Nutrient enrichment and eutrophication in Europe's seas

Moving towards a healthy marine environment

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Acknowledgements

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Executive summary

For decades, European countries have shared a common vision of a marine environment in which human-induced eutrophication is minimised and does not cause adverse effects (Table ES1).

Efforts to achieve this vision have focused mainly on reducing nutrients at source, while since the 1950s, urbanisation and intensive agriculture have reached unprecedented levels. Europe's seas receive nutrients from rivers draining upstream catchments; directly from land-based sources in coastal areas; from sea-based sources such as aquaculture, dumping sites, or discharges from ships; and from the air as atmospheric deposition from industry and traffic. As a result, the question of whether or not we are on track to achieve the policy vision of a healthy marine environment free from eutrophication is as important as ever.

This assessment represents a first attempt to map eutrophication 'problem areas' and 'non-problem areas' at the scale of Europe's seas, while also exploring whether Europe has reversed trends with respect to eutrophication. Consequently, the overarching aims of this report are:

- to establish a baseline for potential problem and non-problem areas for eutrophication across Europe's marine waters;
- to present temporal trends in eutrophication;
- to provide an indicator-based methodology for assessing eutrophication across Europe's seas and, in the process, for highlighting data coverage and gaps;
- to reflect upon the findings.

The assessment is based on publicly available monitoring data, primarily collected in the context of the Water Framework Directive (WFD) and the Marine Strategy Framework Directive (MSFD). It is built on existing assessment thresholds and a harmonised, politically supported and peer-reviewed approach capable of embracing the diversity within and across regional seas, i.e. a new version of the Helsinki Convention eutrophication assessment tool, or HEAT+ (see Chapter 2.1).

Chapter 1 includes relevant definitions and a description of the data and methods used and sets the scene by describing key sources of nutrients in the sea and the potential consequences of increasing levels of nutrients. The key findings are:

- Anthropogenic eutrophication in marine, coastal and estuarine ecosystems is a consequence of nutrient over-enrichment, mostly inputs of nitrogen and phosphorus from land-based sources, marine activities and atmospheric deposition, as well as fluxes from neighbouring water bodies.
- Policy commitments to reduce emissions of nutrients to Europe's seas have been in place for decades.
- A comprehensive EU regulatory framework is in place for the effective management and control of nutrient sources to protect the marine environment and human society from adverse effects of eutrophication.

Chapter 2 focuses on identifying problem and non-problem areas, with respect to eutrophication, from northern regions (Baltic Sea) to southern regions (Mediterranean Sea) and from east (Black Sea) to west (North-East Atlantic Ocean). The key findings are:

- The eutrophication status of 2 400 000 km^2 of sea has been mapped.
- The mapping of problem and non-problem areas is done using a multi-metric indicator-based tool named HEAT+.
- Areas covering 1 837 000 km^2, mainly of offshore waters, were classified as non-problem areas.
- Areas covering 563 000 km^2 have been identified as problem areas.

- Most of these are found near densely populated areas or catchments downstream from agricultural activities.

Chapter 3 describes the results of long-term monitoring of specific eutrophication indicators and the temporal trends in these, and discusses long-term trends in eutrophication status based on case studies. The key findings are:

- Several indications reflect an ongoing recovery process in all of Europe's seas and the fact that efforts to reduce nutrient inputs have begun working as predicted.

- In the Baltic Sea and in the North Sea, eutrophication status has been improving over the past 15-20 years because of reductions in nutrient inputs.

- Overall, temporal trends cannot currently be assessed in the Mediterranean Sea and Black Sea because of a lack of available data.

Chapter 4 focuses on existing strategies and policies to reduce nutrient enrichment and eutrophication of marine waters in Europe, their effectiveness and the needs for additional action and abatement measures. The key findings are:

- EU legislation and Regional Sea Conventions aim for a healthy marine environment and to regulate nutrient enrichment.

- Significant progress has been achieved in understanding and reducing the eutrophication problem, but there are still areas where targets have not been met.

- Management can be improved by effectively using experience and scientific advice and by modelling and researching additional management measures to respond to climate change.

Chapter 5 contains region-specific summaries of the findings, a cross-cutting synthesis and perspectives for the future.

The key findings are:

- Eutrophication caused by inputs of nutrients, especially nitrogen and phosphorus, remains a large-scale problem in the Baltic Sea, the Black Sea, parts of the North-East Atlantic and some coastal areas in the Mediterranean Sea.

- Positive effects of the significant efforts put into nutrient management strategies can be seen in all EU regional seas.

- Management, particularly reducing nutrient inputs, is embedded in several EU policies, but targets remain unlikely to be met within the agreed timeframe for all of Europe's seas.

- To achieve the policy vision of a healthy marine environment in all of Europe's regional seas, further reduction of nutrient inputs is still needed in the most sensitive areas, together with consideration of the effects of climate change.

Table ES1 Summary of the eutrophication status of Europe's seas 2020

	Baltic Sea	Black Sea	Mediterranean Sea	North-East Atlantic Ocean
Classification status (% of area assessed found to be 'problem area')	99.4	53.0	11.8	7.2
Information coverage (000 km^2)	C: 210 out of 215 (97.8 %)	C: 14 out of 111 (12.7 %)	C: 78 out of 611 (12.8 %)	C: 364 out of 649 (56.2 %)
	O: 187 out of 187 (100 %)	O: 30 out of 365 (8.2 %)	O: 15 out of 1 920 (0.8 %)	O: 1 501 out of 6 209 (24.2 %)
Dominating trend	Positive	Unknown	Unknown	Positive

Achievement of agreed policy targets for nutrient inputs or eutrophication status, 2020-21 and beyond

Policy commitments	Objective	Achievements of policy targets by 2020/2021
Directive 2000/60/EC	Good ecological status of surface waters including groundwater, lakes, running water, transitional (estuarine) and coastal waters	2015, 2021, 2027
Directive 2008/56/EC	Good environmental status of marine waters	2020
Directive 91/271/EEC	Reduction of discharges from urban waste water treatment plants to aquatic ecosystems	EU-15: 1998-2005 EU-13: 2006-2023
Directive 91/676/EEC	Reduction of losses of nitrogen from agricultural practices to groundwater reservoirs and surface waters	No specific target year
Directive (EU) 2016/2284	Reduction of emissions of nitrogen to the air	2020, 2030
Baltic Sea action plan 2007	A healthy Baltic Sea unaffected by eutrophication	2021
OSPAR eutrophication strategy, 2010	Maintain a healthy marine environment where anthropogenic eutrophication does not occur	2020
Black Sea strategic action plan, 2009	Protection of the Black Sea against pollution	No specific target year
Strategic action plan for the Mediterranean, 1997	Prevention of emissions from land-based sources	2025

Indicative assessment of:

Status and trends of assessments		Information availability and quality	
Orange	Majority of assessment unit classified as 'problem areas'/deteriorating trend dominates	Orange	Limited information
Yellow	Unknown	Yellow	Unknown
Green	Majority of assessment unit classified as 'non-problem areas'/improving trend dominates	Green	Good information

Notes: The eutrophication status assessments build on the information analysed with HEAT+ in Chapter 2. The trends are as presented in Chapter 3.

C, coastal water; O, offshore water.

1 Eutrophication: too much of a good thing

- Eutrophication in marine, coastal and estuarine ecosystems is a consequence of nutrient over-enrichment, mostly inputs of nitrogen and phosphorus from land-based sources, marine activities and atmospheric deposition, as well as fluxes from neighbouring water bodies.
- Policy commitments to reduce emissions of nutrients to Europe's seas have been in place for decades.
- A comprehensive EU regulatory framework is in place for effective management and control of nutrient sources to prevent protect the marine environment and human society from adverse effects of eutrophication.

Walking or sailing along the diverse shores of the European seas in the North-East Atlantic Ocean, the Baltic Sea, the Mediterranean Sea or the Black Sea can be very pleasant. The different seascapes are scenic, and there are plenty of leisure or commercial activities to catch the eye.

Looking at the water might, however, present a different picture. Now and then, the water resembles green paint because of algal blooms. Sometimes we find foam on the shores. In some areas, there are heaps of drifting macroalgae and, on rare occasions, even dead fish or dead benthic animals are washed ashore. Below the surface, deterioration can be even more severe than that above, with dying plants, impoverished bottom fauna, few signs of life and oxygen depletion.

The currently impaired condition of Europe's seas, which are widespread in a large part of European coastal waters, can be attributed to several, mostly human-generated, causes, such as pollution (nutrients and contaminants), resource exploitation (e.g. fisheries and aquaculture), physical modification of habitats, introduction of non-indigenous species, and climate change. The Earth's systems are now shaped by human actions and we are living in the Anthropocene (Waters et al., 2016).

1.1 What is eutrophication?

Urbanisation and agricultural changes starting in the 1950s have led to pollution from excessive nutrients (i.e. nutrient enrichment, mainly with compounds of nitrogen and phosphorus). This type of pollution is called 'eutrophication' and is a major concern. This term has its root in two Greek words: 'eu', which means 'well', and 'trope', which means 'nourishment'. Several definitions exist, most of which are widely used, but for some reason neither the EU Water Framework Directive nor the EU Marine Strategy Framework Directive include specific definitions (Andersen et al., 2006). The modern use of the word eutrophication is related to the, often negative, effects of inputs of nutrients into aquatic systems.

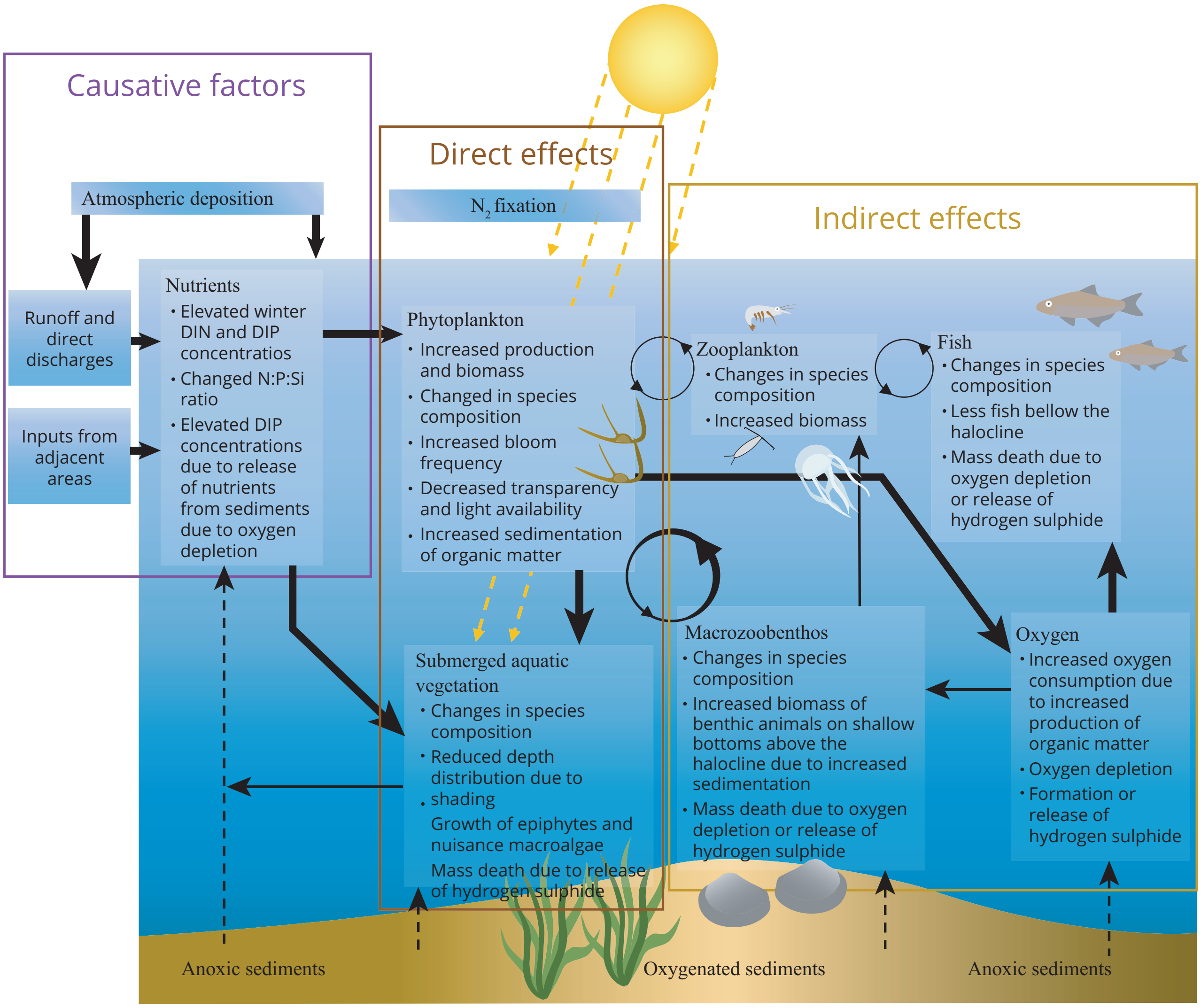
Nutrient enrichment by nitrogen, phosphorus and sometimes organic matter can result in a series of undesirable effects. The major effects of eutrophication include changes in the structure and functioning of the entire marine ecosystem and instability, followed by environmental problems. The reduction in ecosystem health leads to a decreased quality of ecosystem services, such as fisheries, aquaculture and recreation.

The first response to increased nutrient inputs is a corresponding increase in nutrient concentrations and a change in the ratio between dissolved nitrogen and phosphorus in the water. Primary production is most often limited by the availability of light and nutrients. Nutrient enrichment will therefore cause a second response, namely increased phytoplankton primary production. Thus, there will be an increase in phytoplankton biomass (Figure 1.1) and a decrease in light penetrating through the water column.

Decreased light penetration is often measured as a decrease in Secchi depth (a measure of water transparency) and can ultimately reduce the depth of colonisation of macroalgae and seagrasses. The general responses of pelagic ecosystems to nutrient enrichment can, in principle, be a gradual change towards (1) increased planktonic primary production compared with benthic production, (2) a dominance of microbial food webs over linear planktonic food chains, (3) a dominance of non-siliceous phytoplankton species over diatom species, and (4) a dominance of gelatinous zooplankton (jellyfish) over crustacean zooplankton.

Eutrophication issues are often divided into three groups: (1) causative factors; (2) direct effects; and (3) indirect effects (see Figure 1.1). The causative factors deal with inputs, elevated nutrient concentrations, and changes in the ratio between nitrogen and phosphorus concentrations. Direct effects are related to the primary producers, namely (1) phytoplankton and (2) submerged aquatic vegetation. Secondary effects are related to (1) zooplankton, (2) fish, (3) invertebrate benthic fauna, that is, animals living on the sea floor, and (4) oxygen concentrations. These functional relations are generic and well documented on a large scale for many marine waters in Europe, (e.g. see Smith et al., 2006; Diaz and Rosenberg, 2008; EEA, 2015), as well as on a regional scale, for the North Sea (OSPAR, 2008; Claussen et al., 2009), the Baltic Sea (Helcom, 2009; Fleming-Lehtinen et al., 2015), the Black Sea (BSC, 2008; Lazăr et al., 2016) and coastal areas, enclosed bays and river estuaries in the Mediterranean Sea (UNEP/MAP, 2012; Spiteri et al., 2016).

Figure 1.1 Conceptual model of coastal eutrophication

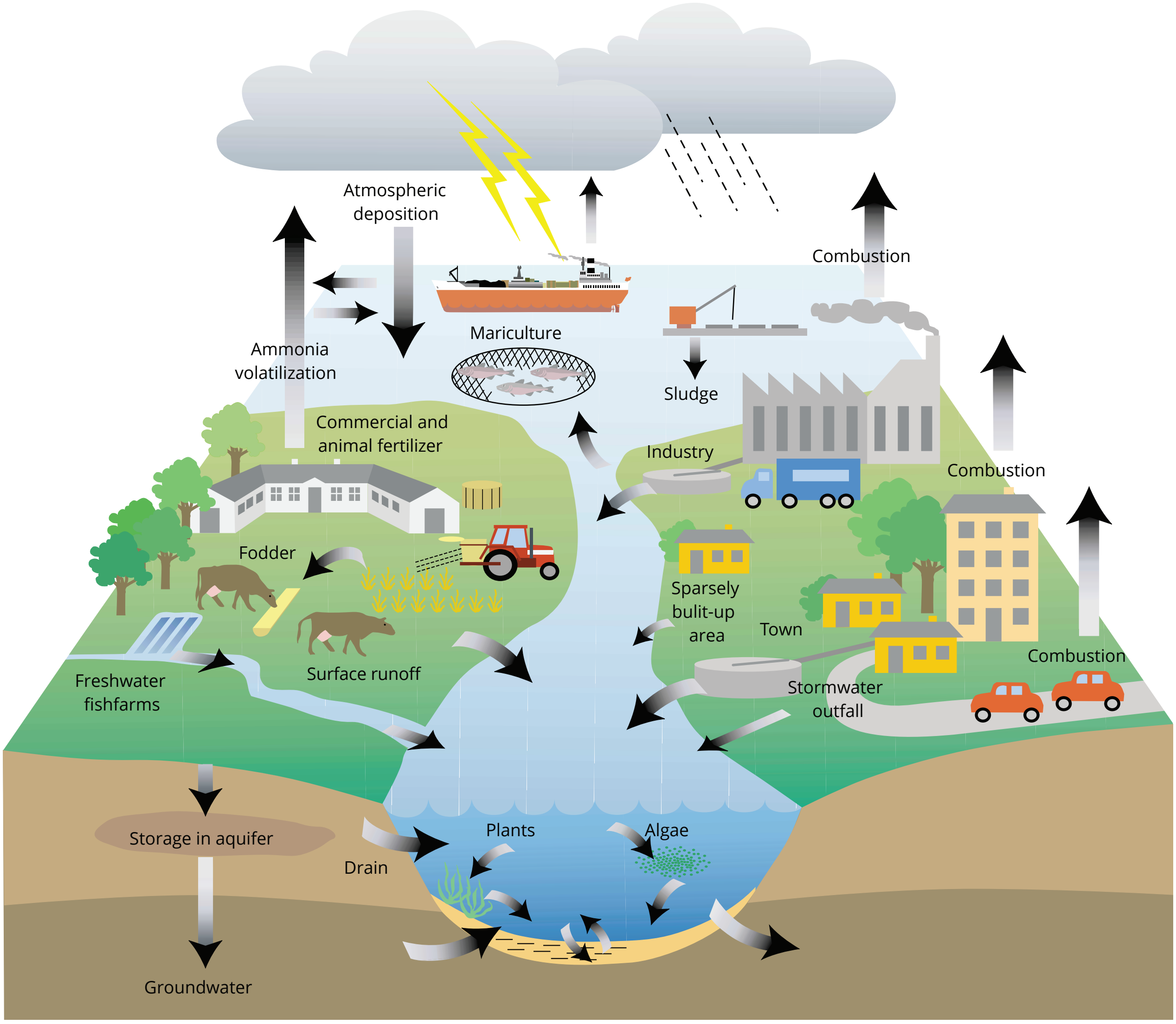


Notes: The compartments are (1) causative factors, sometimes referred to as 'nutrient levels', (2) direct effects, and (3) indirect effects. Connections within and between compartments are illustrated by arrows. Bold arrows indicate key interactions.

DIP, dissolved inorganic phosphorus.

Source: Based on Ærtebjerg et al. (2003).

Figure 1.2 Nitrogen inputs to the sea



Note: Inputs of nitrogen to marine water, where all relevant sources and pathways are shown. Phosphorus inputs show similar sources and pathways, although phosphorus is not emitted to the air and subsequently deposited.

Source: Ærtebjerg et al. (2003).

The circumstance in which nutrient enrichment and eutrophication is triggered by inputs of nutrients is detailed in Helcom, 2007. The sequence illustrated builds on Figure 1.1 and shows the links between (1) inputs of nitrogen (total nitrogen, TN) with concentrations of dissolved inorganic nitrogen (DIN), (2) nutrient concentrations in surface water (measured as DIN) with primary production, (3) nutrient inputs (nitrogen, N) with mean chlorophyll concentration and bloom frequency, and (4) Secchi depth with the depth limits of eelgrass (*Zostera marina*). The examples are taken from the scientific literature (Conley, 2000; Nielsen et al., 2002; Ærtebjerg et al., 2003; Carstensen et al., 2004; Conley et al., 2009).

It is also important to consider the origins of nutrient inputs — this is illustrated in Figure 1.2. The dominating pathways of nutrient inputs to marine waters are (1) riverine inputs from upstream catchments, (2) direct inputs from land-based sources, (3) direct inputs from sea-based sources, and (4) atmospheric deposition and transboundary pollution:

- Riverine inputs: large amounts of nutrients, especially nitrogen, phosphorus and organic matter are transported to downstream estuaries and coastal waters via rivers draining upstream catchments. The inputs are related to two sources: (1) natural background losses and (2) human activities in the catchment. The discharges and losses from human activities mostly originate from urban waste water treatment and discharge, industrial waste water treatment and discharge, discharges from scattered settlements and discharges and losses from farms and agricultural practices.

- Direct inputs from land-based sources: when it comes to direct inputs, discharges from domestic and industrial waste water treatment are the dominating sources. These inputs often have high concentrations of bioavailable inorganic nutrients, which can be taken up directly by primary producers.

- Direct inputs from sea-based sources: inputs from sea-based sources are small compared with land-based sources. Sea-based sources include aquaculture, dumping of dredged material and discharges from ships, in which cruise ships may play an important role.

- Atmospheric deposition and transboundary pollution: emissions of nitrogen compounds (nitrogen oxides (NO_x) and ammonium) to the atmosphere, e.g. from industries, traffic and agriculture, may be transported over long distances and deposited in the sea. Pollution that originates in neighbouring countries or travels long distances across the seas, thereby crossing borders, is known as transboundary pollution.

Furthermore, there may be internal sources of nutrients. Marine sediment can contain large pools of nutrients, which can be released to the overlying water masses. This process is well known in an enclosed regional sea, such as the Baltic Sea, where oxygen depletion (hypoxia) leads to releases of large amounts of phosphorus from the sediment, which in combination with land-based inputs can sustain other eutrophication effects, e.g. blooms of harmful blue-green algae (Vahtera et al., 2007).

1.2 Strategies to reduce nutrient inputs and abate eutrophication

Many initiatives have been launched and much work has been put into preventing and mitigating eutrophication, especially in relation to reducing inputs of nutrients from point sources (e.g. towns and industries), which have been effective (e.g. Riemann et al., 2015; Ibisch et al., 2016). The main management focus is on reducing nutrient inputs at source, because eutrophication is a process that is being fuelled by excessive nutrient releases from various human-related, mainly land-based sources and from atmospheric deposition. The EU Water Framework Directive (WFD; EU, 2000), the EU Marine Strategy Framework Directive (MSFD; EU, 2008) and related legislation with a focus on emission control (e.g. urban waste water treatment) aim to reduce the undesirable perturbations from eutrophication so that fruitful and important work can be carried out.

Many marine, coastal and transitional waters have been identified as eutrophication problem areas for decades. Therefore, many policies and strategies for the abatement of eutrophication have been agreed and implemented over recent decades, especially those addressing land-based sources (Ibisch et al., 2016).

In a European context, key eutrophication policies are implemented by the following directives:

- The WFD focuses on groundwater, freshwater, transitional waters (estuaries) and coastal waters. The key objective is to attain a good ecological status by 2027 at the latest. For coastal waters affected by eutrophication, the WFD is a eutrophication directive that defines environmental objectives.

- The MSFD focuses on marine waters, and the key objective is to attain a good environmental status for 11 descriptors by 2020. One of the descriptors, D5, deals with elevated nutrient levels and eutrophication. Good environmental status and threshold values for marine waters are defined during the MSFD implementation process. The WFD and the MSFD both set targets that would enable the achievement and maintenance of good ecological or environmental quality and may require more stringent targets for waste water treatment plants or more stringent standards for emissions from dispersed pollution sources (such as agriculture).

- The Urban Waste Water Treatment Directive (UWWTD; EU, 1991a) sets requirements for urban waste water treatment. The objective of the UWWTD is to protect the environment from the adverse effects of waste water discharges. The directive defines requirements for collection, treatment, discharge and monitoring of waste waters from urban areas and from certain industrial sectors. The degree of waste water treatment (i.e. emission standards) is defined in relation to the assessment of the sensitivity of the receiving waters. Member States are required to identify areas that are sensitive to eutrophication.

- The Nitrates Directive (ND; EU, 1991b) concerns the protection of waters against pollution caused by nitrates from agriculture. The objective of the Nitrates Directive is to reduce water pollution caused or induced by nitrates from agricultural sources and to prevent further such pollution. EU Member States are required to designate vulnerable zones in river catchments, where the land use indicates a high risk of nitrate pollution due to the use of nitrogen fertilisers. Member States are required to set up action programmes promoting following codes of conduct for good agricultural practice. Member States must also monitor and assess the eutrophication status of freshwater, estuaries and coastal waters every 4 years.

- The Industrial Emissions Directive (IED; EU, 2010) superseded seven previous directives and aims to achieve an integrated approach to management by considering all aspects of environmental performance through the entire life cycle (i.e. emissions to air, water and land; waste generation; use of raw materials; energy efficiency; noise; prevention of accidents; and restoration of the site upon closure). Industrial emissions of NO_x and discharges of nutrients and organic matter are also relevant causes of eutrophication. The directive also contributes to reducing NO_x deposits to the sea.

The Regional Sea Conventions have for decades focused on the reduction of nutrient inputs and the abatement of eutrophication in their respective convention areas:

- The Helsinki Commission (Helcom): the key instrument for attaining a healthy Baltic Sea unaffected by eutrophication is the Baltic Sea action plan (Helcom, 2007). This is a state-of-the-art, ecosystem-based nutrient management strategy based on setting specific targets for multiple eutrophication-related indicators and subsequent modelling and country-wise allocation of maximum nutrient inputs. The target year for achieving good ecological status, which is understood as a Baltic Sea unaffected by eutrophication, is 2021.

- OSPAR: the OSPAR eutrophication strategy is the instrument for combatting eutrophication to achieve and maintain a healthy marine environment where anthropogenic eutrophication does not occur. For problem areas, measures should be taken to reduce or to eliminate the anthropogenic causes of eutrophication.

- The Barcelona Convention and the United Nations Environment Programme Mediterranean action plan collectively aim to prevent human-induced eutrophication. The Barcelona Convention, adopted in 1976, was the first legally binding instrument for the environmental protection of the Mediterranean Sea and included a number of protocols, such as the pollution from land-based sources protocol (UNEP/MAP, 1980).

- The Black Sea Convention: inputs of nutrients leading to nutrient enrichment and eutrophication is recognised as one of the major threats to the marine environment of the Black Sea in the Strategic Action Plan for the Rehabilitation and Protection of the Black Sea (BSC, 2009). The Black Sea Convention aims to protect the Black Sea against pollution, and, in the context of nutrient enrichment and eutrophication, contracting parties should prevent, reduce and control pollution of the marine environment of the Black Sea from land-based sources, in accordance with the Protocol on the Protection of the Black Sea Marine Environment Against Pollution from Land-Based Sources (BSC, 1995).

For more information about nutrients, nutrient enrichment and eutrophication in Europe's seas, please see the following key references: Sutton et al. (2011), Helcom (2017) and OSPAR (2017).

Nutrient enrichment is included in the global 2030 Agenda for Sustainable Development (UN, 2015), which includes 17 Sustainable Development Goals (SDGs). Nutrient pollution is included under SDG 14.1, which sets a target to prevent and significantly reduce marine pollution (including nutrient pollution) by 2025.

2 Eutrophication in Europe's seas

- The eutrophication status of 2 400 000 km^2 of sea has been mapped.
- Areas totalling 1 837 000 km^2, mainly of offshore waters, were classified as non-problem areas.
- Areas totalling 563 000 km^2 have been identified as problem areas.
- Most of these are in found near densely populated areas or catchments downstream from agricultural activities.

The identification of 'problem areas' (areas affected by eutrophication) and 'non-problem areas' (areas unlikely to be affected by eutrophication) is based on the application of a multi-metric indicator-based eutrophication assessment tool named HEAT+. The Helsinki Convention eutrophication assessment tool (HEAT) was originally developed for assessing the eutrophication status of the Baltic Sea (see Helcom, 2009; Andersen et al., 2011). HEAT has been further developed and is now tested and applied in marine waters all over Europe.

The above uses of HEAT and the fact that it is well documented and transparent has prompted the use of HEAT+ in this assessment of eutrophication in Europe's seas. The target values (indicator-specific assessment criteria) used in this assessment are almost exclusively taken from assessments by the Regional Sea Conventions or from Member States' initial assessments under the Water Framework Directive (WFD) and/or the Marine Strategy Framework Directive (MSFD). In a few cases, e.g. for oxygen concentrations, a generic target value has been applied.

2.1 Classification method

HEAT+ follows a stepwise approach ultimately resulting in an integrated assessment of eutrophication states:

- Step 1: indicators are grouped as follows: (1) nutrient levels, (2) direct effects, and (3) indirect effects.
- Step 2: for each indicator, a eutrophication ratio (ER) is calculated based on monitoring data from the period addressed as well as a target value:

  ER = indicator value/target value ([1]).

- Step 3: within groups, an average ER is calculated.
- Step 4: for each group, eutrophication status is classified in five classes based on the average group-specific ER, e.g. high: 0-0.5; good: 0.5-1.0; moderate: 1.0-1.5; poor: 1.5-2.0, bad: > 2.0, where high and good are equivalent to non-problem areas and moderate, poor and bad are equivalent to problem areas.
- Step 5: the classifications are integrated, combining groups based on the 'one out, all out' principle.

2.2 Data sources

The assessment is based on available data from the Regional Sea Conventions and from Member States. Access to data sets and especially target values varies significantly between regions and is explained below.

Baltic Sea

Eutrophication status is being assessed in a harmonised and coordinated way by the Helsinki Commission (Helcom) contracting parties at regular intervals, e.g. 2000-2006, 2007-2011 and 2012-2017.

([1]) And vice versa for indicators with a numerically negative response, e.g. Secchi depth and oxygen concentrations.

The most recent data set (2012-2017) is publicly available and covers all open basins of the Baltic Sea (see, for example, Helcom 2017).

Black Sea

The data sets used originated from two sources, namely the European Marine Observation and Data Network (EMODnet) Chemistry and from a specific supplementary Turkish submission in support of this assessment, with data from 2015. A fully fledged and harmonised Black Sea-wide assessment has not been possible.

Mediterranean Sea

The assessment of the eutrophication status of the Mediterranean Sea is based on data sets submitted to EMODnet Chemistry, in practice on two indicators (chlorophyll-a and oxygen), as well as a specific supplementary Turkish submission of data from 2015 and a Greek submission of data for 2012-2014. A fully fledged and harmonised Mediterranean Sea-wide assessment has not been possible.

North-East Atlantic

OSPAR contracting parties assess the eutrophication status of the North-East Atlantic in a harmonised manner at regular intervals (OSPAR, 2003, 2008, 2017). Hence, this assessment is based on national data sets from the following countries: Belgium, Denmark, Germany, Ireland, the Netherlands, Norway, Sweden and the United Kingdom. Data sets in relation to the OSPAR 2017 assessment from Portugal and Spain were not available. Furthermore, it has not been possible to get access to detailed information on the French threshold levels.

2.3 Nutrient levels

Inputs of nutrients to transitional, coastal and marine waters from upstream catchments, atmospheric deposition and neighbouring waters may result in elevated nutrient concentrations, or nutrient enrichment.

The nutrient concentrations in seas vary considerably, both in time and in space. Over the year, the concentrations often build up over the winter period, then decline because of the spring bloom and are low for most parts of the summer and autumn periods.

High nutrient concentrations are often found near large cities and where rivers discharge into the sea. Land-sea gradients are pronounced in some regions, for example in the Adriatic Sea, the Baltic Sea and the North Sea.

Data coverage for coastal waters is good in the Baltic Sea, the North Sea, the Celtic Sea, Portuguese coastal waters, and in Turkish waters in the Black Sea. However, data coverage is in general unsatisfactory for the Mediterranean Sea and for French, Scottish and Spanish coastal waters in the North-East Atlantic Ocean.

For offshore waters, data coverage is good in the Baltic Sea, the North Sea, the Skagerrak and the Celtic Sea. Data coverage for open parts of the Bay of Biscay, the Black Sea and the Mediterranean Sea is unsatisfactory.

We have in total assessed 2 168 566 km^2 of Europe's seas. The majority of the assessment area is located offshore and 1 669 407 km^2 are classified as non-problem areas. Problem areas have been identified in 499 160 km^2, most of which are found near densely populated areas or catchments downstream from agricultural activities.

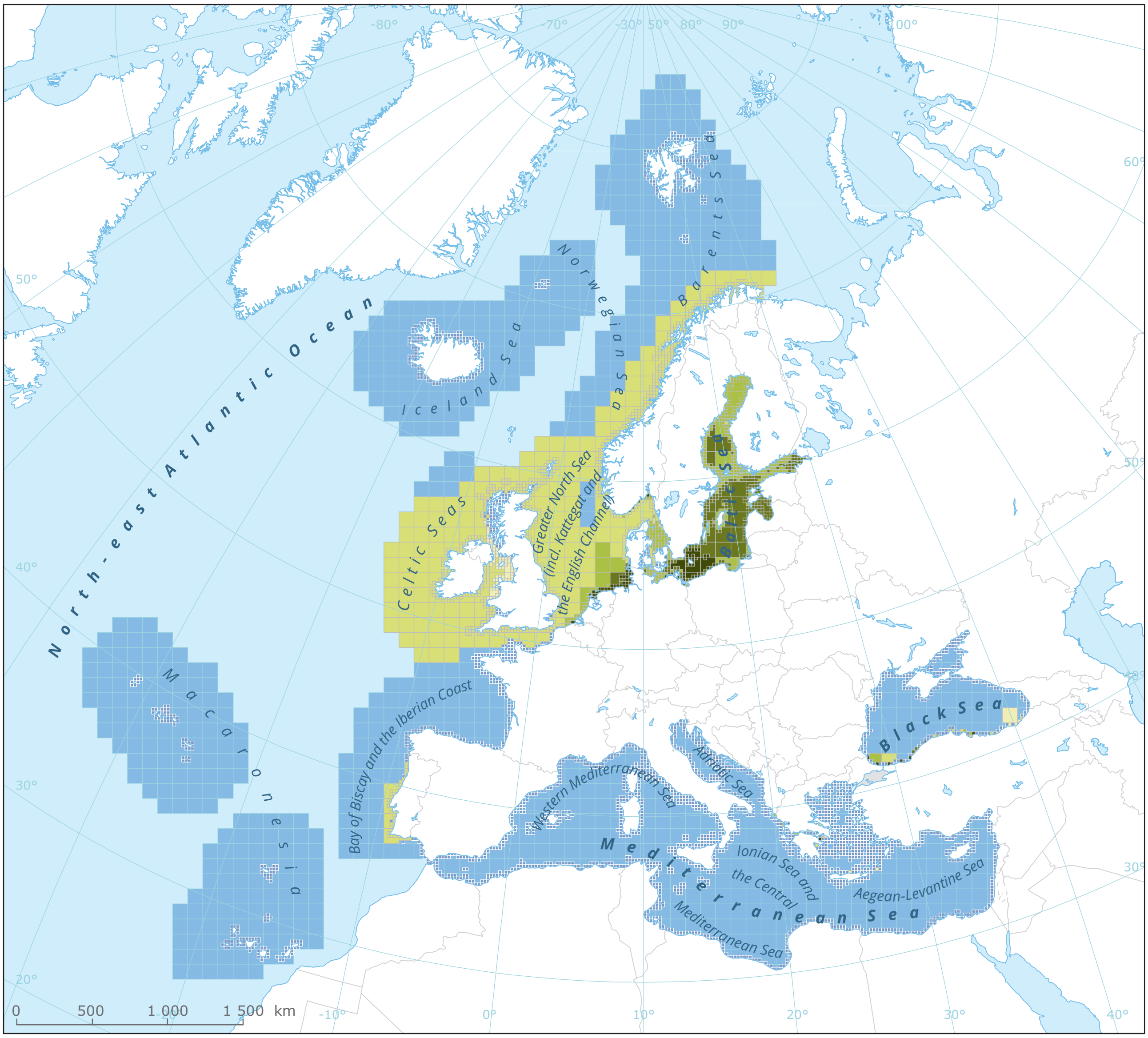
In the Baltic Sea, nutrient levels have been assessed in 390 442 km^2 (Map 2.1 and Table 2.1). Only 7 358 km^2 (2 %) are classified as non-problem areas, while 383 084 km^2 — corresponding to 98 % — are identified as problem areas. The most impacted areas are the Bothnian Sea, the Gulf of Finland, the Baltic Proper and the Bornholm Basin — some of these areas are located downstream from catchments with high population densities and high levels of agricultural activities.

In the Black Sea region, nutrient levels are assessed only in Turkish coastal waters (Map 2.1) because of the lack of information on threshold values in the waters of Bulgaria and Romania. Out of 28 092 km^2 assessed, 19 268 km^2 were classified as non-problem areas (69 %) and 8 824 km^2 as problem areas (31 %).

In the Mediterranean Sea, only 0.2 % of a total area of 2 530 254 km^2 has been assessed because of a lack of information on type- or site-specific threshold values. No offshore units have been assessed. Of the 5 256 km^2 assessed, 3 041 km^2 (58 %) were classified as non-problem areas and 2 214 km^2 (42 %) as problem areas. At some point, indicator- or site-specific threshold values will be developed or disclosed, e.g. as a result of Members States' MSFD reporting. This will enable detailed analyses and classification of 'nutrient levels' and more assessment units in most parts of the Mediterranean Sea.

For the North-East Atlantic Ocean, a total of 1 744 777 km^2 have been assessed. 1 639 739 km^2 of non-problem areas (94 %) were identified together

Map 2.1 HEAT+-based classifications of nutrient levels



HEAT+ based classification of 'nutrient concentration levels'

Non-problem areas: High, Good

Problem areas: Moderate, Poor, Bad

Outside coverage

No data

100x100 km in offshore areas (> 20 km from the coastline)

20x20 km in coastal areas (≤ 20 km from the coastline)

Note:
HEAT+: The HELCOM Eutrophication Assessment Tool (Developed for the pan-European assessment)

Notes: Mapping of spatial variations in the classifications of 'nutrient levels' based on available monitoring data, threshold values and the HEAT+ assessment. See Annex 4 for detailed sub-regional maps.

NPA, non-problem area; PA, problem area.

Table 2.1 Summary of the classifications for nutrient levels and the identification of problem areas and non-problem areas'

Class	Region								Total
	Baltic Sea		Black Sea		Mediterranean Sea		North-East Atlantic Ocean		
	km²	%	km²	%	km²	%	km²	%	
Total area	401 481		476 306		2 530 254		6 857 590		10 265 631
NPA_{High}	63	0.0	11 279	40.1	1 158	22.0	31 299	1.8	43 799
NPA_{Good}	7 295	1.9	7 989	28.4	1 883	35.8	1 608 440	92.2	1 625 608
$PA_{Moderate}$	147 175	37.7	5 403	19.2	1 647	31.3	77 533	4.4	231 758
PA_{Poor}	199 947	51.2	992	3.5	72	1.4	7 616	0.4	208 627
PA_{Bad}	35 962	9.2	2 429	8.6	495	9.4	19 889	1.1	58 775
Total assessed	390 442	100.0	28 092	100	5 256	100.0	1 744 777	100.0	2 168 566

Note: NPA, non-problem area; PA, problem area.

with 105 038 km^2 of problem areas (6 %). The latter are mostly found in the Kattegat, which is the transition zone to the Baltic Sea, and in the southern and eastern parts of the North Sea. A few coastal problem areas regarding nutrient levels have also been identified in Norway and Portugal. However, it should be noted, that the marine waters of France and Spain as well as the coastal waters of Northern Ireland and Scotland are not included in the assessment.

Offshore problem areas are found only in the Baltic Sea, the south-eastern parts of the North Sea and in some western parts of the Black Sea, but this picture might change once data sets with improved spatial coverage, and in some areas more indicators, become available, e.g. the Black Sea and Mediterranean Seas.

Annex 4 to this report contains detailed maps of the assessments of nutrient levels in the various regions.

In addition to the above assessment of nutrient levels — and based on Member States reporting WFD classification results to WISE-Marine (EEA, 2018, 2019) — nutrient conditions in transitional waters (TW) and coastal waters (CW) have been assessed:

- 66 % of TW were assessed for nutrient conditions. The proportion of TW (by area) in less than 'good' status in relation to nutrient conditions is 23 %. The Black Sea (EU area) is the marine region with the highest proportion of TW in less than 'good' status in relation to nutrient conditions (60 % of the EU TW area within that region), followed by the Baltic Sea (58 % of the EU TW area within that region). The proportion of TW in less than 'good' status in relation to nutrients is also high (45 %) in the Greater North Sea, including the Kattegat and the English Channel, and in the Adriatic Seas (31 %) (EEA, 2019).
- 54 % of CW were assessed for nutrient conditions. The proportion of CW (by area) in less than 'good' status in relation to nutrient conditions is 20 %. The Baltic Sea is the marine region with the highest proportion of CW in less than 'good' status in relation to nutrient conditions (58 % of the EU CW area within that region), followed by the Black Sea (29 % of the EU CW area within that region). The proportion of CW in less than 'good' status in relation to nutrients is lower (11 %) in the Greater North Sea, including the Kattegat and the English Channel (EEA, 2019).

Messages from WFD reporting support results from the HEAT+ assessment in coastal waters. For more information on WFD implementation, see EEA (2018).

2.4 Direct effects

The direct effects of nutrient enrichment are well documented and include an accelerated growth of either phytoplankton in the upper part of the water column or perennial macroalgae in shallow coastal waters.

The outcome of accelerated growth of phytoplankton is an elevated phytoplankton biomass, usually measured as an elevated concentration of chlorophyll-a in surface waters or as harmful algal blooms.

An important effect of accelerated growth of phytoplankton is the increase in chlorophyll-a concentrations and subsequently the reduction in water clarity and light penetration. Plankton algae will, for most of the year, be found in the surface water but elevated nutrient concentrations can alter the way the surface water looks and in severe cases make the water look like green paint.

On a European scale, we have assessed 1 995 732 km^2, of which 482 475 km^2 are classified as problem areas (24 %) and 1 513 256 km^2 as non-problem areas (76 %) (see Table 2.2). This picture might, however, change significantly once better data sets become available, e.g. from Member State's WFD and MSFD monitoring and assessment activities.

Data coverage for coastal water is in general good for the Baltic Sea and most parts of the North Sea/Skagerrak/Kattegat regions. It is worrying that more data sets have not been made available or accessible for the coastal waters in the Black Sea and the Mediterranean Sea, especially as chlorophyll concentrations in surface water are assumed to be monitored and assessed regularly under the WFD.

For open waters, data coverage is good for the Baltic Sea, for the southern and eastern parts the North Sea and for the Celtic Sea.

In the Baltic Sea, problem areas with respect to 'direct effects' are found in all basins (see Map 2.2). The most impacted basins are the Gulf of Finland, the Gulf of Riga, the northern and western parts of the Baltic Proper and the south-western parts of the Baltic Proper.

Data coverage regarding 'direct effects' is poor for the Black Sea and only a few square kilometres have been assessed.

Data coverage is also poor for most parts of the Mediterranean Sea, with only 70 868 km^2 having been assessed. Of this area, only 4 794 km^2 (7 %) are classified as problem areas, while 66 074 km^2 (93 %) are identified as non-problem areas. This picture will probably change once better data sets become available for the region as a whole.

In the North-East Atlantic Ocean, affected areas regarding 'direct effects' are found in the south-eastern parts of the North Sea, especially in the Wadden Sea and along the coasts of Belgium, Germany, Denmark, and the Netherlands. In the Celtic Sea, a few coastal areas have been classified as problem areas. The coastal and marine waters of France and Spain, as well as the coastal waters of Northern Ireland and Scotland, are not included in the assessment.

Despite the issues with access to relevant data sets in some regions and sub-regions, it is gradually becoming clear that direct effects can be found in parts of all European regional seas. Large-scale eutrophication problems are found in the Baltic Sea and in the southern and eastern parts of the North Sea, but there are also significant local issues in other regions of Europe.

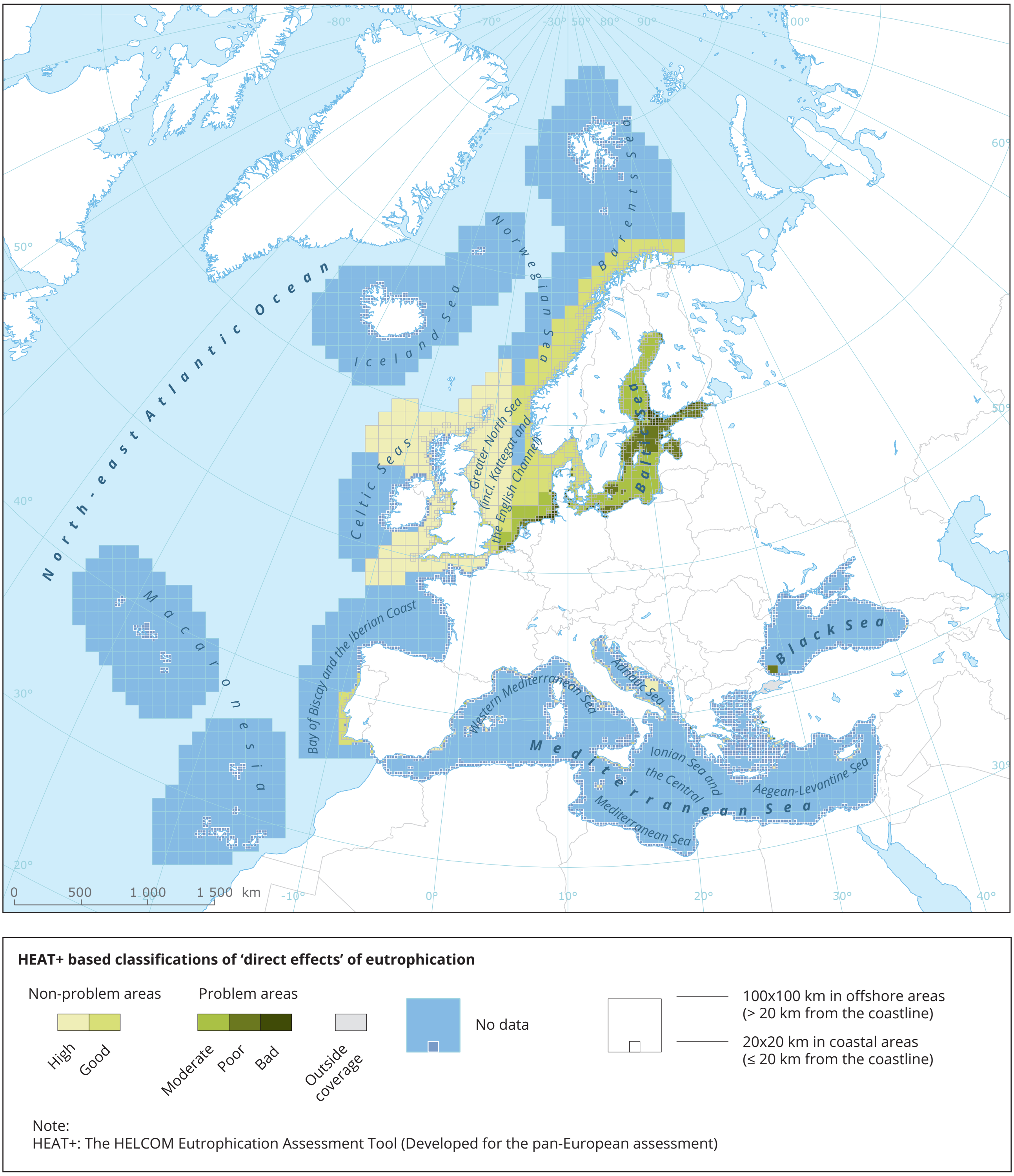
In addition to the above assessment of direct effects — and based on Member States' WFD reporting (EEA, 2018, 2019) — direct effects in TW and CW have been assessed based on phytoplankton indicators. Phytoplankton assessment methods used by Member States include several parameters: mostly 'phytoplankton biomass' (total biomass and chlorophyll-a) but also 'abundance/frequency and intensity of algal blooms', and in a few cases 'taxonomic composition':

- 60 % of TW were not assessed for phytoplankton conditions at the EU level. The proportion of TW (by area) in less than 'good' status in relation to phytoplankton conditions is 9 %. The Baltic Sea is the marine region with the highest proportion of TW in less than 'good' status in relation to phytoplankton conditions (66 % of the EU TW area within that region), followed by the Black Sea (50 % of the EU TW area within that region). The proportion of TW with an 'unknown' status is also high in these two regions. The proportion of TW in less than 'good' status in relation to phytoplankton conditions varies between 5 % and 9 % in other EU marine regions, where TW waters are mainly in 'good' status (or 'unknown') (EEA, 2019).
- The proportion of CW area in less than 'good' status in relation to phytoplankton conditions is 27 %. Results are region-specific: the Adriatic is the sub-region with the highest proportion of coastal waters achieving 'good ecological status' in relation to phytoplankton conditions (89 % of the area is reported to be in 'high' status and 1 % in 'good' status), followed by the Macaronesian subregion (82 % of the area is reported to be in 'high' status and 2 % in 'good' status). The Black Sea is the marine region with the highest proportion of CW in less than 'good' status in relation to phytoplankton conditions (85 % of the EU coastal water area within that region), followed by Baltic Sea (76 % of the EU CW area within that region) and the Greater North Sea, including the Kattegat and the English Channel (28 %). CW status in relation to phytoplankton conditions is mainly 'good' in the Adriatic Sea, where only 3 % of CW are in less than 'good' status, despite the situation reported in the TW (EEA, 2019). Messages from WFD reporting support results from the HEAT+ assessment in coastal waters.

2.5 Indirect effects

Elevated concentrations of nutrients may have direct effects, and these might subsequently lead to secondary effects such as reduced depth distribution of submerged aquatic vegetation (see Image 2.1), changes

Map 2.2 HEAT+-based classifications of direct effects



Notes: Mapping of spatial variations in the classifications of direct effects is based on available monitoring data, threshold values and the HEAT+ assessment. See Annex 4 for detailed sub-regional maps.

NPA, non-problem area; PA, problem area.

Table 2.2 Summary of classifications of direct effects and the identification of problem areas and non-problem areas

Class	Region								Total
	Baltic Sea		Black Sea		Mediterranean Sea		North-East Atlantic Ocean		
	km²	%	km²	%	km²	%	km²	%	
Total area	401 481		476 306		2 530 254		6 857 590		10 265 631
NPA_{High}	0	0	395	8.2	54 533	77.0	822 225	54.0	877 154
NPA_{Good}	13 383	3.4			11 541	16.3	611 179	40.1	636 102
$PA_{Moderate}$	230 528	58.2			2 278	3.2	59 209	3.9	292 015
PA_{Poor}	129 108	32.6	4 400	91.8	916	1.3	18 188	1.2	152 612
PA_{Bad}	23 406	5.9			1 600	2.3	12 843	0.8	37 848
Total assessed	396 425	100.0	4 795	100	70 868	100.0	1 523 644	100.0	1 995 732

Note: NPA, non-problem area; PA, problem area.

in the structure and functioning of benthic invertebrate communities, and oxygen depletion. The inclusion of indirect effects in the assessment of eutrophication is an important and necessary step. Overall, on a European scale, we have assessed 1 967 659 km², of which 1 648 884 km² are classified as non-problem areas (84 %) and 318 775 km² as problem areas (16 %) (see Table 2.3). The latter is an underestimation related to gaps in the data, especially in the Black Sea and Mediterranean Sea, and in the French and Spanish parts of the North-East Atlantic Ocean (see Map 2.3).

Data coverage for coastal waters is in general good for most parts of the Baltic Sea and the North Sea including the Skagerrak and the Kattegat. Data coverage is unsatisfactory for the Black Sea and the Mediterranean Sea. In the North-East Atlantic Ocean data coverage is unsatisfactory for France, Northern Ireland, Scotland and Spain. For open waters, data coverage is good in the Baltic Sea, the North Sea, the Norwegian Sea and in the Celtic Sea, as well as in the south-western parts of the Black Sea and for Portugal. Data coverage is unsatisfactory for the Mediterranean Sea and for the French and Spanish parts of the North-East Atlantic Ocean.

In the Baltic Sea, 'indirect effects' have been assessed in 396 825 km², of which 124 073 km² are non-problem areas (31 %) and 272 753 km² are problem areas (69 %). Non-problem areas are mostly found in the Gulf of Bothnia, while problem areas are found in all other Baltic Sea basins. The indicator that gives rise to the impaired status in the offshore waters is often oxygen concentrations in bottom water, which in turn affects the benthic communities. For the Black Sea, 44 117 km² have been assessed. Thus, the spatial coverage is limited. 22 961 km² (52 %) of non-problem areas have been identified, while 21 156 km² (48 %) have been classified as problem areas, mostly in the western parts. In the Mediterranean Sea, 51 515 km², mostly coastal waters, have been classified. 46 324 km² (90 %) are non-problem areas, while only 5 190 km² (10 %) are problem areas. An area of 1 475 203 km² in the North-East Atlantic Ocean has been assessed for 'indirect effects', corresponding to 21.5 % of the total area. 1 455 527 km² are classified as non-problem areas (99 %) and 19 676 km² as problem areas (1 %). The most impaired areas are found in the eastern part of the North Sea region and in the Celtic Sea and in the south-western parts of the Black Sea.

The assessment of indirect effects could improve considerably once there is appropriate access to relevant data sets from WFD and MSFD monitoring activities.

2.6 Identification of problem areas and non-problem areas

We have, based on a Europe-wide application of the HEAT+ tool described in Section 2.2, provisionally identified problem areas and non-problem areas with respect to nutrient enrichment and eutrophication.

A total of 2 399 595 km² have been assessed, and variations in data coverage and availability within and between the different regional sea regions have been found (see Map 2.4).

Of the area assessed, 1 836 672 km² are classified as non-problem areas (76.5 %) and 562 923 km² as problem areas (23.5 %) (see Table 2.4). The extent of problem areas is likely to be underestimated, but still we show that eutrophication is a large-scale issue in Europe's seas. All regional seas have problem areas, the Baltic Sea more than others.

In the Baltic Sea — perhaps the best studied and monitored of the regional seas in Europe — 396 825 km^2 have been assessed. We identified 394 574 km^2 of problem areas (99 %) and only 2 251 km^2 of non-problem areas (1 %). These results are largely in line with earlier studies (Andersen et al., 2010; Fleming-Lehtinen et al., 2015; Helcom, 2018). The Baltic Sea region sets a high standard for and a high confidence in the indicator-based assessment of eutrophication status.

For the Black Sea, the coverage is focused on coastal waters of Bulgaria, Romania and Turkey, plus a few offshore areas in the south-western parts and off the coast of Turkey. 23 368 km^2 out of 44 117 km^2 assessed are classified as problem areas (53 %), and 20 749 km^2 as non-problem areas (47 %).

The spatial coverage in the Mediterranean Sea is currently limited and is largely restricted to coastal waters. Large parts, both offshore and coastal, are assumed to be oligotrophic, but this fact does not justify the reduced coverage in Croatia, Cyprus, France, Greece, Italy, Malta and Spain. In total, only 93 486 km^2 have been assessed, 82 438 km^2 being classified as non-problem areas (88 %) and 11 048 km^2 as problem areas (12 %).

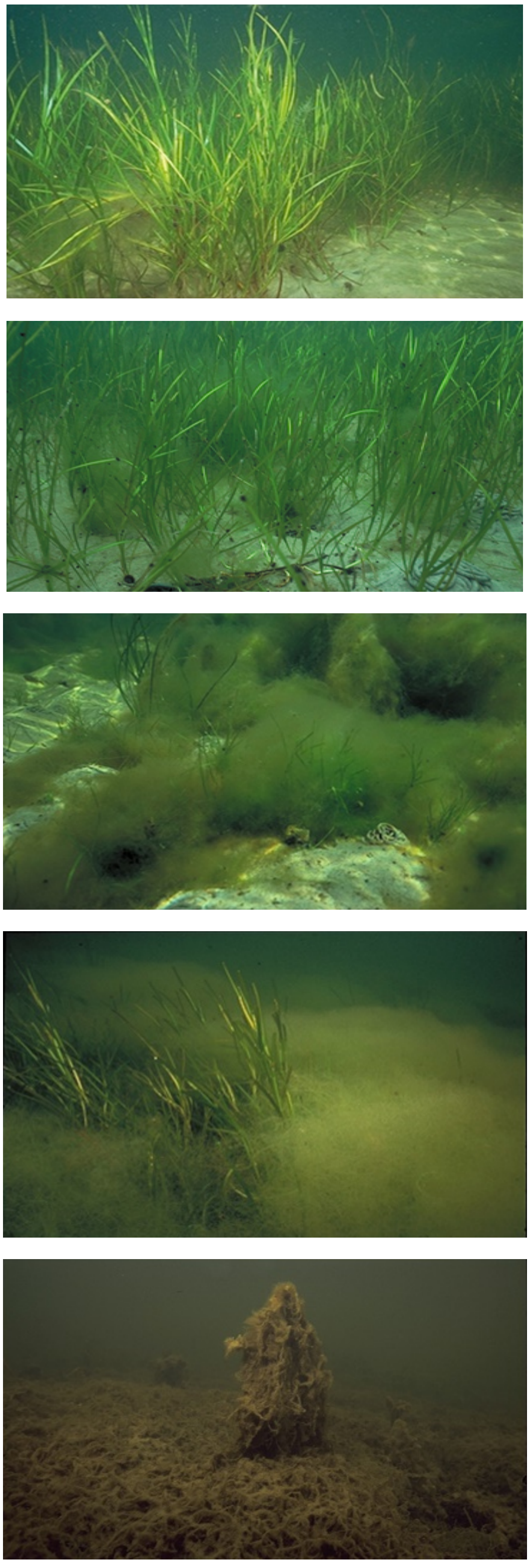
In the North-East Atlantic Ocean, assessments have not been possible for France or Spain. In the case of Spain, it is because Spain has not carried out an OSPAR (2017) assessment; for France the cause is lack of access to threshold values. For Scotland, coastal waters are not included because of the lack of access to relevant data from the WFD assessment for coastal water. Consequently, assessments have only been made for Belgium, Denmark, Germany, the Netherlands, Norway, Portugal and the United Kingdom.

This is the first integrated assessment of the eutrophication status of Europe's seas; however, the spatial coverage could be improved, especially in the Mediterranean Sea and the Black Sea.

It should be noted that the classifications carried out are not fully harmonised between countries and regions. Harmonisation and coordination have been given high priority but, for several reasons, we have not achieved a complete harmonisation:

- Indicators: there is coherence between the indicators used in the Baltic Sea, Black Sea,

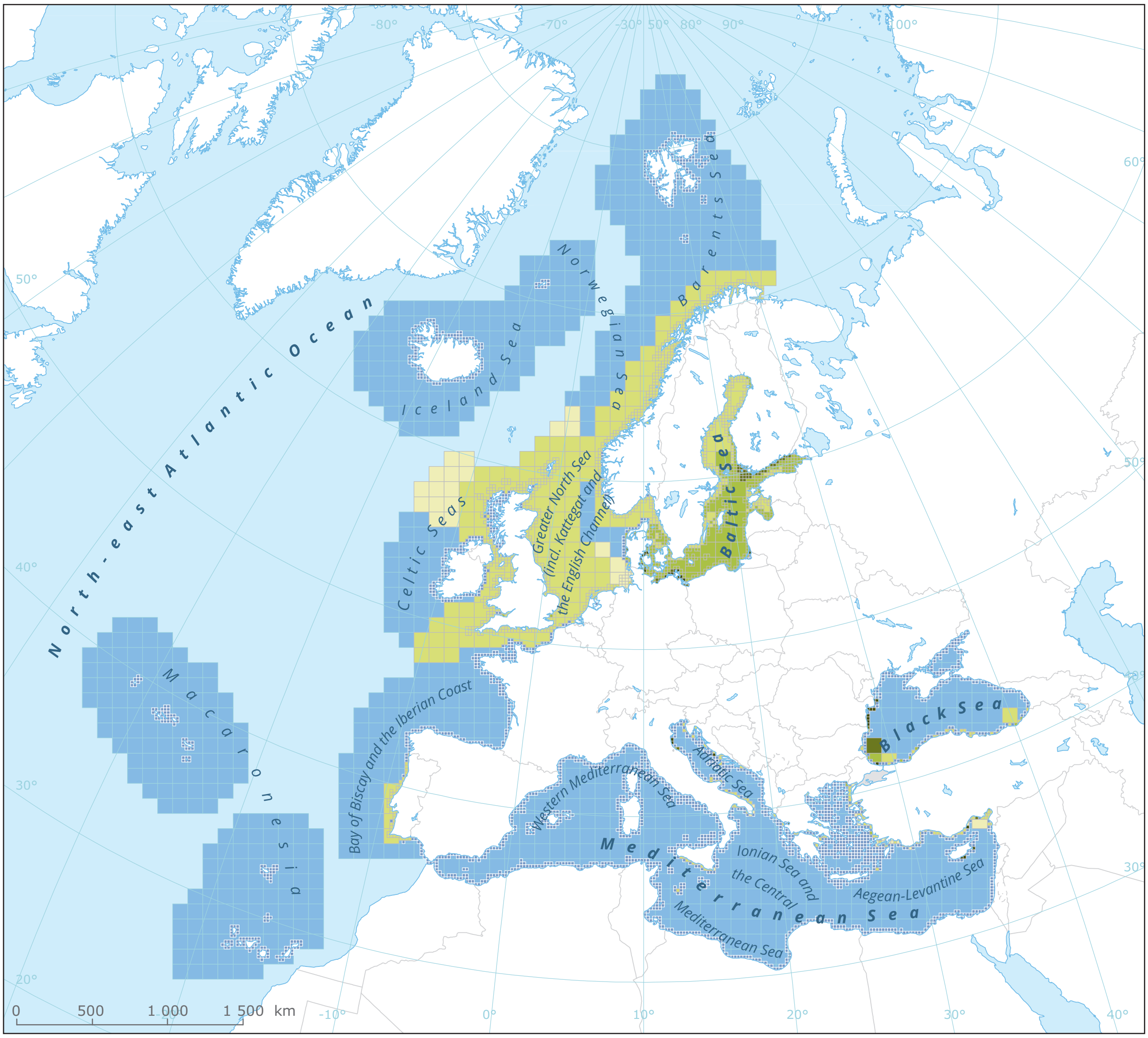
Image 2.1 Reduction in the depth distribution of eelgrass due to eutrophication



Note: Gradient of eutrophication status illustrated by eelgrass (Zostera marina). The top two images represent non-problem areas, and the next three indicate how eelgrass may look in problem areas.

Source: Images provided by Nanna Rask.

Map 2.3 HEAT+-based classifications of indirect effects



HEAT+ based classifications of 'indirect effects' of eutrophication

Non-problem areas: High, Good

Problem areas: Moderate, Poor, Bad

Outside coverage

No data

100x100 km in offshore areas (> 20 km from the coastline)

20x20 km in coastal areas (≤ 20 km from the coastline)

Note:
HEAT+: The HELCOM Eutrophication Assessment Tool (Developed for the pan-European assessment)

Notes: Mapping of spatial variations in the classifications of indirect effects based on available monitoring data, threshold values and the HEAT+ assessment. See Annex 4 for detailed sub-regional maps.

NPA, non-problem area; PA, problem area.

Table 2.3 **Summary of classifications for indirect effects and the identification of problem areas and non-problem areas**

Class	Regions								Total
	Baltic Sea		Black Sea		Mediterranean Sea		North-East Atlantic Ocean		
	km²	%	km²	%	km²	%	km²	%	
Total area	401 481		476 306		2 530 254		6 857 590		10 265 631
NPA_{High}					13 872	26.9	193 415	13.1	207 287
NPA_{Good}	124 073	31.3	22 961	52.0	32 452	63	1 262 112	85.6	1 441 597
$PA_{Moderate}$	248 048	62.5	6 760	15.3	1 312	2.5	18 291	1.2	274 411
PA_{Poor}	17 989	4.5	10 301	23.3	783	1.5	1 118	0.1	30 191
PA_{Bad}	6 716	1.7	4 095	9.3	3 095	6.0	267	0.0	14 173
Total assessed	396 825	100.0	44 117	100.0	51 515	100	1 475 203	100.0	1 967 659

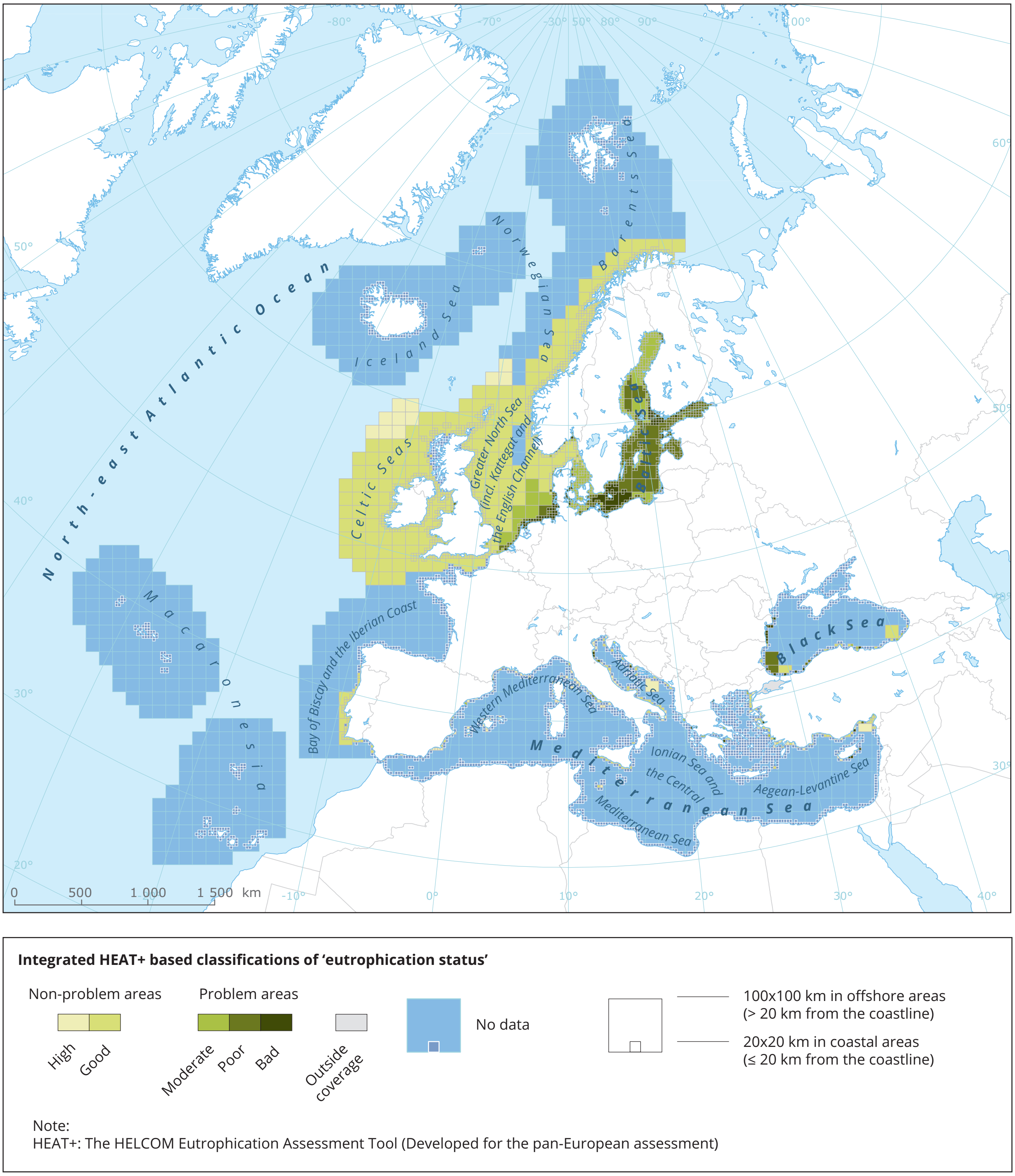
Note: NPA, non-problem area; PA, problem area.

Mediterranean Sea and North-East Atlantic Ocean but also some significant differences. Some differences are ecologically justified (e.g. the oxygen debt in the Baltic Sea), while others are related to a lack of data accessibility or a lack of specific threshold values. For direct effects, chlorophyll-a is widely used; for indirect effects, oxygen concentrations are widely used; and for many coastal waters, either submerged aquatic vegetation or benthic macroinvertebrates are widely used.

- Threshold values: HEAT+ requires synoptic data, both monitoring data for a given period and the associated indicator-specific threshold values. Problem and non-problem areas can be identified only using both types of information. In some regions and countries, this double set of information is easily available, e.g. in the Baltic Sea and among most but not all of the OSPAR contracting parties. In the Black Sea and Mediterranean Sea regions, information on indicator-specific threshold values is scattered and it is sometimes complicated to get access or permission to use it .

- Integrated assessments: the coordinated use of a fully harmonised multi-metric indicator-based eutrophication assessment tool occurs only in the Baltic Sea. OSPAR applies the Comprehensive Procedure (COMPP), which is a harmonised framework, but not in a fully coordinated manner between the countries involved. In the Black Sea and the Mediterranean Sea, some assessment tools have been or are being tested.

Map 2.4 HEAT+-based classifications of integrated eutrophication status



Notes: Mapping of spatial variations in the integrated classifications of eutrophication status is based on available monitoring data, threshold values and the HEAT+ assessment. See Annex 4 for detailed sub-regional maps.

NPA, non-problem area; PA, problem area.

Table 2.4 Summary of integrated classifications of eutrophication status and the identification of problem areas and non-problem areas

Class	Region								Total
	Baltic Sea		Black Sea		Mediterranean Sea		North-East Atlantic Ocean		
	km²	%	km²	%	km²	%	km²	%	
Total area	401 481		476 306		2 530 254		6 857 590		10 265 631
NPA_{High}					47 535	50.8	111 362	6.0	158 897
NPA_{Good}	2 251	0.6	20 749	47.0	34 903	37.3	1 619 871	86.8	1 677 775
$PA_{Moderate}$	108 440	27.3	1 651	3.7	4 429	4.7	92 150	4.9	206 670
PA_{Poor}	227 625	57.4	15 579	35.3	1 564	1.7	19 625	1.1	264 392
PA_{Bad}	58 509	14.7	6 138	13.9	5 055	5.4	22 159	1.2	91 861
Total assessed	396 825	100.0	44 117	100.0	93 486	100	1 865 167	100.0	2 399 595

Note: NPA, non-problem area; PA, problem area.

3 Have the trends been reversed?

- Several indications reflect an ongoing recovery process in all of Europe's seas and the fact that efforts to reduce nutrient inputs have begun working as predicted.
- In the Baltic Sea and in the North Sea the eutrophication status has been improving over the past 15-20 years because of reductions in nutrient inputs.
- Overall, temporal trends cannot currently be assessed in the Mediterranean Sea and Black Sea because of a lack of available data

Assessing long-term temporal trends in eutrophication enables a better understanding of the changes in structure and function of ecosystems that are susceptible to nutrient inputs. 'Problem areas', in which nutrient inputs should be further reduced, were identified in the study. Long-term assessments also provided useful information about the different phases in the eutrophication process. This information can support the implementation of nutrient management strategies (Nixon, 2009).

A prerequisite for carrying out long-term temporal trend assessments is the availability of long-term temporal data series covering several decades. Such compilations have not been done on a European scale, simply because data do not exist or, most likely, have never been brought together, harmonised and used in combination with a multi-metric indicator-based assessment tool. What has been done in the context of this report regarding long-term trend assessment is therefore based on work carried out in the four regional seas, i.e. the Baltic Sea, the North-East Atlantic Ocean, the Mediterranean Sea using the Adriatic Sea as a case study and the Black Sea.

Two assessments in the Baltic Sea are presented, one based on *in situ* measured data spanning 100 years and one based on modelled data spanning 350 years. We identified the different phases in the eutrophication of the Baltic Sea and documented the beginnings of recovery and of oligotrophication (previously described by Nixon, 2009). For the Black Sea, we focus on trends in nutrient concentrations and chlorophyll-a.

For the Mediterranean Sea, we highlighted some coastal problem areas in the Northern Adriatic Sea. For the North-East Atlantic Ocean, we present the overall conclusions of the recent OSPAR (2017) assessments.

It is one of the EEA's key visions to assess long-term temporal trends in eutrophication status on a Europe-wide scale. This is likely to be achievable in 2025, when EU Member States publish the next generation of Marine Strategy Framework Directive (MSFD) descriptor 5 (D5) initial assessments. However, better indicators, especially in the Black Sea and the Mediterranean Sea, better target values and significantly easier access to data are fundamental.

3.1 Baltic Sea

The Baltic Sea is one of the largest estuarine systems in the world. As a result of the prevailing climatological and oceanographic characteristics, e.g. retention time and salinity, it is highly susceptible to nutrient input and eutrophication. Furthermore, the Baltic Sea is one of the best studied regional seas in Europe, which enables the long-term integrated assessment of its eutrophication status.

The overarching vision is a healthy Baltic Sea unaffected by eutrophication but, because of multiple human activities in the catchment area, along the shores and offshore, the Baltic Sea has a large-scale eutrophication problem (see Section 2.4, Map 2.4 and Figure 3.1).

Four phases of eutrophication status in the Baltic Sea can be identified (Figure 3.1):

- Phase 1, or the pre-eutrophication phase, covers the period from 1902 up to around the mid-1950s, when the first signs of eutrophication in the Baltic Proper and the Gulf of Finland emerged.

- Phase 2 covers the period from the mid-1950s to the early 1970s, when eutrophication developed into a large-scale problem in all sub-basins.

- Phase 3 covers the period from the mid-1970s to the late 1990s, which is considered to be the peak period for eutrophication issues in the Baltic Sea. This was the eutrophication stagnation period.

- Phase 4, starting in the late 1990s, is described as a time of trend reversal, recovery and oligotrophication. Improvements have been documented in each sub-basin and in the whole Baltic Sea-wide assessment.

The Baltic Sea case study provides a first, robust example of a long-term trend assessment for an entire regional sea. Perhaps the most import result is that the eutrophication status has been improving over the past 15-20 years because of reductions in nutrient inputs to the Baltic Sea.

With the documented onset of the recovery process in the Baltic Sea, it seems prudent to ask when eutrophication will no longer be a major issue in the Baltic Sea.

An answer would have to be based on modelling of the future expected trends in relevant indicators, i.e. dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) concentrations, chlorophyll-a, Secchi depth and oxygen concentration (see Box 3.1). With this information available, it is possible to combine the indicators into an integrated assessment using HEAT+, the new version of the Helsinki Commission eutrophication assessment tool. The eutrophication process in the open parts of the Baltic Sea can be described as follows: (1) the Baltic Sea has not been in a pristine status for the past 150 years; (2) the first signs of eutrophication (seen as a process) emerged approximately 100 years ago; (3) from the 1960s, eutrophication has been a large-scale problem in the Baltic Sea; (4) eutrophication peaked in the 1980s and 1990s; (5) since then, the very first sign of recovery has been documented; and finally (6) recovery is assumed to continue, eventually resulting in good ecological status in 150-200 years.

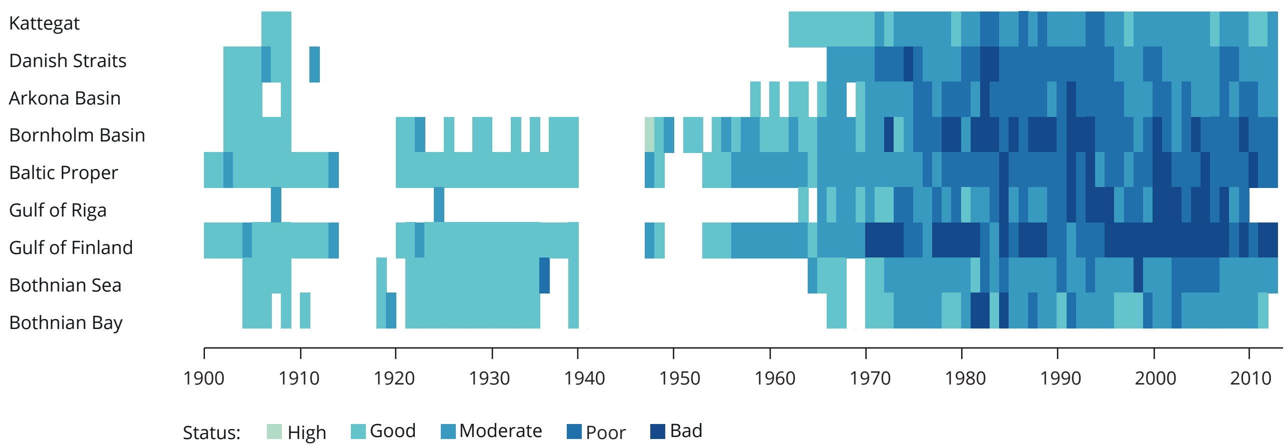
The main messages from this 350-year-long Baltic case study are:

- First, assuming the model output is robust and correct, reductions in nutrient inputs will have consequences and will lead to an improvement for each indicator dealt with.

- Second, recovery processes may take decades and decision-makers should be informed that short-term improvements in eutrophication status should not be expected.

- Third, ultimately, we will at some point fulfil the target of a Baltic Sea that is unaffected by eutrophication for all indicators that entail an integrated assessment.

Figure 3.1 Long-term trends in the eutrophication status of the Baltic Sea



Note: Long-term spatial and temporal trends are assessed for nine sub-basins of the Baltic Sea for the period 1901-2012, based on HEAT+ and a broad range of in situ-measured indicators. White indicates that there were no data for that particular combination of year and basin.

Source: Based on Andersen et al. (2017).

BOX 3.1 Modelling developments in the Baltic Sea's eutrophication status

Based on an existing modelled data set for the open parts of nine Baltic Sea basins, we present long-term temporal trends for the following indicators in Figure 3.2: (a) estimated (1950-2015) and predicted (2015-2100) total populations of seven Baltic countries (Denmark, Estonia, Finland, Latvia, Lithuania, Sweden and Poland); (b) total loads of nitrogen (N); (c) total loads of phosphorus (P); (d-h) modelled trajectories of eutrophication ratio (ER) for dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP), chlorophyll-a, Secchi depth and oxygen debt, averaged over the nine basins, for the best- (lightest blue) and worst-case (darkest blue) load scenarios; and (i) the integrated assessment of eutrophication status. For ER values (d-i), annual values are shown by thin lines and the 10-year moving averages by thick lines (Murray et al, 2019).

3.2 Black Sea

The Black Sea is among the largest enclosed water bodies and has a very long retention time of ~2 000 years and a catchment area that is five times larger than the sea itself. The hydrological conditions, combined with the population density living close to the coast, has made the region extra vulnerable to anthropogenic pressures and especially eutrophication (Yunev et al., 2007).

Eutrophication has increased since the late 1960s with the increased concentrations and loads of winter nutrients, such as phosphorus and nitrogen, as well as increased phytoplankton biomass and decreased silica concentrations (Yunev et al., 2005, 2007). The increase continued until the late 1970s and mid-1980s and was followed by a steep decrease. Nevertheless, an elevated level of nutrient concentrations and loads was still seen in 2000. Frequent harmful algal blooms and changes in phytoplankton composition were seen as the diatom population in Bulgarian waters decreased from a dominating ~86 % before the 1970s to ~42 % in the period 1970-1990 (Yunev et al., 2007).

The Black Sea has handled mass mortality of benthic species caused by a decrease in oxygen levels between 1960 and 1992. Decreased Secchi depths between 1960 and 1990, from ~25 m to 5 m, have led to reduced light levels and have been one of the pressures leading to degraded seaweed populations (Yunev et al., 2005, 2007; Capet et al., 2016).

Climate change effects and the introduction of the invasive snail *Rapana thomasiana* and the ctenophore *Mnemiopsis leidyi* have added to the pressures in the Black Sea. It continues to be a challenge for the region to mitigate the large-scale ecological shifts and effects of anthropogenic actions in the Black Sea, and some suggest that the sea has reached a new irreversible steady state, with altered phosporus:nitrogen:silica ratios.

3.3 Mediterranean Sea case study: Adriatic Sea

The Adriatic Sea region is stratified during the summer and has restricted water column mixing. Anthropogenic inputs of nutrients, and pollution from agriculture and large coastal cities, as well as from rivers such as the Po, had a large impact and caused gradual eutrophication of the ecosystem from the 1970s until the mid-1980s (Giani et al., 2012). The eutrophication has led to higher primary production, shifts in trophic levels and hypoxic events.

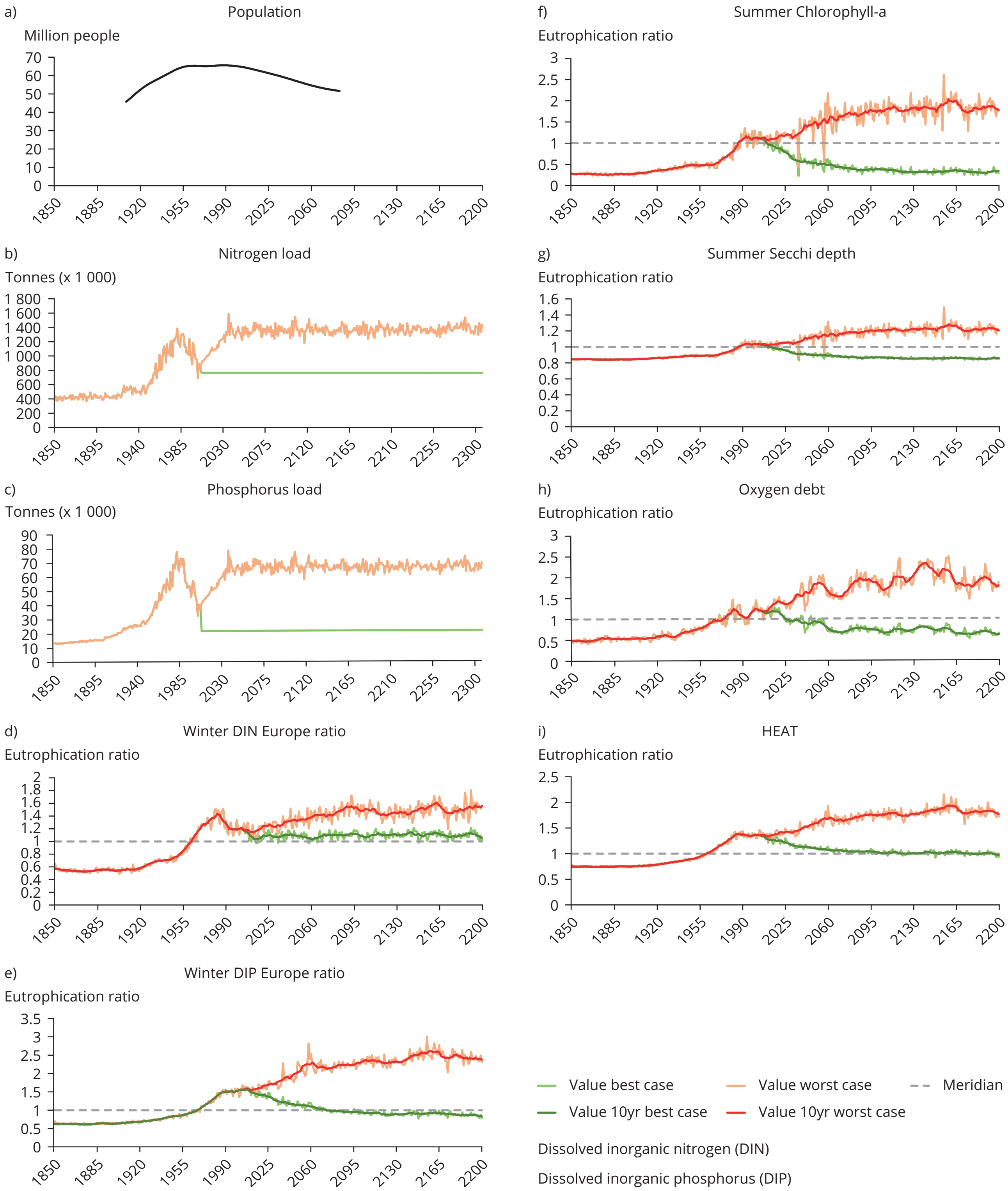
Time-series from 1972 to 2010 indicate a trend reversal since the 2000s, with lower chlorophyll-a concentrations; decreased loads of river nitrogen (except from the Po river, for which the load has increased), phosphorus and silica; fewer hypoxic events than during the late 1980s and 1990s; but an increased DIN:phosphate ratio (Giani et al., 2012). The changed nutrient ratio was caused by a reduction in phosphate concentration in the late 1980s due to new regulations preventing polyphosphate in detergents as well as decreased inputs from the Po river between 2000 and 2008, resulting from a dry climatic period with reduced precipitation.

However, a constant increase in seawater nitrogen concentrations indicates that inputs of nitrogen, together with phytoplankton being limited by nitrogen concentrations , are still affecting the ecosystem, altering the phytoplankton community, by reducing the number of heterotrophic flagellates, and decreasing the total biomass (Giani et al., 2012).

As a result of high fishing pressure, the biomass of commercial fish stocks decreased between 1975 and 2000 (Giani et al., 2012). Since the changes in primary productivity in the 1950s, the increase in lower trophic-level organisms has reflected the decrease in large predators/fish stocks (Piroddi et al., 2017).

As well as eutrophication, the Adriatic ecosystem is subject to additional pressures: regional effects of climate change (sea level rise, increased salinity, decreased precipitation, and increased seawater temperature and acidification) (Giani et al., 2012).

Figure 3.2 **Long-term temporal trends in the eutrophication status of the Baltic Sea**



Note: Based on an existing modelled data set for the open parts of 9 Baltic Sea basins, we present long-term temporal trends for the following indicators: (a) Estimated (1950–2015) and predicted (2015–2100) total population of seven Baltic countries (Denmark, Estonia, Finland, Latvia, Lithuania, Sweden, and Poland), (b) total loads of N (c) total loads of P, (d–h) modelled trajectories of Eutrophication Ratio (ER) for dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorous (DIP), chlorophyll-a, Secchi depth, and Oxygen Debt averaged over the nine basins, for the best- (green) and worst-case (orange) load scenarios, and (I) the integrated assessment of eutrophication status. For ER values (d–i), annual values are shown in light colours and the 10-year moving averages with dark colours. For panels d-i, the dashed line indicates the boundary between non-eutrophic status (ER <= 1.0) and eutrophic status (ER>1.0).

Source: Murray et al, 2019

3.4 North-East Atlantic Ocean

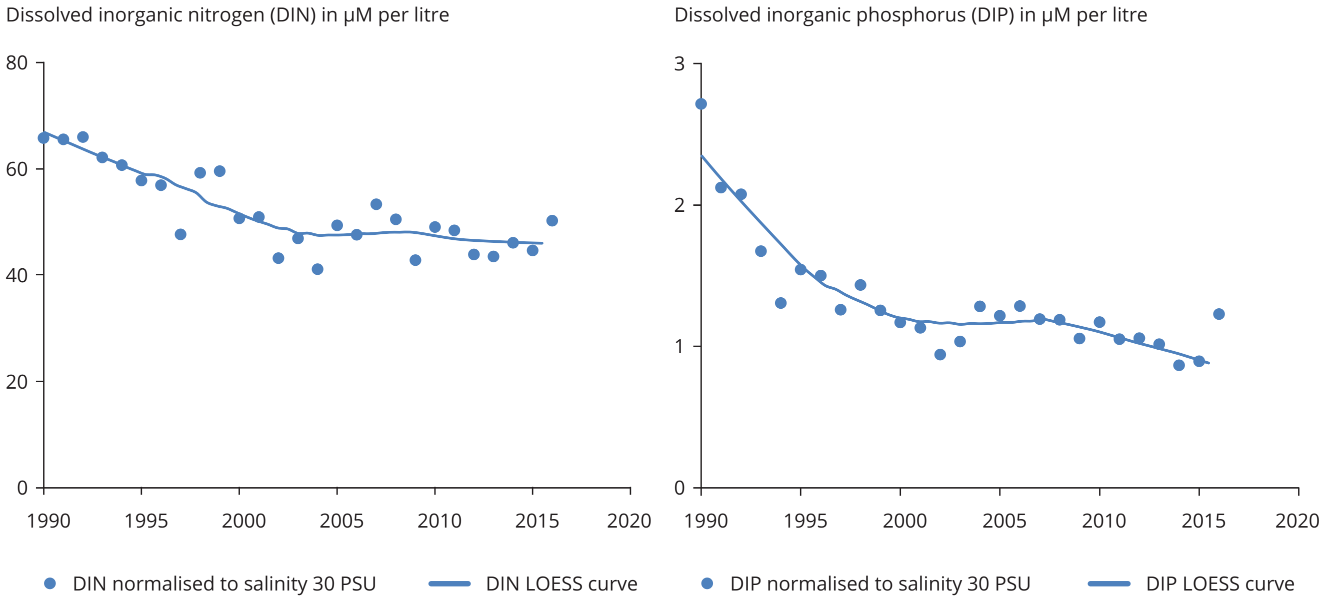
OSPAR published assessments of the eutrophication status of the North-East Atlantic Ocean in 2003, 2008 and 2017 (OSPAR 2003, 2008, 2017). The assessment period in the first assessment differs between contracting parties, but, in general, the assessments cover the period 1990-2014. In the last report, an analysis was made of the trend in eutrophication status in the OSPAR area for all contracting parties except Portugal and Spain. The surface area in the North-East Atlantic Ocean that was classified as either a potential problem area or a problem area decreased from around 180 000 km^2 in 2003 to nearly 160 000 km^2 in 2008 and around 125 000 km^2 in 2017, which is a 30 % decrease overall. Eutrophication is still observed in 7 % of the assessed area. The areas affected are mainly located in the south-eastern parts of the Greater North Sea and in some coastal waters of the Celtic Sea and the Bay of Biscay.

For the Greater North Sea, assessment results were available for all contracting parties. In the recent OSPAR assessment, approximately 17 % of the Greater North Sea was classified as being problem areas or potential problem areas. The HEAT+ classifications arrive at similar results. The surface area of (potential) problem areas has decreased by 40-50 % since the first assessment in 2003. This decrease is mainly caused by the improved status of the offshore areas in the southern North Sea. In some of the problem areas the underlying parameters for causative factors (nutrient concentrations) or direct effects (chlorophyll concentrations) show improvements, but this is not yet visible in the overall assessment.

Atmospheric deposition is a significant additional source of nitrogen in the Greater North Sea, where it is estimated to contribute about 30 % of the total nitrogen input (OSPAR, 2017). The reduction in the surface area of problem and potential problem areas reflects the decreases in nutrient inputs since 1990, with about 50 % reduction in phosphorus and 25 % reduction in nitrogen (OSPAR, 2017). Roughly similar decreases in phosphorus inputs were observed in the other sub-regions (Celtic Sea, Bay of Biscay and Iberian coast), but nitrogen inputs in those two sub-regions decreased less or not at all. An example of the gradual improvement in the Greater North Sea comes from Dutch coastal waters. Nutrient concentrations in Dutch coastal waters are strongly influenced by riverine nutrient discharges (Scheldt, Meuse, Rhine). Riverine nutrient loads are dominated by the River Rhine, which has by far the largest catchment area, consisting of a densely populated area of 197 000 km^2 and a population of 60 million inhabitants.

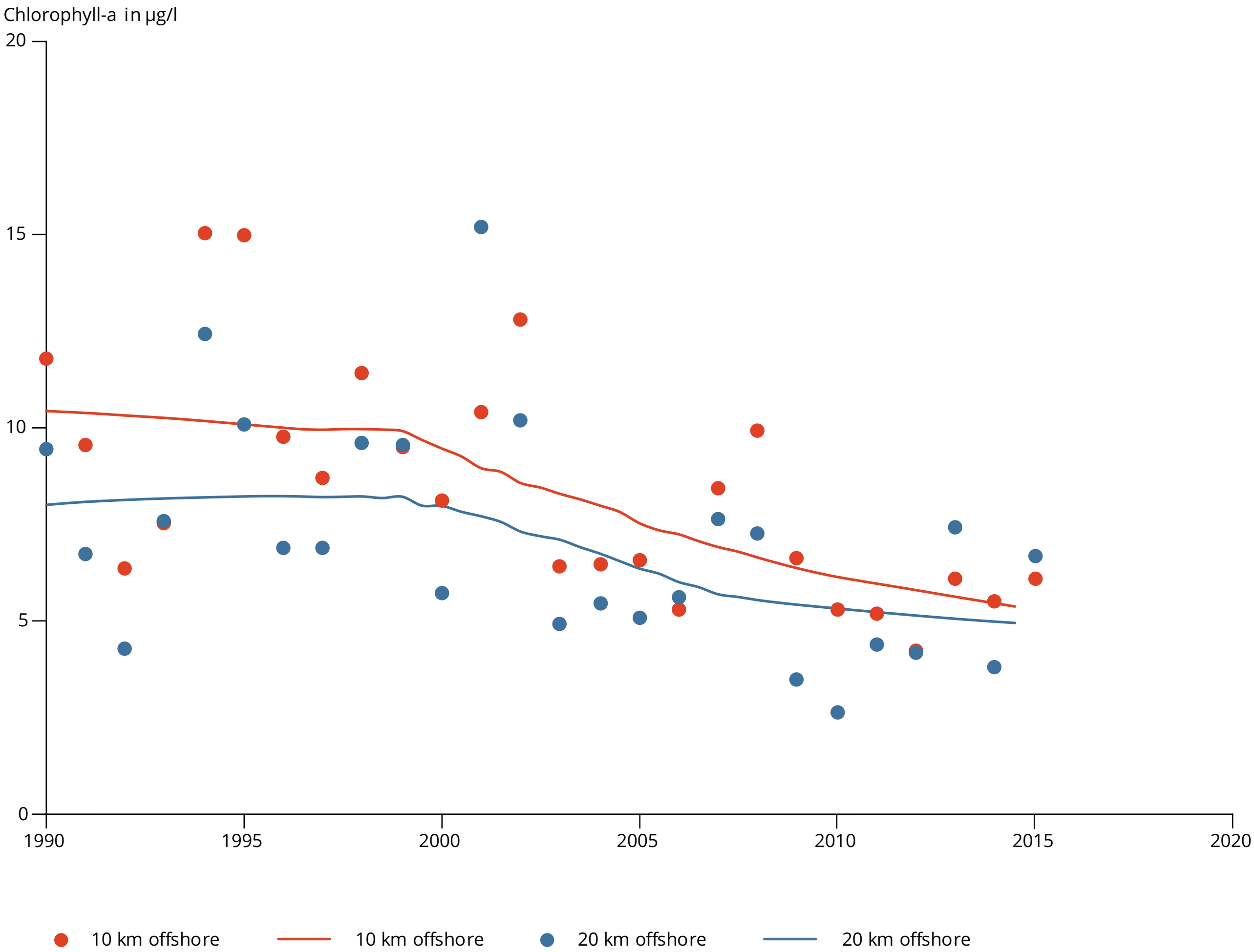
The riverine loads have decreased since 1990 by 30 % (total nitrogen) and 60 % (total phosphorus. Consequently, the mean winter nutrient concentrations

Figure 3.3 Normalised winter dissolved inorganic nitrogen and dissolved inorganic phosphorus concentrations



Note: Mean winter concentrations of dissolved inorganic nitrogen (left) and phosphorus (right), normalised to salinity 30 PSU, in a transect running from the Meuse-Rhine river mouth to offshore of the Dutch part of the North Sea. Curves are plotted by locally estimated scatterplot smoothing.

Figure 3.4 Mean growing season chlorophyll-a concentrations



Note: Mean (March-September) concentration of chlorophyll-a at two monitoring stations in Dutch coastal waters (10 km and 20 km off the coast near Noordwijk, downstream of the Rhine-Meuse discharge points). Line plotted by locally estimated scatterplot smoothing.

in the coastal waters downstream from the main discharge points of the Rhine and Meuse rivers have decreased proportionally (Figure 3.3). For this figure, nutrient concentrations were normalised to a salinity 30 PSU by using nutrient-salinity mixing plots. The salinity normalised concentrations showed a significant decreasing trend for both nitrogen and phosphorus.

In Dutch coastal waters, decreasing nutrient concentrations have resulted in decreasing chlorophyll-a concentrations in some parts. Because of the relatively high suspended matter concentrations in the coastal waters, reduced light levels are an important growth-limiting factor for phytoplankton, resulting in high interannual variability in chlorophyll-a concentrations that are not related to variations in nutrient concentrations. This relatively strong light limitation also partly masks the effects of nutrient loads on phytoplankton biomass. Nevertheless, chlorophyll-a concentrations at stations at 10 km and 20 km off the coast in the downstream plume of the Rhine-Meuse (Figure 3.4) show a significant decrease over the period 1990-2016 (Mann-Kendall test, $p < 0.05$).

4 Towards a healthy sea unaffected by eutrophication

- EU legislation and the Regional Sea Conventions aim for a healthy marine environment and regulate nutrient enrichment.
- Significant progress has been achieved in understanding and reducing the eutrophication problem, but there are still areas where targets have not been met.
- Management can be improved by effectively using experience and scientific advice and by modelling and researching additional management measures to respond to climate change.

Eutrophication was recognised as a problem in the 1950s, and the first reduction targets were introduced in legislation in the 1970s. In the new millennium, the holistic, ecosystem-based management approach was introduced within the Water Framework Directive (WFD) and the Marine Strategy Framework Directive (MSFD). The WFD aims to achieve good ecological status (GEcS), and the MSFD aims to achieve good environmental status (GEnS). The novelty in relation to older legislation is that the limit values for pressures are required to be defined based on the responses of relevant biological elements to pressures.

4.1 What are our common goals?

Overall, the MSFD 2020 goal aims to provide 'ecologically diverse and dynamic oceans and seas which are clean, healthy and productive'. The eutrophication aspect is pinned down by specific goals to achieve a state in which 'Human-induced eutrophication is minimised, especially adverse effects thereof, such as losses in biodiversity, ecosystem degradation, harmful algae blooms and oxygen deficiency in bottom waters.' The vision of marine areas that are not affected by eutrophication in the terms of our assessments means that we are aiming to achieve 'non-problem areas'.

In the context of eutrophication abatement in Europe (ECT/ICM, 2016), significant reductions in pressures from land-based nutrient pollution across Europe were achieved, but there are still gaps between the goals and actions that will ultimately lead to a healthy marine environment unaffected by human-induced eutrophication. Legislation that addresses emissions aims to reduce the inputs of nutrients, mostly nitrogen and/or phosphorus, that cause eutrophication (e.g. the Nitrates Directive, ND, and the Urban Waste Water Treatment Directive, UWWTD).

The WFD sets standards for the management of inland (lakes and rivers), coastal and transitional waters. The overarching objective and the direction set by the WFD implies the following:

- For phytoplankton, the composition and abundance of phytoplankton taxa as well as biomass show only slight signs of disturbance compared with type-specific reference conditions.
- For submerged aquatic vegetation, macroalgal cover and angiosperm abundance show only slight signs of disturbance compared with reference conditions.
- For benthic macroinvertebrates, the diversity and abundance of invertebrate taxa is only slightly outside the range associated with the type-specific reference conditions.

The overarching objectives are set by a combination of the MSFD and the Regional Sea Conventions and can be summarised as follows:

- For nutrients, concentrations are not at levels indicating eutrophication close to natural levels and thus not elevated above these.
- For 'direct effects', chlorophyll concentrations are not at levels indicating eutrophication.

- For 'indirect effects', either the distributions or compositions of benthic communities are at natural levels or oxygen concentrations in bottom water are at natural levels.

In addition to the above EU directives, there are regional agreements and action plans (such as the Helsinki Convention, or Helcom, Baltic Sea action plan), but these plans are normally not legally binding.

4.2 Where are we?

Chapter 2 documents where we are now — despite management under many directives (the Nitrates Directive, UWWTD, WFD and MSFD) and regional and national action plans, eutrophication is still a widespread issue in parts of all of Europe's regional seas. Although 'problem areas' are present, we can conclude that efforts to reduce nutrient inputs and eutrophication have not been in vain — improvements are documented in many regions, sub-regions and countries (Chapter 3).

In addition to the progress made over recent decades, we have significantly improved the understanding of eutrophication/oligotrophication. It is well documented that the prescribed cure — reducing nutrient inputs — will reduce eutrophication problems and lead to recovery of ecosystem structure and functions. Although ecosystem recovery is partial, examples of it are found in all four marine regions of Europe (Chapter 3).

Over the past three decades, we have learned a lot regarding not only understanding, monitoring and assessing eutrophication but in particular about how transitional, coastal and marine ecosystems may recover when nutrient inputs are reduced as prescribed. The beginning of the recovery of the Baltic Sea, described in Chapter 3, is among the best examples of how reducing inputs leads to an improvement in environmental status.

Another good example is based on the monitoring of Danish coastal waters after the implementation of three national action plans on the aquatic environment (for details, see Riemann et al., 2016). Based on monitoring in coastal waters since 1990, the ecological effects of reducing nutrient inputs and loads from cities, industries and agricultural activities show clear signs of improvement for both physical and chemical parameters and for biological indicators (Riemann et al., 2016).

Relative to 1990, inputs of nitrogen (total nitrogen, TN) and phosphorus (total phosphorus, TP) have been reduced as prescribed and the concentrations (TN and TP) in seawater have decreased accordingly. For biological indicators, also relative to 1990, the response to lowered nutrient levels is straightforward regarding 'direct effects', here illustrated by chlorophyll concentrations that have decreased as expected. For 'indirect effects' we see improvements for both eelgrass and macroalgae and also for benthic macroinvertebrates, including both filter feeders and deposit feeders. Similar responses and improvements can be expected in other sub-regions and water bodies with a high anthropogenic nutrient pressure, once ecologically relevant target nutrient reduction measures have been enacted and implemented.

Hence, we do have a very good starting point for taking the next steps towards a healthy sea without anthropogenic eutrophication. We share a vison and objectives on a European scale — and it is well documented that reducing nutrient inputs will lead to ecosystem recovery.

4.3 Is there a gap between goals and actions?

One of the challenges of eutrophication abatement is to implement load reduction targets that are likely to fulfil agreed visions and objectives, where targets would consider ecological characteristics. The second challenge is to identify relevant measures, because many measures have already been implemented, especially to reduce emissions from point sources, while the emissions from diffuse sources (e.g. agriculture and urban areas) are more challenging to tackle (Ibisch et al., 2016). The visions and objectives are therefore both well justified and timely — the problem is the lack of adequacy of the actions, understood as achieving the agreed load reductions required to meet the visions and objectives and not anything less. There does, in our opinion, seem to be a gap between the visions and the action currently implemented. Therefore, the agreed management strategies are often not enough to achieve the required nutrient reductions:

1. There is a significant gap between the current eutrophication status and the reduction in inputs achieved so far in some areas. We fear that the agreed reductions still to be implemented may not be adequate because, in some areas, the distance to target seems larger than the expected result of the agreed load reduction, e.g. in the context of the WFD. It is important to bridge this mismatch — and the load reductions required to attain GEcS should be calculated using state-of-the-art biogeochemical models. Such model-based nutrient reductions

are more reliable than the load reductions agreed as a result of non-scientific processes, e.g. the 50 % reduction targets.

2. For offshore waters, there might also be a gap between the current status and the nutrient reduction agreed so far. The planned reductions might not be enough to attain GEnS in all regional seas. For offshore water, the application of state-of-the-art biochemical models is required to link target values for different indicators with maximum allowable inputs to sub-basins and to regions.

3. All threshold values used in this study originate either from national reports/reporting or from the work by the Regional Sea Conventions. The methods used for setting these values differ significantly. Some are well documented, e.g. those from the WFD implementation and those for offshore waters of the Baltic Sea; for other areas, the quality and the scientific underpinning of the values are less transparent and lack good documentation.

4. We have identified a mismatch between the ways coastal waters and offshore waters are monitored and assessed. Better coordination between WFD and MSFD implementation and reporting processes is likely to bridge this gap — thus, it is a job for Member States, the Regional Sea Conventions and the EU.

5. Multi-metric indicator-based eutrophication assessment tools are currently used neither widely nor on a Europe-wide scale. Some regional conventions are applying tools or assessing eutrophication within a harmonised framework; other conventions are not even close to providing an understanding and an overview of eutrophication within their respective convention areas.

6. There is a mismatch between the expected data availability and what we were able to achieve. Better access to relevant data sets should be possible, given that the WFD was adopted in 2000, the MSFD in 2008 and that most Regional Sea Conventions are proactive in principle when it comes to sharing data.

7. As a follow-up to this assessment of eutrophication in Europe's seas, there is a need to cross-check the problem areas identified by this study and the designation of 'nitrogen vulnerable zones' under the Nitrates Directive, to verify potential mismatches. If a problem area is situated downstream of an agricultural catchment, this catchment, or parts of it, should as a rule of thumb be considered a 'vulnerable zone'; however, there may be a few exceptions to this rule.

8. In some areas there is probably a mismatch between the identified problem areas and the 'sensitive waters' designated via the UWWTD. A problem area is in principle equivalent to a 'sensitive water body' — the key question is the source(s) of nutrients. If inputs from urban waste water treatment plants play a role in a specific problem area, then this area is sensitive, and the nutrient reduction should in principle include biological treatment at urban waste water treatment plants that are discharging to the area.

9. This assessment represents a leap forward by being the first ever pan-European overview of eutrophication in Europe's coastal and marine waters. It could, however, in many regions, have been better with respect to spatial coverage and robustness. Thus, there is a gap between what is doable and what we have done so far.

Bridging the gaps between visions and objectives on the one hand and the actions that are required to be taken to fulfil to objectives on the other will be important steps in the process leading to a healthier marine environment.

4.4 Where do we go from here?

In view of the described gaps between the overarching goals and the current monitoring activities and measures taken to reduce inputs to achieve the objectives, we outline where to go from here:

1. To get better access to relevant monitoring data sets including input data, we believe that a focused effort is needed at several levels: (1) at national levels; (2) at regional levels; and (3) at the EU level. We believe that, as a follow up to this assessment, a strategy should be developed jointly by the regional conventions and the EEA. Furthermore, there might be a need to revisit the European Environment Information and Observation Network (Eionet) marine data flow, to safeguard all relevant information (e.g. monitoring data, threshold values, georeferencing and typologies).

2. To develop science-based threshold values, especially for offshore waters, we believe that a focused effort is required. First, any progress will mobilise a large amount of monitoring data in the context of HEAT+ (the new version of the Helsinki Convention eutrophication assessment tool), especially in the Black Sea and Mediterranean Sea but probably also in parts of the North-East Atlantic Ocean. Second, better threshold values will mean more accurate classifications of

eutrophication status. There is no doubt that science- and ecosystem-based target setting will improve the quantification of the required nutrient load reductions through more accurate determination of the 'distance to target'.

3. This study has identified an urgent need to clarify whether problem areas in areas affected by riverine inputs from agricultural catchments are reflected in the designation of 'nitrogen vulnerable zones' in the catchment or parts of it. It is outside the scope of this report to carry out such cross-checking; hence, it should be done as a follow-up activity.

4. Along the same lines, we have identified a need to clarify problem areas in areas affected by discharges from urban waste water treatment plants that are not yet designated as 'sensitive water bodies'. Again, we suggest a follow-up activity be carried out to document the degree of compliance or, as we fear, mismatch.

5. Model-based calculations of nutrient reductions from upstream catchments to coastal waters is a prerequisite. Reductions agreed based on a generic percentage reduction or on simple models that do not take account of the flow of water and substances (i.e. nutrients) between adjacent water bodies are below par. Ideally, all reductions in nutrient inputs should be calculated using complex biogeochemical models and should also take climate change into account. Otherwise, the nutrient reduction required to attain GEcS or GEnS may potentially be underestimated.

6. As for coastal waters, there is a need for more observations in combination with model-based calculations of load reductions in offshore waters. The Helcom Baltic Sea action plan (BSAP) can be used as an example of best practice. However, there may be a need to use slightly more complex marine biogeochemical models and to include climate change in the work.

7. To improve coordination between the monitoring and assessment of coastal water (i.e. the WFD domain) and of offshore water (i.e. the MSFD domain), we suggest a focused effort at the EU level. A first step would be to develop a framework for harmonisation and coordination of the WFD and the MSFD in problem areas. Taking a wider perspective, streamlining the assessment and reporting activities to make better use of the relatively inadequate resources that are currently allocated to such activities is needed.

8. There is a need to develop, test and apply multi-metric indicator-based eutrophication assessment tools on a European scale. Only Helcom and OSPAR assess eutrophication status regularly. There is also a need for better coordination within the regions — otherwise the results will not be comparable between countries and regions. This step is technically straightforward — thus, a joint framework could be developed by the regional conventions and the EEA that takes scientifically justified regional differences into account.

9. To get from this first assessment of eutrophication in Europe's seas to a comprehensive assessment without any gaps in spatial coverage, the EEA suggests (1) that future consultations with Eionet are planned and executed in a manner that enables additional data sets to be provided and included before publication, and (2) that a follow-up assessment is carried out 4-6 years from now, taking relevant data sets from WFD and MSFD monitoring into account.

Agreeing on these steps and subsequently agreeing on follow-up actions may lead to a healthier marine environment, including a decrease in the intensity and spatial extent of the eutrophication issues identified by this assessment of nutrient enrichment and eutrophication in Europe's seas.

5 Synthesis and outlook

- Eutrophication caused by inputs of nutrients, especially nitrogen and phosphorus, remains a large-scale problem in the Baltic Sea, the Black Sea, parts of the North-East Atlantic and some coastal areas in the Mediterranean Sea.
- Positive effects of the significant efforts put into nutrient management strategies can be seen in all EU regional seas.
- Management, particularly reducing nutrient inputs, is embedded in several EU polices, but targets remain unlikely to be met within the agreed timeframe for all of Europe's seas.
- To reach the policy vision of achieving a healthy marine environment in all of Europe's regional seas, further reduction of nutrient inputs is still needed in the most sensitive areas, together with considering the effects of climate change.

For the analysis, Europe's seas were divided to assessment units by a grid system. We assessed a total of 10 404 units, of which 9 502 are coastal and 902 are offshore (Table 5.1). Data coverage varies considerably between regions, sometimes due to issues with data accessibility. A direct comparison between regions is therefore complex. However, there are a few differences, which should be highlighted:

- For offshore waters, 20.5 % or only 902 out of 4 391 assessment units have been assessed and classified.
- For coastal waters, 34.0 % or only 9 502 out of 27 928 units have been assessed and classified.

For the regional seas, the data coverage ranges between 5.6 % and 84.1 % for coastal waters and from 0.5 % to 100 % for offshore waters. The lowest levels for each are seen in the Black Sea region, and the highest levels for each are seen in the Baltic Sea region. (see Table 5.1).

In Europe, there is a common understanding of what human-induced eutrophication is about, what the root causes are and how human activities that cause eutrophication should be managed.

First, eutrophication is well defined by EU directives, by the Regional Sea Conventions and by the scientific community.

Second, there is almost a common approach to the monitoring of eutrophication in Europe's seas. For nutrient levels, monitoring focuses on the concentrations of nitrogen and phosphorus, often the annual averages of total nitrogen/total phosphorus or dissolved inorganic nitrogen/dissolved inorganic phosphorus concentrations. For direct effects, there is a strong focus on chlorophyll a concentrations and in some regions on Secchi depth. For indirect effect, the focus is on benthic communities (i.e. submerged aquatic vegetation, especially in coastal waters), on benthic macroinvertebrates and on oxygen concentrations in bottom waters.

Third, and despite the above common indicators, a pan-European assessment of eutrophication status has not been attempted so far. There are probably several reasons for this shortcoming: (1) a lack of science-based threshold values, especially in the Black Sea and Mediterranean Sea; and (2) differences in assessment approaches, ranging from fully fledged and coordinated applications of multi-metric indicator based assessment tools (Helsinki Convention, or Helcom) and harmonised assessment procedures (OSPAR) to initial testing of assessment tools (Black Sea).

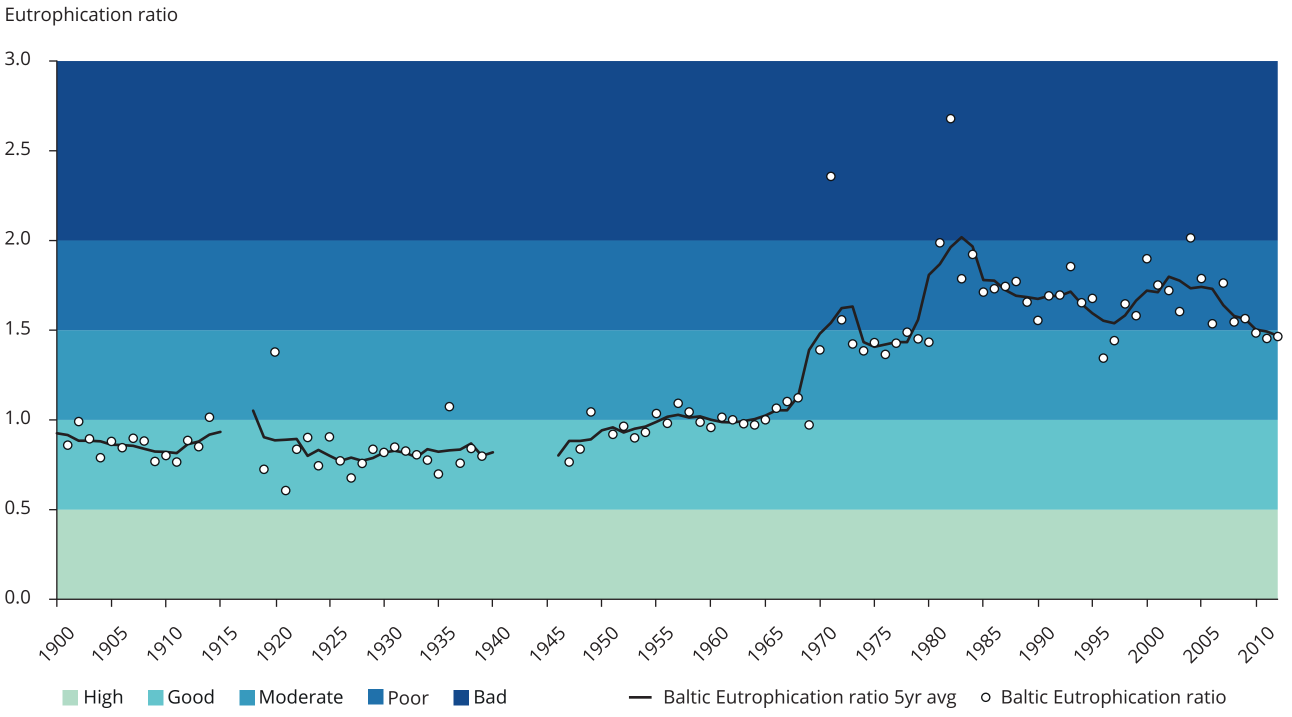
Fourth, nutrient reductions have been implemented all over Europe, primarily via the Urban Waste Water Treatment Directive (UWWTD) and the Nitrates Directive (ND), and have in some areas resulted in trend reversal but not recovery.

However, we are surprised to conclude — despite the adoption of the Water Framework Directive (WFD) in 2000 and the Marine Strategy Framework Directive

Table 5.1 Data coverage

Region	Coastal	Offshore
Baltic Sea		
• Number of units	3 684	168
• Assessed units	3 099	168
• Percentage	84.1	100.0
Black Sea		
• Number of units	2 352	224
• Assessed units	132	12
• Percentage	5.6	5.4
Mediterranean Sea		
• Number of units	10 000	1 160
• Assessed units	825	6
• Percentage	8.3	0.5
North-East Atlantic Ocean		
• Number of units	11 892	2 840
• Assessed units	5 446	716
• Percentage	45.8	25.2
European scale		
• Number of units	27 928	4. 92
• Assessed units	9 502	902
• Percentage	34.0	20.5

Figure 5.1 Long-term trends in integrated Baltic Sea eutrophication status



Note: Trends in eutrophication status and, since the mid-1980s, recovery of the Baltic Sea.

Source: Andersen et al. (2017).

(MSFD) in 2008 — that access to relevant data sets still might be an issue. Although there is significant room for improvement, we can take stock of the situation and progress made in the European regional seas.

5.1 Baltic Sea

Eutrophication is still a large-scale problem in the Baltic Sea, a fact acknowledged by most, if not all, of the bordering countries.

The Helcom Baltic Sea action plan (BSAP) sets a high standard, and the eutrophication segment, especially the underlying science-based target setting and the modelling by the Baltic Nest Institute at Stockholm University, is probably one of the best ecosystem-based nutrient management strategies developed to date.

Eutrophication can be found in all parts of the Baltic Sea — from the northernmost parts to the central and southern parts. The most impacted areas are the Gulf of Finland and the Baltic Proper, while the Bothnian Bay is among the least impacted. Furthermore, it should be noted that coastal 'non-problem areas' are reported as a part of the EU Member State's WFD initial assessments (see Helcom, 2017). Temporal trends are well documented (Figure 5.1) and recovery is under way on a Baltic-wide scale because of reductions in nutrient inputs over recent decades.

However, additional reductions are required to meet the objectives of the BSAP, the WFD and the MSFD. The effects of climate change, e.g. higher temperatures, have not been addressed so far and will need attention if the vision of a healthy Baltic Sea unaffected by eutrophication is to be met in the near future.

Another thing that needs attention is the long recovery times due to the long residence times of nutrients. Clearly, reducing inputs of nutrients should have the highest possible priority, but, in some cases, measures focusing on reducing internal loading could be considered. More research is needed, and proper environmental impact assessments (EIAs) are also required, e.g. in relation to Natura 2000 areas and habitat types protected under the Habitats Directive.

5.2 Black Sea

Eutrophication is, although probably not as severe as in the past, a large-scale problem in the western and southern coastal waters in the Black Sea. More reductions in nutrient inputs are therefore required to restore the Black Sea to being unaffected by eutrophication.

Eutrophication 'problem areas' are found along the southern and western shores of the Black Sea and in a few offshore areas, the latter mostly in the south-western parts. Eutrophication is a large-scale problem and its spatial coverage is probably greater than documented in this study.

Data access is a major issue in the Black Sea region. There might be good reasons, for example limited resources for monitoring, but at least Bulgaria and Romania carry out monitoring and assessments in accordance with the WFD and MSFD, although data are not available.

Science-based target values for the assessment is also an issue. Black Sea-specific target values need to be developed, especially for the offshore parts. Here, oxygen concentration needs careful consideration, as the Black Sea is permanently anoxic and it might be reasonable to use this indicator in only well-mixed coastal waters.

Obtaining data and information from more countries, e.g. Georgia, Russia and Ukraine, would mean a significant expansion of the area covered. In this case, more problem areas are likely to be included.

On the more positive side, temporal trends indicate improvements in eutrophication due to a reduction in inputs, mostly from point sources and from activities in the Danube river catchment area.

Overall, there is room for improvement, and the Black Sea Commission should play a pivotal role by not only coordinating but also reporting work on:

- the development of science-based threshold values for key eutrophication indicators;
- testing, followed by a Black Sea-wide application of a multi-metric indicator-based eutrophication assessment tool;
- hosting of data on which the above-suggested assessment of nutrient enrichment and eutrophication in the Black Sea is based.

Transboundary transport of nutrients between the Black Sea and the Mediterranean Sea should also be addressed.

5.3 Mediterranean Sea

The Mediterranean Sea is the regional sea with fewest eutrophication problem areas. This is partly related to the fact that the offshore parts of the Mediterranean

Sea are characterised by very low nutrient concentrations; thus, the Mediterranean is among the most oligotrophic seas worldwide.

The Mediterranean Sea has the highest relative proportion of non-problem areas among all four regional seas in Europe (82 %). However, several coastal areas near the largest cities have been classified as eutrophication problem areas.

This cannot, however, overshadow the fact that the spatial coverage in the Mediterranean Sea is disappointing. Data access and lack of information on indicator-specific threshold values has been a major issue (see Map 2.4).

Better data access is the key to improving the assessment in the Mediterranean Sea. Assuming that data should exist in principle, it seems that it is a coordination issue rather than a lack of data. Key steps towards better assessments of eutrophication in the Mediterranean Sea should focus on the key elements:

- developing science-based threshold values, especially for offshore areas;

- developing a monitoring and assessment strategy with a stratified sampling programme in which areas at risk are given a higher priority than those areas unlikely to be affected by eutrophication;

- developing and testing a multi-metric indicator-based eutrophication assessment tool, applying it across the Mediterranean Sea, and setting up a data repository.

5.4 North-East Atlantic Ocean

Eutrophication is a problem in parts of the North-East Atlantic. River discharges are the main sources of elevated nutrient levels caused by human activities. Consequently, eutrophication problems mainly occur in areas with a relatively high freshwater influence, such as estuaries, fjords and bights, and coastal waters. In addition, some areas are sensitive to eutrophication due to physical conditions (limited mixing). The most extensive eutrophication problem areas are found along the continental coast from France to Denmark, in the Kattegat and the Sound. Smaller problem areas are found along the Norwegian coast and the coasts of the United Kingdom and Ireland.

The sub-region of the Greater North Sea has the largest number of areas with eutrophication problems, which reflects the relatively high nutrient input from river discharges and atmospheric deposition. In the other sub-regions (Celtic Sea, Bay of Biscay and Iberian coast) nutrient inputs are lower, and because of hydrographical conditions (strong mixing with oceanic water) eutrophication problems are limited to smaller embayments and coastal areas.

Reductions in nutrient inputs through river discharges and atmospheric deposition (for nitrogen) are most clearly seen in the Greater North Sea. This has resulted in a trend towards lower concentrations of nutrients and chlorophyll, and a slight improvement in the assessment. However, there are still areas showing direct and indirect effects of eutrophication. At this point there is a need for a further reduction in nutrient loads to achieve good status. At the same time, the observed trend towards an improved status shows that the implementation of nutrient reduction measures is effective in the abatement of eutrophication.

Access to relevant data sets is an issue in the OSPAR region, and the OSPAR (2017) results are not readily available in a common repository (as are Helcom data). There is significant room for improvement, and we are aware that OSPAR is currently considering taking steps to improve this unfortunate situation.

Measures to reduce nutrient emissions have resulted in an improvement in the degree of eutrophication in several areas, e.g. Dutch coastal waters (see Section 3.4) but also in the waters of Denmark, Norway and Sweden.

Another thing needing attention is the OSPAR eutrophication assessment framework, which is well coordinated but, due to its flexibility and few options for interpretation, harmonised only at a national level — not between all contracting parties. Furthermore, there is room for improvement regarding offshore areas that are assumed not to be at risk, similar to the OSPAR Common Procedure — in which large areas are monitored infrequently and may accordingly slip under the radar.

5.5 Steps towards bridging the implementation gap

Perhaps the most important findings of this first attempt to map eutrophication problem areas and non-problem areas on a European scale are the following:

- Eutrophication is a significant issue in all European regional seas.

- Policies and strategies to abate nutrient enrichment and eutrophication were adopted a long time ago and are in the process of being implemented.

However, there is a gap between the overall vision of having a healthy marine environment without eutrophication and the reduction measures required by the WFD and the MSFD, as well as by regional action plans and the actions taken under the UWWTD and the Nitrates Directive. Furthermore, there seems to be an additional gap when it comes to following up assessment results, e.g. WFD, MSFD and regional seas assessments.

Bridging the gap between the results of eutrophication assessments (including WFD and MSFD assessments) and the overall visions of a healthy marine environment without eutrophication is essential. We see no reason for adopting new policies but rather favour strengthening strategies to fully implement existing policies and action plans to align the existing visions and the measures needed to fulfil these.

Based on the mapping of problem areas, which we believe underestimates the spatial extent of the issues, and the eutrophication management policies, strategies and plans that are in place, we recommend the following actions and reviews:

- **Better access to relevant data sets:** getting better access to existing data sets, both monitoring data and threshold values, is the single most important step to reduce uncertainties in the present pan-European assessment of eutrophication. In our understanding, it is a low-hanging fruit, as it is a question of smart planning and better coordination of Member States and/or conventions.

- **Development of science-based target values:** only for the Baltic Sea region have science-based target values for offshore waters been developed. Other regions or conventions should develop science-based target values in order to produce more reliable assessments.

- **Review of problem areas versus designation of vulnerable zones under the Nitrates Directive:** for downstream water susceptible to nutrient inputs from agricultural activities, upstream catchments should be designated as 'vulnerable zones' under the Nitrates Directive. Problem areas are by definition susceptible, and hence a cross-check comparing problem areas with implementation of the Nitrates Directive should be carried out to ensure that relevant upstream catchments are or will be designated 'vulnerable zones'.

- **Cross-check problem areas with 'sensitive waters' under the UWWTD:** water bodies that are susceptible to eutrophication should, according the UWWTD, be designated as 'sensitive areas'. Problem areas in this study in principle equal 'sensitive areas'. Hence, cross-checks should be carried out to ensure that all problem areas have been or will be designated 'sensitive areas'.

- **Accurate calculation of required nutrient reductions under the WFD:** estimation of the required nutrient reduction in problem areas should be calculated and not estimated. Several coastal model systems are fit for purpose, and lessons can be learnt from national case studies.

- **Model-based maximum inputs under the MSFD:** the setting of maximum allowable inputs to regional seas or sub-regions should be model-based and not generic (50 % reduction target). The Helcom BSAP sets a standard from which others could learn.

- **Better coordination between the WFD and the MSFD:** in problem areas, monitoring and assessment of good ecological status (WFD) and good environmental status (MSFD descriptor 5) is about the same. In many regions, sub-regions and countries, better coordination could be achieved, leading to more cost-effective activities.

- **Europe-wide application of eutrophication assessment tools:** application of multi-metric indicator-based eutrophication tools by countries and the Regional Sea Conventions would contribute to providing a complete European perspective.

- **A follow-up to this assessment:** it is the EEA's intention that this report will be updated at regular intervals with more and new data, leading to a better understanding of how to achieve more non-problem areas in terms of marine eutrophication in Europe. We can, beyond any doubt, achieve a healthier marine environment in Europe and together address climate change challenges more effectively.

List of abbreviations

BSAP	Baltic Sea action plan
CW	Coastal waters
D5	Descriptor 5 (eutrophication) under the MSFD
DIN	Dissolved inorganic nitrogen
DIP	Dissolved inorganic phosphorus
EEA	European Environment Agency
EMODnet	European Marine Observation and Data Network
ER	Eutrophication ratio
ETC/ICM	European Topic Centre for Inland, Coastal and Marine Waters
GEcS	Good ecological status (used in the WFD)
GEnS	Good environmental status (used in the MSFD)
HEAT	The Helcom eutrophication assessment tool
HEAT+	The new version of HEAT developed for this pan-European assessment
Helcom	Baltic Marine Environment Protection Commission — Helsinki Commission
IED	Industrial Emissions Directive
Medpol	Programme for the assessment and control of marine pollution in the Mediterranean
MSFD	Marine Strategy Framework Directive
ND	Nitrates Directive
NO_x	Nitrogen oxides
NPA	Non-problem area
OSPAR (Convention)	Convention for the Protection of the Environment of the North-East Atlantic
PA	Problem area
PSU	Practical Salinity Unit
SDG	Sustainable Development Goal

TN	Total nitrogen
TP	Total phosphorus
TW	Transitional waters
UWWTD	Urban Waste Water Treatment Directive
WFD	Water Framework Directive

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Supplementary material

The following annexes are available as online supplementary material:

- Annex 1: Definition of assessment units
- Annex 2: HEAT+ R script
- Annex 3: Detailed maps of HEAT+ classifications
- Annex 4: Summary of individual HEAT classifications including the assessment threshold values applied

The following European Topic Centre for Inland, Coastal and Marine Waters (ETC/ICM) technical background reports have been produced in preparation and support of this thematic report on nutrient enrichment and eutrophication in Europe's seas:

- Andersen, J. H., et al., 2016, Coding and initial testing of an indicator-based tool for integrated assessment of eutrophication status. Current status and next steps, ETC/ICM task 1.6.1.g deliverable 2.
- Harvey, T., et al., 2016, Steps toward indicator-based assessments of 'environmental status' in European sea, ETC/ICM task 1.6.1.g deliverable 4.
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- Korpinen, S., et al., 2015, Review of thematic multi-metric indicator-based assessment tools, EEA/NSV/13/002-ETC/ICM, 51 pp.

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