

Review #4

First of all, we would like to thank the referee again for the thorough review of our manuscript and the helpful recommendations. We provide our response on how to consider the referee's suggestions in a revised version of our manuscript.

In the following, we respond to the referee's #3 remarks. Remarks are shown in black and our response in red, and text modifications in blue.

Regard model description, while I understand that not all details need to be included, the paper should be self-explained. For critical model components, a brief explanation is needed followed by reference to previous papers, rather than requiring readers to find answers in another paper without any hints. The authors should do a better job of explaining their model for the reader. For example:

1. Sediment Processes: The text mentions the binding and release of PO₄ with iron oxides. However, it is unclear whether this is just a description of a natural process or if your model actually simulates it. There also lacks discussion of this mechanism in the following part of this manuscript. Also, it seems this process is simulated by a sediment model, but this sediment model is not mentioned until the Discussion section. This makes it very hard for most readers unless they already know your work well.

Firstly, we wish to clarify that our sediment representation is properly characterized as a module rather than a fully resolved model. This component constitutes a highly parameterized, two-dimensional representation of early diagenetic processes. We explicitly acknowledge this simplified approach as a model limitation in the Discussion section, where we critically evaluate its implications for our simulation results.

Text added to section 2 "Model Setup":

The sediment module parameterizes key early diagenetic processes, including coupled nitrification-denitrification, organic matter remineralization, iron-phosphate complex formation/dissolution dynamics, and permanent burial. These processes are vertically integrated and represented through a two-dimensional model variable.

Under oxic conditions at the sediment-water interface, phosphate binds to ferric iron Fe³⁺ to form particulate complexes. Hydrodynamic erosion may subsequently resuspend these iron-bound phosphate particles, facilitating their transport via bottom currents to depositional zones. Conversely, under anoxic conditions, iron oxides undergo reductive dissolution, releasing phosphate into the overlying water column as dissolved inorganic phosphorus, following established redox-sensitive phosphorus cycling mechanisms (Neumann and Schernewski, 2008).

2. Atmospheric Deposition: Similarly, it is still not stated whether the model's forcing data includes atmospheric deposition fluxes of nitrogen and phosphorus. The authors should clearly state which external drivers are included in their model.

We appreciate the referee's suggestion and have attempted to address this comment by explicitly specifying "nitrogen and phosphorus" in line 131 of the revised manuscript.

Changed text:

Atmospheric deposition of nitrogen and phosphorus is realized as a boundary condition (air-sea fluxes) based on data provided by HELCOM assessments (e.g. HELCOM) which are originated from EMEP (<https://www.eea.europa.eu/data-and-maps/data/external/emep-n-atmospheric-deposition>).

Regarding model validation,

1. The appendix still states that the model results are more realistic than the observations. Although this was acknowledged and corrected in the response letter, the corresponding text in the manuscript has not been revised.

While we maintain that our model's high-resolution near-bottom oxygen simulations (20 cm above seafloor) likely provide a more accurate representation of true benthic conditions than standard observations taken at 1 m depth above sea ground, we acknowledge the current limitations in empirical validation. The methodological challenges associated with traditional observational techniques at this depth have been previously discussed in our manuscript.

In the absence of direct, high-resolution observational data for near-bottom oxygen concentrations in this specific region, we have removed our previous definitive statements regarding oxygen dynamics. The only available evidence suggesting potential anoxic conditions in the Oder Lagoon remains indirect, as documented by Schernewski et al. (2025b), which we have appropriately cited.

Removed text:

~~We assume the model is closer to reality due to common shortcomings in observational techniques.~~

2. The authors note that a key reason for the bottom dissolved oxygen (DO) underestimation is that observations are from the lowest ~1 meter, while the model output is from the lowest 20 cm. However, they keep using the 20 cm model data for comparison. This doesn't make sense as it produces severely underestimated oxygen levels (reaching hypoxic levels), which would significantly alter the simulated

fate of N and P in the bottom water. It would be more scientifically sound to use model data comparable to the observed depth (1 m). Currently, the 1-meter comparison is only provided for one station as appendix; please add this comparison for the other station as well.

We recognize that this comment is directly related to the previous point regarding near-bottom oxygen representation. To comprehensively address the referee's concerns, we have made the following revisions:

- Included the model's 1-meter above bottom oxygen values in our validation analysis (directly comparable to observational data)
- Completely revised the corresponding paragraph

These modifications ensure our validation approach directly addresses the referee's specific concerns while maintaining scientific rigor in our oxygen dynamics assessment.

Deleted text:

~~The near-bottom oxygen levels exhibit clear differences between the model and observations. We assume the model is closer to reality due to common shortcomings in observational techniques. The model data are collected approximately 20 cm above the seafloor, while observations are typically taken from 1 m above the seafloor. Fredriksson (2024) demonstrate that strong oxygen gradients exist above the seafloor in coastal waters, which cannot be resolved with traditional CTD instruments. Furthermore, the measurement platform—typically a vessel—may disrupt the vertical structure of the water column.~~

Added text:

For our near-bottom oxygen comparisons, we utilized model data from 1 meter above the seafloor, corresponding directly to the standard observational measurement depth. However, we note that oxygen concentrations in our highest-resolution model output (20 cm above the seafloor) are systematically lower. This vertical gradient is consistent with recent findings by Fredriksson (2024), who demonstrated that strong oxygen gradients commonly exist in the bottom boundary layer of coastal systems - gradients that typically exceed the resolution capabilities of conventional CTD instrumentation. Additionally, we acknowledge that traditional measurement platforms (typically research vessels) may introduce artifacts by disrupting the natural vertical stratification of the water column during sampling operations.

Our model-data comparison at 1 m above the seafloor reveals a slight negative bias in simulated oxygen concentrations. Despite this, our analysis confirms that within the 10th-90th percentile range of observations, anoxic conditions are never encountered, indicating persistent oxic conditions and stable redox potential throughout most of the study period. While anoxic events remain rare and temporally limited in this system, these episodic occurrences exert disproportionate influence on:

- Phosphorus biogeochemical cycling
- Benthic community structure and function

Notably, these conclusions remain robust even when considering our highest-resolution near-bottom simulation data (20 cm above the sediment-water interface, not shown).

3. Concerning the validation of stratification, if the authors refuse to include a statistical analysis, please improve the figure. In their current form, it is difficult to assess whether the model correctly simulates the stratification process.

To enhance visual clarity and better illustrate seasonal stratification patterns, we have condensed the time series presentation. This focused representation more effectively highlights the pronounced seasonal variability in water column stratification, particularly the recurrent summer intensification that represents the period of highest potential for anoxic conditions.

Added and deleted text:

For visual clarity, we focus the analysis on the period from January 1997 to December 2000.

~~The comparative analysis presented in this figure reveals consistent stratification patterns between empirical observations and model simulations.~~

Our comparative analysis demonstrates strong agreement between observed and simulated stratification patterns, with both datasets showing peak stratification intensity during summer months.

Regarding sections 3.3, it would be better if this section ended after you show the long term changes in nutrient loads. The parts that come after would fit much better in the Discussion section. In addition, you can also connect these results with your earlier finding in Section 3.2 about the relationship between load and retention, and strengthen the Discussion by addressing the following points:

We appreciate the referee's guidance regarding the manuscript structure and offer the following clarifications regarding sections 3.2–3.4:

Section References

We suspect there may be a minor typographical clarification needed: the intended sections for revision are likely 3.3 and 3.4 (rather than 3.2 and 3.3), as these align more closely with the substantive content discussed.

Structural Approach to Section 3.4

While we acknowledge the suggestion to split Section 3.4 into separate Results and Discussion components, we have instead adopted an alternative approach that addresses the referee's earlier advice to relocate discussion-oriented content to the Results section. Specifically:

- We have retained the integrated presentation of findings in Section 3.4, as this maintains the logical flow of our analysis.
- To align with the referee's recommendation, we have moved the management-related implications (originally in Section 3.4) within the Discussion section, ensuring a clearer separation of results and broader interpretations.

This approach allows us to preserve the narrative coherence of our findings while addressing the referee's structural concerns.

As part of our restructuring of the Results and Discussion sections, we have incorporated a new subsection (4.3) titled 'Implications for water quality' within the Discussion:

Implications for water quality

Our 25-year simulation (1995-2019) indicates mean annual nutrient exports from the Oder Lagoon to the Baltic Sea of 28,988 tonnes for nitrogen and 1,945 tonnes for phosphorus. When accounting for these retention-mediated reductions, the resulting nutrient loads to the Baltic Sea consistently remained below the target thresholds established by the Baltic Sea Action Plan (BSAP) throughout the simulation period. However, the Oder Lagoon case demonstrates that achieving water quality targets in connected river systems and the Baltic Sea does not necessarily translate to good ecological status in transitional water bodies, highlighting the need for ecosystem-specific management approaches.

A good ecological status in the lagoon would require significant additional nutrient load reductions and the implementation of measures in the river catchment at high and likely unrealistic costs. It is likely that the lagoon must be regarded as a naturally eutrophic ecosystem with limited management possibilities. A re-evaluation of water quality targets in the lagoon requires a more detailed study that includes neighboring coastal waters to address interrelationships, relates model data to field data with a focus on the assessment stations, and carefully considers evaluation aspects such as water depth and evaluation period.

1. The implications of the long-term load trends for nutrient retention within the system.

We have relocated and rephrased the following paragraph from Section 4.1 to Section 4.2 of the Discussion, as its content is more thematically aligned with the latter section's focus:

"Coarse-grained models, typically employed for long-term simulations of the entire Baltic Sea basin, often fail to adequately resolve coastal hydrodynamic features and associated biogeochemical processing (i.e., the coastal filter function). For large river systems discharging into lagoons prior to reaching the open Baltic Sea, we therefore recommend utilizing load-corrected riverine inputs. Such corrections should ideally be informed by locally-specific retention estimates derived from high-resolution lagoon models. Where possible, these retention capacity assessments should further account for load-dependent variability in nutrient processing efficiency."

We added the following paragraph to 4.2:

Current state-of-the-art approaches typically apply empirically-derived bioavailability factors, determined through model calibration, to account for coastal nutrient retention. However, these conventional methods present several limitations:

- They generally employ globally uniform factors that neglect the heterogeneity of coastal filter systems
- They assume temporal constancy, ignoring potential variability in retention efficiency

Our proposed mechanistic approach offers two key advantages:

- Enhanced regional realism: By explicitly quantifying lagoon-specific retention capacities using high-resolution local models, we generate more accurate, spatially-resolved nutrient load estimates
- Improved model performance: The mechanistic representation of retention processes facilitates more realistic ecosystem model calibration, potentially reducing compensatory errors in other model components

This mechanistic approach necessitates quantitative assessment of lagoon retention capacities through dedicated, high-resolution local modeling efforts. Particular emphasis should be placed on characterizing load-dependent variability in retention efficiency, as nutrient processing rates often exhibit nonlinear responses to input concentrations.

For comparable coastal filter systems, particularly lagoons, established empirical relationships (e.g., retention capacity as a function of water residence time) may serve as valuable initial approximations. Such relationships provide scientifically grounded starting points that can be subsequently refined through site-specific high-resolution local modeling effort.

2. A comparison of your findings with larger-scale models that apply a fixed retention value: do your results suggest these models tend to overestimate or underestimate retention? This discussion should be clearly and explicitly

We have addressed this comment through the additional paragraph included in our response to the previous point. Regarding the specific question of whether fixed retention values systematically lead to over- or underestimation:

The direction and magnitude of potential bias introduced by fixed retention values cannot be definitively determined a priori, as this depends on:

- The specific retention value selected (which may be higher or lower than actual site-specific retention capacities)
- Spatial variability in coastal filter efficiency across different lagoonal systems
- Temporal dynamics in retention processes that are not captured by static values

This inherent context-dependency precludes a universal statement about bias directionality. Our mechanistic approach explicitly accounts for this variability, thereby reducing the uncertainty associated with fixed retention assumptions.

3. A direct discussion on the limitations of the fixed retention approach used in previous larger-scale models, in light of your evidence that retention is load dependent. This is a key motivation for your study (as stated in introduction) but currently lacks sufficient discussion.

We note that this concern has been comprehensively addressed in our response to the referee's first comment. The detailed explanation provided there regarding limitations of the conventional approach and advantages of our mechanistic modeling approach directly applies to this related point as well.