IOW press release, February 16, 2026

Why the eutrophicated Baltic Sea struggles with recovery – New IOW review highlights key processes and causes

The Baltic Sea has been under pressure for decades: Although phosphorus and nitrogen river loads, the main cause for its eutrophication, have been significantly reduced, adverse effects such as algal blooms and oxygen depletion still massively occur, leading to further ecological problems. Scientists at the Leibniz Institute for Baltic Sea Research Warnemünde (IOW) have now published a comprehensive review showing how nutrient pollution, internal matter cycles and global warming interact, thereby delaying the impact of protective measures. They also identify potential approaches for effective Baltic Sea management. The study was recently published in the Annual Review of Marine Science.

It has been known for more than half a century that the Baltic Sea suffers from eutrophication. Through EU and national legislation, protection programmes such as the Baltic Sea Action Plan of the Helsinki Commission for the Protection of the Baltic Sea (HELCOM) have led to a marked reduction of nutrient pollution from human sources: Since the 1980s, phosphorus loads in rivers have fallen by around 50%, and nitrogen loads by around 30%. More recent data also show this trend: While total phosphorus loads into the central Baltic Sea still exceeded 20,000 tonnes per year in 1995, they had dropped to around 12,400 tonnes by 2017; nitrogen loads from around 520,000 tonnes to just under 400,000 tonnes over the same period.

Despite this, there has been no significant improvement in surface water quality to date. In order to understand how ecosystem processes interact and slow down the recovery of the Baltic Sea, the recently published review by a team of IOW authors brings together findings from more than six decades of Baltic Sea research and combines long-term IOW observational data with an extensive synthesis of scientific literature to provide a comprehensive picture of the changing Baltic Sea based on process understanding and current modelling approaches.

A sea in transition: Warming meets a fragile balance

As a brackish sea, the Baltic Sea is highly stratified: Less salty surface water lies above denser, saltier water. This makes it difficult for oxygen from the atmosphere to reach the deep layers. Organic matter decomposition therefore often leads to oxygen depletion in depths, which can only temporarily be aerated by rare inflow events of salt water from the North Sea.

Climate change has caused the Baltic Sea to warm significantly. Surface temperatures in the central Gotland Basin have risen by an average of almost 2 °C since 1960. According to modelling in the new IOW study, a warming trend can also be observed in the deeper water layers, which can be explained by more frequent summer inflow events. Since warmer water absorbs less oxygen than cold water, these summer inflows have less potential to aerate the deep Baltic Sea basins than winter inflows. In addition, oxygen is consumed more quickly. The result: So-called dead zones, areas with less than 20 µmol O_2 per litre, become larger and persist longer. This is confirmed by the study's long-term data analysis.

In this context, the review highlights the role of small-scale 'lateral intrusions': Narrow layers of oxygen rich water, only a few metres thick, penetrate into areas between the layers of the stratified Baltic Sea water body and, in the long term, transport around ten times more oxygen than the large inflow events. Existing numerical models, however, do not take this process sufficiently into account and should be adjusted accordingly.

Phosphate from the depths: Why the past has lasting effects

The review primarily focuses on the phosphorus cycle, which plays an important role in the ongoing eutrophication of the Baltic Sea. Under anoxic conditions, phosphate is released from the sediment and accumulates in the water. This is due to the absence of oxidised iron compounds, which would otherwise bind the nutrient permanently. Based on long-term series of measurements, the IOW author team has now found that phosphate concentrations in the deep waters of the Baltic Sea increase between inflow events, reaching values well above 5 µmol per litre. Annual winter mixing causes some of this dissolved phosphate to enter the surface water layers. According to the current

study, this internal phosphorus source, averaging 27 mmol per square metre, is now so large that it almost entirely compensates for the reduction of external phosphate loading from rivers. Even strong inflow events only reduce these values to a limited extent: During the large inflow in the winter of 2014, only about 30% of the phosphate was removed from the water, and only around 5% was permanently buried in the sediment.

The feedback loop between oxygen depletion and phosphate release in the deep basins of the Baltic Sea also alters the phytoplankton in the surface water. The reduction of nitrate in deep waters and an increase in internal phosphate loading has caused a change in the ratio of the two nutrients in the Baltic Sea water: Long-term data show that from 1969 to 2023, the ratio of dissolved nitrogen to dissolved phosphorus fell by around 4 mol mol^{-1} in winter – with major ecological consequences, as this favours blue-green algae blooms in summer. These algae can use nitrogen from the air and their growth is therefore primarily limited by the phosphorus supply.

Summertime blue-green algae blooms are less easily utilised in the food web than other algae. Consequently, after they die off, large quantities of organic matter sink to the bottom of the Baltic Sea. This transports phosphorus compounds into the sediment, where they continue to accumulate, and stimulates oxygen depletion through decomposition processes. Thus, it becomes clear why declining external nutrient inputs do not automatically result in declining nutrient concentrations in the sea: The Baltic Sea carries a substantial 'nutrient debt' from past decades.

Approaches for effective Baltic Sea management

"The internal release of phosphate from Baltic Sea sediments, which we have now documented over long time periods with actual figures, is largely responsible for the fact that the Baltic Sea cannot recover based on a simple cause-and-effect principle," comments Joachim Kuss, lead author of the IOW study. "Successful Baltic Sea protection requires sustained effort – and a management approach that takes internal cycles just as seriously as external loads," says the marine chemist. Based on current research-based process understanding, the team sees the following areas for action:

- Nutrient pollution must be consistently reduced even further, as this is the only way to overcome feedback loops in the long term.
- Natural coastal filters must be enhanced or restored: Transition zones such as lagoons, fjords, estuaries, wetlands or reed beds can retain nutrients and bind them permanently.
- Nature-based measures should be expanded, such as promoting seagrass beds or the deliberate cultivation of macroalgae to actively remove nutrients from the water. Reefs and mussel beds also contribute to this.
- Long-term observation and modern measuring systems must be expanded. Only through continuous monitoring – increasingly with new sensor systems for high-resolution phosphate measurements – can improvements or setbacks be detected at an early stage.

Original publication: Joachim Kuss, Peter Holtermann, Lars Umlauf, Olaf Dellwig, Ralf D. Prien, & Joanna J. Waniek (2026). *The Changing Baltic Sea: Between Nutrient Load Reduction and a Warming Climate*. Annu. Rev. Mar. Sci. 2026. 18:16.1–16.26, doi.org/10.1146/annurev-marine-040324-020707

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