disruption. In the Mediterranean, three airports were ranked in the top 20 at risk by 2100 which are Venice and Pisa in Italy, and Ioannis Kapodistrias Intl in Greece.

In coastal areas, SLR is the most important and *likely* climate change-driver to affect infrastructure in general (de Almeida and Mostafavi 2016), and transport networks in particular (H. Demirel et al. 2015). This is especially evident when coastal plains supporting such infrastructure are flooded episodically or permanently (e.g. Armaroli et al. 2019; Antonioli et al. 2020). In some cases, SLR will increase the number of disruptions currently taking place under the impact of storms in transport networks close to the shoreline, such as the coastal railway along Catalonia (Jiménez et al. 2018). The location of such infrastructure very close to the shoreline significantly increases the risk due to high exposure that usually forces them to implement specific protection measures (e.g. see Pranzini (2018) for protection works in Italian coastal railways). In any case, it should be kept in mind that this infrastructure will be subject to greater risks of disruption not only due to increased overtopping under SLR, but also due to a future scenario of narrowing protective beaches in front of them due to SLR-induced erosion.

For the Thessaloniki area in Greece, Papagiannakis et al. (2021) estimated that under a SLR of 0.5 m and 1 m, about 1.87% and 3.07% respectively of the total length of the coastal road network will be covered by the sea by 2100, and the access road to the airport might be interrupted. For Türkiye, Karaca and Nicholls (2008) found that capital loss from the impacts of a 1 m rise in sea level could be significant (about 6% of current GNP). For Malta, Attard (2015) highlighted that environmental change could heavily damage the island's infrastructure and disrupt the transport systems.

Izaguirre et al (2021) estimated an increase in risk for Mediterranean ports by 2100 under the RCP8.5 scenario, which changes from medium or low risk to very high or high future risk, respectively due to increased overtopping and coastal flooding risk. The western African

Mediterranean ports were identified as subject to very high risks. Furthermore, it is essential to take into account indirect impacts, as highlighted by Christodoulou et al. (2019), who estimated that disruptions in northern European ports due to SLR could significantly affect the operations of Mediterranean ports.

At regional scale, Sierra et al. (2016) assessed the impact of SLR on the operability of harbours along the Catalan coast in the western Mediterranean due to increasing overtopping during storms. They found a significant increasing risk in nearly all harbours under a high-end scenario of SLR of about 1.8 m, although results obtained for the median RCP8.5 scenario presented significantly less risk.

In Egypt, the Nile Delta's four principal fishing harbours are at high risk (Abutaleb et al. 2018). Port Said in the Nile Delta would be the most affected in the MENA region (Dasgupta et al. 2009), and the economic damage due to the 0.5 m and 1.25 m SLR scenario is estimated to be more than US$2.0 billion and US$4.4 billion, respectively (El-Raey et al. 1999). For Rosetta, this number is expected to be US$2.9 billion (El-Raey 2010). Refaat and Eldeberky (2016) estimated that almost 7% of the Nile Delta area would be at risk of inundation due to future sea-level rise. In addition, El-Masry et al. (2022) predicted that climate change might damage the coastal infrastructure in El Hammam-EL Alamein, and 34 to 36 (about 46.5% to 49.3%) of the existing coastal resorts could be inundated. For Morocco, Kasmi et al. (2020) highlighted the risk of erosion and soil loss in response to SLR (the loss of more than 50% of width with a 2m SRL scenario on many beaches). In the Tangier Bay, Morocco, Snoussi et al. (2009) noted that coastal defences and the port, tourist coastal infrastructure, the railway, and the industrial area are expected to be at risk due to climate change and estimated that erosion of the shoreline would affect nearly 20% of the total beach areas by 2050 and 45% by 2100. Snoussi et al. (2010) calculated climate change impacts on the various Moroccan coasts, finding that 70% of most of the urbanised sections of the Tetouan coast would suffer from erosion,

In Israel, Zviely et al (2015) found that SLR is expected to cause extensive damage to port infrastructure, including seaports, power plants, marinas, desalination plants, sea walls, detached breakwaters, and bathing beach infrastructure, and to the vessels moored inside, as well. For 0.5 m and 1 m SLR, respectively, at a cost of approximately US$200 million and US$500 million (0.07% and 0.17% of Israel's GDP for 2012), the current level of operation of this infrastructure can be maintained (Zviely et al. 2015).

Finally, in terms of existing coastal protection measures, one of the most sensitive structures to SLR are parallel breakwaters since their protection capacity depends on the relative height with respect to mean water level which controls wave energy transmission. Consequently, sea-level driven changes in wave characteristics and the structure relative height may significantly change their design conditions and increase the exposure of the protected area (Arns et al. 2017). In simple terms, the (economic) impact will be associated with the need to increase the height of the structure to maintain its design conditions. As an example, Vousdoukas et al. (2018) estimate that upgrading existing coastal protection would imply increasing elevations by an average of at least 25 cm by 2050 and by more than 50 cm by 2100, although local required increments can be significantly higher. The importance and relevance of this impact along the Mediterranean will be determined by the local conditions of the existing structures, although due to the extensive and intensive use of parallel coastal breakwaters as a protection measure, it is expected that one of the areas with the greatest impact will be the Italian coast.

In conclusion, the coastal infrastructure of the Mediterranean region faces imminent threats from the challenges posed by climate change. Failure to act could result in significant disruptions to the region's economic prosperity and environmental health. To mitigate these risks, a proactive stance is essential in both designing and managing infrastructure capable of withstanding the increasing hazards associated with climate change.

3.4 Impacts on human systems

3.4.1 Impacts on cultural heritage (natural and built)

The cultural and natural heritage of the Mediterranean, encompassing ancient ruins and stunning landscapes, faces threats from sea level rise and increasingly harsh climates. The potential impact on natural and built heritage in coastal regions is caused both by on-going variations of climate and environmental parameters responsible for slow cumulative damage processes and by hydrometeorological extreme events. Natural landscapes, archaeological sites and monuments are exposed to an aggressive and worsening environment, characterised by local land subsidence, coastal flooding, and erosion (see *Chapter 2*). Sea level rise risks submerging natural landscapes and built heritage. The Mediterranean coast includes several natural landscapes with their wildlife, such as the biodiverse wetlands of Camargue on the delta of the Rhône River, France (Fraixedas et al. 2019) and Doñana National Park, Spain (Camacho et al. 2022). Detailed maps of the UNESCO cultural World Heritage Sites (WHS) located in the coastal zone at risk, and their projections to 2100 have been reported by Reimann et al. (2018b), who, based on the analysis of spatially explicit WHS data and the development of an index-based approach, show that of 49 cultural WHS located in low-lying coastal areas of the Mediterranean, 37 are at risk of flooding for a 100-year return period and 42 from coastal erosion, already today. Until 2100, flood risk may increase by 50% and erosion risk by 13% across the region. Projections are provided under RCP2.6, RCP4.5 and RCP8.5. Analysis done by Kapsomenakis et al. (2023) shows evidence that coastal UNESCO heritage sites in the Aegean Sea, the Adriatic coastline and the Gulfs of Genoa and Venice could be significantly at risk in the future period 2071-2100 under the RCP8.5 scenario due to sea level rise. The most famous city at risk is Venice, sinking under the combined action of sea level rise and local land subsidence (Lionello et al. 2021; Camuffo 2022). In the long run, currently still subaerial archaeological sites risk being completely submerged as has been the case for Capo Rizzuto (southern Italy), Alexandria (Egypt), Pavlopetri and Peristera (Greece), Caesarea Maritime (Israel), Kizlan (Türkiye), and several other Mediterranean harbours (Marriner et al. 2017). At present, storm surges are affecting buildings and archaeological sites. In the future, this challenge will continue with increasing frequency and flooding depth.

The available projections of the impact that climate change will have on built heritage in terms of slow cumulative deterioration processes developed in the framework of the two EU funded programmes, Noah's Ark (Bonazza et al. 2009a,b; EC et al. 2010) and Climate for Culture (Leissner et al. 2015), highlight that the Mediterranean coastal heritage sites are *likely* expected in the far future (2071–2100):

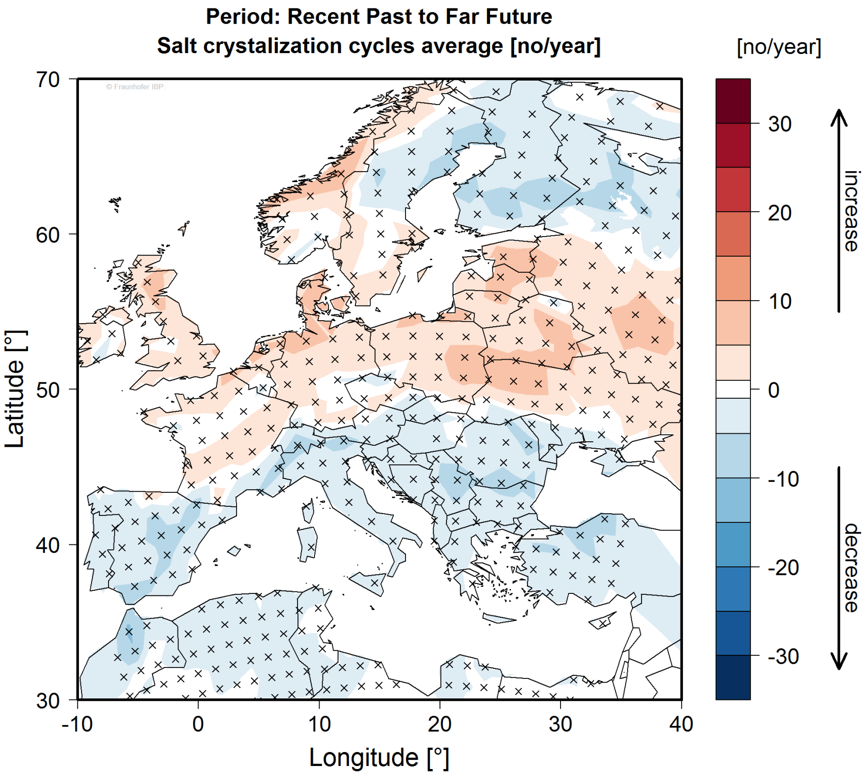

Figure 3.8 | Projected change in the yearly frequency of NaCl crystallisation indoors. The data are calculated as a difference between the far future the far future (2071–2100) and the 1961–1990 reference period. Project Climate for Culture, simulation for an unconditioned building type 02 (average brick structure), under the RCP4.5 emission scenario (Camuffo et al. 2015; Leissner et al. 2015).

- to undergo more than 30 events per year of relative humidity cycles crossing 75.5%, implying a potential risk of decohesion and fracturing of porous building materials, such as sandstones, mortars and brick, caused by crystallisation pressure of soluble salts (Camuffo 2019). Salt weathering is mainly driven by a phase change. The damage arises during the crystallisation-dissolution cycles, which occur under precise temperature and humidity conditions. Non-hydrated salts, such as sodium chloride (NaCl), crystallise at a fixed relative humidity (RH) virtually independent of temperature (RH threshold = 75.5%), whereas phase transitions in hydrated salts, such as sodium sulphate, are sensitive to both relative humidity and temperature (Bonazza 2022);

- to presumably experience higher levels of biodeterioration, with a value of total biomass accumulation from 5 to 15 mg cm^{-2} (EC et al. 2010);

- to undergo surface recession linked to chemical dissolution of 5–35 μm yr^{-1}, particularly monuments in marble and compact limestone located in highly polluted coastal areas (Bonazza et al. 2009a);

- to increasingly suffer from thermal stress caused by solar radiation with more than 150 events per year of internal tension >20 MPa. This threshold of internal tension is considered particularly dangerous for marbles and can cause decohesion and powdering (Bonazza et al. 2009b).

Examples of the projected change in the yearly frequency of the NaCl crystallisation cycles calculated for building materials exposed to indoor climate variations are shown in *Figure 3.8.* This map has been expressed in terms of change as a difference between the far future (2071–2100) and the recent past reference period (1961–1990). The projection shows a slight decrease of the structural risk for the built heritage across the whole Mediterranean coastal area.

Research has only recently started to focus on the development of projections of extreme events (i.e.

heavy rain, flash floods, drought) linked to climate change to assess the risk consequently imposed on natural and cultural heritage. This has been specifically addressed in the framework of two EU funded Projects ProteCHt2save[42] and STRENCH[43]. The analysis demonstrated that the impact linked to extreme variations of precipitation and temperature on monuments and archaeological sites in the Mediterranean regions is *likely* to increase in the near and far future (Bonazza et al. 2021).

3.4.2 Impacts on human health

3.4.2.1 Impacts of climate and geological hazards on human health

Climate and geological shifts in the Mediterranean Basin pose increasing risks to human health, with longer, hotter summers and severe weather events such as floods and fires. These environmental changes threaten the physical and mental well-being of coastal populations.

The Mediterranean Basin is one of the world regions most profoundly influenced by changes in climate and geological factors (Giorgi 2006; MedECC 2020b; Tuel and Eltahir 2020). Serious health issues can emerge from longer and warmer summers, more sever heatwaves (or extreme events such as floods and fires in coastal areas (Habib et al. 2010; Linares et al. 2020a; Neira et al. 2023). In addition, coastal populations are the most vulnerable to sea level rise.

The increase in storm-induced floods and gradual inundation will be accentuated in the future through climate change and this can lead to water-borne and respiratory diseases. The increased atmospheric pressure during thunderstorms can lead to the occurrence of severe asthma epidemics and initiate Idiopathic Spontaneous Pneumothorax (ISP). Increased humidity can also lead to mould allergies and the development of asthma in susceptible individuals (Habib et al. 2010). Extreme events, such as floods, often also disrupt medical care, with a particular impact on vulnerable populations such as those with chronic illnesses. Hospitals may be evacuated, transport of medication is more challenging, etc. In addition, electrical failures impact critical infrastructure (power, water, sanitation and sewer), with potential associated infectious diseases (waterborne pathogens). The impact on mental health is also to be considered, with potential post-traumatic disorder and depression.

Rising temperatures causing droughts, fires and heat waves (Wedler et al. 2023) are a serious threat to health in Mediterranean populations. Extreme droughts, which impact freshwater resources, can cause public health problems, including drinking water shortages and poor-quality drinking water. Reduced river flow can increase the concentration of pollutants in water and cause stagnation. Having water available for drinking, cleaning, sanitation, and hygiene is crucial for reducing many diseases. In the Mediterranean:

- 30% of the population lives in water-scarce countries;
- 220 million people suffer from water scarcity;
- 26 million do not have access to safely managed drinking water services;
- 160 million do not have access to safe sanitation (UNEP/MAP and Plan Bleu 2020).

Extreme heat leads to a significant increase in mortality and illness, including heat stroke and heat exhaustion (Lubczyńska et al. 2015; Gauer and Meyers 2019). As example, it is projected that in Israel, there will be approximately 330 additional deaths each summer under the RCP8.5 scenario in the late 21st century, especially among individuals aged 65 and above (Wedler et al. 2023), and other susceptible populations, including people with chronic health problems, outdoor labourers and military personnel were identified as individuals at greatest risk (Gauer and Meyers 2019; Watts et al. 2019). In Cyprus, Heaviside et al. (2016) anticipated that a 1°C temperature increase would lead to a doubling of heat-related mortality and a 5°C increase would result in a rate eight times

42 https://programme2014-20.interreg-central.eu/Content.Node/ProteCHt2save.html

43 https://programme2014-20.interreg-central.eu/Content.Node/STRENCH.html

higher than the baseline. In addition, heat exposure triggers multiple physiological mechanisms that cause damage to the brain, heart, intestines, kidneys, liver, lungs, and pancreas. The increased risk of heat-related mortality is particularly prominent in densely urbanised regions bordering the Mediterranean Sea, primarily attributed to the widely recognised phenomenon known as the Urban Heat Island (UHI) effect (Pyrgou and Santamouris 2018; Martinelli et al. 2020).

Lastly, more frequent wildfires (naturally or human induced) will impact air quality, particularly, affecting people with asthma, Chronic Obstructive Pulmonary Disease (COPD), or heart disease, and children, pregnant women, and firefighters.

Sea level rise is also associated with a greater risk of exposure to mould from increased humidity, which is responsible for respiratory diseases. Saltwater migrating upstream in freshwater systems increases salinity in rivers but also in groundwater basins, thereby directly or indirectly affecting human coastal population nutrition, through lower crop production or reduced availability of safe drinking water. Associated health impacts include higher risk of hypertension and diarrheal disease.

Furthermore, SLR-induced impacts are expected to lead to population displacement as livelihoods in coastal regions become increasingly threatened (Hauer et al. 2020). Reimann et al (2023) estimated that up to 20 million people could face permanent displacement within the Mediterranean region (within the same country) by 2100 in the absence of adaptation policies *(low confidence).* This projection considered various combinations of SLR scenarios and Shared Socioeconomic Pathways (SSP), with the primary determinant being the population exposed in the Low Elevation Coastal Zone (LECZ). Consequently, it is more *likely* that the impact of population displacement will be significantly higher in the southern and eastern Mediterranean countries, as the exposure in these regions is approximately three times greater than that in the northern countries *(medium confidence).*

3.4.2.2 Impacts of biological hazards on human health

Variable weather conditions (mainly temperature, rainfall and humidity) strongly influence the emergence of vector-borne diseases (diseases transmitted through insects) and water-borne diseases. Recently, several outbreaks have been observed and associated with local climate changes in the Mediterranean Basin region (Paz and Albersheim 2008; Paz et al. 2013). Currently, the main vector-borne diseases transmitted by mosquitoes and potentially exacerbated by the changing climate in the Mediterranean Basin, are West Nile Fever, Dengue, Chikungunya, Malaria, and Leishmaniasis (Paz et al. 2008; Colón-González et al. 2021). In addition, higher sea surface temperatures and heavy rainfall leading to an abrupt decrease in salinity can have a major effect on the abundance of pathogenic bacteria (Vibrio species) found in Mediterranean marine, lagoon and estuarine environments. These bacteria are recognised throughout the world as agents of gastroenteritis in humans resulting from the consumption of raw or undercooked seafood and serious infections caused by exposure of skin wounds to seawater (Guégan et al. 2018). In addition, when sewers carrying urban and industrial wastewater are overloaded, untreated sewage can flow into rivers, lakes, and coastal areas. This can lead to greater exposure of populations to contaminants, inadequate sanitation and unsafe drinking water (UNEP/MAP and Plan Bleu 2020).

3.4.2.3 Impacts of chemical hazards on human health

Coastal populations suffer from the cumulative burden of environmental pollution resulting from intense local activities and from upstream and inland development. When concentrated in small, confined, and overcrowded areas such as Mediterranean coastal zones, air and water pollution poses great threats to human health.

Two-thirds of the Mediterranean countries exceed the global WHO recommended threshold for air pollution from particulate matter and ozone even though air pollution has been linked to a broad spectrum of non-communicable diseases (diabetes, cardiopulmonary diseases, neurodegenerative diseases, etc.). In addition, high levels of noise caused by traffic can cause heart conditions and reduce cognitive functions in children.

Some areas around the Mediterranean Basin have concentrations of fine particulate matter ($PM_{2.5}$)

up to 100 µg m^{-3} (world average: 39.6 µg m^{-3}, EU average: 14.2 µg m^{-3}) (UNEP/MAP and Plan Bleu 2020). In the Mediterranean, air pollution is the main environmental burden with 228,000 deaths per year (UNEP/MAP and Plan Bleu 2020). The impact of air pollution on health is generally much higher in SEMCs (southern and eastern Mediterranean Countries) than in NMCs (Northern Mediterranean Countries). Egypt is the country in the world with the highest death rate attributed to ambient air pollution (UNEP/MAP and Plan Bleu 2020).

Agriculture, coastal tourism and recreation, transport, port and harbour activities, urban and industrial development, mining, fisheries, and aquaculture are all sources of marine pollution. Marine pollution refers to thousands of physical, chemical, and biological entities such as toxic metals, petroleum, plastics, manufactured chemicals such as pharmaceuticals or pesticides, excessive nutrient load from agricultural runoff or sewage, Harmful Algal Blooms (HABs), etc. The Mediterranean is one of the regions of the world most affected by pollution with half of its coastal waters failing to achieve good environmental status (UNEP/MAP and Plan Bleu 2020). Above a certain level, these agents threaten the health of living beings. Coastal populations are particularly exposed to sea pollution (especially populations from low and middle-income countries) (Landrigan et al. 2020). In the Mediterranean, more than 500,000 deaths occur each year as a result of unhealthy environments. The rate of these premature deaths is two to three times higher in the southern and eastern Mediterranean countries and the Balkans than in EU countries (UNEP/MAP and Plan Bleu 2020). People can be exposed to chemicals through dermal contact, ingestion, inhalation or during development. Methylmercury and PCBs are ocean pollutants whose human health effects are best understood. Exposure of infants in utero to these pollutants through maternal consumption of contaminated seafood can damage developing brains, reduce intelligence quotient (IQ) and increase children's risks for autism, attention deficit hyperactivity disorder (ADHD) and learning disorders. Adult exposure to methylmercury increases the risks of cardiovascular disease and dementia. Because of their small size, microplastics are easily absorbed by organisms. Recently, studies have shown that microplastics are present in the human bloodstream and that microplastics cause damage to human cells at the levels known to be eaten by people via their food (Danopoulos et al. 2022; Leslie et al. 2022). In addition, plastics can provide transport and shelter to hazardous microorganisms, including vectors for human disease. Toxic chemical pollutants in the sea have been shown to be capable of causing a wide range of diseases in humans. Manufactured chemicals such as phthalates, bisphenol A, flame retardants and perfluorinated chemicals can disrupt endocrine signalling, reduce male fertility, damage the nervous system, increase the risk of cancer and cause cardiovascular and metabolic diseases. Harmful algal blooms (HAB) produce potent toxins that accumulate in fish and shellfish. When ingested, these toxins can cause severe neurological impairment and rapid death. HAB toxins can also become airborne and cause respiratory disease. Pathogenic marine bacteria cause gastrointestinal diseases and deep wound infections (Landrigan et al. 2020).

There are many thousands of types of man-made marine pollution for most of which available knowledge is very scarce, especially on the levels of exposure and magnitude of human health impacts. The majority of manufactured chemicals have never been tested for safety or toxicity: only about 700 out of 70,000 chemical substances on the market have been studied for their risk impacts (UNEP/MAP and Plan Bleu 2020). In addition, pollutants are rarely present in the environment in isolation but instead are found in complex mixtures. This creates even more uncertainties about the possible combined effects of exposure to mixtures of contaminants. Lastly, there are synergistic effects between climate change and chemical pollution. For example, climate change appears to increase the toxicity of metals and increase the frequency of toxic algal bloom and pathogenic bacteria outbreaks as a result of rising temperatures and extreme precipitation events (Cabral et al. 2019).

Despite the severity of sea pollution and growing recognition of its effects on health, significant uncertainties remain. Because of these knowledge gaps, the impacts of sea pollution on human health and well-being are surely underestimated. Therefore, in order to protect the public from exposure to such harm, decision-makers should adopt a precautionary approach and control pollution in a coordinated manner because pollution is transboundary, and all of the health impacts of sea pollution fall disproportionately on vulnerable populations of southern and eastern Mediterranean countries.

As a concluding remark, the Mediterranean is faced with the complex health impacts of climate change, ranging from waterborne diseases to heat-induced illnesses. The need for a comprehensive, precautionary approach to mitigate these risks is clear. Tackling the environmental determinants of health through coordinated pollution control and adaptation strategies will be important in protecting the well-being of the region's most vulnerable communities in the face of an unpredictable climate future.

3.5 Impacts on natural systems

Coastal natural systems such as wetlands and deltaic systems, in particular, are under the direct and indirect impacts caused by high population density and related human activities. Among these activities, those that are most significant and the most harmful include expanded agriculture to the detriment of coastal wetlands and coastal urbanisation which have generated adverse impacts on hydrological fluxes and the salinity of surface water, overexploitation of coastal groundwater which in turn have caused and are still adversely impacting ecological systems. Sea level rise due to climate change and due to coastal subsidence continue to exacerbate unfavourable conditions on Mediterranean low-lying natural systems.

3.5.1 Impacts on coastal low-lying areas, wetlands and deltaic systems

The Mediterranean wetlands occupy 2 to 3% of the land area of the Mediterranean Basin and include a diversity of ecosystems, including lagoons and salt marshes, freshwater lakes, karstic cave systems, temporary ponds, artificial wetlands such as reservoirs, Salinas, fishponds and rice paddies, small and scattered peatlands, and several large rivers with their corresponding deltas. At the same time, 30% of the region's vertebrate species depend on Mediterranean wetlands (N. G. Taylor et al. 2021), and across history, these ecosystems have contributed multiple ecosystem services to different civilizations and cultures, and to the identity and well-being of communities, making them an important component of Mediterranean social-ecological systems (Balbo et al. 2017) *(Figure 3.9).*

Since 1900, 50% of wetlands have been lost, with significantly high figures observed for various wetland ecosystems across the region. 73% of marshes have been drained in northern Greece since 1930, 86% of the 78 most important wetlands of France were degraded by 1994, 60% of primary wetland area has been lost in Spain; and 84% of the wetland area in the Medjerda Basin, Tunisia, was lost during the 20th century (Balbo et al. 2017). While this trend may have slowed down in recent years

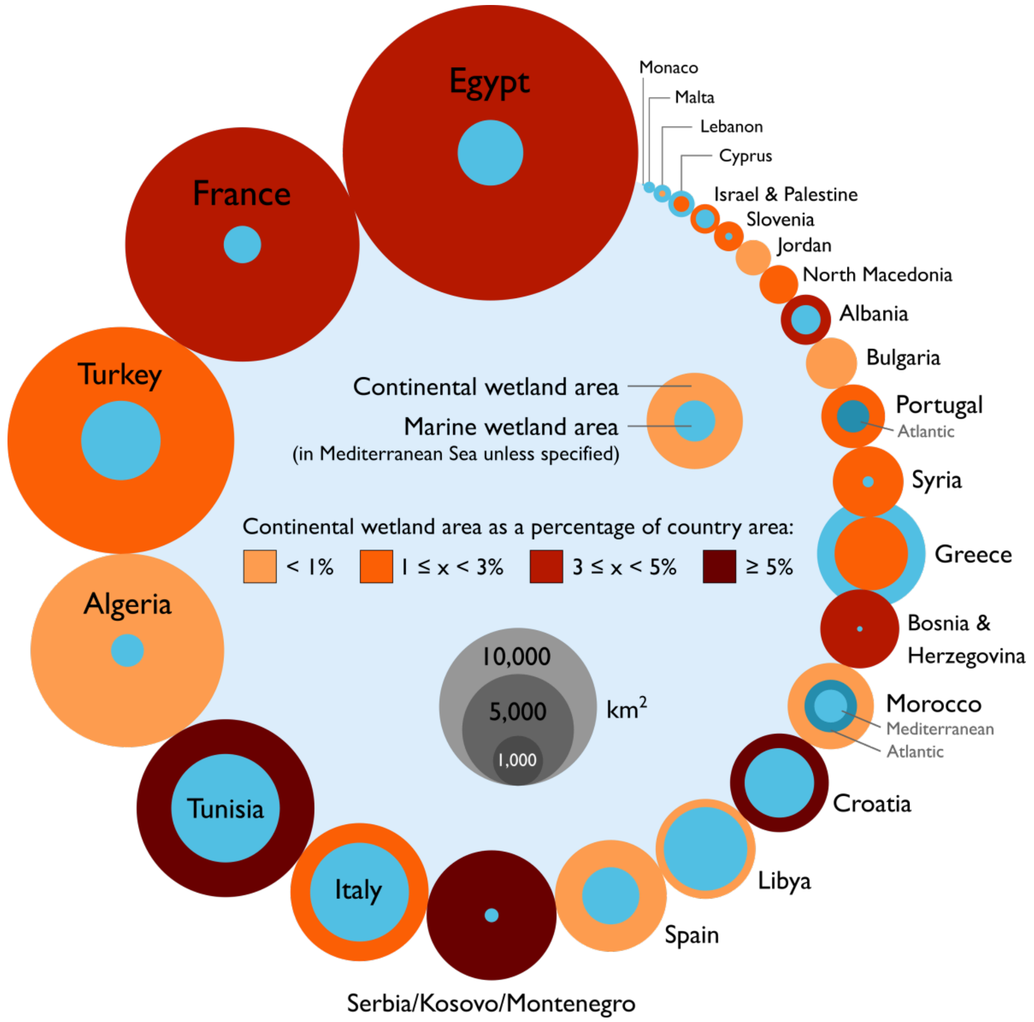

Figure 3.9 | Overview of the extent of Mediterranean wetlands. The area of each circle is proportional to the wetland area. Yellow-orange-red circles represent continental surface wetlands; shading indicates the percentage of each country covered by wetlands. Blue circles represent marine wetlands (< 6 m water depth at low tide) on the Mediterranean coast of each country, plus Atlantic coasts for Morocco and Portugal. Data from Perennou et al. (2012) and MWO (2018), as presented in N. G. Taylor et al. (2021).

(Balbo et al. 2017), the level of protection varies, and recent research indicates that wetland sites in the southeastern Mediterranean combined low or no protection with the highest increases in temperature and losses in natural habitats (Leberger et al. 2020). In the Mediterranean, the largest coastal wetlands are found in delta areas, such as those of the Nile (Egypt), Rhône (France), Po (Italy) and Ebro (Spain) rivers. Delta areas are vulnerable to human modification and climate change, with sea-level rise considered a key threat causing increased flooding, coastal erosion, extreme events, salinity intrusion and habitat degradation.

Cultural uses of coastal wetlands, and particularly the expansion of irrigated agricultural areas and urban development, have led to significant and complex changes to Mediterranean coastal wetlands, with impacts on hydrological fluxes and the salinity of surface water, in turn affecting ecological communities. For example, in the case of Doñana wetlands, situated within the delta of the Guadalquivir River (south-west Spain), 80% of its original marsh surface area has been converted, mainly for agriculture. Agricultural runoff, intense urban development, inadequate wastewater treatment, and extensive hydrological modifications

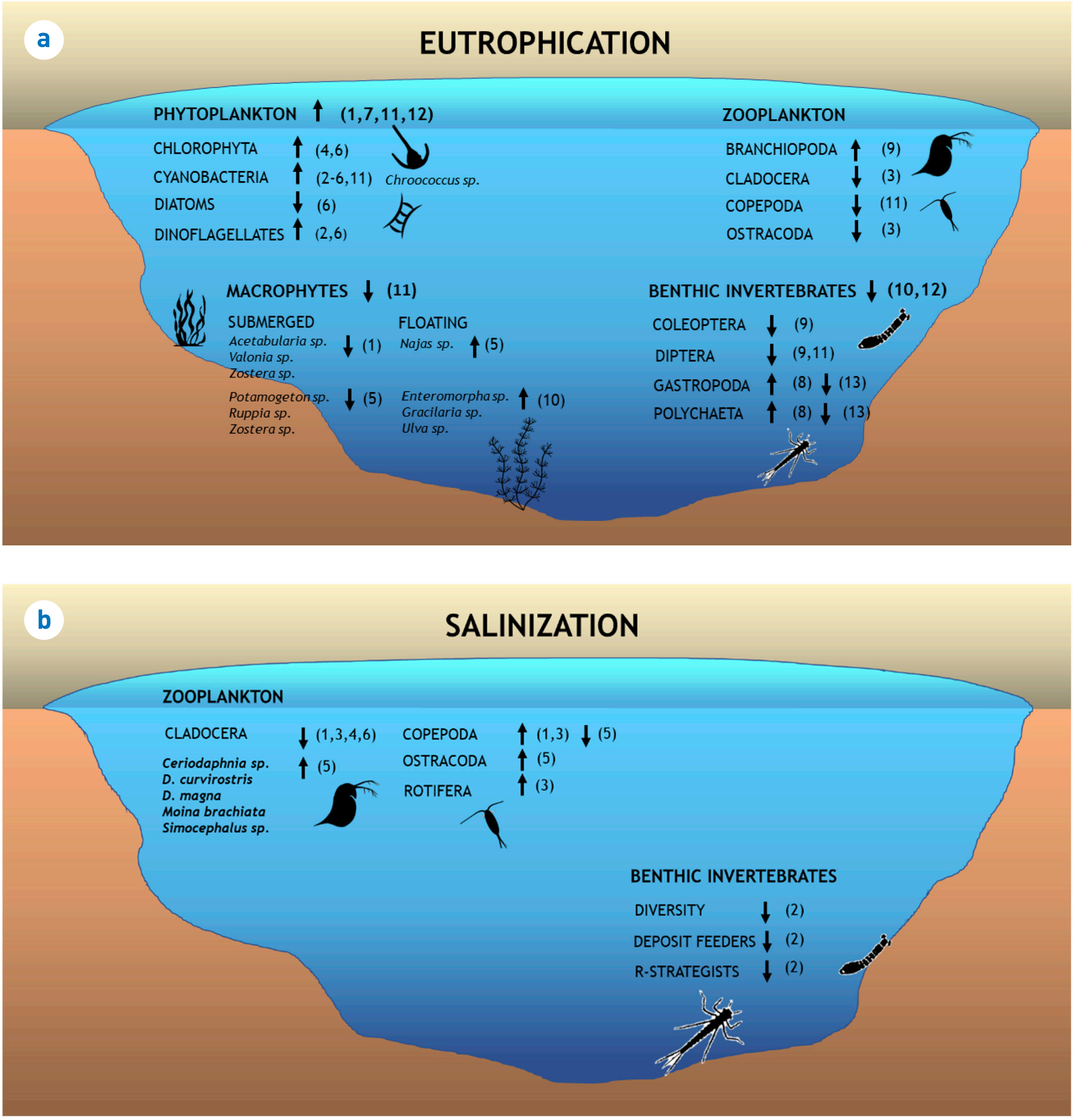

Figure 3.10 | Scheme showing the influence of eutrophication and salinisation on different aquatic organisms of Mediterranean coastal wetlands. Arrows indicate an abundance increase or decrease caused by (a) eutrophication and (b) salinisation. The summary is based on the reviewed studies by Martínez-Megías and Rico (2022).

have led to high nutrient loading in the remaining wetlands (Green et al. 2017). Furthermore, water management associated with the expansion of coastal tourism, combined with the effect of climate change, could lead to reductions in groundwater storage and saltwater intrusion (Maneas et al. 2019).

Rising temperatures will *likely* increase evapotranspiration rates, which, combined with reduced rainfall will enhance plant water stress and increase water demands for crop irrigation. These conditions will influence the water biota by favouring species more tolerant to drought (*high agreement, medium evidence).* Macroinvertebrate communities

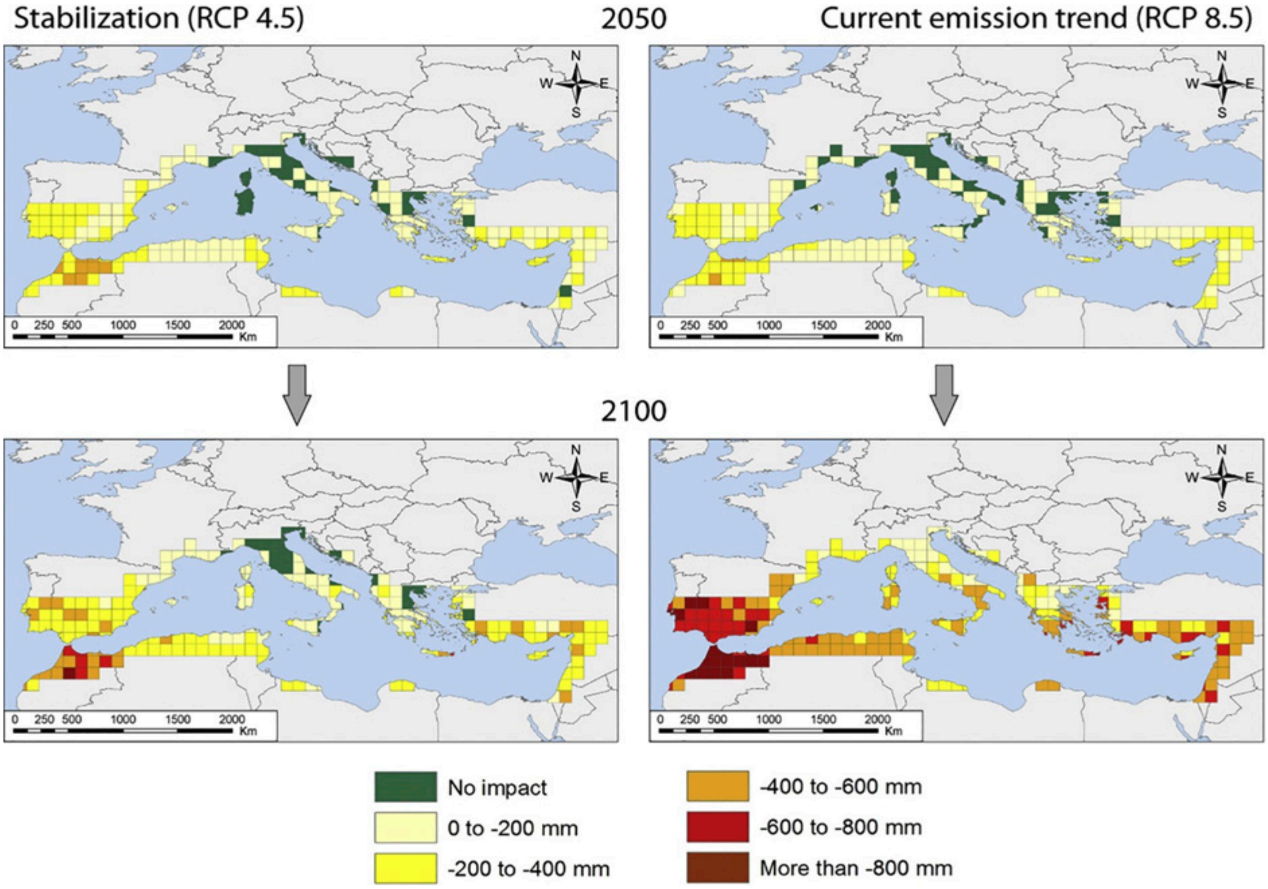

Figure 3.11 | Contemporary (1981–2013) annual water balance (precipitation minus evapotranspiration) for each of the 229 Mediterranean localities under constant flood conditions. The thirteen localities for which seasonal flooding patterns could not be simulated under the current climate conditions are shown in grey. Source: Lefebvre et al. (2019).

are moderately resilient to salinity increases but salinity increases to polyhaline conditions cause drastic community simplifications in terms of functional evenness, and loss of biodiversity (Muresan et al. 2020). On the other hand, temperature and salinity increases, combined with insecticide exposure, contributed to a decline in zooplankton diversity, but increased temperature was associated with increased abundance while increased salinity was associated with reduced abundance across all zooplankton groups (*Figure 3.10*) (Vilas-Boas et al. 2021; Martínez-Megías and Rico 2022). Excessive nutrient loading also leads to changes in the biotic community and may lead to dominance by blue-green algae (cyanobacteria) or floating plants, triggering losses in biodiversity and ecosystem services. Eutrophication and higher temperatures work in combination to reduce levels of dissolved oxygen, causing lethal and non-lethal effects (Green et al. 2017).

Decreases in mean precipitation and precipitation variability during the dry season are *likely* to have profound effects on Mediterranean wetlands, however, the impact of climate change on wetlands will be closely tied to changes in water deficits, which are currently heterogeneous across the Mediterranean region *(Figure 3.11).* In a study investigating how climate change will affect the values and functions of Mediterranean seasonally-flooded wetlands with emergent vegetation, using future projections of the relevant climate variables under two Representative Concentration Pathway scenarios assuming stabilisation (RCP4.5) or increase (RCP8.5) in greenhouse gas emissions, increases in water deficits in most localities around 2050 under both RCP scenarios were recorded. Simulations performed under current conditions show that 97% of localities could have wetland habitats in a good state. By 2050, however, this proportion would decrease to 81% and 68% under the RCP4.5 and RCP8.5 scenarios, decreasing further to 52% and 27% by 2100. Results from this study indicate that wetlands can persist with up to a 400 mm decrease in annual precipitation, with this resilience being attributed to the semi-permanent character of wetlands and their capacity to function as reservoirs. Countries at the highest risk of wetland degradation and loss were identified as Algeria, Morocco, Portugal, and Spain (Lefebvre et al. 2019).

A rise in sea level of 0.16 m (RCP8.5) in the short term (2026–2045) and 0.79 m (RCP8.5) by the end of the 21st century (2081–2100) are predicted by the CMIP5 models. On the other hand, the extreme proposed scenarios indicate rises from 1.35 m to 1.92 m by the end of the 21st century. The IPCC scenarios will lead to the loss of coastal wetlands *(high agreement, robust evidence)*. For example, the IPCC scenarios are expected to lead to the loss of 96 km^2 of the Júcar River Basin District in Spain, with wetlands having high ecological value and protected under the RAMSAR convention[44] and as part of the Natura 2000 Network[45]. The high-end scenarios significantly increased the areas at high risk to 142 km^2 and impacted an urban area of 27 km^2 (Estrela-Segrelles et al. 2021). Sea level rise interacts with other climate factors such as temperature rise and frequency of storms, and non-climate drivers such as the lack of sedimentary contributions due to the regulation of riverbeds, the overexploitation of water resources and coastal aquifers, and associated coastal erosion and seawater intrusion *(high agreement; limited evidence)* (Maneas et al. 2019; Estrela-Segrelles et al. 2021; Ferrarini et al. 2021; Rodríguez-Santalla and Navarro 2021).

3.5.2 Impacts on coastal ecosystems

Coastal ecosystems and people are facing significant risks from sea-level rise which are susceptible to increase tenfold before 2100 if no adaptation options and mitigation scenarios have been taken into consideration and implemented in accordance with the Paris Agreement. With extreme emission scenarios that do not limit warming to 1.5°C, the rising sea level will increase the risk of coastal erosion and coastal land submergence, loss of coastal habitat, and ecosystem loss. It will also cause groundwater salinisation, compromising coastal ecosystems and livelihoods. The Mediterranean is known for its micro-tidal nature, which would increase the susceptibility to coastal hazards related to climate change. The coastal zone refers to the physical region from the edge of the continental shelf to the intertidal and near-shore terrestrial area. It includes a wide range of near-shore terrestrial, intertidal, benthic, and pelagic ecosystems with some main categories being estuaries, coastal marshes, seagrass, and benthic systems (X. Yang 2008; Oppenheimer et al. 2019). Coastal ecosystems are highly impacted by a combination of conditions, including sea level rise, coastal erosion, acidification, and other climate-related ocean changes. They are also experiencing some adverse effects derived from urbanization and human activities on the ocean and land. The Mediterranean Basin is experiencing continuous changes in environmental conditions, creating major challenges, and introducing new vulnerabilities to its natural and human systems. Coastal ecosystems could progressively lose their ability to adapt to climate-induced changes and consequently their services, including acting as coastal protective barriers (Oppenheimer et al. 2019). Loss of breeding substrate, including mostly coastal habitats such as sandy beaches, can reduce the available nesting or pupping habitat for land-breeding marine animals and seabirds.

Coastal erosion is a major cause of the loss of ecosystem services provided by beaches, as most habitats in coastal areas could be affected, degraded, or disappear as erosion progresses (Paprotny et al. 2021). In a study to evaluate the effect of coastal erosion along the northern Mediterranean Basin (the European coast) for ecosystem services under the RCP4.5 and RCP8.5 scenarios estimates a 5% decline in services by 2100 under RCP8.5 showing high spatial variability with the largest estimated declines in the eastern Mediterranean. The value of ecosystem services declined by €323 million between 2000 and 2018. The majority of the coastal services decline was mainly attributed to forest contraction and intense agriculture, which was partially offset

44 https://www.ramsar.org/

45 https://environment.ec.europa.eu/topics/nature-and-biodiversity/natura-2000_en

by the expansion of wetlands, mainly salt marshes. Salt marshes are among the most climate-affected coastal habitat, although they are well-known for wave attenuation and for their role in reducing erosion and flooding (Kirwan and Guntenspergen 2010; Temmerman et al. 2012, 2023; Arkema et al. 2013; Vuik et al. 2016). Erosion-destroyed salt marshes or sand dunes along coastlines are more endangered than others. Saline bodies, estuaries, inland marshes, and natural grasslands would also be among the most affected habitats.

Coastal erosion has been affecting most of the Mediterranean coastal zones with growing intensity along the European coasts due to climate change (Terefenko et al. 2018a, 2018b, 2019; Paprotny et al. 2021). The Mediterranean hotspots of erosion impacts are discussed in detail in *Section 3.2.2* of this report. The major losses were in beaches, sand, and dunes and the most affected countries in the Mediterranean Basin are Albania, Greece and France and could be among those to lose the largest share of their coastal ecosystem services. Erosion could also create a new challenge with regard to flooding, affecting coastal lagoons by causing beach loss and changing their characteristics and services. Climate-induced saltwater intrusions could also vigorously affect many other coastal habitats (Barlow and Reichard 2010).

Annual damage is projected to rise by 90 to 900 times if future climate change scenarios and socio-economic trends are combined. Rising sea levels increase storm wave frequency, and reduce the sediment supply to the coast, while anthropogenic degradation, and coastal transformation could lead to an irretrievable loss of ecosystem services (Barbier et al. 2011; Ranasinghe 2016).

With regards to systems and habitats close to shore, it is still uncertain how anthropogenic CO_2 inputs and the resulting rapid acidification could affect coastal systems, mainly due to the lack of data. However, some research in the Mediterranean has examined changes in ocean chemistry and how it affects marine and coastal ecosystems, as well as socio-economic sectors. These studies have identified tourism and recreation, red coral extraction, and fisheries as the sectors more *likely* to be affected (Rodrigues et al. 2013; Peled et al. 2018; Hassoun et al. 2022). Ramajo et al. (2019) and others have suggested treating the acidification problem with seagrasses which may provide 'refugia' from ocean acidification for associated calcifying organisms as their photosynthetic activity can raise pH above the thresholds for impacts on calcification and/or limit the time spent below some critical pH thresholds. It has been proven that seagrass covers are effective in decreasing runoff and reducing soil losses particularly during the summer and under intense events (Ramajo et al. 2019).

Any changes in sediment supply, industrial development, and urban processes can enhance the vulnerability of coastal sandy beaches and saltmarshes to sea-level rise. Mediterranean aquifer systems and other water bodies are experiencing high exploitation levels with increased water demand and salinisation. In addition, growing population increases the human demand for water, and this puts additional pressure on water resources and increases the severity of water scarcity dramatically (Iglesias and Garrote 2018; Bond et al. 2019). The long-term changes induced by climate, particularly marine heatwaves, are significantly affecting marine ecosystems, causing mortality or bleaching of coral and mass mortalities of other species leading to a decline of kelp forests, loss of seagrass-meadow habitats, invasion of new species, and acute changes in the community structure of several marine ecosystems and increased carbon emissions. Harmful blooms of algal species and other waterborne diseases have increased as a consequence of climate change and this disturbance threatens human health and livelihoods of coastal communities (see *Chapter 2*). However, most of these risks are still uncertain at transboundary and regional levels, which may pose major challenge for cooperation among Mediterranean countries (Reimann et al. 2018b; Vafeidis et al. 2020).

In conclusion, the Mediterranean natural system is facing continued adverse impacts leading to increased vulnerabilities to the environment and humans. Coastal ecosystems that act as protective barriers (e.g. sandy beaches, marshlands, sand dunes) and mitigate climate change impacts are under severe risks *(high confidence).* It is *very likely* that the consequence may result in progressive loss of ecosystem services or loss of their ability to adapt to climate-induced changes. Bearing in mind that the prosperity of the Mediterranean population relies on the health of natural systems, proactive planning is essential in mitigating the increasing risks and hazards associated with climate change.

3.6 Final remarks

Regardless of the underlying causes triggering coastal hazards in the Mediterranean Basin, their extent, and their cumulative action under current conditions on existing assets and values along the coastline designate it as a high-risk area. Despite inherent uncertainties, anticipated changes in these hazards will escalate risks to people, infrastructure, and natural resources. While some risks are localised, many transcend national borders, underscoring the necessity for robust transboundary and regional cooperation among Mediterranean countries to effectively address these significant challenges.

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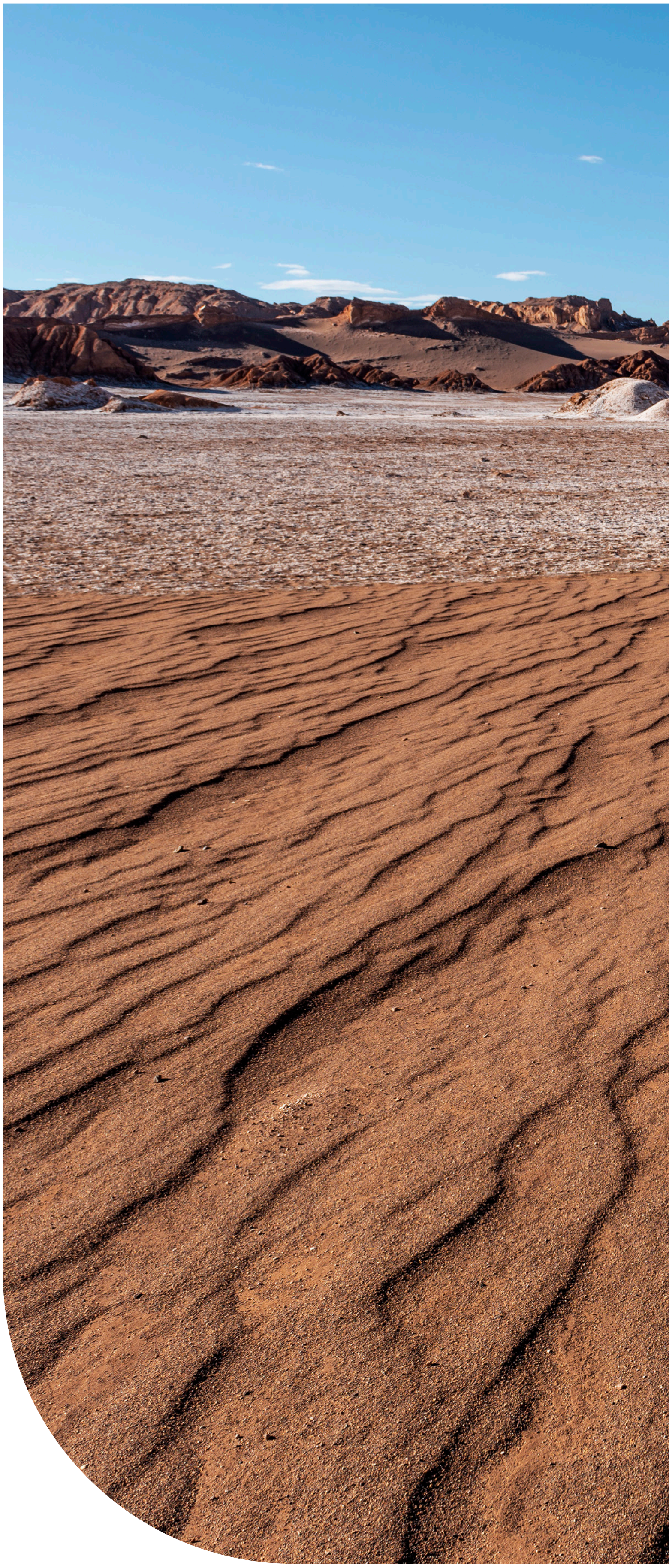

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ISBN: 978-2-493662-02-6
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