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Final report

The Baltic Sea Action Plan – Modelling of Eutrophication Aspects

by:

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Leibniz Institute for Baltic Sea Research Warnemünde (IOW), Rostock

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On behalf of the German Environment Agency

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Abstract: The Baltic Sea Action Plan – Modelling of Eutrophication Aspects

HELCOM has formulated a target for the Baltic Sea to achieve "good ecological status" by 2030. Eutrophication is one of the main problems in the Baltic Sea.

In this R&D project, spatio-temporally high-resolution simulations of the 3D ecosystem model ERGOM-MOM were used to review existing nutrient reduction targets in the western Baltic Sea. Scenario simulations were used to estimate the effects of single or multiple mitigation measures to improve water quality. We assumed that the nutrient reduction targets of the HELCOM BSAP, the German WFD implementation and the EU NEC Directive (limitation of atmospheric nitrogen deposition) will be met in order to analyze their impact on water quality in the western Baltic Sea. Our results show that there is no improvement for all eutrophication indicators and that only in one assessment unit (Kiel Bay) the good status is achieved after 30 simulated years, while the other basins clearly miss the targets. Furthermore, the simulation results were used to analyze the influence of the Odra river plume on the eutrophication assessment in the Bornholm Basin, as well as to evaluate the areal extent and temporal duration and variability of seasonally occurring oxygen deficiency areas in order to create a better assessment basis for this indicator. The results were utilized for the development of the HELCOM pre-core indicator "Shallow-water oxygen". The indicator is being evaluated for the purposes of the State of the Baltic Sea report (HOLAS III) and is expected to be developed into a core indicator in the future. This report also discusses an approach for integrating model simulations and measured data for a monitoring system for near-bottom oxygen.

Kurzbeschreibung: Der Ostseeaktionsplan – Modellierung von Eutrophierungsaspekten

HELCOM hat für die Ostsee das Ziel formuliert, bis 2030 einen "guten ökologischen Zustand" zu erreichen. Die Eutrophierung ist dabei eines der Hauptprobleme der Ostsee.

Im vorliegenden FuE-Projekt wurden räumlich-zeitlich hochaufgelöste Simulationen des 3D-Ökosystemmodells ERGOM-MOM genutzt, um bestehende Nährstoffreduktionsziele der westlichen Ostsee zu überprüfen. Mit Hilfe von Szenario-Simulationen wurden die Auswirkungen einzelner oder mehrerer Minderungsmaßnahmen zur Verbesserung der Wasserqualität abgeschätzt. Wir gingen davon aus, dass die Nährstoffreduktionsziele des HELCOM BSAP, der deutschen WRRL-Umsetzung und der EU-NEC-Richtlinie (Begrenzung der atmosphärischen Stickstoffeinträge) erreicht werden, um deren Auswirkungen auf die Wasserqualität in der westlichen Ostsee zu analysieren. Unsere Ergebnisse zeigen, dass es nicht für alle Eutrophierungsindikatoren zu einer Verbesserung kommt und dass nur in einer Bewertungseinheit (Kieler Bucht) der gute Zustand nach 30 simulierten Jahren erreicht wird, während die anderen Becken die Ziele deutlich verfehlen. Darüber hinaus wurden die Simulationsergebnisse genutzt, um den Einfluss der Oderfahne auf die Eutrophierungsbewertung im Bornholmbecken zu analysieren, als auch die flächenhafte Ausdehnung und zeitliche Dauer und Variabilität von saisonal auftretenden Sauerstoffmangelgebieten zu evaluieren, um für diesen Indikator eine bessere Bewertungsgrundlage zu schaffen. Die Ergebnisse flossen in die Entwicklung des HELCOM Flachwasser-Sauerstoffindikators der als „Pre-Core“ Indikator derzeit für den Bericht über den Zustand der Ostsee (HOLAS III) ausgewertet wird und in Zukunft zu einem Kernindikator weiterentwickelt werden soll. Dafür wird in diesem Bericht auch ein Ansatz zur Integration von Modellsimulationen und Messdaten in ein Monitoringsystem für bodennaher Sauerstoff diskutiert.

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List of abbreviations

Abbreviation	Explanation
AB	Arkona Basin
AE	Average error
BALTSEM	Baltic Sea Long-Term Large Scale Eutrophication Model
BB	Bornholm Basin
BSAP	Baltic Sea Action Plan
CDOM	Colored dissolved organic matter
Chl-a	Chlorophyll-a
CMEMS	Copernicus Marine Environment Monitoring Service
CO_2	Carbon dioxide
conc.	Concentration

Abbreviation	Explanation
DIC	Dissolved inorganic carbon
DIN	Dissolved inorganic nitrogen
DIP	Dissolved inorganic phosphorus
DO	Dissolved oxygen
DOC	Dissolved organic carbon
EMEP	European Monitoring and Evaluation Programme
ERGOM	Ecological Regional Ocean Model
EU-MSFD	European Marine Strategy Framework Directive
EuNäP	"Eutrophierung, Nährstoffe und Plankton" national expert working group
EU-NEC	National Emission reduction Commitments (NEC) Directive
EU-WFD	European Water Framework Directive
GES	Good Environmental Status
H_2S	Hydrogen sulfide
HELCOM	Helsinki Commission
HOLAS	Holistic assessment
ICES	International Council for the Exploration of the Sea
IOW	Leibniz Institute for Baltic Sea Research Warnemünde
K	Kelvin
KB	Kiel Bay
kg	Kilogram
km	Kilometer
km^2	Square kilometer
l	Liter
LfU-SH	State Agency for Environment Schleswig-Holstein
LUNG-MV	State Agency for Environment, Nature Conservation and Geology Mecklenburg-Vorpommern
m	Meter
MB	Bay of Mecklenburg
mg	Miligram
MOM	Modular Ocean Model
N or N_2	Nitrogen
NBO	Near-bottom oxygen
NetCDF	Network Common Data Form

Abbreviation	Explanation
NH_4	Ammonia
NIC	Nutrient input ceiling
NM	Nautical mile
NO_3	Nitrate
O_2	Oxygen
P	Phosphorus
PB	Pomeranian Bay
PLC	Pollution Load Compilation
PO_4	Phosphate
POC	Particulate organic carbon
R&D	Research and Development
r	Correlation coefficient
RMSE	Residual mean squared error
SI	Supplementary information
t	Metric tons
TN	Total nitrogen
TP	Total phosphorus
UBA	German Environment Agency
WRRL	Wasserrahmenrichtlinie
µg	Microgram
µmol	Micromol

Summary

Although nutrient inputs to the Baltic Sea are declining, eutrophication is still one of the most noticeable and persistent environmental pressures in the Baltic Sea, affecting many aspects of the Baltic marine environment. In terms of eutrophication, according to the latest HELCOM assessment period 2016-2021, about 93.8% of the area is not in a good environmental status (https://helcom.fi/wp-content/uploads/2023/06/HELCOM-Thematic-assessment-of-eutrophication-2016-2021.pdf). As a coastal sea with low water exchange and long residence time, the Baltic Sea is particularly sensitive to nutrient inputs and its negative effects, which continue to impact the ecosystem for decades. Years of excessive nutrient inputs from the land and the atmosphere have led to the proliferation of phytoplankton beyond natural levels. The associated microbial degradation of the material settling on the seafloor also leads to oxygen deficiency to the point of anoxia (absence of oxygen), making higher life in these areas no longer possible. A key objective of the HELCOM Baltic Sea Action Plan (BSAP) is to ensure that the Baltic Sea is not affected by the negative impacts of eutrophication (HELCOM 2021). For this reason, management plans with specific maximum allowable nitrogen and phosphate inputs (input ceilings) for both waterborne inputs and atmospheric deposition have been in place since 2007 and are implemented within the HELCOM BSAP (HELCOM 2007, 2013, 2021a, 2021b) (NICs = Nutrient Input Ceilings). In addition, there are various directives at the EU level (EU-MSFD, EU-WFD, EU-NEC) that have similar objectives and, among other things, limit the discharge of nutrients into the oceans. However, it is worth questioning whether the current "Good Environmental Status" (GES) target values of the indicators, assessment approaches and management plans need revision. For example, the recent HELCOM holistic assessment showed that the reduction targets for nutrients from the HELCOM BSAP in the basins of the western Baltic Sea (Danish Straits, Kattegat) have largely been met (https://indicators.helcom.fi/indicator/inputs-of-nutrients/), while eutrophication problems persist (HELCOM 2023a). At the same time, the western Baltic Sea is under high utilization pressure, e.g. from further expanding aquaculture (Maar et al. 2020). Due to the existing uncertainties and the potentially increasing utilization pressure, it must therefore be examined whether the nutrient reduction targets agreed in the HELCOM BSAP for the western Baltic Sea are sufficient to achieve the GES with regard to eutrophication. In addition, inconsistencies within assessments need to be identified and resolved in order to achieve more reliable results and develop efficient management plans in the future. For example, the last assessment revealed problems related to the spatial assessment units. In this last assessment the unit "Bornholm Basin" was rated the worst in terms of eutrophication status, while the two neighboring units had better results. This pattern can be explained by the influence of the Odra River in this area, resulting in strong gradients in all major eutrophication indicators. These gradients were not covered representatively by the previous assessment approach and led, among other things, to unrealistically low GES target values. When assessing the state of the environment, it is further essential to evaluate the effects of eutrophication on the biodiversity of the ecosystem in addition to the eutrophication parameters directly influenced by anthropogenic nutrient inputs (such as the concentrations of the dissolved nutrients nitrogen (DIN) and phosphorus (DIP)). In this context, dissolved oxygen is a key indicator of ecosystem health, as it is essential to the survival of nearly all aquatic life forms. In the HELCOM assessment of eutrophication, "oxygen debt" is already used as an indicator to assess permanent hypoxia in deep areas. This refers to areas with a permanent halocline where vertical mixing with oxygen-rich surface water is limited and oxygen concentrations fall below a critical level of 2 mg*l^{-1}. In addition to the permanently stratified areas of the Baltic Sea, which can be "ventilated" by the influx of oxygen-rich bottom water from the North Sea, hypoxia is also increasingly occurring in shallow water areas, although it is not as long-lasting as in the deep basins. For those shallow areas that are not

permanently stratified, there are several national assessment approaches with different methods, parameters, and thresholds. However, all current approaches have two major limitations. First, observations are limited in their temporal and spatial distribution. And second, the entire water column is not always monitored, so little information is available on the vertical distribution of oxygen-depleted water. Consequently, current oxygen measurements do not provide the high spatial and temporal resolution needed to comprehensively assess highly dynamic seasonal oxygen deficiency in shallow areas. To address the aforementioned challenges and develop better management approaches, we used IOW's high-resolution 3D biogeochemical model system ERGOM-MOM to analyze whether:

a) the model tools can be used both to identify the region significantly influenced by the Odra River plume as well as to develop a new spatial assessment unit and to determine new GES indicator target values for this unit.

b) the oxygen concentrations determined from the model can be used to support the development of appropriate indicators for the shallow water areas of the western Baltic Sea. For this purpose, both the spatial-temporal variability of oxygen concentrations are investigated, but also the long-term development of the derived indicators from 1950 to the present, in order to facilitate the derivation of target values for this indicator.

c) the reductions of water-borne and atmospheric nutrient inputs decided by HELCOM and EU member states (extended by the German reduction targets discussed to achieve the WFD targets) are sufficient to achieve GES in the western Baltic Sea.

For our analysis, we considered the entire Baltic Sea in the model but focused on the western Baltic Sea and the HELCOM assessment units for which Germany shares responsibilities, i.e. Kiel Bay, Bay of Mecklenburg, Arkona Basin and the new assessment unit Pomeranian Bay. The model simulations were performed with the biogeochemical model ERGOM coupled to a 3D circulation model (MOM). The horizontal resolution of the model grid is three nautical miles, while the model is vertically resolved into 152 layers with a layer thickness ranging from 0.5 to 2 meters. The model grid is also used for the simulations. The simulation covers the period from 1948 to 2019. Nutrient inputs to the Baltic Sea from river discharges and point sources (especially nutrient discharges directly to the Baltic Sea from urban, industrial, and aquaculture facilities) were compiled based on the HELCOM PLC database, data from HELCOM assessments (HELCOM 2015, HELCOM 2021b), and before 1995 data from Gustafsson et al. (2012) was utilized. Atmospheric deposition of nitrogen inputs was provided by European Monitoring and Evaluation Programme (EMEP; https://emep.int/mscw/mscw_moddata.html; Gauss et al. 2019, 2021) and before 1995 data from Ruoho-Airola et al. (2012) was used. For atmospheric phosphorus deposition, the constant value of 5 kg P/km^2 was used in accordance with HELCOM (2013, 2021), while a gradient (calculated from nitrogen deposition) was used to reflect deposition differences in nearshore and offshore waters.

First, we utilized the model simulations in order to delimit the assessment unit "Pomeranian Bay", which is particularly strongly influenced by the Odra plume, from the Bornholm Basin in order to assess this area separately. It was further necessary to adjust the GES thresholds of the eutrophication indicators for the new assessment unit and the remaining part of the Bornholm Basin. Based on our model simulations, we derived new thresholds for the Pomeranian Bay (IN-EUTROPHICATION 21-2021) by transferring the GES thresholds of the Bornholm Basin, which had already been coordinated within HELCOM. The new GES thresholds were implemented within HELCOM and used for the latest eutrophication assessment (HOLAS III). Following the natural gradients from the river plume to the deep basins, the threshold values for the Pomeranian Bay are higher than those for the original Bornholm Basin (IN-EUTROPHICATION

21-2021). The proposed method for deriving GES thresholds for the new assessment units seems to be appropriate as the deduced thresholds are consistent with existing (and already adopted) thresholds and follow natural gradients. However, the Odra plume is highly variable in extent and shape over time. Typically (with prevailing westerly winds), the transport of Odra water entering the Pomeranian Bay occurs offshore (often eastward). In easterly wind conditions, the Odra plume may also be transported into the western Baltic Sea. Using a passive tracer to identify the Odra plume, we were thus able to show, based on our model simulations, how the area of the new assessment unit "Pomeranian Bay" could have been alternatively delineated if both freshwater and nutrient inputs from the Odra River were used as the basis for defining the assessment unit. The method is applicable to other assessment units in the Baltic Sea that currently do not account for natural gradients, like those caused by high waterborne nutrient inputs. In future, model simulations can be used both, to create assessment units according to their hydrodynamic conditions and the influence of freshwater inputs as well as a basis for a more representative distribution of monitoring stations in the future.

When estimating the oxygen situation, it should be noted that the assessment is currently complicated by several limitations in the western Baltic Sea, where seasonal and episodic rather than year-round hypoxia and oxygen deficiency situations (oxygen concentrations <6 mg*l^{-1}) occur. For instance, the current German methodology evaluates entire assessment units solely on their compliance or non-compliance with thresholds at individual monitoring stations, without considering the extent of actual oxygen-depleted areas within those units. Thus, the current assessment approach lacks an area reference, as well as information on the vertical extent of oxygen deficiency. In addition, the estimation of the duration of oxygen deficiency is restricted by monthly sampling. By using 3D model simulations, these limitations can be overcome and suitable indicators for seasonal oxygen deficiency in shallow waters can be provided, which take into account the spatial, vertical and temporal components of the oxygen situation (Piehl et al. 2022). The main advantage of the model simulations is that, in addition to the analyzed near-bottom areas and volumes of oxygen deficiency, the temporal component can also be included. This is particularly important for assessing the negative effects on organisms and biodiversity (Piehl et al. 2022). Furthermore, we were able to show that the situation in the 1950s can be considered as "good status", similar to nutrients and chlorophyll-a. Although there was already an increase in nutrient inputs, the water quality in this period can still be considered good. At the same time, the model indicated already naturally occurring oxygen deficiency in the western Baltic Sea, even if the extent of e.g. hypoxic areas was much smaller. However, since the absolute oxygen concentrations and the resulting oxygen metrics were overestimated by the three nautical mile model, the approach needs to be further developed to derive appropriate reference and associated GES targets for oxygen deficiency. An important step forward in this regard is the transition to a model system with finer spatial resolution. With the new spatially higher resolved model run, it will now be possible to determine whether the target values and assessments of shallow water oxygen proposed by HELCOM for the latest assessment period (HOLAS III) are plausible and achievable. The main challenge is to align and ensure consistency between the target values obtained through different methods, which are partly also based on different reference periods. The refinement of the horizontal resolution of our model has improved the quality of the modeled oxygen dynamics in the coastal waters and open sea areas of the southwestern Baltic Sea. Nevertheless, model simulations are always only a simplification of reality and have many uncertainties. Therefore, an integrated approach was sought to meaningfully combine model results and observations and to exploit the respective benefits. In order to reduce the discrepancy between the simulated and the observed values, we investigated the factors that may influence this discrepancy (such as distance from the coast or measurement depth). Based on these results, we developed a correction function that we used to fit the simulated data to the measured data. Although our integrated approach resulted in better model quality parameters for individual components, the results and improvement were not consistent for all sub-basins and/or stations considered (Piehl et al: Biogeosciences Discuss. [preprint], https://doi.org/10.5194/bg-2023-152). One reason for this is probably the heterogeneous measurement data used to derive the correction functions, which are not consistent in their temporal and vertical resolution. Using the Arkona Basin as an example, we were able to demonstrate a future path in which only observations with high temporal and/or vertical resolution are integrated into the model data to achieve the highest possible confidence in the assessment. The development of an integrated oxygen assessment in the future must involve end users to develop an appropriate confidence assessment strategy that meets the requirements for management decisions.

For the review of the nutrient reduction targets, future scenarios (30 years) were created, each with three implementations, which depict the weather between 2010 and 2019 (including interannual variability). To account for the different options on how to achieve the nutrient reduction targets of the different legislations, several scenarios were developed that differ in terms of nutrient inputs from waterborne sources (rivers, point and diffuse sources) and from atmospheric deposition. For example, the implementation of the EU-NEC Directive foresees a significant reduction in emissions of hazardous substances to the atmosphere, so that less nitrogen would enter the Baltic Sea via the atmosphere if implemented (Gauss et al. 2021). On the other hand, both the HELCOM BSAP and the national management plans from the EU-WFD provide explicit reduction targets on waterborne nutrient inputs. The result of the scenario simulations was that all considered eutrophication indicators showed improvements due to the changed nutrient inputs in all scenarios. This means that the consistent implementation of the management plans has a positive effect on the water quality in the western Baltic Sea. At the same time, winter concentrations of DIN and DIP in the Best-Case Scenario were shown to almost reach GES targets in the assessment units of the western Baltic Sea, while summer chlorophyll concentrations, which are a measure of the intensity of algal blooms during the summer months, remain far from the GES target. This may be due to the long residence times in the Baltic Sea in particular for phosphate, such that 30 years of simulation is not sufficient to see the full effect of the input reductions. However, the inconsistencies in meeting the various indicator target values in the western Baltic may be due to other factors. For example, the sensitivity of the ERGOM-MOM biogeochemical model to the effects of reduced nutrient inputs differs substantially from the BALTSEM model used to set the BSAP NICs. On the other hand, the GES thresholds currently used were defined based on the reference condition, which refers to the undisturbed situation of 1880. However, due to the already changing climate of the last decades, temperature-dependent phytoplankton groups (e.g., cyanobacteria) are much more dominant today than in the reference condition. Among other things, this leads to (natural) elevated summer chlorophyll concentrations, which can be less strongly controlled by nutrient inputs. Thus, it is recommended to adapt the GES target values to the changed climate conditions, and to consider future extreme events in the assessment. A future robust and reliable water quality management requires a consistent and harmonized approach that covers all relevant eutrophication indicators and target values in rivers, inner coastal waters, and the open Baltic Sea. Despite the uncertainties described above, implementing the HELCOM BSAP and ensuring that nutrient inputs do not exceed critical upper limits is essential and of great benefit to water quality, biodiversity, and the provision of key ecosystem services. The scenario simulations have also shown that the consistent implementation of the EU-NEC Directive (to reduce atmospheric nitrogen deposition, among other things) has significant positive effects on water quality. The western Baltic Sea in particular benefits from this, but also the waters near the coast, which are more affected by nitrogen inputs due to their proximity to land-based emission sources. This effect is very rapid and immediate, unlike the reductions in phosphorus inputs, because nitrogen has a much shorter residence time in the Baltic Sea. In addition to the described changes in direct eutrophication parameters, the scenario simulations also showed that hypoxic areas can be significantly reduced by a consistent reduction of nutrient inputs. Thus, especially in the Kiel Bay and the Pomeranian Bay, there is a high risk that areas with low oxygen concentrations will continue to increase if nutrient inputs remain at current levels. In contrast, compliance with all international and national nutrient reduction targets resulted in a significant decrease in hypoxic areas in all assessment units, especially in Kiel Bay (-50%) and the Arkona Basin (-40%).

It also had to be considered that in several parts of the Baltic Sea the national nutrient loads from the HOLAS II period are already below the NICs of the BSAP. This leads to ongoing discussions on whether countries can fully utilize their allowed inputs, e.g., by expanding marine aquaculture. As this issue is currently highly debated in Denmark, another scenario ("Danish Scenario") was developed and evaluated, focusing on the potential impacts on water quality in the western Baltic Sea. Here, we assumed that Denmark fully exhausts its BSAP NICs, while all other Baltic Sea countries follow the Best-Case Scenario, assuming that each country implements the BSAP NICs or that inputs remain at HOLAS II period levels if they were already below the BSAP NICs. Use of the maximum allowable Danish nutrient loads would result in additional annual nutrient loads of approximately 14,700 t TN and 450 t TP compared to the Best-Case Scenario, corresponding to 2.7% and 1.9% of the total waterborne loads entering the Baltic Sea, respectively. The achieved water quality improvements in the Best-Case Scenario are significantly weakened for all three parameters in the Danish Scenario, even estimating a deterioration of the winter DIN compared to the HOLAS II period, especially near the Danish coast. Looking at the assessment units in the southwestern Baltic Sea, the impacts of the Danish Scenario are strongest in the Kiel Bay. Winter DIP concentrations in the Bay of Mecklenburg are also affected, while in the Arkona Basin and the Pomeranian Bay the differences between the scenarios are less than 1%. Although the changes in water quality are not relevant to the achievement of GES objectives in these assessment units, they are relevant to assessment units directly connected to Danish coastal waters. For example, the GES in the Great Belt area for winter DIN is achieved in the Best-Case Scenario, but not in the Danish Scenario. The results presented rely on the assumption that the input points of waterborne nutrient loads do not change in the Danish Scenario compared to the reference period. However, as the location and size of the proposed aquaculture operations remain unknown, our described method seems the most suitable for now. It could be revised in the future as more information becomes available.

Zusammenfassung

Auch wenn die Nährstoffeinträge in die Ostsee rückläufig sind, ist die Eutrophierung immer noch eine der spürbarsten und dauerhaftesten Umweltbelastungen in der Ostsee, die viele Aspekte ihrer marinen Umwelt beeinflusst. Im Hinblick auf die Eutrophierung befinden sich gemäß dem jüngsten HELCOM Bewertungszeitraum 2016-2021 etwa 93,8 % der Region in einem unzureichenden ökologischen Zustand (https://helcom.fi/wp-content/uploads/2023/06/HELCOM-Thematic-assessment-of-eutrophication-2016-2021.pdf). Als Küstenmeer mit geringem Wasseraustausch und langer Verweilzeit reagiert die Ostsee besonders empfindlich auf übermäßige Nährstoffeinträge und dessen negativen Effekte, welche sich noch über Dekaden auf das Ökosystem auswirken. Jahrelange übermäßige Nährstoffeinträge vom Land und aus der Atmosphäre haben zur starken Vermehrung des Phytoplanktons über das natürliche Maß hinausgeführt. Der damit verbundene mikrobielle Abbau am Meeresboden führt zudem zu Sauerstoffmangel bis hin zur Anoxie (Abwesenheit von Sauerstoff), wodurch höheres Leben in diesen Gebieten nicht mehr möglich ist. Ein Hauptziel des HELCOM Baltic Sea Action Plans (BSAP) besteht darin, dass die Ostsee nicht von den negativen Auswirkungen der Eutrophierung betroffen ist (HELCOM 2021). Aus diesem Grund gibt es seit 2007 Bewirtschaftungspläne mit spezifischen maximal zulässigen Stickstoff- und Phosphateinträgen (Eintragshöchstgrenzen) sowohl für wassergebundene Einträge als auch für die atmosphärische Deposition, die im Rahmen des HELCOM BSAP (HELCOM 2007, 2013, 2021a, 2021b) umgesetzt werden (NICs = Nutrient Input Ceilings). Hinzukommen auf EU-Ebene verschiedene Richtlinien (EU-MSRL, EU-WRRL, EU-NEC), die ähnliche Ziele haben und u.a. die Einleitung von Nährstoffen in die Meere begrenzen. Allerdings ist zu hinterfragen, ob die derzeitigen "Guten Umweltzustand" (GES) -Zielwerte, Bewertungsansätze und Bewirtschaftungspläne einer Überarbeitung bedürfen. Zum Beispiel hat die jüngste ganzheitliche Bewertung durch HELCOM gezeigt, dass die Reduktionsziele für Nährstoffe aus dem HELCOM BSAP in den Becken der westlichen Ostsee (Dänische Straßen, Kattegat) größtenteils erreicht wurden (https://indicators.helcom.fi/indicator/inputs-of-nutrients/), während die Eutrophierungsprobleme fortbestehen (HELCOM 2023a). Gleichzeitig steht die westliche Ostsee unter hohem Nutzungsdruck, z.B. durch weiter expandierende Aquakultur (Maar et al. 2020). Aufgrund der bestehenden Unsicherheiten und des potenziell ansteigenden Nutzungsdrucks ist daher zu prüfen, ob die im HELCOM BSAP vereinbarten Nährstoffreduktionsziele für die westliche Ostsee ausreichen, um den " GES in Bezug auf die Eutrophierung zu erreichen. Darüber hinaus müssen Inkonsistenzen bei den Bewertungsgrundlagen identifiziert und gelöst werden, um in Zukunft zuverlässigere Ergebnisse ableiten und effiziente Managementpläne entwickeln zu können. Zum Beispiel zeigten sich bei der letzten Bewertung Probleme in Bezug auf die räumlichen Bewertungseinheiten. So wurde das Bewertungsgebiet „Bornholm-Becken“ am schlechtesten bezüglich des Eutrophierungszustandes bewertet, während die beiden benachbarten Becken bessere Ergebnisse erzielten. Dieses Muster lässt sich durch den Einfluss der Oder in diesem Gebiet erklären, was zu starken Gradienten bei allen wichtigen Eutrophierungsindikatoren führt. Diese Gradienten wurden durch den bisherigen Bewertungsansatz nicht repräsentativ abgedeckt und dies führte u.a. zu unrealistisch geringen GES-Zielwerten. Bei der Bewertung des Umweltzustandes ist es essenziell neben den direkt durch anthropogene Nährstoffeinträge beeinflussten Eutrophierungsparametern (wie den Konzentrationen der im Wasser gelösten Nährstoffe Stickstoff (DIN) und Phosphor (DIP)) die Auswirkungen der Eutrophierung auf die biologische Vielfalt des Ökosystems zu beurteilen. Dabei ist der im Wasser gelöste Sauerstoff ein Schlüsselindikator für die Gesundheit eines Ökosystems, da er für fast alle aquatischen Lebensformen überlebenswichtig ist. Im Rahmen der HELCOM-Bewertung der Eutrophierung wird die "Sauerstoffschuld" bereits als Indikator verwendet, um den kumulativen

Sauerstoffmangel in tiefen Gebieten mit anhaltender Hypoxie zu bewerten. Gemeint sind damit Gebiete mit einer permanenten Halokline, in denen die vertikale Durchmischung mit sauerstoffreichem Oberflächenwasser begrenzt ist und die Sauerstoffkonzentration unter einen kritischen Wert von 2 mg/l fällt. Neben den permanent geschichteten Gebieten der Ostsee, die durch das Einströmen von sauerstoffreichen Bodenwasser aus der Nordsee „belüftet" werden können, treten zunehmend auch in Flachwassergebieten Hypoxien auf, die jedoch nicht so langanhaltend sind wie in den tiefen Becken. Dabei gibt es verschiedene nationale Bewertungsansätze mit unterschiedlichen Methoden, Parametern und Schwellenwerten für die nicht permanent geschichteten Flachgewässer. Alle derzeitigen Ansätze haben jedoch zwei wesentliche Einschränkungen. Erstens sind die Beobachtungen in ihrer zeitlichen und räumlichen Verteilung begrenzt. Und zweitens wird nicht immer die gesamte Wassersäule überwacht, so dass nur wenig Information über die vertikale Ausbreitung von sauerstoffarmem Wasser vorhanden sind. D.h., die derzeitigen Sauerstoffmessungen bieten nicht die hohe räumliche und zeitliche Auflösung, die erforderlich ist, um den hochdynamischen saisonalen Sauerstoffmangel in flachen Gebieten umfassend zu bewerten. Um die genannten Herausforderungen anzugehen und bessere Managementansätze entwickeln zu können, haben wir das hochauflösende biogeochemische 3D-Modellsystem ERGOM-MOM des IOW verwendet, um zu analysieren, ob:

a) mit Hilfe der Modellwerkzeuge sowohl die Region, die maßgeblich von der Oder-Fahne beeinflusst wird, identifiziert werden kann, um so eine neue räumliche Bewertungseinheit zu entwickeln, und ob auch neue GES-Zielwerte bestimmt werden können.

b) die aus dem Modell bestimmten Sauerstoffkonzentrationen genutzt werden können, um die Entwicklung geeigneter Indikatoren für die Flachwassergebiete der westlichen Ostsee zu unterstützen. Hierfür ist sowohl die räumlich-zeitliche Variabilität der Sauerstoffkonzentrationen zu untersuchen, aber auch die Langzeitentwicklung der abgeleiteten Indikatoren von 1950 bis heute, um die Ableitung von Zielwerten für diesen Indikator zu erleichtern.

c) die von den HELCOM- und EU-Mitgliedsstaaten beschlossenen Reduktionen der wassergebundenen und atmosphärischen Nährstoffeinträge (erweitert um die deutschen Reduktionsziele, die zur Erreichung der WRRL-Ziele diskutiert werden) ausreichen, um den GES in der westlichen Ostsee zu erreichen.

Für unsere Analyse haben wir die gesamte Ostsee im Modell betrachtet, wobei der Schwerpunkt der Auswertungen auf der westlichen Ostsee und den HELCOM-Bewertungseinheiten liegt, für die Deutschland mitverantwortlich ist, das heißt Kieler Bucht, Mecklenburger Bucht, Arkona-Becken und die neue Bewertungseinheit Pommersche Bucht. Die Modellsimulationen wurden mit dem biogeochemischen Modell ERGOM durchgeführt, das mit einem 3D-Zirkulationsmodell (MOM) gekoppelt ist. Die horizontale Auflösung des Modellgitters beträgt drei Seemeilen, während das Modell vertikal in 152 Schichten mit einer Schichtdicke von 0,5 bis 2 m aufgelöst ist. Die Simulation umfasst den Zeitraum von 1948 bis 2019. Die Nährstoffeinträge in die Ostsee aus Flusseinleitungen und Punktquellen (insbesondere Nährstoffeinleitungen direkt in die Ostsee aus städtischen, industriellen und Aquakulturanlagen) wurden auf der Grundlage der HELCOM-PLC-Datenbank, Daten aus HELCOM-Bewertungen (HELCOM 2015, HELCOM 2021b) und vor 1995 aus Gustafsson et al. (2012) zusammengestellt. Die atmosphärische Deposition von Stickstoffeinträgen wurde von EMEP (https://emep.int/mscw/mscw_moddata.html; Gauss et al. 2019, 2021) und vor 1995 von Ruoho-Airola et al. (2012) bereitgestellt. Für die atmosphärische Phosphordeposition wurde der konstante Wert von 5 kg P/km2 in Übereinstimmung mit HELCOM (2013, 2021) verwendet, während ein Gradient (berechnet aus der Stickstoffdeposition) genutzt wurde, um die Depositionsunterschiede in küstennahen und küstenfernen Gewässern widerzuspiegeln.

Zunächst wurde mit Hilfe der Modellsimulationen nach einem Weg gesucht, die von der Oderfahne besonders stark beeinflusste Bewertungseinheit "Pommersche Bucht" vom Bornholm Becken abzugrenzen, um diese Region separat zu bewerten. Nach der räumlichen Abgrenzung war es außerdem notwendig, die GES-Schwellenwerte der Eutrophierungsindikatoren für die neue Bewertungseinheit anzupassen. Anhand unserer Modellsimulationen wurden diese neuen Schwellenwerte für die Pommersche Bucht abgeleitet (IN-EUTROPHICATION 21-2021) und für die aktuelle Eutrophierungsbewertung (HOLAS-III) verwendet. Hierfür wurden basierend auf den Modellergebnissen die bereits im Rahmen von HELCOM abgestimmten GES-Zielwerte des Bornholmbeckens unter Berücksichtigung der natürlichen Gradienten transferiert und inzwischen im Rahmen von HELCOM implementiert. Den natürlichen Gradienten von der Flussfahne zu den tiefen Becken folgend, sind die GES-Schwellenwerte für die Pommersche Bucht höher als die für das ursprüngliche Bornholm-Becken (IN-EUTROPHICATION 21-2021). Die vorgeschlagene Methode zur Ableitung von GES-Schwellenwerten für die neuen Bewertungseinheiten erscheint angemessen, da die abgeleiteten Schwellenwerte konsistent mit den bestehenden (und bereits angenommenen) Schwellenwerten sind und den natürlichen Gradienten folgen. Die Oderfahne ist allerdings in ihrer Ausdehnung und Form zeitlich hochvariabel. Üblicherweise (bei vorherrschendem westlichem Wind) findet der Transport des in die Pommersche Bucht eintretenden Oderwassers küstennah (oft ostwärts) statt. Bei Ostwindlagen kann die Oderfahne auch in die westliche Ostsee transportiert werden. Unter Nutzung eines passiven Tracers zur Identifikation der Oderfahne konnten wir so basierend auf unseren Modellsimulationen zeigen, wie das Gebiet der neuen Bewertungseinheit „Pommersche Bucht“ alternativ hätte abgegrenzt werden können, wenn sowohl die Süßwasser- wie auch die Nährstoffeinträge der Oder als Grundlage zur Definition der Bewertungseinheit genutzt werden. Der Ansatz kann auf andere Bewertungseinheiten der Ostsee übertragen werden, die ebenfalls die natürlichen Gradienten, wie sie z.B. durch hohe wassergebundene Nährstoffeinträge entstehen, nur unzureichend berücksichtigen. Modellsimulationen können sowohl zur Ableitung von Bewertungseinheiten entsprechend ihrer hydrodynamischen Bedingungen und des Einflusses von Süßwassereinträgen als auch als Grundlage für eine zukünftig repräsentativere Verteilung von Messstationen genutzt werden.

Bei der Abschätzung der Sauerstoffsituation ist zu berücksichtigen, dass die Bewertung durch mehrere Einschränkungen in der westlichen Ostsee derzeit erschwert wird, in der eher saisonale und episodische als ganzjährige Hypoxie und Sauerstoffmangelsituationen (Sauerstoffkonzentrationen <6 mg/l) auftreten. So werden beispielsweise nach dem derzeitigen deutschen Konzept die kompletten Bewertungseinheiten auf der Grundlage der Einhaltung oder Nichteinhaltung von Schwellenwerten an einzelnen Überwachungsstationen bewertet, nicht aber in Bezug auf das Ausmaß der Ausbreitung der tatsächlichen sauerstoffarmen Gebiete innerhalb dieser Bewertungseinheiten. So fehlt bei dem aktuellen Bewertungsansatz bislang ein Flächenbezug, wie auch die Informationen über die vertikale Ausdehnung der sauerstoffarmen Zonen. Daneben sind die monatlichen Probenahmen nur bedingt geeignet, um die Dauer von Sauerstoffmangelzuständen abzuschätzen. Diese Einschränkungen konnten durch die Nutzung der 3D-Modell-Simulationen überwunden werden, die es erlauben, die räumlich-zeitliche Variabilität der Sauerstoffkonzentrationen in der westlichen Ostsee zu analysieren. So konnten geeignete Indikatoren für den saisonalen Sauerstoffmangel in flachen Gewässern entwickelt werden, die die räumliche, vertikale und zeitliche Komponente des Sauerstoffsituation adressieren (Piehl et al. 2022). Der entscheidende Vorteil der Modellsimulationen ist, dass zusätzlich zu den analysierten bodennahen Flächen und des Volumens des Sauerstoffmangels die zeitliche Komponente mitberücksichtigt werden kann. Am wichtigsten für die Bewertung der negativen Auswirkungen auf die biologische Vielfalt ist neben der flächenhaften Ausdehnung die Analyse der Zeiträume, in denen der Sauerstoffgehalt unter kritische Werte gesunken ist. Hier können Flächeninformationen über die Dauer und die Häufigkeit des Auftretens von Sauerstoffmangelsituationen künftig wertvolle Informationen liefern (Piehl et al. 2022). Des Weiteren konnten wir zeigen, dass die Situation in den 1950er Jahren ähnlich wie bei Nährstoffen und Chlorophyll-a als "guter Zustand" angesehen werden kann. Zwar gab es bereits einen Anstieg der Nährstoffeinträge, aber die Wasserqualität in dieser Phase kann noch als gut betrachtet werden. Gleichzeitig zeigte sich, dass es bereits ein natürlich auftretendes Sauerstoffdefizit in der westlichen Ostsee gab, auch wenn die Ausdehnung z.B. der hypoxischen Gebiete deutlich geringer war. Da jedoch die absoluten Sauerstoffkonzentrationen und die aus ihnen berechneten Sauerstoff Metriken durch das 3 Seemeilenmodell überschätzt wurden, muss der Ansatz noch weiterentwickelt werden, um geeignete Referenz- und damit verbundene GES-Zielwerte für den Sauerstoffmangel abzuleiten. Ein wichtiger Schritt vorwärts ist dabei der Übergang zu einem Modellsystem mit einer feineren räumlichen Auflösung. Mit dem neu entwickelten feineren Modell wird nun zu prüfen sein, ob die von HELCOM für den letzten Bewertungszeitraum (HOLAS III) vorgeschlagenen Zielwerte und Bewertungen des Flachwassersauerstoffs plausibel und erreichbar sind. Eine zentrale Herausforderung dabei ist es, die auf unterschiedlichen Methoden abgeleiteten und teilweise auch auf unterschiedlichen Referenzzeiträumen beruhenden Zielwerte zu harmonisieren und konsistent zu gestalten. Die Verfeinerung der horizontalen Auflösung unseres Modells hat die Qualität der modellierten Sauerstoffdynamik in den Küstengewässern und offenen Seegebieten der südwestlichen Ostsee verbessert. Nichtsdestotrotz sind Modellsimulationen immer nur eine Vereinfachung der Realität und haben viele Unsicherheiten. Daher wurde ein integrierter Ansatz gesucht, um Modellergebnisse und Beobachtungen in geeigneter Weise zu kombinieren und die jeweiligen Vorteile nutzen zu können. Um die Abweichung zwischen den simulierten Werten und den beobachteten Werten zu reduzieren, haben wir daher die Faktoren untersucht, die diese Abweichung beeinflussen können (wie z.B. Distanz zur Küste oder Messtiefe). Basierend auf diesen Ergebnissen haben wir eine Korrekturfunktion entwickelt, mit der wir die simulierten Daten an die gemessenen Daten angepasst haben. Obwohl unser integrierter Ansatz bei einzelnen Komponenten zu besseren Modellgüteparametern führte, waren die Ergebnisse und Verbesserung nicht für alle betrachteten Teileinzugsgebiete und/oder Stationen konsistent (Piehl et al: Biogeosciences Discuss. [preprint], https://doi.org/10.5194/bg-2023-152). Ein Grund dafür sind wahrscheinlich die heterogenen Messdaten, die zur Ableitung der Korrekturfunktionen verwendet wurden und die in ihrer zeitlichen und vertikalen Auflösung nicht konsistent sind. Am Beispiel des Arkonabeckens konnten wir einen zukünftigen Weg aufzeigen, bei dem nur zeitlich und/oder vertikal hoch aufgelöste Beobachtungen in die Modelldaten integriert werden, um ein möglichst hohes Vertrauen in die Bewertung zu erreichen. Bei der Weiterentwicklung der integrierten Sauerstoffbewertungen müssen künftig Endnutzer weiter einbezogen werden, um eine geeignete Strategie für die Bewertung der Verlässlichkeit zu entwickeln, die den Anforderungen für Managemententscheidungen entspricht.

Für die Überprüfung der Nährstoffreduktionsziele wurden Zukunftsszenarien (30 Jahre) mit jeweils drei Realisierungen erstellt, die das Wetter zwischen 2010 und 2019 (einschließlich der interannuellen Variabilität) abbilden. Um den verschiedenen Optionen Rechnung zu tragen, wie die Eintragshöchstgrenzen der verschiedenen Gesetzgebungen erreicht werden können, wurden mehrere Szenarien entwickelt, die sich hinsichtlich der Nährstoffeinträge aus wassergebundenen Quellen (Flüsse, Punkt- und diffuse Quellen) und aus der atmosphärischen Deposition unterscheiden. So sieht die Umsetzung der EU-NEC-Richtlinie eine deutliche Reduktion der Emissionen von gefährlichen Stoffen in die Atmosphäre vor, so dass bei der

Umsetzung auch weniger Stickstoff in die Ostsee über die Atmosphäre eingetragen werden würde (Gauss et al. 2021). Auf der anderen Seite sehen sowohl der HELCOM BSAP als auch die nationalen Managementpläne aus der EU-WFD explizite Obergrenzen für die wassergebundenen Nährstoffeinträge vor. Das Ergebnis der Szenario- Simulationen war, dass alle betrachteten Eutrophierungsindikatoren Verbesserungen aufgrund der veränderten Nährstoffeinträge in allen Szenarien zeigten. Das heißt, die konsequente Umsetzung der Managementpläne an Land hat einen positiven Effekt auf die Wasserqualität in der westlichen Ostsee. Gleichzeitig zeigte sich, dass die Winterkonzentrationen von DIN und DIP im Bast-Case-Szenario die GES-Ziele in den Bewertungseinheiten der westlichen Ostsee fast erreichen, während die Sommer-Chlorophyllkonzentration, die ein Maß für die Intensität der Algenblüten während der Sommermonate darstellt, weiterhin weit vom GES-Ziel entfernt bleiben. Dies ist möglicherweise auf die langen Verweilzeiten insbesondere von Phosphat in der Ostsee zurückzuführen, so dass 30 Jahre Simulation nicht ausreichen, um die volle Wirkung der Eintragsreduzierungen zu sehen. Die Inkonsistenzen bei der Erfüllung der verschiedenen Indikatorzielwerte in der westlichen Ostsee kann aber durch andere Faktoren begründet sein. So unterscheidet sich die Sensitivität des biogeochemischen Modells ERGOM-MOM in Bezug auf die Auswirkungen der reduzierten Nährstoffeinträge wesentlich von dem Modell BALTSEM, das zur Festlegung der BSAP NICs verwendet wurde. Auf der anderen Seite wurden die derzeit verwendeten GES-Schwellenwerte auf der Grundlage des Referenzzustandes definiert, der sich auf die ungestörte Situation von 1880 bezieht. Aufgrund des sich bereits veränderten Klimas der letzten Dekaden dominieren heute jedoch temperaturabhängige Phytoplanktongruppen (z.B. Cyanobakterien) viel stärker als im Referenzzustand. Dies führt u.a. zu erhöhten (natürlichen) Sommer-Chlorophyllkonzentrationen, die weniger stark über die Nährstoffeinträge kontrolliert werden können. So empfiehlt es sich, die GES-Zielwerte an die veränderten Klimabedingungen anzupassen, und auch zukünftige Extremereignisse bei der Bewertung zu berücksichtigen. Hierfür ist ein konsistenter und harmonisierter Ansatz notwendig, der alle relevanten Eutrophierungsindikatoren und die Zielwerte in Flüssen, inneren Küstengewässern und der offenen Ostsee abdeckt und gleichzeitig ein robustes Management der Wasserqualität ermöglicht. Trotz der beschriebenen Unsicherheiten ist die Umsetzung der HELCOM BSAP und die Sicherstellung, dass die Nährstoffeinträge kritische Obergrenzen nicht überschreiten, von grundlegender Bedeutung und von großem Nutzen für die Wasserqualität, die Biodiversität und die Bereitstellung zentraler Ökosystemleistungen. Dabei hat sich in den Szenario- Simulationen auch gezeigt, dass die konsequente Umsetzung der EU-NEC-Richtlinie (zur Reduktion u.a. der atmosphärischer Stickstoffeinträge) erhebliche positive Auswirkungen auf die Wasserqualität hat. So profitieren insbesondere die westliche Ostsee wie auch die küstennahen Gewässer, die aufgrund der Nähe zu den Emissionsquellen an Land stärker von den Stickstoffeinträgen betroffen sind. Dieser Effekt zeigt sich anders als bei den Reduktionen der Phosphoreinträge sehr schnell und unmittelbar, da Stickstoff eine deutlich geringere Verweilzeit in der Ostsee hat. Neben den beschriebenen Veränderungen der direkten Eutrophierungsparameter zeigte sich in den Szenario- Simulationen auch, dass die hypoxischen Gebiete durch eine konsequente Reduktion der Nährstoffeinträge deutlich reduziert werden können. So besteht insbesondere in der Kieler Bucht und der Pommerschen Bucht ein hohes Risiko, dass die Gebiete mit niedrigen Sauerstoffkonzentrationen weiter zunehmen, wenn die Nährstoffeinträge auf dem bisherigen Niveau verbleiben. Das Einhalten aller internationaler und nationaler Eintragshöchstgrenzen führte dagegen zu einer erheblichen Abnahme der hypoxischen Gebiete in allen Bewertungseinheiten, insbesondere in der Kieler Bucht (-50%) und im Arkonabecken (-40%).

Zu berücksichtigen war zudem, dass in mehreren Teilen der Ostsee die nationalen Nährstofffrachten aus der HOLAS II-Periode bereits unter den vorgegebenen Reduktionszielen des BSAP liegen. Dies führt zu anhaltenden Diskussionen darüber, ob die Länder ihre zulässigen

Einträge voll ausschöpfen können, z. B. durch den Ausbau mariner Aquakulturbetriebe. Da dieses Thema in Dänemark derzeit stark diskutiert wird, wurde ein weiteres Szenario ("dänisches Szenario") entwickelt und bewertet, das sich auf die möglichen Auswirkungen auf die Wasserqualität in der westlichen Ostsee konzentriert. Dabei haben wir angenommen, dass Dänemark seine BSAP NICs vollständig ausschöpft, während alle anderen Ostseeanrainerstaaten dem Best-Case-Szenario folgen, wobei wir davon ausgehen, dass jedes Land die BSAP NICs umsetzt oder die Einträge auf dem Niveau der HOLAS-II-Periode bleiben, wenn sie bereits unter den BSAP NICs lagen. Die Nutzung der maximal zulässigen dänischen Nährstofffrachten würde zu zusätzlichen jährlichen Nährstoffbelastungen von ca. 14.700 t TN und 450 t TP im Vergleich zum Best-Case-Szenario führen, was 2,7 % bzw. 1,9 % der gesamten in die Ostsee gelangenden wassergebundenen Frachten entspricht. Die erzielten Verbesserungen der Wasserqualität im Best-Case-Szenario werden für alle drei Parameter im dänischen Szenario deutlich abgeschwächt, wobei sogar eine Verschlechterung des Winter-DIN im Vergleich zur HOLAS II Periode insbesondere in der Nähe der dänischen Küste geschätzt wird. Betrachtet man die Bewertungseinheiten in der südwestlichen Ostsee, so sind die Auswirkungen des dänischen Szenarios in der Kieler Bucht am stärksten. Die Winter-DIP-Konzentrationen in der Mecklenburger Bucht sind ebenfalls betroffen, während im Arkonabecken und in der Pommerschen Bucht die Unterschiede zwischen den Szenarien weniger als 1 % betragen. Auch wenn die Veränderungen der Wasserqualität für die Erreichung der GES-Ziele in diesen Bewertungseinheiten nicht relevant sind, sind sie für Bewertungseinheiten relevant, die direkt mit den dänischen Küstengewässern verbunden sind. Zum Beispiel wird der GES im Gebiet des Großen Belts für Winter-DIN im Best-Case-Szenario erreicht, nicht aber im dänischen Szenario. Die dargestellten Ergebnisse beruhen stark auf der Annahme, dass sich im dänischen Szenario die Eintragspunkte der wassergebundenen Nährstofffrachten im Vergleich zum Referenzzeitraum nicht ändern. Da die Lage und Größe der geplanten Aquakulturbetriebe noch nicht bekannt sind, scheint das oben beschriebene Verfahren jedoch derzeit am besten geeignet zu sein, kann aber in Zukunft angepasst werden, wenn bessere Erkenntnisse vorliegen.

1 Introduction

The latest holistic assessment of the status of the Baltic Sea by HELCOM (Helsinki Convention on the Protection of the Marine Environment of the Baltic Sea Area) based on data from 2016-2021 has shown that the eutrophication status of the Baltic Sea has hardly changed since the previous assessment period (2011-2016) (https://helcom.fi/baltic-sea-trends/holistic-assessments/state-of-the-baltic-sea-2023/). Eutrophication is induced by excessive anthropogenic nutrient inputs from land and the atmosphere and causes phytoplankton to proliferate strongly above the natural levels. These high algae densities lead to turbidity of the water and their microbial degradation on the seabed leads to oxygen deficiency. The Baltic Sea has the largest hypoxic areas (O_2 < 2 mg/l) and even anoxia (O_2 = 0 mg/l) occur so that higher life is no longer possible due to the lack of oxygen. As a semi-enclosed coastal sea with a low water exchange and long residence time, the Baltic Sea reacts particularly sensitive to excessive nutrient inputs, while the ecological balance is strongly disturbed by eutrophication.

In 2007, the HELCOM Parties adopted the Baltic Sea Action Plan (BSAP; HELCOM 2007). It contains ambitious nutrient reduction targets. The Swedish Baltic Nest Institute has subjected these targets to scientific revision. At the 2013 HELCOM Ministerial Meeting, new reduction targets were adopted (HELCOM 2013a), which for the first time also took atmospheric nitrogen deposition into account. In addition to the reduction commitments of HELCOM Parties, the Ministerial Declaration also formulated specific reduction requirements for non-Parties and shipping. In the Ministerial Declaration, Germany committed to reduce its annual nitrogen inputs by 7,670 metric tons (t) and its phosphorus inputs by 170 t. The nutrient reduction targets in the BSAP were adopted as a national environmental target for Germany in the EU Marine Strategy Framework Directive (EU-MSFD) and adjusted to meet the targets of the EU Water Framework Directive (EU-WFD) (BLANO 2014). Since both Germany and all other HELCOM contracting states have not achieved the agreed nutrient reduction targets by 2021, a continuation of the reduction efforts was made in the revised Baltic Sea Action Plan adopted in 2021 (HELCOM 2021).

For the derivation of the national input ceilings (NICs) and the resulting nutrient input reduction targets of the HELCOM BSAP, the BALTSEM model (Baltic Sea Long-Term Large Scale Eutrophication Model) was used. It divides the Baltic Sea into 13 large boxes and assumes a homogeneous horizontal distribution of the water masses within each box. As the BALTSEM boxes refer mainly to the deep basins, the model shows especially in the western Baltic Sea weaknesses, due to the complicated water exchange with the North Sea and the strong gradients. Using a high-resolution three-dimensional ecosystem model such as ERGOM (Ecological Regional Ocean Model, https://ergom.net/), has therefore a higher potential to reproduce the water quality parameters in a more realistic way. ERGOM was applied in the past to derive consistent and harmonized target concentrations of key eutrophication parameters in the western Baltic Sea (Schernewski et al. 2015).

The latest holistic assessment by HELCOM shows that the nutrient reduction targets of the BSAP in the basins of the western Baltic Sea (Danish Straits, Kattegat) have mostly been achieved https://helcom.fi/baltic-sea-action-plan/nutrient-reduction-scheme/national-nutrient-input-ceilings/ while the eutrophication problems persist (HELCOM 2023a). At the same time, the western Baltic Sea is under high and still growing exploitation pressure, e.g. by further expanding aquaculture farms (Maar et al. 2020).

Besides, severe inconsistencies of the present management hamper to achieve the goal of a good environmental state. Very noticeable was that the assessment area Bornholm Basin achieved the poorest eutrophication status result (>2.0), while both neighbouring basins achieved better results (1.5-2.0). One explanation for this imbalance is the influence of the Oder River, the fourth largest river flowing into the Baltic Sea, leading to strong gradients in all key water quality parameters. In addition, the distribution of monitoring stations in the Bornholm Basin is not representative, as many stations are located close to the coast and therefore strongly influenced by the river bloom, so that the integrated state of the Bornholm Basin is significantly influenced by the river plume.

Due to the described utilization pressure, it is necessary to examine whether the nutrient reduction targets agreed in the Baltic Sea Action Plan for the western Baltic Sea are sufficient to achieve the “Good Environmental Status” (GES) with regard to eutrophication. In addition, it is necessary to improve the assessment basis for eutrophication in the western Baltic Sea to be able to determine more reliably in the future how strongly this part of the Baltic Sea is eutrophic. Further it is crucial to assess effects of eutrophication on biodiversity of the ecosystem. Thereby, oxygen is a key indicator for the health of an ecosystem as it is essential for survival of almost all aquatic life forms. Within the HELCOM eutrophication assessment “oxygen debt” is already utilized as an indicator to evaluate the cumulative lack of oxygen in deep areas with persistent hypoxia. Meaning areas with a permanent halocline, where vertical mixing with oxygen rich surface water is limited and where oxygen concentrations drop below a critical level of 2 mg /l. Although different national assessment approaches, using different methods, parameters, and thresholds, for the non-permanent stratified shallow waters exist, a HELCOM-wide coordinated oxygen indicator for shallow water is still missing. All current approaches generally have two major limitations. First, observations are limited in their temporal and spatial distribution. And second, the entire water column is not always monitored. Therefore, current oxygen measurements do not provide the high spatial and temporal resolution needed to fully assess highly dynamic seasonal oxygen deficiency in shallow areas.

Therefore, to address the above-mentioned challenges, we used the high-resolution 3D biogeochemical model system ERGOM-MOM in the western Baltic Sea in order to analyse

d) whether the nutrient input reductions adopted by the HELCOM member states (expanded by the German reduction targets discussed to achieve the WFD targets) are sufficient to achieve the GES in the western Baltic Sea

e) the spatio-temporal variability of oxygen concentrations from 1950 to present to support the development of a HELCOM near-bottom oxygen indicator and to support the derivation of target values for this indicator

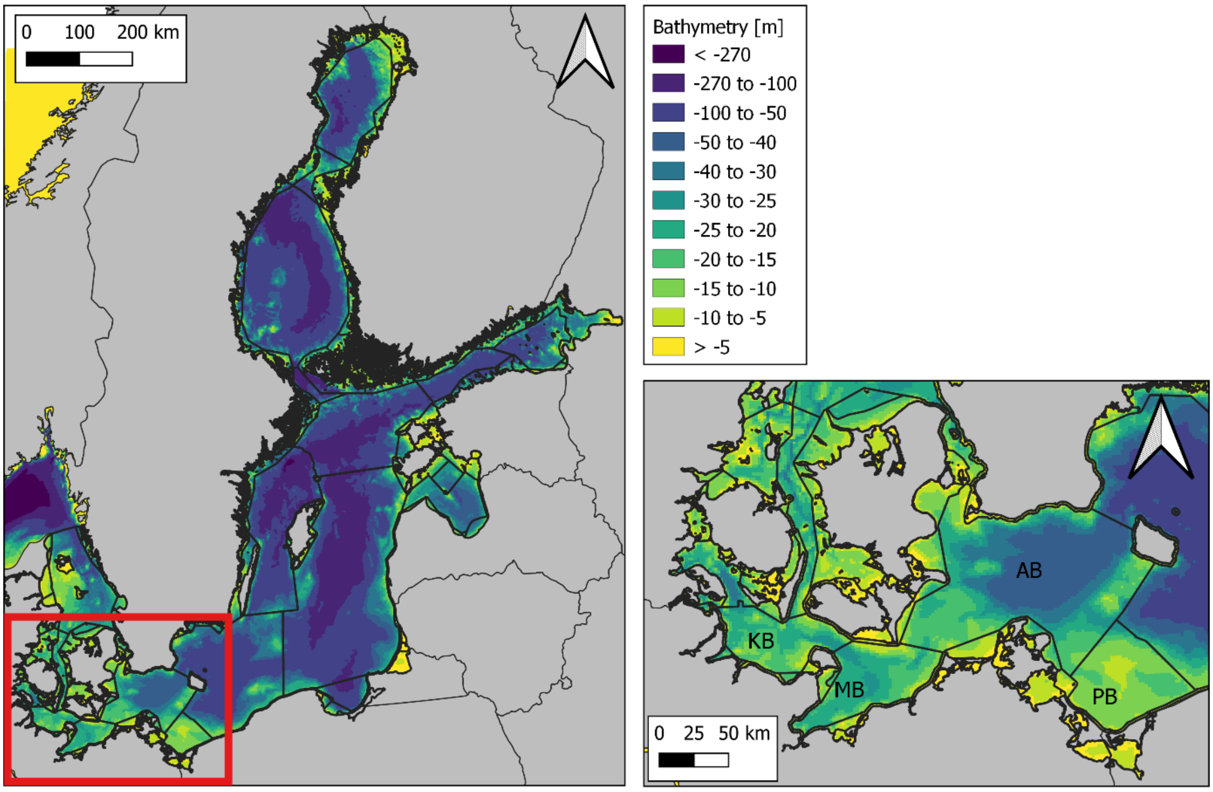
f) the spatio-temporal variability of the Oder river plume in order to help to shape a new assessment unit for a more representative assessment, including the derivation of new target values for both the new assessment unit as well as the remaining part of the Bornholm Basin

2 Materials and Methods

2.1 Study area

The Baltic Sea is a semi-enclosed, low-salinity sea in north-western Europe (Fig. 1). Its circulation is characterised by the exchange of water with the North Sea through the Belts and the Sound. In the near-surface layer, relatively low-saline water from the Baltic Sea flows into the North Sea via the Kattegat, while in the near-bottom layer saline North Sea water enters the Baltic Sea. Our focus area, the south-western Baltic Sea, is thus characterized by a strong west-east gradient of salinity and a complex bottom topography with deep channels separated by shallow sills. During the calm summer period a vertical stratification is characteristic, which is broken up by storms during autumn and winter.

Figure 1: The Baltic Sea in Northwest Europe with the division of sub-basins according to HELCOM (black lines) and our study area with the sub-basins Kiel Bay (KB), Bay of Mecklenburg (MB), Arkona Basin (AB) and the new assessment unit Pomeranian Bay (PB).



Source: own illustration, Leibniz Institute for Baltic Sea Research Warnemünde

For our analysis the entire Baltic Sea is considered in the model, whereby the focus of all analysis is on the western Baltic Sea (Fig. 1) and the HELCOM assessment units for which Germany shares a responsibility, i.e., Kiel Bay, Bay of Mecklenburg, Arkona Basin, and the new assessment unit Pomeranian Bay.

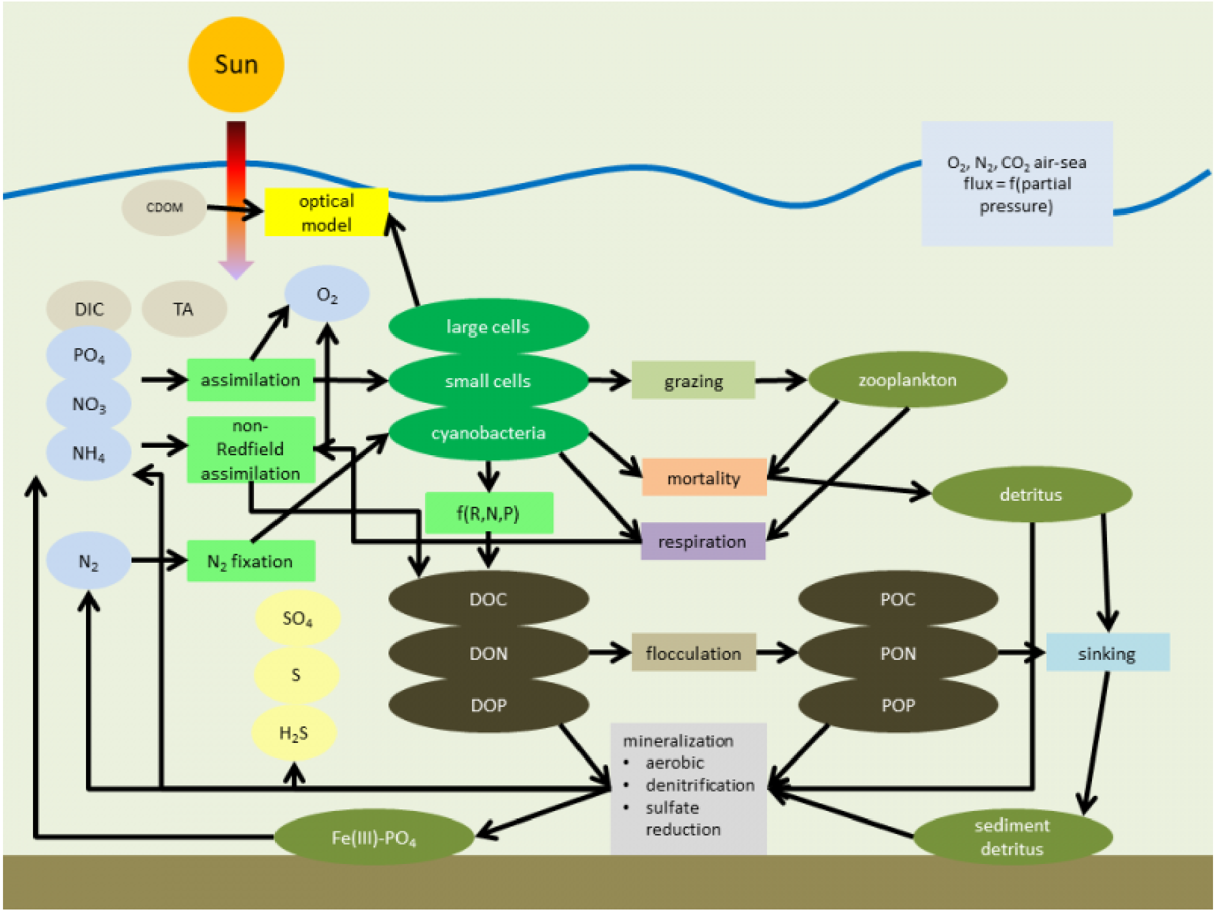
In Kiel Bay, the water depths are between 5 and 42 m (BLANO 2018). The Fehmarn Belt, which lies between the Kiel and Mecklenburg Bay, is, together with the Great Belt, the most important passage for the exchange of high-saline water between the Kattegat and the adjacent basins to the east of the Baltic Sea. The Mecklenburg Bay, which borders the Fehmarn Belt to the east, is on average deeper than the Kiel Bay, but only has a maximum depth of 28 m (BLANO 2018). The

Darß Sill, with an average water depth of 17 m, separates the Mecklenburg Bay and the adjacent Arkona Basin to the east, both of which have silt accumulation areas at greater depths. The Arkona Basin has a maximum water depth of >50 m and is connected to the Bornholm Basin to the north-east via the Bornholmsgat (BLANO 2018).

2.2 Modelling framework

The model simulations were performed with the integrated biogeochemical model ERGOM (https://ergom.net/), which is coupled to a 3D circulation model (MOM). The model setup ERGOM-MOM has been applied to variety of studies before (e.g., Neumann & Schernewski 2008, Neumann 2010, Friedland et al. 2012, Meier et al. 2019) and is highly validated using recent observations (e.g., Eilola et al. 2011, Schernewski et al. 2015, Neumann et al. 2021). A scheme of the biogeochemical model is shown in Figure 2. Essentially, it simulates the marine nitrogen and phosphorus cycle, i.e., the nutrients dissolved in the water, ammonium, nitrate, and phosphate, which form the basis for primary production. This, in turn, is represented in the model by three functional groups of phytoplankton (large cells, small cells and cyanobacteria). A dynamically evolving bulk zooplankton variable is used in the model to exert grazing pressure on the phytoplankton. Dead organic material is represented by a detritus state variable. The nitrogen and phosphorus cycles are coupled with a carbon cycle. This is described by Kuznetsov & Neumann (2013). Under oxic conditions, some mineralised phosphate is bound by iron oxides and retained in the sediment and released back to the water column when conditions become anoxic. Oxygen development is coupled to biogeochemical processes via stoichiometric ratios, with oxygen levels in turn controlling processes such as denitrification and nitrification.

Figure 2: Schematic illustration of the biogeochemical model ERGOM. State variables (round objects) and key processes (boxes) are highlighted.



Source: https://ergom.net/, Leibniz Institute for Baltic Sea Research Warnemünde

The physical part of the model is based on the MOM circulation model (version 5.1; Griffies et al. 2004, 2012). It has been adapted to the Baltic Sea with an open boundary condition to the North Sea and riverine freshwater input. The MOM model is complemented by a sea ice model to estimate the thickness and extent of the ice cover (Winton 2000). The atmospheric forcing is based on a dynamic downscaling was provided by the coastDat data set (Weisse et al. 2009, Geyer & Rockel 2013). The horizontal resolution of the model grid is three nautical miles, while vertically the model is resolved into 152 layers with a layer thickness ranging from 0.5 to 2 m. The simulation covers the period from 1948 to 2019. Nutrient loads to the Baltic Sea from river discharge and point sources have been compiled based on the HELCOM database (https://nest.su.se/helcom_plc//), data from HELCOM assessments (HELCOM 2015, HELCOM 2021b) and prior to 1995 from Gustafsson et al. (2012). Atmospheric deposition of nitrogen inputs was provided by EMEP (https://emep.int/mscw/mscw_moddata.html; Gauss et al. 2019, 2021) and before 1995 by Ruoho-Airola et al. (2012).

3 Review of current nutrient reduction targets

The Baltic Sea has been suffering from excessive nutrient inputs for almost a century now, resulting in concentrations of DIN, DIP, and chlorophyll-a well above the thresholds defining the "Good Environmental Status" (GES). In recognition of this, management plans have been in place for decades with specific maximal allowable inputs (input ceilings) for both waterborne inputs and atmospheric deposition, implemented within the HELCOM BSAP (HELCOM 2007, 2013, 2021a, 2021b) and different EU Directives (MSFD, WFD, NEC Directive). In order to assess the potential impacts of reducing the nutrient inputs according to the ceilings of the different legislatives, we have performed several scenario simulations with our model system ERGOM-MOM.

3.1 Materials and Methods

3.1.1 Input data

To provide a suitable model simulation for the present-day conditions, the model was run with the current nutrient loads as input data. Therefore, the latest available HELCOM data on annual nutrient loads (1995-2019) for rivers as well as point sources (urban, industrial, aquaculture) was extracted from the HELCOM-PLC database. These data were processed, checked for errors, and gaps in the time series were filled. For the western Baltic Sea, monthly nutrient loads were gathered from UBA, LUNG-MV and LfU-SH and provided by Denmark, Sweden, and Poland. The monthly river inputs for the other HELCOM states were calculated based on annual loads in an approach consistent with the Baltic Nest Institute.

The atmospheric nitrogen deposition to the Baltic Sea for 1995-2019 was taken from EMEP, which are harmonised with HELCOM and freely available as NetCDF files. For the atmospheric phosphorus deposition, the constant value of 5 kg P/km^2 was used in accordance with HELCOM (2013, 2021), whereas a gradient (computed out of the nitrogen deposition) was utilized to reflect the deposition differences in near- and offshore waters. To estimate the impact of the atmospheric P deposition, three comparison runs were performed using 0 kg P/km^2, 5 kg P/km^2 or 16.7 kg P/km^2 (Berthold et al. 2019), but model results showed that by using 5 kg P/km^2/year the best agreement between model and observed water quality could be gained. Therefore, this value was further used.

3.1.2 Scenarios

For the future scenarios (30 years), three realizations were prepared in each case, which reproduce the weather between 2010 and 2019 (including the interannual variability), without considering climate-change scenarios. This ensures that the future scenarios are based on realistic weather conditions of the last decade, but also that the natural (but not foreseeable) variability (visible e.g., in the different inflow dynamics of the three realizations) are taken into account. To account for the different options, how to reach the input ceilings of the different legislatives, several scenarios were developed (see the list below and Table 1 for details), which differ substantially with respect to the nutrient inputs from waterborne sources (rivers, point and diffusive sources) and from atmospheric deposition. For the later, we followed the reductions calculated by Gauss et al. (2021) and HELCOM (2020), which were kindly provided.

First, a model run was conducted using the average nutrient loads from the HOLAS II period ("Reference Run"), which served as baseline scenario to compare the impact of the reduced nutrient inputs to the case, when no additional efforts are undertaken. Next, we assumed the waterborne nutrient loads correspond to the BSAP NICs ("BSAP-NIC"), although for some countries and basins this might imply an increase of the nutrient inputs compared to the HOLAS II period. To account for the EU MSFD restriction that a worsening of water quality should be prevented, the more restrictive scenario "EU-NEC & BSAP+" was applied, where the waterborne inputs of each country and region are equal to the lower value from the reference inputs and the BSAP NICs, so that the loads are not worse compared to the HOLAS II period. In addition to this scenario, two scenarios were applied, restricting the German waterborne nitrogen inputs to the mean value of 2.6 mg TN/l, while the waterborne phosphorus inputs were set either to 0.1 or to 0.04 mg TP/l. Overall, 6 different input scenarios were applied (see Table 1 for details).

Table 1: The applied nutrient input scenarios differ substantially with respect to the assumed inputs from atmospheric deposition and waterborne nutrients.

Name of model run	Atmospheric inputs	Waterborne inputs	German inputs
Reference	Inputs according to 2011-2016		
EU-NEC	EU-NEC	Reference run	
BSAP-NIC	Reference run	BSAP-NIC (inputs as allowed by NICs)	
EU-NEC & BSAP	EU-NEC	BSAP-NIC	
EU-NEC & BSAP+	EU-NEC	Minimum of Reference run and BSAP-NIC	
German scenario I	EU-NEC	EU-NEC & BSAP+	2.6 mg TN/l & 0.1 mg TP/l
German scenario II	EU-NEC	EU-NEC & BSAP+	2.6 mg TN/l & 0.04 mg TP/l

As described above, the national nutrient loads from the HOLAS II period are in several parts of the Baltic Sea already below the BSAP NICs. This leads to ongoing discussions, if the countries may exploit their full allowable inputs, e.g., by expanding marine aquaculture farms. As this issue is nowadays heavily discussed in Denmark, a scenario (afterwards called "Danish scenario") was developed and assessed focussing on the potential impacts on the water quality in the western Baltic Sea. Thereby, we prescribed that Denmark exploits its BSAP NICs fully, while all other Baltic Sea country follow the Best-Case scenario ("EU-NEC & BSAP+"), assuming that each country implements the BSAP NICs or the inputs stay on the level of the HOLAS II period, if they were below the BSAP NICs.

3.1.3 Post-Processing/Data analysis

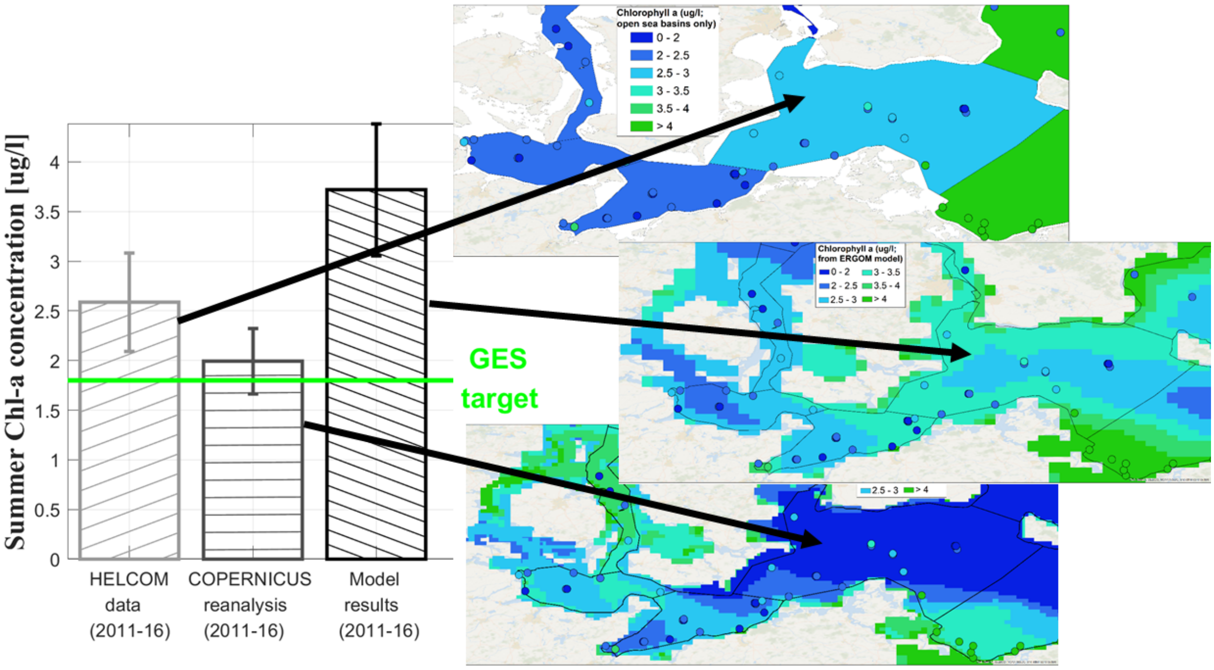
All analyses were performed for the spatially averaged assessment units (level 2; see Fig. 1) using the HELCOM water quality indicators shown in Table 2: Summer-Chl-a (Chlorophyll-a; HELCOM 2023b), Winter-DIN (dissolved inorganic nitrogen; HELCOM 2023c), Winter-DIP (dissolved inorganic phosphorus; HELCOM 2023d) and hypoxic area (near-bottom oxygen below 2 mg/l, averaged for July to November).

Table 2: Evaluation period and evaluation depth of the analysed eutrophication indicators.

Indicator	Unit	Evaluation period	Depth
DIN (NO_3 + NH_4)	µmol/l	Dec, Jan, Feb	0-10m
DIP (PO_4)	µmol/l	Dec, Jan, Feb	0-10m
Chl-a	µg/l	May, Jun, Jul, Aug, Sep	0-10m
Hypoxic area	km^2	Jul, Aug, Sep, Oct, Nov	Near-bottom layer

It was found that there is a substantial difference between the current state of HOLAS II results of the indicators (DIN, DIP, Chl-a) and the model, if analysed on level of the spatially averaged assessment units (Fig. 3). The reason for this is that the model represents the spatial mean of the entire assessment areas, while the observations do not reflect all gradients in some cases. Therefore, not the absolute values of each water quality indicator were evaluated but the relative changes of the model results (compared to the modelled state of 2011-16) as well as of GES target compared to the present state, as published by HELCOM were computed and compared.

Figure 3: Spatially averaged Summer-Chlorophyll-a concentrations from the HOLAS II period for the Arkona Basin, values are taken from HELCOM (2023b), the COPERNICUS reanalysis (CMEMS 2023) and our model results. The maps on the right hand show the full spatial picture, highlighting the strong spatial gradients and the uneven distribution of data points.



Source: own illustration, Leibniz Institute for Baltic Sea Research Warnemünde

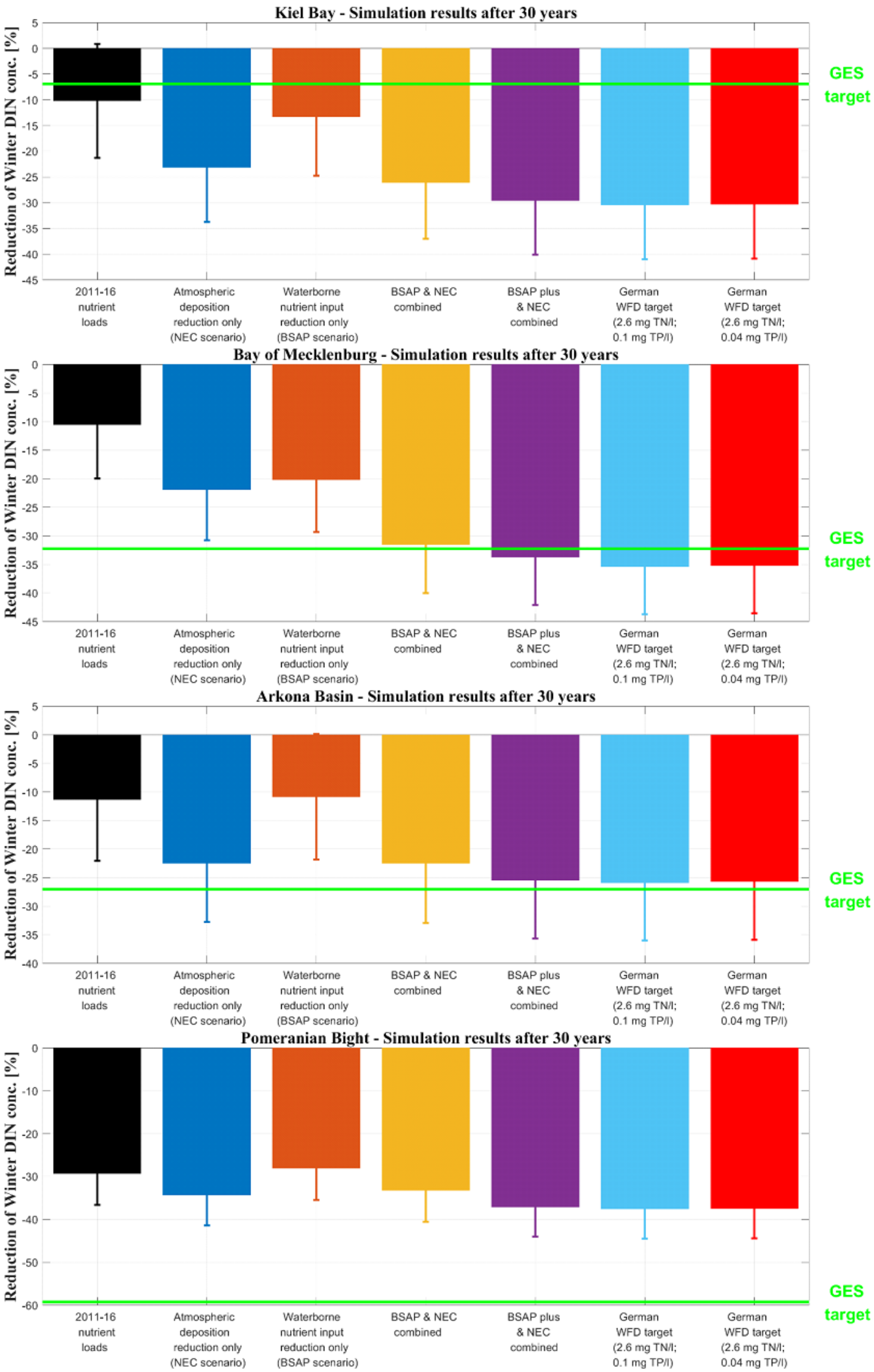
3.2 Results and discussion of the nutrient scenarios

All water quality indicators show improvements due to the changed nutrient inputs in all scenarios. Although Winter-DIN and Winter-DIP nearly reach the GES targets in the analysed assessment units, Summer-Chlorophyll is far off the target. This was maybe induced by the long residence times of especially phosphate, so that 30 years of simulation were not sufficient to gain the full impact of input reductions. Nevertheless, implementing the BSAP NIC and securing that there is no worsening of the inputs from the present state is essential, important and highly beneficial. Implementing the EU-NEC has also a significant impact on the water quality – at least in the western Baltic Sea and the near-shore waters, which are more affected by the nitrogen inputs (not shown).

3.2.1 Winter-DIN

The results for Winter-DIN are shown in Fig. 4. It got clear that even if the nutrient inputs stay on the level of 2011-16, Winter-DIN will decrease already substantially. The reduction of the waterborne nitrogen inputs alone has nearly an effect, but reducing the atmospheric nitrogen deposition is the key to manage the Winter-DIN concentrations. Having all legislations in place and having implemented also the German WFD targets will likely allow to reach GES for Winter-DIN in Kiel Bay, Mecklenburg Bay and Arkona Basin.

Figure 4: Comparison of relative change of Winter-DIN concentration [%] averaged over Kiel Bay, Mecklenburg Bay, Arkona Basin and Pomeranian Bay from the different nutrient input scenarios (see Table 1) compared to the current status assessment by HELCOM (2011-16).

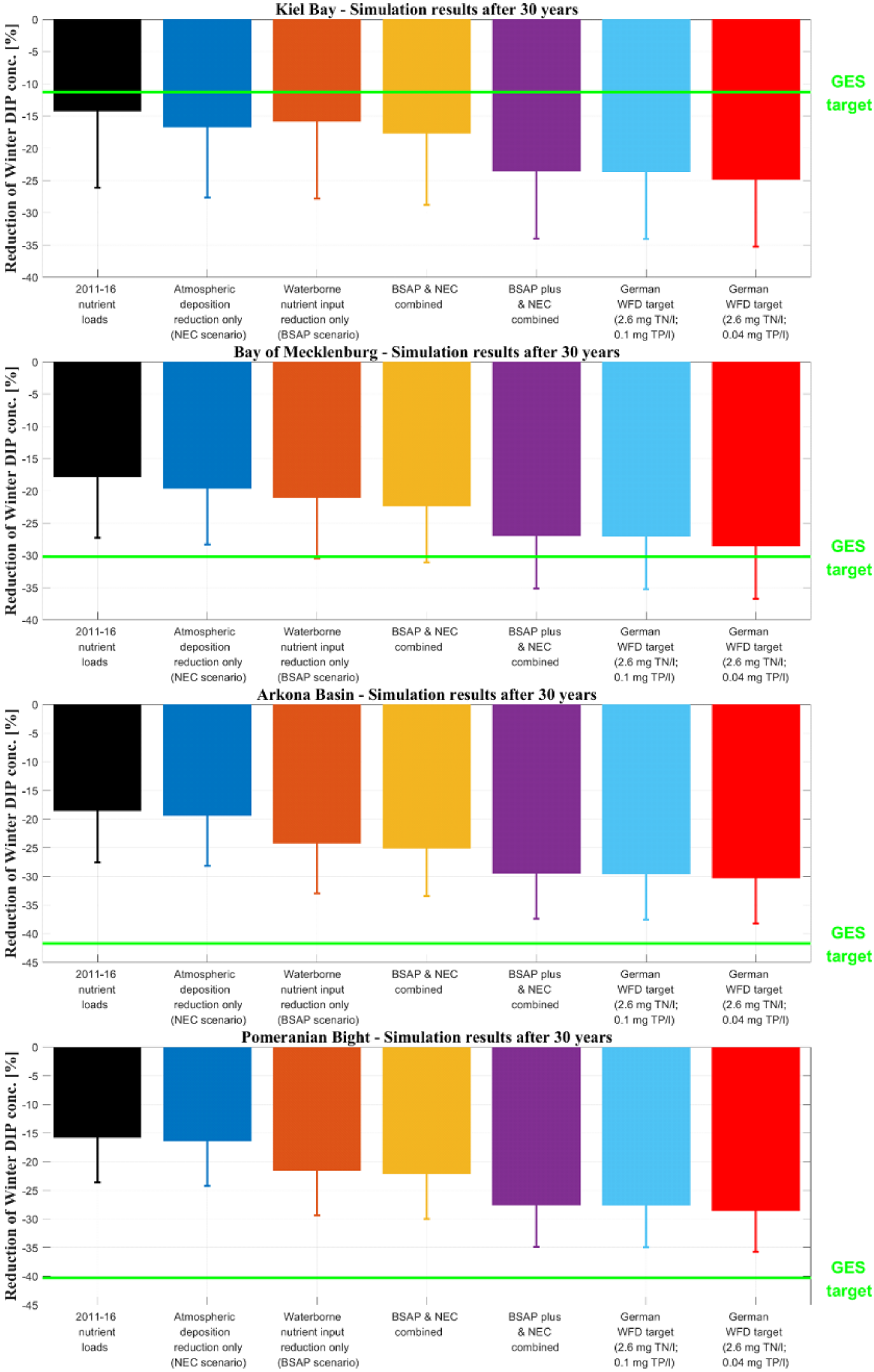


Source: own illustration, Leibniz Institute for Baltic Sea Research Warnemünde

3.2.2 Winter-DIP

The results for Winter-DIP are shown in Fig. 5. It got clear that even if the nutrient inputs stay on the level of 2011-16, Winter-DIP will decrease already substantially and even more than Winter-DIN. Further reductions of the waterborne inputs are beneficial, while there is even a tiny impact of reducing the atmospheric N deposition due to shifts of N:P ratios. Having all legislations in place and implemented also the strictest German WFD target (0.04 mg TP/l) will have a positive effect on Winter-DIP in the western Baltic Sea, but GES for Winter-DIP will only for sure be reached in Kiel Bay. In Mecklenburg Bay the probability is high, while Winter-DIP in Arkona Basin and Pomeranian Bay reaches not the GES, although it is reduced by more than 30% within the simulation period.

Figure 5: Comparison of relative change of Winter-DIP concentration [%] averaged over Kiel Bay, Mecklenburg Bay, Arkona Basin and Pomeranian Bay from the different nutrient input scenarios (see Table 1) compared to the current status assessment by HELCOM (2011-16).

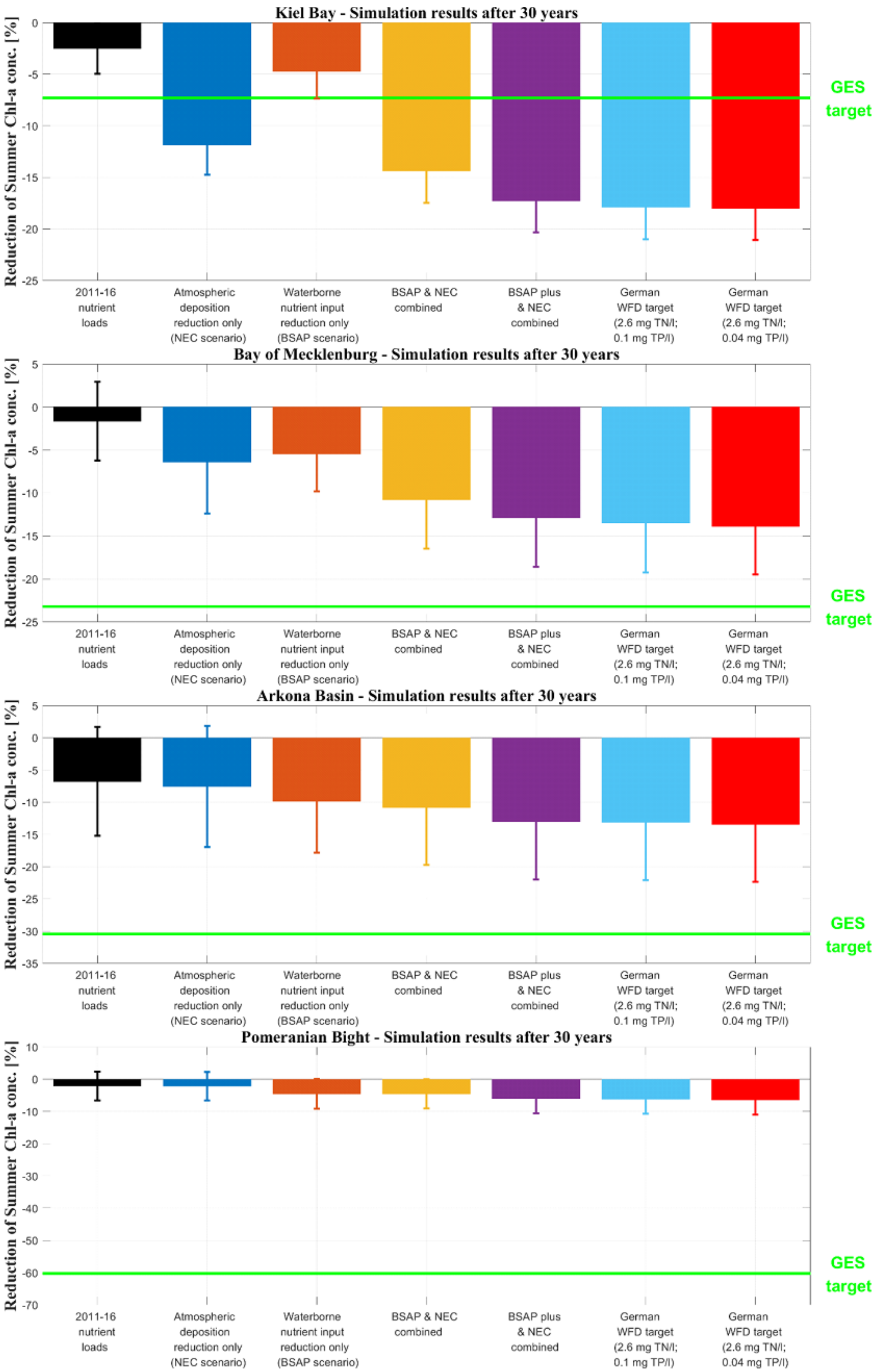


Source: own illustration, Leibniz Institute for Baltic Sea Research Warnemünde

3.2.3 Summer-Chlorophyll

The results for Summer-Chlorophyll are shown in Fig. 6. It got clear that even if the nutrient inputs stay on the level of 2011-16, Chlorophyll-a will decrease slightly and with a less pronounced reduction than for the nutrients. Further reductions of the waterborne inputs are beneficial, while there is only a tiny impact of reducing the atmospheric N deposition except for Kiel Bay, where implementing the EU-NEC directive is the key to reach the GES with respect to Chlorophyll-a. Having all legislations in place will have a positive effect on Summer-Chlorophyll in the western Baltic Sea, as concentration will be reduced by approx. 15 to 20%, but GES will only for sure be reached in Kiel Bay, while in all other assessment units the reduction demands to reach the Chlorophyll-GES-targets are much stronger, e.g. 30% for Arkona Basin.

Figure 6: Comparison of relative change of Summer-Chlorophyll concentration [%] averaged over Kiel Bay, Mecklenburg Bay, Arkona Basin and Pomeranian Bay from the different nutrient input scenarios (see Table 1) compared to the current status assessment by HELCOM (2011-16).

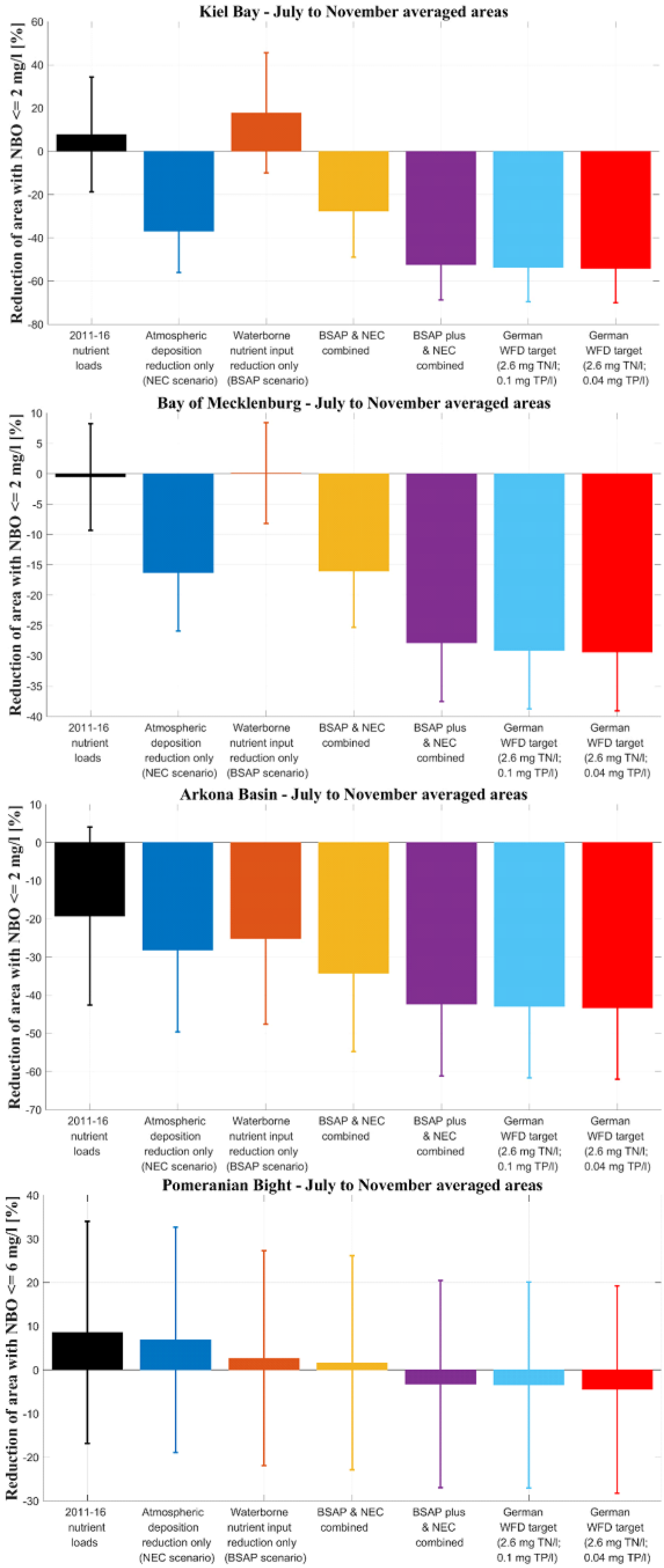


Source: own illustration, Leibniz Institute for Baltic Sea Research Warnemünde

3.2.4 Hypoxic Areas

The results for the hypoxic areas are shown in Fig. 7. In contrast to the other eutrophication indicators, hypoxic areas decreased not in all scenarios. Especially in Kiel Bay and Pomeranian Bay, there is high risk that the areas with low oxygen concentrations increase, if the nutrient inputs stay just on the recent level. Implementing all legislations led on the other hand to substantial decreases of the hypoxic areas in all assessment units, especially in Kiel Bay (-50%) and Arkona Basin (-40%).

Figure 7: Comparison of relative change of the hypoxic areas [%] averaged over Kiel Bay, Mecklenburg Bay and Arkona Basin, as well as the area with near-bottom oxygen concentrations below 6 mg/l for Pomeranian Bay from the different nutrient input scenarios (see Table 1) compared to the current status assessment by HELCOM (2011-16).



Source: own illustration, Leibniz Institute for Baltic Sea Research Warnemünde

3.2.5 Conclusions

The model simulations show an imbalance of fulfilment of the different eutrophication target values in the western Baltic Sea. Possible reasons are:

- The simulation times were not long enough to gain the full impact of the input reductions.
- The sensitivity of the biogeochemical model ERGOM-MOM with respect to the effect of the reduced nutrient inputs is substantially differing to the BALTSEM model, which was used to define the BSAP NICs.
- The presently used GES threshold for Summer-Chlorophyll were defined based on the reference state, referring to the undisturbed situation of 1880. But due to the already changed climate (HELCOM 2021a) including an increase of summer temperatures of approx. 1K, temperature-depending phytoplankton groups (like Cyanobacteria) are more dominant, resulting in increased summer-Chlorophyll concentrations, which are less strong affected by the nutrient loads.
- Yet, a consistent, spatially explicit, harmonized approach covering all relevant eutrophication indicators and the target values in rivers, inner coastal waters and the open Baltic Sea is missing.

3.3 Results and discussion of the „Danish scenario“

Exploiting the maximal Danish allowable nutrient loads, would result in additional annual nutrient loads of approx. 14,700 t TN and 450 t TP compared to the EU-NEC & BSAP+ scenario (see Table 1, afterwards referred to as “Best Case scenario”) accounting for 2.7% resp. 1.9% of the total waterborne loads entering the Baltic Sea (see Table 3).

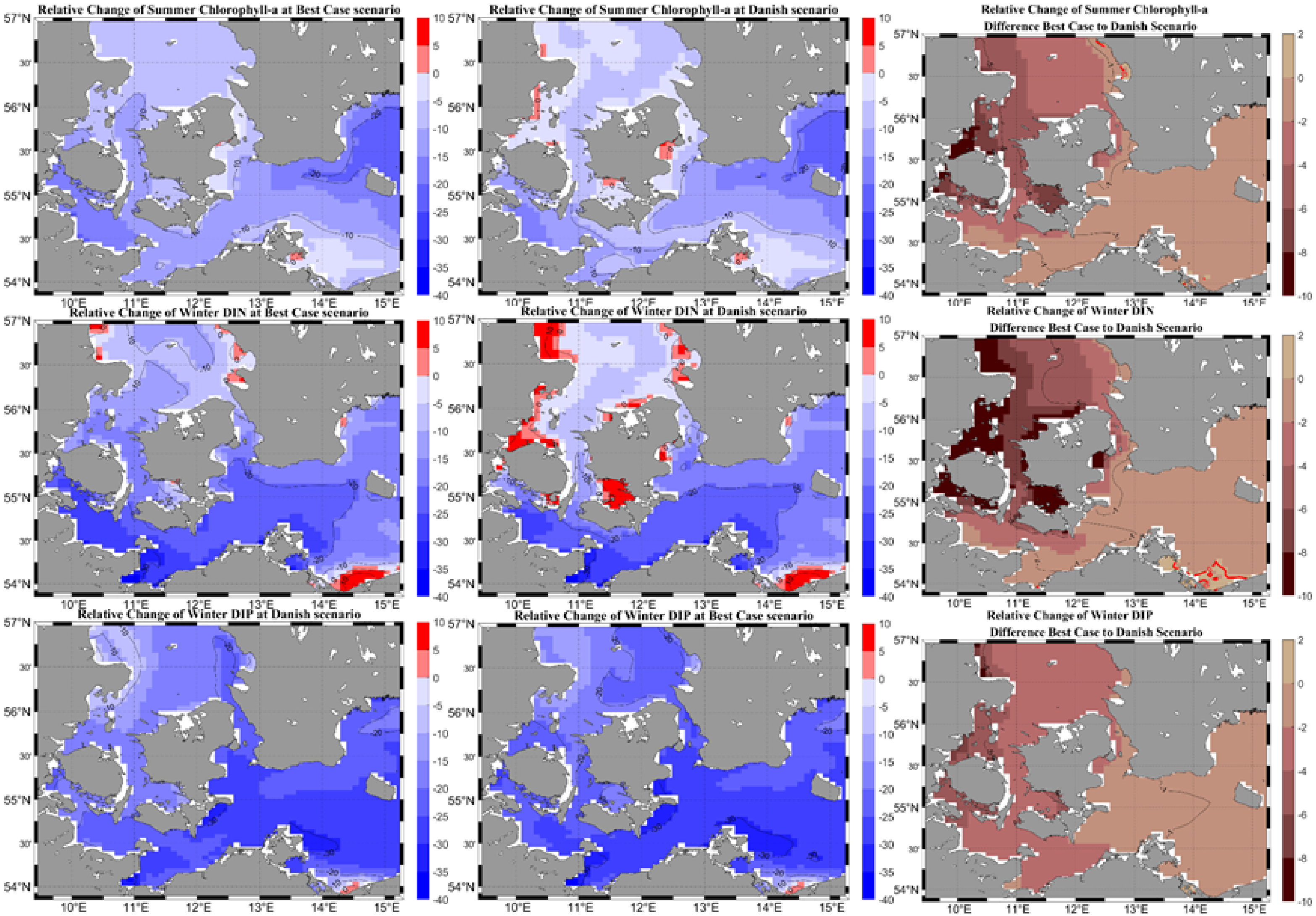
Table 3: Waterborne nitrogen and phosphorus loads in the “Best Case” (EU-NEC & BSAP+scenario) and the Danish scenario.

	EU-NEC & BSAP+ scenario		Danish scenario		Difference	
	Waterborne TN-load [t/a]	Waterborne TP-load [t/a]	Waterborne TN-load [t/a]	Waterborne TP-load [t/a]	TN-load [t/a]	TP-load [t/a]
Kattegat	48,552	1,807	54,432	1,973	5,880 (12.1%)	166 (9.2%)
The Sound	6,925	355	8,070	435	1,145 (16.5%)	80 (22.5%)
Western Baltic Sea	23,860	872	31,532	1,074	7,672 (32.2%)	202 (23.2%)
Total Baltic Sea	551,387	23,163	566,084	23,611	14,697 (2.7%)	448 (1.9%)

The analysis of the main water quality parameters summer chlorophyll, winter DIN and winter DIP (see Fig. 8) shows a clear decrease of all of them (especially in the Best-Case scenario) when comparing the concentrations with the mean (model-based) from the reference period. A local increase in winter DIN is modelled only at certain locations, because in the future simulation a climatology of freshwater runoff and nutrient inputs is assumed, while for the reference period the real observed runoffs and nutrient loads were used.

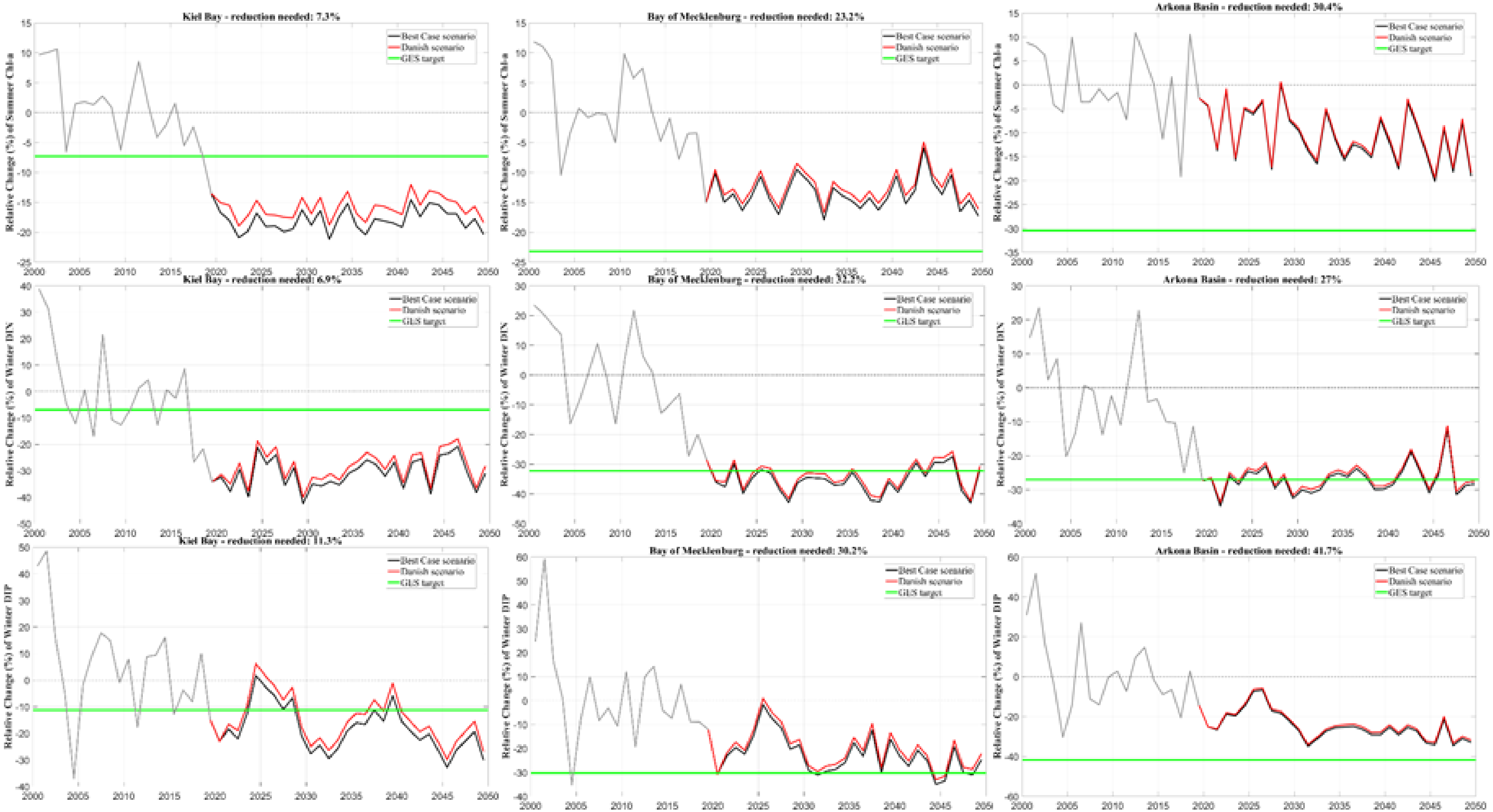
These water quality improvements are clearly weakened for all three parameters in the Danish scenario, where even a worsening of the winter-DIN compared to the HOLAS II especially near the Danish coast is estimated (see Fig. 8). Looking at the assessment units of the south-western Baltic Sea, the impact of the Danish scenario is strongest in the Kiel Bay. The winter DIP concentrations in the Bay of Mecklenburg are also affected, while in the Arkona Basin and the Pomeranian Bay the differences between the scenarios are less than 1%. This also has an impact on the mean values at the level of the 15 assessment units (see Fig. 9), which all show an improvement compared to the reference period, but this is weakened in the Danish scenario. However, the difference between the two scenarios does not affect whether or not the GES is reached.

Figure 8: Relative change (in %) compared to the mean state from the HOLAS II period for summer-chlorophyll, winter-DIN and winter-DIP in the two scenarios and the difference between both.



Source: own illustration, Leibniz Institute for Baltic Sea Research Warnemünde

Figure 9: Relative change (in %) of the spatially averaged mean concentrations from the assessment units Kiel Bay, Bay of Mecklenburg and Arkona Basin compared to the mean values from the HOLAS II period with respect to summer-chlorophyll, winter-DIN and winter-DIP. Color-coded are the scenario runs (black: Best-Case scenario; red: Danish scenario) and the necessary reductions to fulfill the GES targets (green).



Source: own illustration, Leibniz Institute for Baltic Sea Research Warnemünde

As shown, exploiting the maximal allowable nutrient inputs by Denmark will result in an increase of the nutrient inputs. This increase differs between the PLC assessment units but is with up to 32% severe (see Table 3) and may result in deteriorating water quality, especially along the Danish coast (see Fig. 8). In the assessment units of the south-western Baltic Sea (Kiel Bay, Bay of Mecklenburg, Arkona Basin and Pomeranian Bay) the additional nutrient inputs lead to water quality changes only to a limited extent, which are not relevant for reaching the GES targets (see Fig. 9). Nevertheless, the impact is stronger in the assessment units directly connected to the Danish coastal waters, e.g. in the Great Belt area for winter DIN GES is reached in the best-case scenario, but not in the Danish scenario.

The results shown base strongly on the assumption that in the Danish scenario the entry points of the waterborne nutrient loads do not change compared to the reference period. This means that the pathways correspond to the current rivers and point sources as stored in the HELCOM database. This assumption is highly pragmatic, but is not in agreement with the point that the additional loads can be used to promote new aquaculture farms. However, due to the horizontal resolution of the model grid (three nautical miles), there is a high probability that these new farms would be located in the same grid cells that are already used as nutrient inputs. As the position and sizes of the planed aquaculture farms are yet unknown, the above-described procedure seems to be the most appropriate, but may be adjusted in the future if better knowledge is available.

3.3.1 Conclusions

Meeting all nutrient input reduction targets will result in strongly decreased concentrations of Winter DIN and DIP. Due to the over proportional reduction of phosphorus inputs, the DIP concentrations are reduced stronger than DIN, although the DIP pools react much slower due to large residence times (Radtke et al. 2012). Especially in the western Baltic Sea, reducing the atmospheric nitrogen deposition is a key to improved water quality. The bottom oxygen deficiency improves in the shallow waters, but hypoxia will still occur. Despite the decrease of DIN and DIP concentrations, summer chlorophyll-a is reduced only to a low extent, so that GES thresholds will not be fulfilled in our model simulations, even if all nutrient input ceilings are kept. This raises the question, whether the GES target concentrations are reachable at all just by limiting the nutrient inputs, or if a revision and a new GES target setting approach is needed.

Furthermore, the simulations have shown that the German scenarios are of little importance for the open Baltic Sea, but could be crucial for the coastal waters, which could only get analyzed with a model having a higher spatial resolution. This would have also an added value by allowing to estimate the retention potential of the coastal waters, which is yet not considered when the HELCOM BSAP input ceilings are calculated. First of all, a more tailor-made eutrophication management seems necessary that incorporates the specific reduction needs of coastal waters and deep basins for the two key nutrients nitrogen and phosphorous.

4 Analysis of seasonal oxygen deficiency

The Baltic Sea has the largest hypoxic areas in the world (oxygen concentration < 2 mg/l; (Carstensen and Conley 2019). The frequency of hypoxia as well as the extent of the hypoxic areas have continuously increased over the last century due to excessive nutrient inputs (Meier et al. 2019). Therefore, oxygen debt in the permanently stratified waters is already a HELCOM indicator for the eutrophication status of the Baltic Sea. Nevertheless, there is still no indicator in the shallower parts of the Baltic Sea where episodic and/or seasonal oxygen deficiency occurs, although various national approaches exist. However, several limitations make assessing oxygen deficiency difficult. For example, under the current German approach, areas of overall assessment units (WFD or HELCOM basins) are assessed based on compliance or non-compliance with thresholds at specific monitoring stations, but not on the basis of the extent of actual oxygen depleted areas within those assessment units, thus lacking an area reference. Moreover, the monthly sampling is not adequate for evaluating the duration of oxygen deficiency situations.

Therefore, the aim of the sub-task was to analyse the spatio-temporal variability of the oxygen concentrations in the western Baltic Sea in order to develop a suitable indicator for seasonal oxygen deficiency in shallow waters. In particular, the 3D model simulations were used to achieve the following four objectives

1. Analyses of the spatio-temporal variability of near-bottom oxygen concentrations in the western Baltic Sea
2. Estimation of the mean duration and volume (additional metrics) of oxygen deficiency in the western Baltic Sea
3. Long-term analysis (1950-2019) to support setting of threshold values and environmental goals for a shallow-water oxygen indicator
4. Recommendations for an integrated monitoring system for oxygen, combining observations & model simulations

To achieve the first three objectives, we utilized the coupled hydrodynamic-biogeochemical model MOM-ERGOM with a resolution of three nautical miles, as described above. For the final step a model run with a higher spatial resolution of one nautical mile was used, which better represents the coastal waters. The higher spatial resolution was necessary to give a recommendation for a monitoring approach that integrates measured data and model data. As the results on the first three objectives have been published (Piehl et al. 2022), and the fourth objective is subject of an article currently under review by the journal Biogeosciences within the special issue "Low-oxygen environments and deoxygenation in open and coastal marine waters" (Piehl et al. [preprint – rejected in its current form], https://doi.org/10.5194/bg-2023-152, 2023), this report provides only a brief summary of the main results.

4.1 Materials and Methods

The model set-up as described in section 2.2 was utilized for all analysis. In an additional model run the horizontal resolution was adjusted to 1 NM to address objective 4. The skill of the model runs was assessed based on the spatial (horizontal and vertical) and temporal agreement with observations (see Piehl et al. 2022). Observational data was provided by local authorities (State Agency for Environment Schleswig-Holstein (LfU) and State Agency for Environment, Nature Conservation and Geology Mecklenburg-Vorpommern (LUNG)) and enhanced by data from the Leibniz Institute for Baltic Sea Research Warnemünde (https://odin2.io-warnemuende.de//) and data from the ICES oceanographic database (https://www.ices.dk/data/data-portals/Pages/ocean.aspx). We gathered the available data in a harmonized and freely accessible data set (Vock 2021, Vock et al. 2023). From the different databases, we extracted the measured dissolved oxygen concentrations or oxygen saturation, which was converted. Aiming to unify the data in the joint dataset, the different datasets were transformed to mg/l, duplicates were removed and measurements at the same time and location obtained by different methods were combined.

The root mean squared error (RMSE), the average error (AE), and the non-parametric Spearman Rank Correlation coefficient (r), three statistics most commonly used to quantify model-data misfits (Fennel et al. 2022), were calculated to assess model skill.

For the analysis of the oxygen metrics (e.g., area, volume), mean values were not based on daily oxygen concentrations, but on whether oxygen concentrations dropped below critical levels (2, 4 or 6 mg/l oxygen). In the following, all situations below 2 mg/l will be referred to as hypoxia and all situations between 6 mg/l and 2 mg/l will be referred to as oxygen deficiency.

In order to reduce the estimation bias of the modelled oxygen concentrations an integrated approach was tested (objective 4), combining observations and model simulations (Piehl et al. 2023; under review by BGS). The correction parameters were: 1) observational depth; 2) bathymetric depth of the station; 3) ratio of the depth of the mixed layer compared to the total depth (according to Große et al., 2016); and 4) distance of the station from the coastline. All parameters are available through the model to allow a correction for the entire model domain. The correction function was then calculated using the available data points as a third-degree polynomial for each parameter as follows:

$$corr_{func(depth,bath,MLD,dist)} = \sum_{i=1}^{3}(a_i \times depth^i + b_i \times bath^i + c_i \times MLD^i + d_i \times dist^i \quad (1)$$

where *depth* is the observation depth, *bath* the bathymetric depth, *MLD* the ratio of the mixed layer depth compared to total depth, and *dist* the distance to shoreline.

Based on the optimized constants *a1* to *d3* for each month and sub-basin, the correction function was computed for the model grid, following Eq. (1). The values were then added to the originally modelled oxygen concentrations, accepting inconsistencies and non-continuous transitions along the sub-basin's edges as well as between single months of the posterior corrected oxygen concentrations (Piehl et al. [preprint – rejected in its current form], https://doi.org/10.5194/bg-2023-152, 2023).

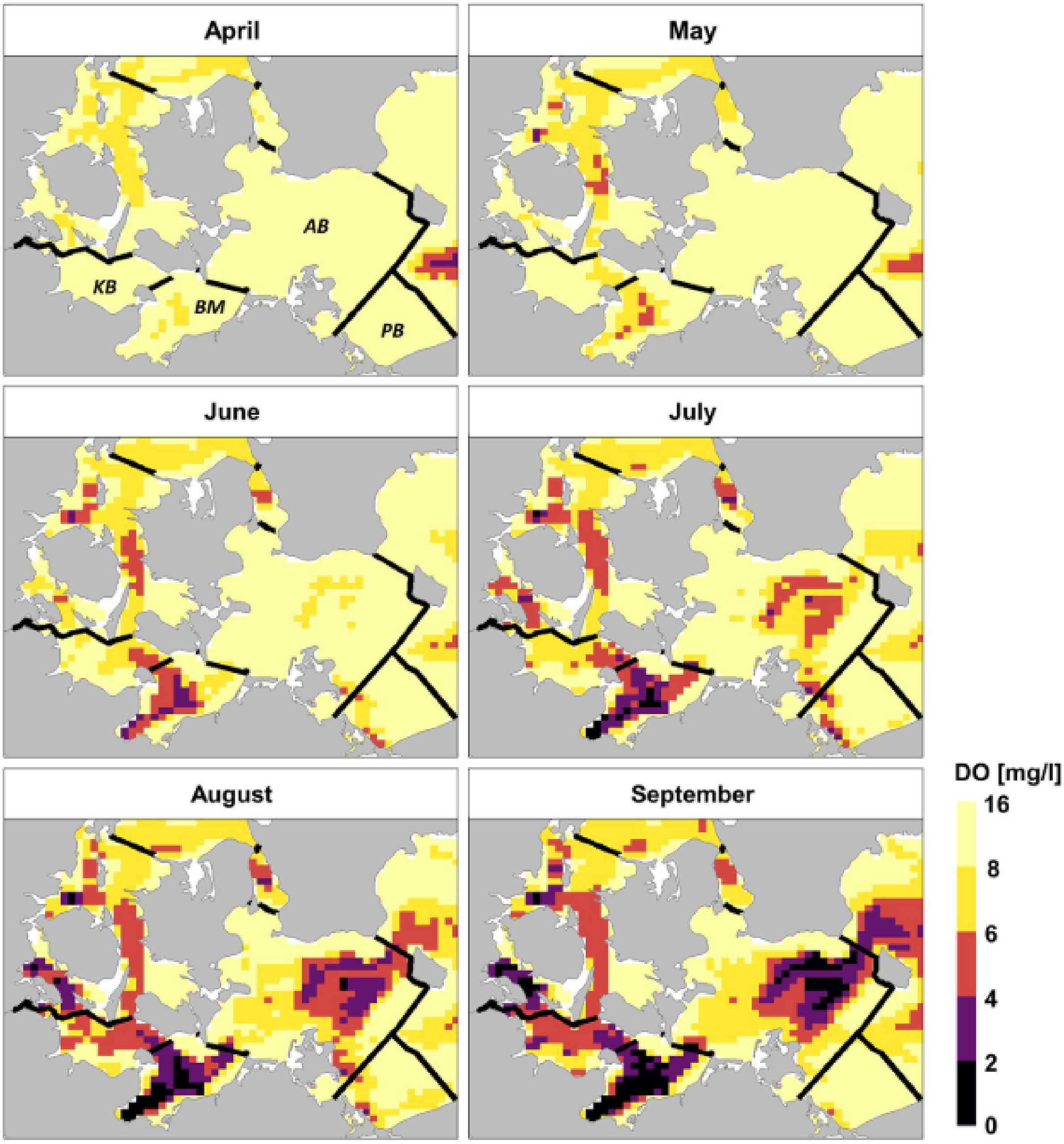
Exemplarily, two alternative approaches were tested for the Arkona Basin whereby only the temporal highly resolved data from the MARNET station Arkona Becken was used (https://www.bsh.de/EN/TOPICS/Monitoring_systems/MARNET_monitoring_network/_Module/Karussell/_documents/measuring_stations_baltic_sea_node.html).

4.2 Results and discussion

4.2.1 Analysis of spatio-temporal variability of near-bottom oxygen deficiency

In general, the simulation results showed that the spatial extent and duration of oxygen deficiencies differed between sub-basins (Fig. 10, Table 4).

Figure 10: Modelled average monthly oxygen concentrations (DO [mg/l]) in the near-bottom water layer from April to September for the period 2011 to 2016 in the western Baltic Sea (for standard deviation see SI 3). Black lines indicate sub-basin divisions according to HELCOM (KB, Kiel Bay; BM, Bay of Mecklenburg; AB, Arkona Basin; PB, Pomeranian Bay). Country borders in grey.



Source: Piehl et al. 2022

According to our results critical periods of hypoxia were observed within the HOLAS II period (2011-2016) in the Bay of Mecklenburg (21 % in September) and in the Arkona Basin (10 % in September), which coincides with the fact that they have on average the greater depths in terms of area as compared to the other two. But, during summer, hypoxia was also observed in a small area in the Kiel Bay (7 % in September) and in the Pomeranian Bay (2 % in July; Fig 10, Table 4). The fact that the maximum hypoxic area in the Pomeranian Bay is reached as early as July could be explained by faster rising water temperatures rise in this area due to the shallower water depth, and thus algal growth starts earlier than in the other deeper basins. However, the results should be treated with caution due to the limitations of the model and the only marginal differences between the values.

Table 4: Percentage (%) area affected by critical oxygen concentrations (mg/l) as average over the HOLAS II assessment period (2011–2016). (Source: Piehl et al. 2022)

	Kiel Bay			Bay of Mecklenburg			Arkona Basin			Pomeranian Bay		
Oxygen threshold	< 2	< 4	< 6	< 2	< 4	< 6	< 2	< 4	< 6	< 2	< 4	< 6
April	0	0	0	0	0	3	0	0	0	0	0	0
May	0	0	3	0	3	16	0	0	0	0	0	1
June	0	1	17	0	19	43	0	0	3	1	3	7
July	0	7	31	7	43	63	2	7	16	2	5	10
August	3	19	51	17	56	71	7	17	30	1	4	9
September	7	34	74	21	64	74	10	21	36	0	1	2

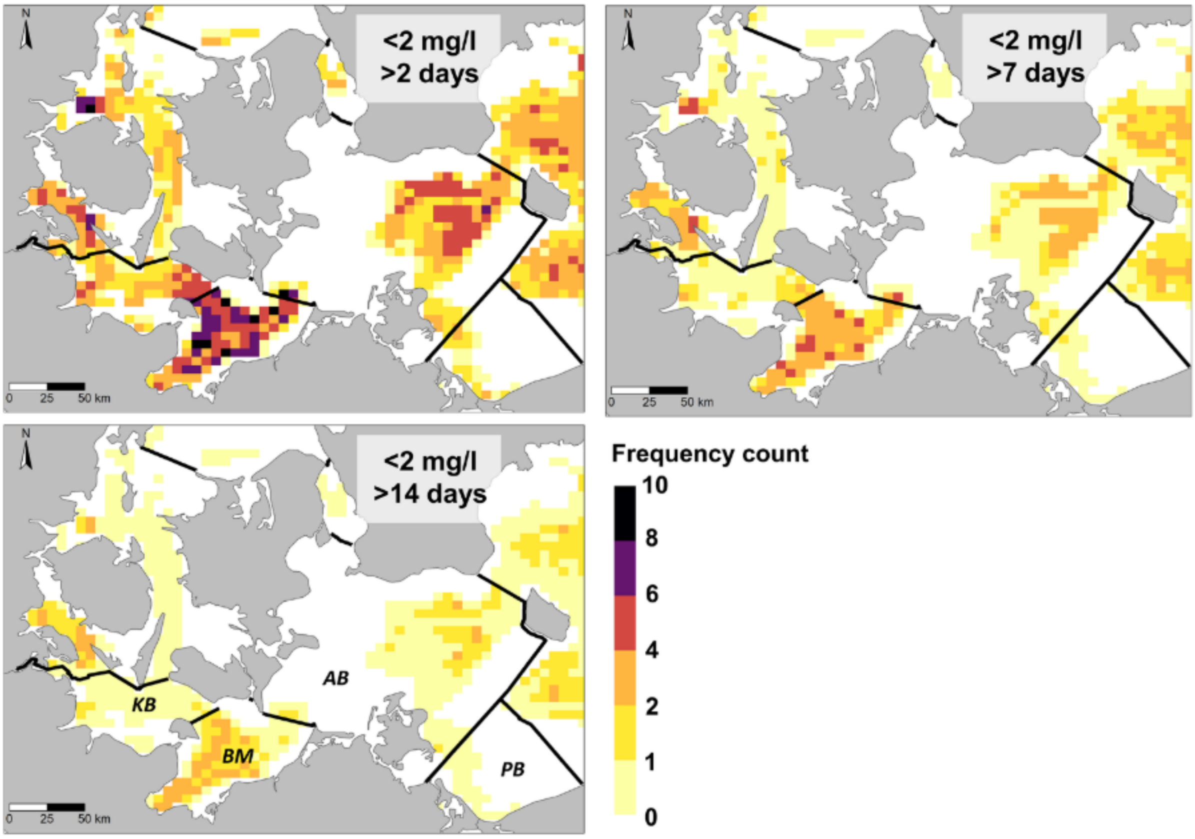
When comparing average annual oxygen concentrations between individual years, differences were not as pronounced as between individual months (SI Piehl et al. 2022); therefore, seasonal variability appears to be more important than inter-annual variability for an assessment. This should be considered in an assessment of long-term trends, i.e., focusing on months with maximum intensity, for example. It should also be considered that the spatial extent and time period of oxygen deficiency were different in each sub-basin, which could become relevant for some assessment units and on a Baltic wide scale. Our model results underline the high spatio-temporal variability of oxygen concentrations for the shallower western Baltic Sea. The non-permanently stratified shallow near-shore areas of the western Baltic Sea are subject to completely different oxygen dynamics than the permanently oxygen depleted deep basins of the Baltic Sea, which needs to be considered within regular oxygen monitoring and assessments.

4.2.2 Assessment of additional oxygen indicator metrics

Besides analysing the near-bottom area affected by oxygen deficiency we also tested various other metrics to be used as oxygen indicator, such as the affected water volume or the average number of days with oxygen concentrations below critical values in the near-bottom water layer.

Considering the water volume affected by oxygen deficiency (<6 mg/l), the Bay of Mecklenburg was most affected (27% in September) followed by Kiel Bay (22% in September). In the Arkona Basin, hypoxia can spread further into the area before it affects the volume of water because of the larger areas of deeper parts, resulting in lower affected areas (9%) as compared to the other two basins (Piehl et al. 2022). The analysis of days with near-bottom oxygen concentrations below 2 mg/l for the western Baltic Sea in the period from 2011 to 2016 showed, that especially the Bay of Mecklenburg is affected by hypoxia with on average 25% of its area experiencing hypoxia between 96 to 180 days per year (Piehl et al. 2022).

Figure 11: Maps showing the modeled frequency of occurrence of hypoxic situations (dissolved oxygen < 2 mg/l) in the near- bottom water layer for specific time periods in the western Baltic Sea. White areas indicate areas where no hypoxic situations occurred during the periods studied. Black lines indicate sub-basin divisions according to HELCOM (KB, Kiel Bay; BM, Bay of Mecklenburg; AB, Arkona Basin; PB, Pomeranian Bay). Country borders in gray.



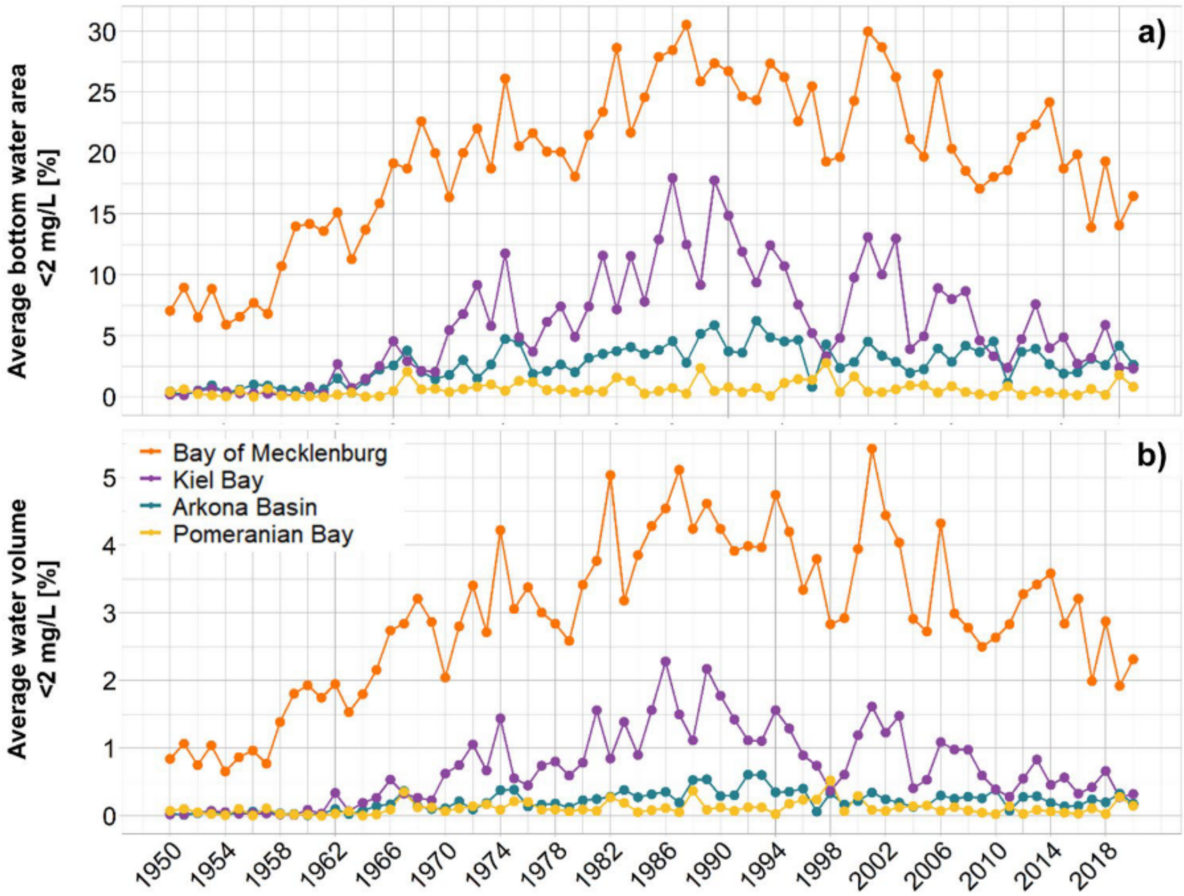
Source: Piehl et al. 2022

Most important for assessing adverse impacts on biodiversity is the analysis of the periods during which oxygen levels have dropped below critical levels. Most critical here would be again the Bay of Mecklenburg, exhibiting large areas which experience hypoxia for more than 2 weeks about 2 to 4 times per year (Fig. 11). A time span which can lead to the collapse of benthic communities due to the oxygen deficiency and/or the associated release of toxic hydrogen sulphide from the sediments (Diaz and Rosenberg 1995; Janas et al. 2004; Villnäs et al. 2012).

4.2.3 Long-term analysis of oxygen deficiency

Long-term analysis of the percentage of the near-bottom water layer (and water volume) affected by hypoxia shows for the Kiel Bay and the Bay of Mecklenburg that the affected areas were at a similar level from about 1950 to 1960, despite annual fluctuations, before increasing steadily until the late 1980s (Fig. 12). However, the observed trend reversal from the 21st century onwards must be viewed critically in view of the current model limitations and other studies that come to contradictory conclusions (Kõuts et al. 2021; Krapf et al. 2022).

Figure 12: Modeled long-term trend of the average spatial extent of the near-bottom water area (a) and water volume (b) with oxygen concentrations < 2 mg/l as percentage from 1950 to 2019 for the four HELCOM sub-basins of the western Baltic Sea.



Source: Piehl et al. 2022

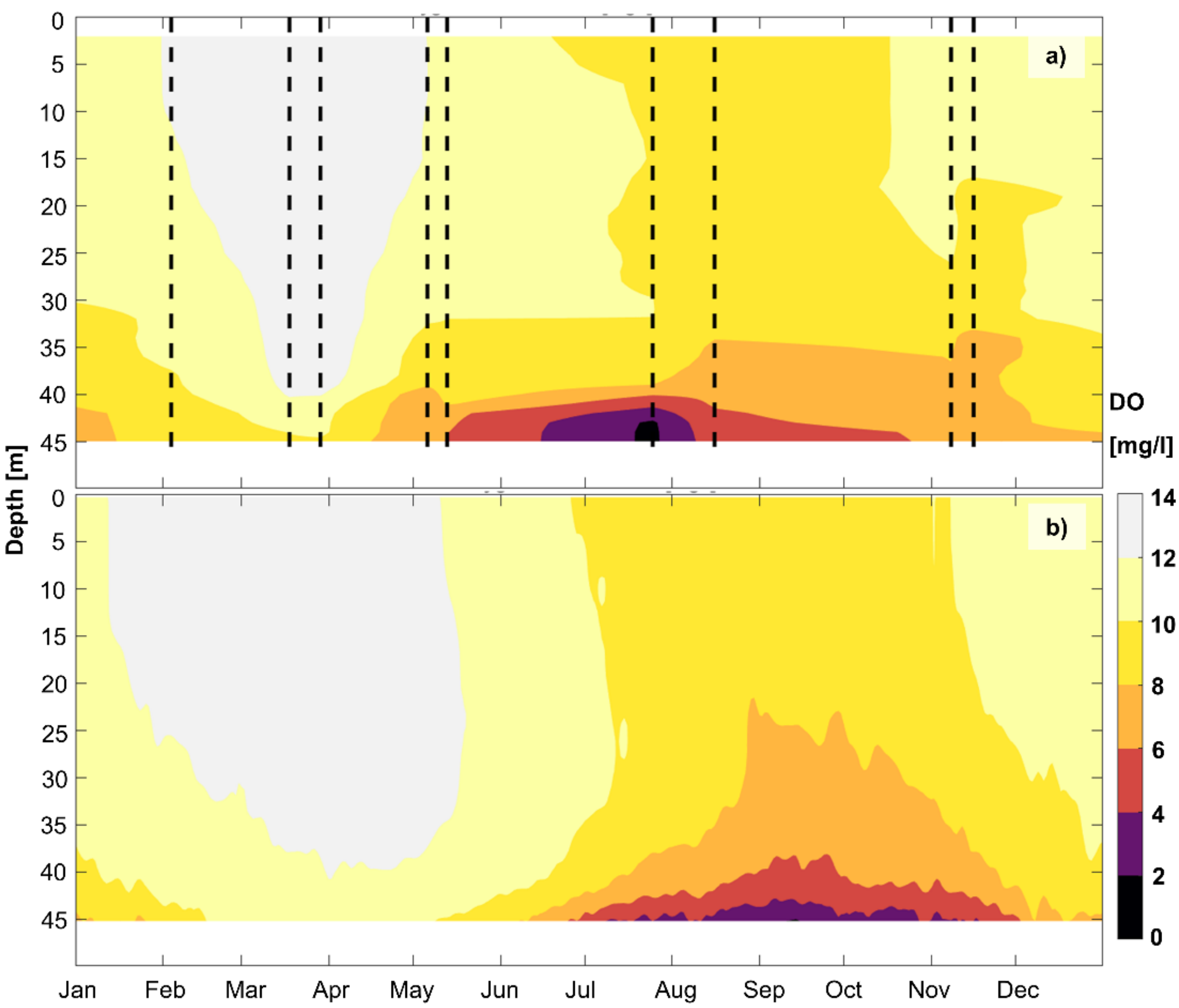
Further research is needed to clarify whether improvements in the hypoxic near-bottom layer and water volume are a result of reductions in nutrient inputs as agreed in 1988 (HELCOM 1988). In addition, the effects of climate change on oxygen levels need to be studied in the future, as this could counteract any improvements. A warmer Baltic Sea is expected to favor hypoxic conditions in the future due to increased water temperature and microbial activity (Meier et al. 2012, HELCOM 2021a). The oxygen consumption caused by the transport of organic material and zooplankton into the depths counteracts the natural ventilation, which further increases the risk (Meier et al. 2018).

However, our long-term analysis shows that the relatively stable situation in the 1950s could be indicative of a situation where oxygen concentrations were not influenced by eutrophication and its natural fluctuations. This is in agreement with other authors referring to a still good ecological status in the 1950s and early 1960s for the eutrophication indicators nutrients and chlorophyll-a (Carstensen et al. 2019, Neumann et al. 2008). However, due to the aforementioned limitations of the 3 NM resolution, it was not yet possible to derive water quality targets for the oxygen indicator. However, as different methodologies have been used to determine reference status and the GES for the new HELCOM shallow water oxygen indicator (https://indicators.helcom.fi/indicator/shallow-water-oxygen/), the provisional target and threshold values for the indicator should be critically considered and reviewed in future.

4.2.4 Model performance

Generally, the model results are available in daily resolution over the entire water depth, allowing a better reproduction of the 3-dimensional distribution of oxygen depleted areas than could be achieved by interpolations of single point observations (Fig. 13).

Figure 13: Comparison of vertically fully resolved dissolved oxygen (DO) concentrations from Arkona Basin station TF113 (see Fig. 1 Piehl et al. 2022) from the year 2015. Observations (a) were interpolated in time between the single measurements (the dashed line indicate the single measurements), while model results (b) are already available in daily resolution.

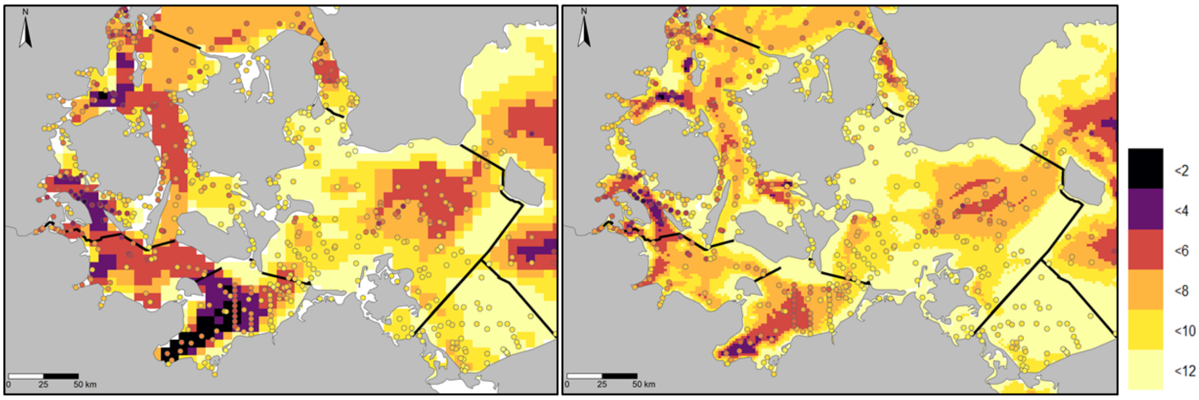


Source: Piehl et al. 2022

For example, our 3 NM model achieves about a 10 times higher resolution than the current national approach in Germany, which is based on spatial integration of observations. Moreover, due to the high effort involved, current monitoring methods can only provide sporadic measurements over weeks, months, or years. To obtain information on whether hypoxia or oxygen deficiency situations can be threatening for organisms, daily resolved data is required at least for the critical period.

Despite a generally good fit, the model results have weaknesses. The validity of our results is mainly affected by the fact that the model does not reflect the measured oxygen data everywhere in the western Baltic Sea, especially in the coastal areas (Fig. 14). This is probably due to the complicated topography of the western Baltic Sea, where fine structures cannot be represented by the current horizontal model resolution of three nautical miles. On the other hand, the observation of oxygen minima near the ground is difficult because the area with very low oxygen concentrations is limited to a thin layer above the ground ("fluffy layer"), which is hardly accessible with in-situ measurements, resulting in near-bottom measurements within a range of 0.5 to 4 m above the bottom. This makes a direct comparison of difficult and could explain why the measured oxygen concentrations are mostly higher than the model results, especially in the mud-dominated areas such as the Mecklenburg Bay. In order to better resolve both the coastal areas and the fine structures of the bottom topography, and thus further improve the model results, a 1 NM run was carried out as a next step.

Figure 14: Comparison of the multiannual mean near-bottom oxygen concentrations (mg/L) for the period 2010-2019 from observations (circles) and model predictions with a spatial resolution of 3 NM (left) and 1 NM (right).



Source: adapted from Piehl et al. [preprint – rejected in its current form], https://doi.org/10.5194/bg-2023-152, 2023)

The 1 NM model system generally reproduces the spatial gradients in the western Baltic Sea better than the 3 NM model system (Fig. 14, Table 5), except for the Pomeranian Bay. Model predictions and measurements agree particularly well in Bay of Mecklenburg (r=0.80, RMSE=1.24, AE=0.03) and Arkona Basin (r=0.76, RMSE=1.19, AE=0.50). The largest differences between measured and model values of the near-bottom oxygen values appear in the Kiel Bay (r=0.36, RMSE=1.61, AE=0.69) and Pomeranian Bay (r=0.05, RMSE=1.71, AE=0.95). The smaller number of measurements for comparison with the model data could play a role here, so that contradictory measurements from neighbouring stations have a stronger effect (Piehl et al. [preprint – rejected in its current form], https://doi.org/10.5194/bg-2023-152, 2023).

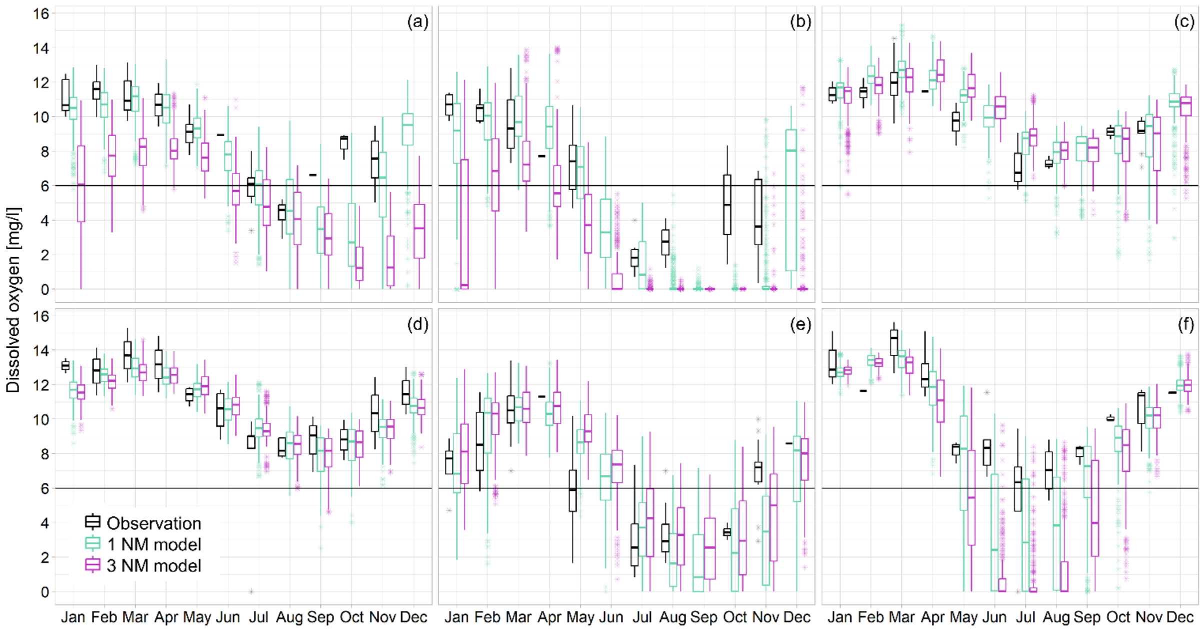
Table 5: Error statistics to assess model-data misfits of the multiannual mean near-bottom oxygen concentrations (2010-2019) for the two model resolutions. Spearman Rank correlation coefficient (r), Root Mean Squared Error (RMSE), Average Error (AE). (Source: Piehl et al. [preprint – rejected in its current form], https://doi.org/10.5194/bg-2023-152, 2023)

Error statistic	r		RMSE		AE	
Model resolution	**1NM**	**3NM**	**1NM**	**3NM**	**1NM**	**3NM**
Kiel Bay (34/25)	0.36	-0.25	1.61	2.41	0.69	-1.01
Bay of Mecklenburg (78/72)	0.80	0.73	1.24	3.69	0.03	-2.80
Arkona Basin (187/168)	0.76	0.61	1.19	1.42	0.50	0.00
Pomeranian Bay (43)	0.05	0.36	1.11	1.38	0.57	-0.36
SW Baltic Sea (692/570)	0.79	0.60	1.71	2.09	0.95	-0.15

Comparing the spatial model skill of the 1NM model with those of the 3NM model, the correlation improves by 32% and the error (RMSE) decreases by 18% for the south-western Baltic Sea, with the largest improvements in the Kiel and Mecklenburg Bays (Table 5). In contrast to the 1NM model, the 3NM model underestimates near-bottom oxygen concentrations for all sub-basins (AE >0; Table 5).

Generally, the 1NM model represents the seasonal cycle better than the 3NM model as can be seen for the stations TF0360, TF0022, and OB2 (Fig. 15). Particularly for the two near-shore stations TFO5 in the Bay of Mecklenburg and O9 in the Arkona Basin the seasonal cycle is well reproduced by both models (Fig. 15 c,d; Piehl et al. [preprint – rejected in its current form], https://doi.org/10.5194/bg-2023-152, 2023).

Figure 15: Comparison of the seasonal cycle of near-bottom oxygen concentrations (2010-2019) from observations (black) and model predictions at the same time with two different spatial resolutions (1NM in turquoise and 3NM in pink) in (a) the Kiel Bay (station TF0360), (b) and (c) the Bay of Mecklenburg (stations TF0022 and TFO5 respectively), (d) and (e) the Arkona Basin (stations O9 and TF0113 respectively), and (f) the Pomeranian Bay (station OB2).



Source: adapted from Piehl et al. [preprint – rejected in its current form], https://doi.org/10.5194/bg-2023-152, 2023)

Even though the agreement between modeled and measured values is generally good, there are still some discrepancies. In order to reduce the bias between the modeled values and the observed values, in a next step we have investigated the factors that influence the bias. Based on this, we derived a correction function which was used to retrofit the modeled data to the measured data.

4.2.5 Evaluation of retrospective model corrections

If all available observations are included (near-bottom oxygen values and profiles) the bias between observations and model predictions is mainly influenced by sampling depth (improvement of the RMSE by about 10%) followed by maximum depth and percentage of mixed layer depth (improvement of RMSE ~8% each), and finally distance to shore (improvement of RMSE of ~7%). When only taking the near-bottom oxygen measurements into account the maximum depth is equally important than sampling depth (improvement of RMSE ~16% each). When analyzing oxygen profiles alone, the most important factor is sampling depth (improvement of RMSE ~10%) followed by all other parameters (improvement of RMSE ~7% each; Piehl et al. [preprint – rejected in its current form], https://doi.org/10.5194/bg-2023-152, 2023).

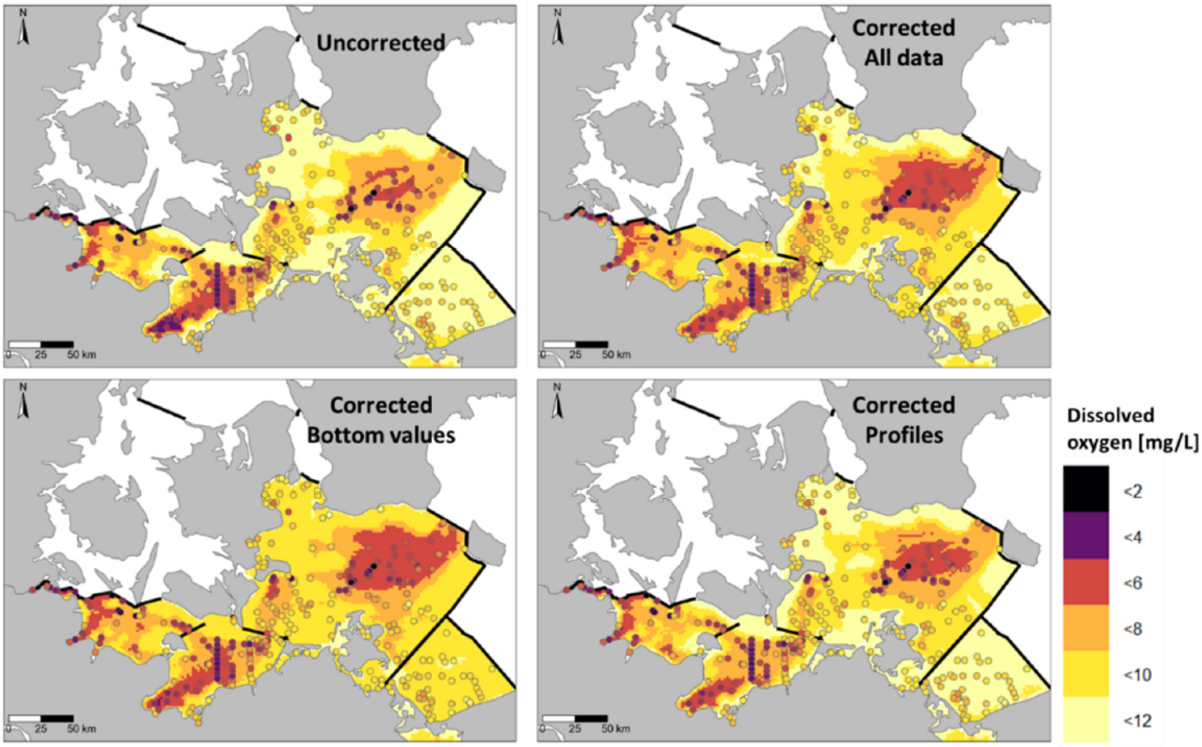
Considering the four sub-basins and including all data in the correction function of the corrected 1NM run, the spatial fit of the near-bottom oxygen values increases (decrease in RMSE by ~10% compared to the uncorrected run) and leads to an improvement in model skill in almost all basins (except correlation coefficient r, Table 6). Correction based only on bottom values results in poorer model skill in the Arkona Basin (increase in RMSE by ~12%) and correction based only on profiles results in poorer model skill in the Pomeranian Bay (increase in RMSE by ~40%) compared to the uncorrected model results (Table 6; Piehl et al. [preprint – rejected in its current form], https://doi.org/10.5194/bg-2023-152, 2023).

Table 6: Error statistics to assess model-data misfits of the multiannual mean near-bottom oxygen concentrations (2010-2019) for the corrected model results either based on near-bottom oxygen values (Bottom values), oxygen profiles (Profiles) or both data sources (All data). Spearman correlation coefficient (r), Root Mean Squared Error (RMSE), Average Error (AE), Modelling Efficiency (ME). (Source: Piehl et al. [preprint – rejected in its current form], https://doi.org/10.5194/bg-2023-152, 2023)

Basin	Correction	R	RMSE	AE	ME
Kiel Bay	None	**0.28**	**1.61**	**0.69**	**-0.41**
	All data	0.23	1.42	0.22	-0.10
	Bottom values	0.26	1.41	0.15	-0.09
	Profiles	0.27	1.57	0.49	-0.35
Bay of Mecklenburg	None	**0.78**	**1.24**	**0.03**	**0.38**
	All data	0.78	0.99	-0.01	0.60
	Bottom values	0.79	1.04	-0.39	0.56
	Profiles	0.78	1.14	0.36	0.48
Arkona Basin	None	**0.72**	**1.19**	**0.50**	**0.39**
	All data	0.72	1.11	-0.23	0.47
	Bottom values	0.72	1.34	-0.73	0.23
	Profiles	0.72	1.17	0.24	0.41
Pomeranian Bay	None	**0.19**	**1.11**	**0.57**	**-1.51**
	All data	0.30	1.05	0.57	-1.27
	Bottom values	0.34	0.88	-0.47	-0.58
	Profiles	0.12	1.55	1.11	-3.91
All basins	None	**0.78**	**1.23**	**0.41**	**0.46**
	All data	0.79	1.11	-0.04	0.57
	Bottom values	0.77	1.23	-0.54	0.46
	Profiles	0.77	1.25	0.39	0.45

With changes of r<0.1 the improvement of the linear correlation between observations and model predictions is only marginal besides the Pomeranian Bay. Here, a maximum improvement in r of 0.28 if considering only the bottom values for correction is achieved (e.g., Pomeranian Bay, Table 6).

Figure 16: Comparison of the multiannual mean near-bottom oxygen concentrations (2010-2019) from observations (circles) and model predictions with a spatial resolution of 1NM for the uncorrected and retrospective corrected model results. Black lines indicate sub-basin divisions.



Source: Piehl et al. [preprint – rejected in its current form], https://doi.org/10.5194/bg-2023-152, 2023)

Major influences of retrospective model corrections are seen for the Bay of Mecklenburg and the Arkona Basin as compared to the uncorrected model results (Fig. 16). Looking at all three aspects of model performance (spatial near-bottom oxygen, near-bottom oxygen and oxygen profiles of selected stations), the correction of the model results mostly improves the RMSE in the Bay of Mecklenburg and Kiel Bay, followed by the Arkona Basin and Pomeranian Bay (Piehl et al. [preprint – rejected in its current form], https://doi.org/10.5194/bg-2023-152, 2023).

The comparison of the retrospective corrected model results with the uncorrected ones of the 1 NM model run has shown that the correction led to only minor improvements in the linear correlation (r) of observations and model predictions. Overall, the RMSE for the corrected model results improves compared to the uncorrected 1 NM run. However, the improvements in the RMSE for individual stations must be contrasted with a deterioration in the RMSE of other stations. Although the ME improves when a correction is based on either all oxygen data or oxygen profile data alone, the improvement is <0.2 when considering near-bottom oxygen, and marginal when comparing oxygen profiles (~0.04 of the ME value). Considering the Kiel Bay and the Bay of Mecklenburg, the results of the different correction functions do not show a consistent pattern (Piehl et al. [preprint – rejected in its current form], https://doi.org/10.5194/bg-2023-152, 2023).

Most of the limitations of a retrospective correction and a subsequent assessment of the model skill can probably be explained by the spatio-temporal heterogeneous observational data, as well as a non-homogeneous bias between measurements and model values among the available observational data (Fig. 14). The latter leads to the problem that corrected model results derived from correction functions that include all stations do not always lead to improved model skill for individual stations. In general, correcting model data retrospectively means sacrificing transparency and is very difficult to evaluate externally. Furthermore, none of the correction functions was superior in the sense that it gave significantly better results for all sub-basins. The use of different correction functions (based on different databases) might improve the model results but would reduce the comprehensibility and the transparency of the method further (Piehl et al. [preprint – rejected in its current form], https://doi.org/10.5194/bg-2023-152,).

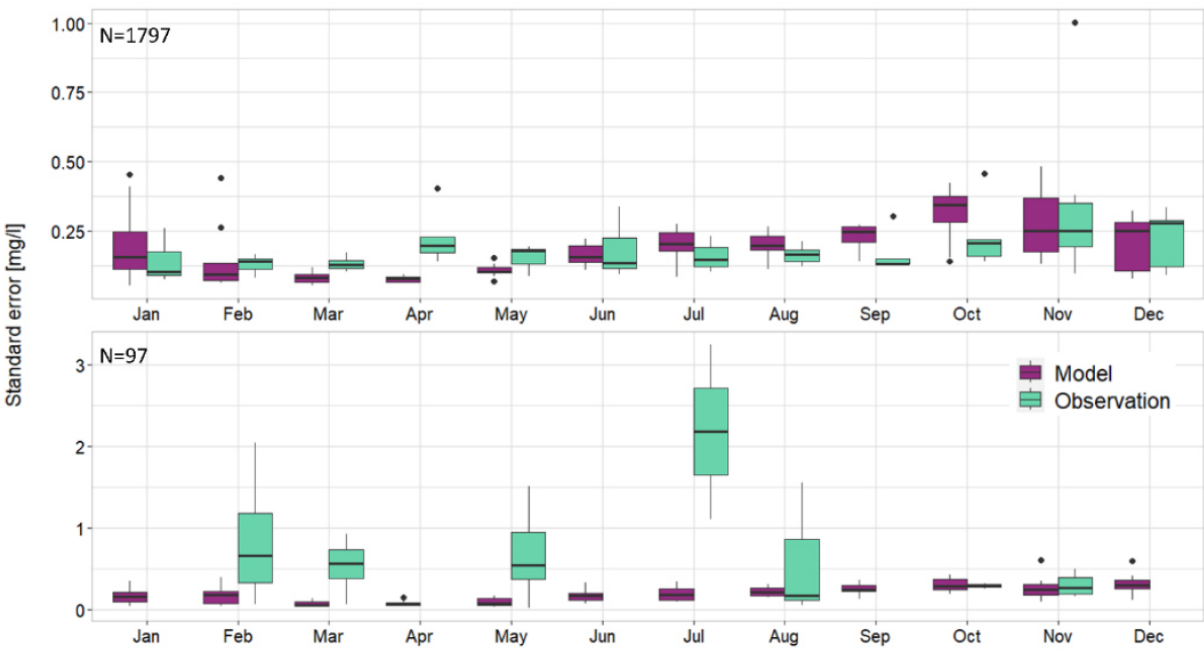
The outcome of correcting model data using observational data relies on the quality of the observational data utilized for the correction. Although the observational data set initially seemed large, a vast amount of unusable data was excluded due to selection based on specific regions, years, and/or months as well as removing implausible data. It should be noted that, at some stations, data for monthly measurements were available only once over a ten-year period, and for some months data were not available at all (Piehl et al. [preprint – rejected in its current form], https://doi.org/10.5194/bg-2023-152, 2023).

Thus, our second approach was focusing exemplarily on the Arkona Basin and where high temporal resolved data from one representative station located in the center of the sub-basin was available.

4.2.6 Correction based on one temporal highly resolved station

As can be seen by the comparison of the standard error of the temporally high resolved MARNET station and e.g., the station TF0113 in the Arkona Basin (Fig. 17) the precision of the estimate of the mean increases (i.e., decreasing SE) drastically with increasing observations. The high temporal resolution of the MARNET station is especially advantageous in the critical month of the development of seasonal oxygen deficiency from July to November, resulting in lower standard errors as compared to the uncorrected model results (Piehl et al. [preprint – rejected in its current form], https://doi.org/10.5194/bg-2023-152, 2023).

Figure 17: Average monthly standard error (2010-2019) of observed and modelled oxygen concentrations at 40 m depth for the MARNET station (top) and the station TF0113 (bottom) in the Arkona Basin.



Source: Piehl et al. [preprint – rejected in its current form], https://doi.org/10.5194/bg-2023-152, 2023)

If only utilizing the MARNET station data for comparison, the linear correlation increases from 0.79 to 0.82 and the RMSE decreases from 2.19 to 1.67 for the corrected model results based on the same station. The tendency of the uncorrected model result to overestimate oxygen concentrations (AE = 1.34) changes for the corrected model results to a slight underestimation (AE = -0.18). A significant improvement is seen in model efficiency, which nearly doubles from 0.32 to 0.6 (Piehl et al. [preprint – rejected in its current form], https://doi.org/10.5194/bg-2023-152, 2023).

The average observed and modelled oxygen concentration at 40 m depth for the assessment period (2011-2016) are 7.40 mg/l and 8.68 mg/l, respectively. The correction factor applied to the model data is 0.85 accordingly. After application of the correction factor the one-to-one comparison of corrected model values and observations from the MARNET stations leads overall to improved model skill metrics for the station (r = 0.79, RMSE = 1.64, AE = 0.01, ME = 0.62).

Comparison of modelled and observed values after applying the correction function as well as the correction factor resulted in the expected improved model skill metrics for that station. A reliable improvement in the model's results can only be attained if high reliable measurement data is utilized, i.e., with a high precision of the estimate of the mean as it is the case for the MARNET station. Nevertheless, it should be noted that the station observations are not taken at the maximum depth, but five meter above bottom, which may has influenced the derived correction function as well as correction factor. Moreover, if the hypoxic water volume needs to be assessed, a correction factor preferably should also be derived from a station which combines both, a high temporal as well as vertical resolution (Piehl et al. [preprint – rejected in its current form], https://doi.org/10.5194/bg-2023-152, 2023).

4.2.7 Conclusion

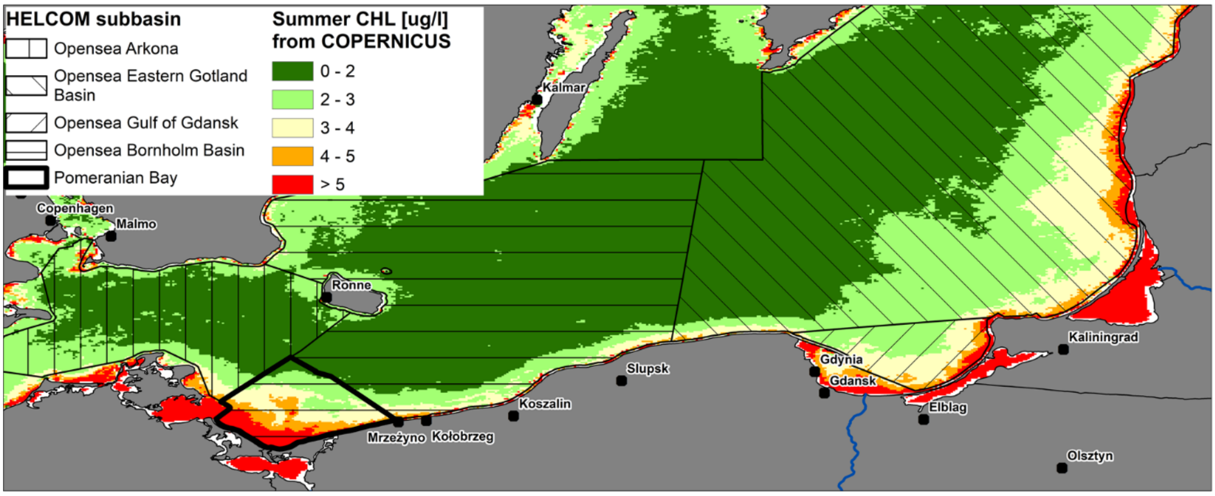
Our model simulations with a spatial resolution of 3 NM showed that seasonal oxygen deficiency is a suitable indicator for describing the ecological status of the western Baltic Sea, where seasonal and episodic rather than perennial hypoxia and oxygen deficiency occurs. Depending on the objective of the assessment, all examined metrics are suitable for use. Combining the temporal and the spatial component can play a crucial role to assess the ecosystem health. Further we could show, that likewise to nutrients and chlorophyll-a, the situation in the 1950s may be regarded as “good status,” including naturally occurring oxygen deficits in the western Baltic Sea. However, because the absolute values of the calculated metrics were overestimated by the 3 NM model, our current approach was not yet suitable for deriving reference and related target values for the oxygen indicator metrics. With the 1 NM model, it remains to be verified whether the target values and assessments of shallow water oxygen proposed by HELCOM for the latest assessment period (HOLAS III), which are based on different methods and also include a somewhat different reference period (1949-1969), are plausible.

A major advantage of model simulations is that they provide spatio-temporal high-resolution data, which is especially important for dynamic water parameters such as seasonal oxygen deficiency. Refining the horizontal resolution of our model to 1 NM, improved the oxygen dynamics in the coastal and open sea areas (EU-MSFD) of the southwestern Baltic Sea. Nevertheless, model simulations always have some short-comings and thus an integrated approach is needed to combine model results with observations in a suitable way. Although for some aspects our combined approach resulted in partly better model skill metrics, this was not consistent across all sub-basins and/or stations considered, and aspects of model skill analyzed. One reason for this is likely the heterogeneous measurement data utilized to derive the correction functions, which are not consistent in their temporal and vertical resolution. Using the Arkona Basin as an example, we show a future path in where only temporal and/or vertical high-resolution observations are integrated with model data to achieve the highest possible confidence in the assessment. End-user need to be involved in the next steps in order to develop a strategy for confidence assessment (considering the scope, aims and resolution of the application domain of the model) meeting the requirements for management decisions.

5 Influence of the Oder river plume

All water quality indicators have substantial gradients in Bornholm Basin (see Fig. 18), induced by the strong import of nutrients from the major rivers, like Oder (Odra) or Vistula. The combination of this natural gradients with an unrepresentative distribution of monitoring stations resulted in the Bornholm Basin in a strong bias of the eutrophication assessments, like HOLAS II. Therefore, an additional assessment unit was introduced to separate the region highly influenced by the Oder River plume from the Bornholm Basin. The new assessment unit is called "Pomeranian Bay". Therefore, it was necessary to adjust the GES thresholds of the eutrophication indicators for the new assessment unit. Using our model simulations (described in the sections before), these new thresholds were derived for Pomeranian Bay and introduced by UBA at the HELCOM State & Conservation meeting on September 7 (STATE&CONSERVATION 15-2021), where they got adopted by the HELCOM member states. A summary of our work is presented here, while detailed information can be found at Friedland et al. (2021).

Figure 18: Mean Summer-Chlorophyll conc. (taken from COPERNICUS CMEMS 2023) in the southern Baltic Sea.

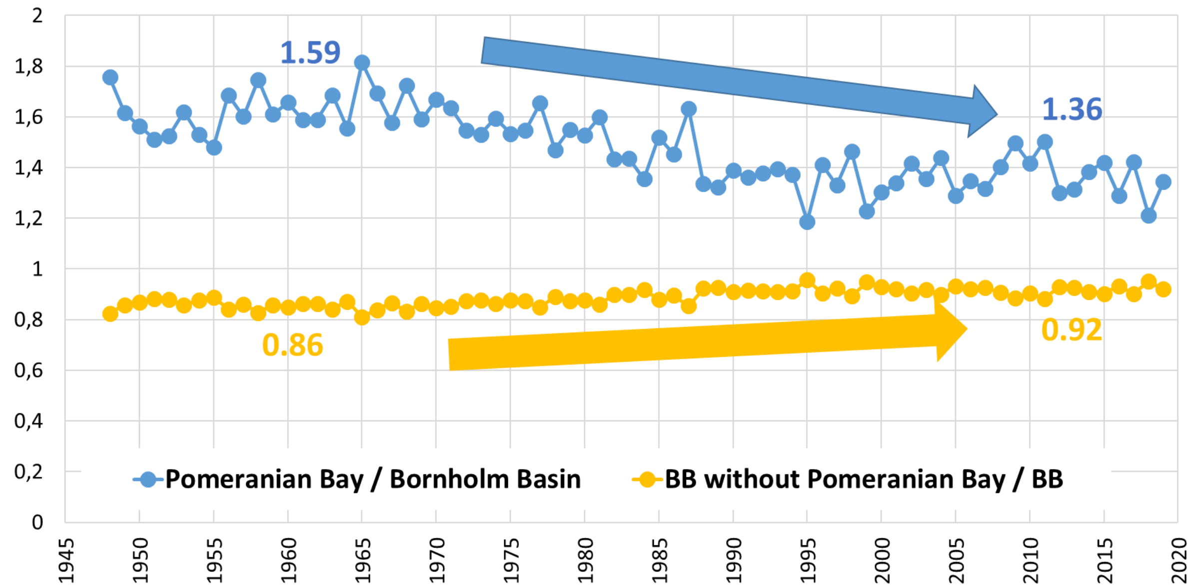


Source: Friedland et al. 2025

5.1 Materials and Methods

The model set-up as described in section 2.2 was utilized for all analysis. Oder river loads are of special interest for the Pomeranian Bay and are in agreement with publications by Friedland et al. (2019) and Schernewski et al. (2008). To derive the target values for the new area the spatially averaged concentrations of the relevant eutrophication indicators were calculated for the original Bornholm Basin assessment unit, as well as for Pomeranian Bay and the remaining part of Bornholm Basin. By bringing those values in relation to each other (see Fig. 19, showing the long-term development of Summer-Chlorophyll from Pomeranian Bay compared to the whole Bornholm Basin), we were able to transfer the currently valid target values of the Bornholm Basin to the new region. As GES thresholds for total nutrients (concentrations of TN and TP) have not yet been established for the original Bornholm Basin, we used the three GES thresholds proposed by TARGREV (HELCOM): TARGREV (HELCOM 2013b), Germany (IN-EUTROPHICATION 5-2016 Doc 4-4) and Poland (HELCOM IN-EUTROPHICATION 5-2016).

Figure 19: Ratio of the mean Summer-Chlorophyll concentration of Pomeranian Bay divided by the original Bornholm Basin assessment unit (blue), as well as for the remaining part of it (yellow). The spatially averaged Chlorophyll concentrations are taken from ERGOM-MOM.



Source: own illustration, Leibniz Institute for Baltic Sea Research Warnemünde

5.2 Results and discussion

5.2.1 Proposed GES thresholds

Our suggested target values for Pomeranian Bay for Summer-Chlorophyll as well as Winter-DIN and -DIP from the STATE & CONSERVATION 15-2021 document are shown in Table 7 and for total nutrients in Table 8 accordingly. The results of our model approach are highlighted in grey in both tables. The suggested new GES thresholds were computed by multiplying the existing threshold values with the factors computed from the spatially averaged model results (Fig. 19). By following this approach, harmonized GES targets were derived, which based on the already agreed ones.

Table 7: Present GES threshold concentrations for winter nutrients and summer chlorophyll-a as applied in the HOLAS II assessment (HELCOM 2018a, b, c) and proposed threshold values in the new assessment units. The Arkona Basin is shown for reference. Table from IN-EUTROPHICATION 21-2021 document.

		Summer Chl-a [µg/l]	Winter DIN [µmol/l]	Winter DIP [µmol/l]
Present threshold	Arkona Sea	1.8	2.9	0.36
	Bornholm Basin (BB)	1.8	2.5	0.30
Proposed threshold value for HOLAS III	Pomeranian Bay (PB)	2.86	5.53	0.40
	Remaining part of BB	1.55	1.80	0.28

Following the natural gradients from the river plume to the deep basins, the suggested GES thresholds for the Pomeranian Bay were all higher than the existing ones (from TARGREV) for the original Bornholm Basin, while the suggested ones for the remaining part of Bornholm Basin were lower (Tables 7, 8).

Table 8: Derived GES thresholds for TN and TP concentrations following the different proposals (HELCOM 2013; IN Eutrophication 52016 Doc 4.4; CORE-EUTRO 7-2012 Doc 3/9/Add. 1). In the original TARGREV report (HELCOM 2013b) the German data from the 1-12 nm area were missing, therefore different targets were proposed. An update of results is included in CORE EUTRO 7-2012 Doc. 3/9/Add. 1). The Arkona Basin is shown for reference. Table from IN-EUTROPHICATION 21-2021 document.

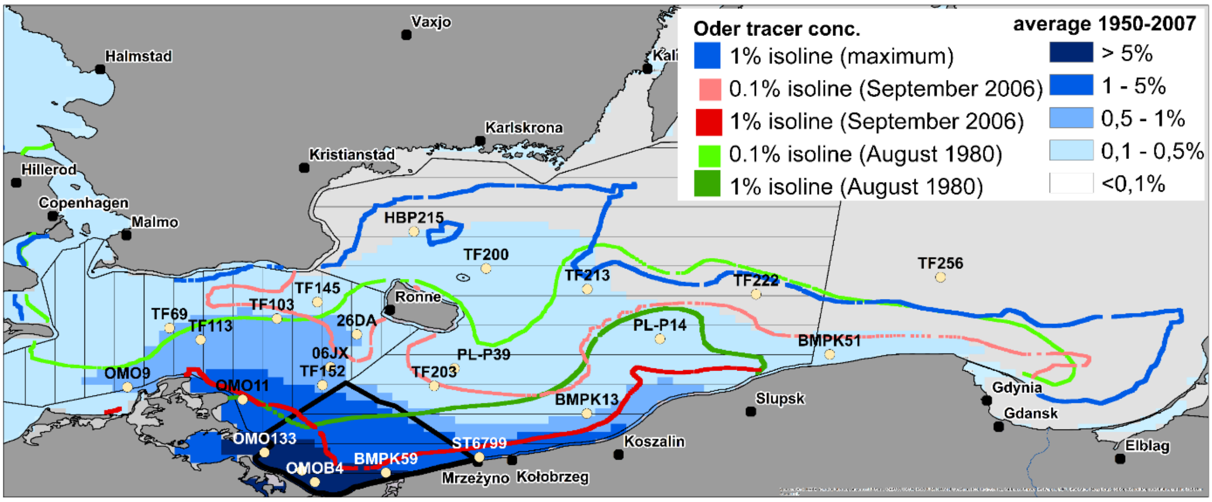
	Arkona Sea	Bornholm Basin	New proposal for Pomeranian Bay based on	New proposal for Remaining part of BB based on
Total Nitrogen concentration [µmol/l] – annually averaged				
TARGREV target (<) without/with German data	17.39/17.25	16.05/16.05	21.2	14.8
German threshold proposal	19.5	18.0	**23.8**	16.7
Polish threshold proposal		14.4	19.1	13.3
Total Phosphorus concentration [µmol/l] – annually averaged				
TARGREV target (<) without/with German data	0.67/0.66	0.54/0.55	0.68/0.69	0.51/0.52
German threshold proposal	0.48	0.59	**0.74**	0.55
Polish threshold proposal		0.61	0.77	0.57

5.2.2 Using model-based techniques to derive an optimized assessment unit

To allow an improved identification of the region strongest affected by the Oder plume, our model setup was expanded to be able to follow the Oder plume in its temporal and spatial distribution. Thereby, we distinguished the region purely influenced by the freshwater runoff (see Fig. 20) and the region affected by the imported nutrients. Depending on the weather conditions, the area with high river tracer concentration extended as far as Denmark and Sweden, but also along the Polish coast into the Gulf of Gdansk. The extent of the plume area is strongly dependent on the freshwater discharge of the Oder (with a phase shift of 5 months) and partly shaped by wind conditions. On the other hand, the marine regions where nitrogen and phosphorous originated from the Oder can also be identified (as shown by Radtke et al. 2012). By combining both regions, we proposed an alternative shape of the newly developed Pomeranian Bay assessment unit (see Fig. 21), which was purely basing on the Oder plume. Showing that the model simulations are a beneficial tool for analyzing the spatial-temporal dynamics of the river plumes in the Baltic Sea basins, the model-based methods may additionally allow to adjust other assessment units in future.

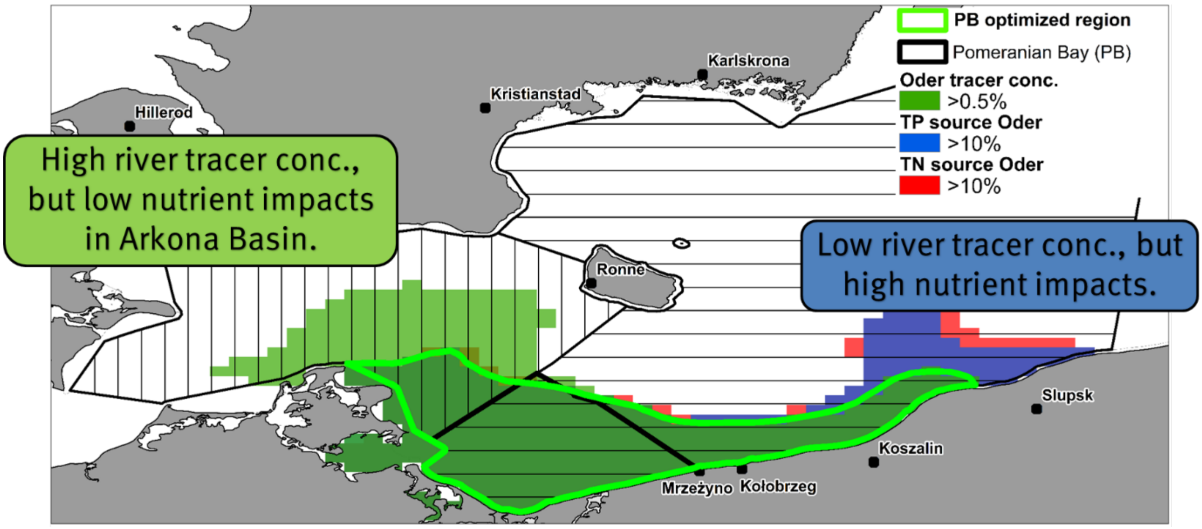
Figure 20: Distribution of the Oder river tracer (scaled to 100% at the river mouth). Color-coded is the average over the simulation period. The green contour lines indicate the maximal distribution, where still 1% of the tracer occurred, while the red and

black isolines reflect situations with extraordinary low values (red) or a strong eastward dispersion.



Source: Friedland et al. 2025

Figure 21: Suggestion for a refined area referring to the Pomeranian Bay based on the modelled distribution of the Oder tracer and the nutrient source appointment.



Source: Friedland et al. 2025

5.2.3 Conclusion

The proposed method to revise the GES thresholds for the new assessment units seems appropriate as the derived thresholds are consistent with the existing (and already adopted) ones, while following also the natural gradients. We were further able to show how the area of the new assessment unit Pomeranian Bay could have been delimited, if only the influence of the Odra plume is considered. It was possible to distinguish the regions that are particularly strongly influenced by freshwater inputs and nutrient inputs. The approach may get transferred to other assessment units of the Baltic Sea, which also insufficiently take the natural gradients into account, as they arise, for example, due to high water-bound nutrient inputs. Model simulations can be used both to identify appropriate assessment units according to their hydrodynamic conditions and the influence of freshwater inputs, and as a basis for making the distribution of monitoring stations more representative in the future.

6 Reporting, Management, Discussion rounds

In addition to regular project meetings to discuss the status of the work and current developments of the HELCOM work, discussion forums led by UBA and IOW were an essential part of the project. At the national level, the state offices (LUNG, LfU-SH) and other interested representatives of national expert working groups (e.g. EuNäP) and scientific institutions were involved. The main objective of the discussion forum accompanying the project was to steer the project in such a way that the results are practical and directly applicable for the implementation of the MSFD and the Baltic Sea Action Plan. The following list includes all project meetings and discussion forums within the project:

- 02.10.2020, Project meeting: Kick-off meeting
- 14.12.2020, Discussion forum: Introduction of the project
- 15.06.2021, Project meeting: Status-quo of work, presentation of first results
- 10.08.2021, Focus group meeting: Oxygen indicator, Target values for new assessment units (proposal to HELCOM)
- 14.10.2021, Discussion forum: Results oxygen indicator and target values for new assessment units
- 25.02.2022, Project meeting: Results nutrient reduction scenarios
- 17.08.2022, Meeting LUNG-MV: Exchange between LfU and IOW on focus areas and thematic priorities
- 31.08.2022, Discussion forum, Results nutrient reduction scenarios, discussion about future relevant topics
- 05.06.2023, Meeting LfU-SH: Exchange with LfU on focus areas and thematic priorities

In addition, the results were presented in relevant HELCOM expert groups, (inter)national symposia and conferences, which are listed in Table 9.

Table 9: List of events where the results of the project have been presented and discussed.

Event	Contribution	Date	Place
IN-EUTROPHICATION 19A-2021	Presentation of our oxygen modelling work to the expert group	22.04.2021	Online
IN-EUTROPHICATION 21-2021	Talk “The project UBA-Eutro: Supporting the HELCOM shallow-water oxygen indicator” Talk “The new assessment unit Pomeranian Bay – Proposal for the GES thresholds and status assessment”	01.-02.09.2021	Online
BSSC 2021: Baltic Sea Science Congress	Talk “Using river plumes to shape assessment units” Talk “Modelling of Water Quality Indicators: Oxygen”	18.-22.10.2021	Aarhus, Denmark
EUNäP	Participation	10.11.2021	Online

Event	Contribution	Date	Place
BfG Workshop zur Gewässergüte-modellierung	Talk “Zur Wasserqualität im Oderhaff: Zustand, Langzeitentwicklung und Zukunftsperspektiven”	15.-16.11.2021	Online
EUNäP	Participation	07.03.2022	Online
53rd Ocean Liège Colloquium / 3rd GO2NE Oxygen Conference	Talk “Modelling of Water Quality Indicators: Seasonal Oxygen Deficiency”	16.-20.05.2022	Liège, Belgium
MUS-BSH: Meeres-umweltsymposium	Poster “Modellsimulationen zur zukünftigen Wasserqualität in der westlichen Ostsee”	18.-19.05.2022	Hamburg, Germany
EUNäP	Participation	28.06.2022	Online
Trilateral discussion on HELCOM oxygen indicator	Results of the comparison of the 1-NM model run with the Danish approach	28.09.2022	Online
KüNO Symposium	Poster “Developing indicators for responses to multiple stressors: seasonal oxygen deficiency”	9.-10.11.2022	Hamburg, Germany
IC PLC WS 1-2022 workshop	Talk “Modelling scenarios demonstrating the achievability of BSAP nutrient reduction targets in the Western Baltic Sea”	22.-23.11.2022	Berlin, Germany
EUNäP	Participation	14.12.2022	Online
OSPAR workshop (ICG-EUT & ICG-EMO)	Participation	21.-23.03.2023	Online
LfU-SH Minisymposium	Participation	21.03.2023	Flintbek, Germany
ICES AG (WGIPEM)	Participation	27.-30.03.2023	Online
MUS-BSH: Meeres-umweltsymposium	Poster “Integrierte Modelle als Managementwerkzeug für die Ostsee“	09.-10.05.2023	Hamburg, Gemany
EUNäP	Participation	04.07.2023	Online
BSSC 2023: Baltic Sea Science Congress	Talk “Biogeochemical models as a tool for improved water quality management in the Baltic Sea” Talk “The effect of further nutrient input reductions on the water quality in the western Baltic Sea”	21.-25.08.2023	Helsinki, Finland

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A Appendix

A.1 Peer reviewed publications

- Arlinghaus, R., T. Rittweg, F. Dhellemmes, D. Koemle, R. van Gemert, H. Schubert, D. Niessner, S. Möller, J. Droll, R. Friedland, W.-C. Lewin, M. Dorow, L. Westphal, E. Ehrlich, H. V. Strehlow, M. S. Weltersbach, P. Roser, M. Braun, F. Feldhege and H. Winkler (2023): A synthesis of a coastal northern pike (Esox lucius) fishery and its social-ecological environment in the southern Baltic Sea: Implications for the management of mixed commercial-recreational fisheries. In: Fish. Res., 2023, 263, Elsevier. doi: 10.1016/j.fishres.2023.106663
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- van Leeuwen, S. M., Lenhart, H.-J., Prins, T. C., Blauw, A., Desmit, X., Fernand, L., Friedland, R., Kerimoglu, O., Lacroix, G., van der Linden, A., Lefebvre, A., van der Molen, J., Plus, M., Ruvalcaba Baroni, I., Silva, T., Stegert, C., Troost, T. A., Vilmin, L. (2023): Deriving pre-eutrophic conditions from an ensemble model approach for the North-West European seas. In: Front. Mar. Sci., 2023, 10, Frontiers. doi: 10.3389/fmars.2023.1129951

A.2 Other publications

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