

May 25th, 2026

Dear Dr. Rammig,

On behalf of all the co-authors, we thank you for the opportunity to revise our manuscript *bg-2024-3338*, titled '*Physicochemical and urban land-use characteristics associated with resistance to precipitation in estuaries vary across scales*'. We appreciate the reviewers' constructive feedback, which helped improve the clarity and the framing of the study.

Minor revisions to the manuscript include:

- Clarified that estuarine resistance does not inherently indicate ecosystem health.
- Expanded the Introduction to better describe mechanistic DO responses to precipitation across estuary types.
- Condensed and reduced the nitrogen discussion.
- Added discussion on the variability and weak explanatory power of many relationships between resistance and physicochemical and land use/land cover factors.
- Revised the conceptual model and conclusions to emphasize context dependence and hypothesis-generating interpretation.

We believe these revisions substantially improved the clarity, balance, and conceptual framing of the manuscript. Thank you for your time and consideration and we look forward to your decision.

Sincerely,

Anna Turețcaia

Anonymous referee #1

I appreciate the authors' detailed responses to my comments and the additional analyses that they completed. The paper is much improved, and the conceptual figure is a nice addition.

Thank you for your time and comments. They are invaluable and continue to improve our manuscript.

That said, I still have a few remaining critiques.

I think the Introduction can be more specific on how oxygen is expected to be impacted by precipitation in different types of estuaries. It currently discusses how flashiness can impact primary productivity and discusses vague "impacts" on DO, but it does not specifically refer to factors expected to increase or decrease DO. I agree with the other reviewer that resistance is one step removed from understanding the processes that impact DO, and it would be helpful to cover the theory behind these processes explicitly in the Introduction.

It does not seem necessary to discuss the effects of excess precipitation on nitrogen dynamics in the Introduction when the primary focus is on the effect of precipitation on oxygen dynamics.

Thank you for this helpful suggestion. We revised the paragraph discussing nitrogen and expanded the Introduction to more explicitly describe the mechanisms by which precipitation can increase or decrease DO in different estuarine settings. Please see below and in the amended manuscript.

Lines 75-85: "In addition to impacts on hydrology, extreme precipitation events can increase nutrient delivery and salinity change, both of which influence DO dynamics, particularly in waterways adjacent to urban-type LULC (Walsh et al., 2005). Elevated nitrogen (N) influx can overstimulate primary production leading to short-term DO increases followed by spikes in microbial respiration and DO demand. Freshwater influx (i.e., runoff) and storm surges can alter salinity, strengthen stratification, reduce DO replenishment to bottom waters and induce hypoxia (Rabalais et al., 2010; Wetz and Yoskowitz, 2013; Zhang et al., 2010). However, the relative importance of these processes is expected to vary among estuaries and across spatial scales. For example, in well-mixed estuaries, precipitation-driven mixing may temporarily increase DO through reaeration, whereas in stratified or poorly flushed estuaries, enhanced nutrient loading combined with reduced vertical mixing may promote sustained DO depletion."

Regarding the statistical analyses—

It makes sense that differences in data collection and reporting conventions across estuaries make it infeasible to develop a multivariate statistical model, and I am sympathetic to the authors' argument. However, I remain concerned about non-independence of the datapoints in the univariate regressions in Figure 3 (see more below).

Although many of the regressions are significant, they explain very little variance in the dataset and are affected by a few points with high leverage. Temperature and perhaps depth do, however, seem to have convincing relationships. I continue to contend that these across-estuary relationships are challenging to interpret because of non-independence of the datapoints and the possible issue of pseudoreplication inflating significance levels; indeed, each point may represent a different storm/monitoring location combination, but many points come from the same estuary (with same monitoring location nested within it), so there could be strong nested site effects. It is difficult to interpret whether there is a univariate effect of a variable on resistance across estuaries without accounting for these nested site effects. While this could theoretically be done with a separate statistical model, I don't think it's necessary, as Figure 4 illuminates site-specific relationship, thus exemplifying the complexity. What I would recommend instead is that, rather than emphasizing the p-value-indicated significance of very noisy relationships in Figure 3, you could instead state that looking at results across estuaries yields few clear signals (not surprising given the diversity of relationship in Figure 4), but some core drivers emerge as having a universally significant association with resistance, such as temperature and a few others.

The reviewer raises an important point. We agree that the relationships across estuaries are largely variable. Although the coefficients of determination were reported in the manuscript (please see Section 3.3), the implications of the low explanatory power were not explicitly discussed. In the revised manuscript, we now highlight that many significant relationships explained little of observed variance and may have been influenced by non-independence among repeated observations from the same monitoring sites. We also highlight that stronger relationships (i.e., $R^2 > 0.5$) were more common in the high-salinity group (see revisions below). We also revised the manuscript throughout to avoid overstating the findings (please see the revised manuscript).

Lines 373-376: "The strength of the relationships between resistance, physicochemical and LULC factors generally increased with estuarine salinity. In the 'high-salinity' group in five of eight significant relationships the coefficient of determination was above 0.5, whereas all significant relationships identified in the 'low-salinity' group and in the continental-scale analysis had R^2 values below 0.5."

Lines 421-422: “The strength of the relationships varied among groups, with higher coefficients of determination present in ‘high-salinity’ estuarine group (i.e., most $R^2 > 0.5$, Fig. 3, Table S5).”

Lines 601-604: “Although several factors were significantly associated with resistance, these relationships explained relatively little of the observed variance and may have been influenced by non-independence among reported observations from the same monitoring sites and estuaries.”

Along similar lines, I recommend revisiting Figure 5, which I like in principle. But some of the drivers that are identified as universal (presumably based on tenuous p-values) do not seem to have a clear and convincing relationship in the scatterplots (particularly if the fitted trendlines are removed).

We agree with the reviewer that Figure 5 should be rotated to emphasize the existent high variability in the relationships that we define as generalizable. Please see the amended Figure 5 and figure caption below.

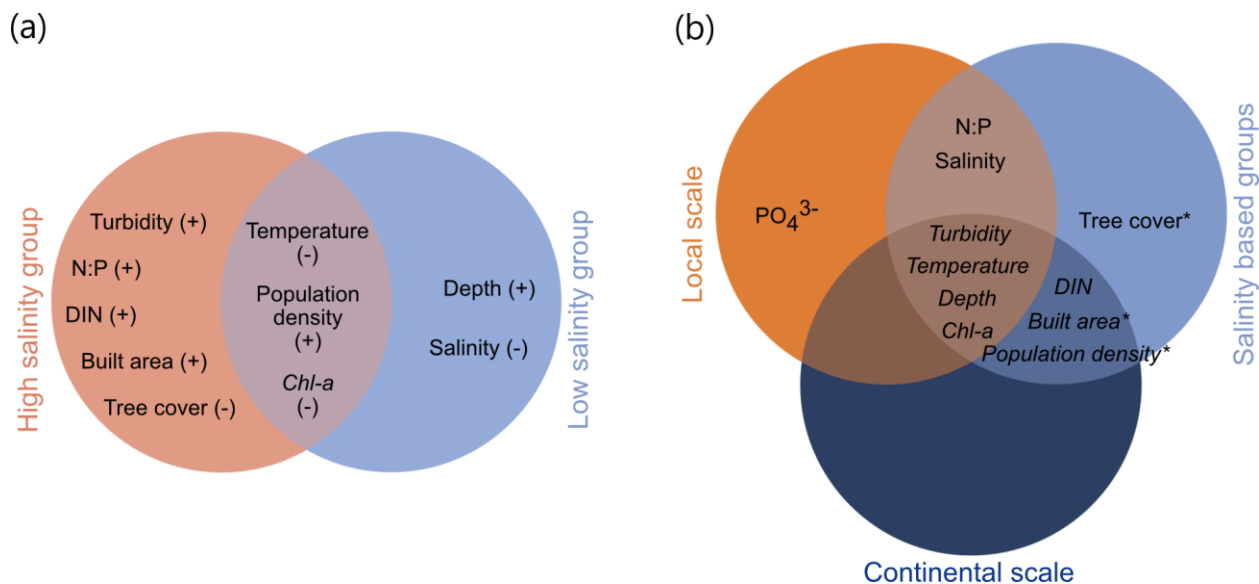


Figure 5. Cross-scale significant relationships between estuarine resistance and physicochemical and land-use factors. a) Venn diagram of resistance relationships with physicochemical and land-use factors in high- vs. low-salinity estuaries. Positive or negative relationships are indicated with ‘+’ and ‘-’, respectively. Italicized text identifies relationships with coefficient of determination (R^2) < 0.5 across both high- and low- salinity groups. Factors in the overlapping zone in regular text have contrasting R^2 across groups.

b) Venn diagram of relationships between resistance and physicochemical and land-use factors in continental, local, and salinity-based groups. Estuarine resistance with land use/land cover and population density marked with asterisks (*) were not evaluated at local-scale due to overlap in the spatial domains of some monitoring locations. Italicized text identifies continental-scale relationships with $R^2 < 0.5$.

Additional comments:

- Line 448-449: This might be an overstatement, given that only 3/5 estuaries showed a decrease in DO with precipitation.

Agreed. The revised paragraph now reads:

Lines 458-463: “There were vast differences in geometry, circulation, and hydrologic conditions among urbanized estuaries versus estuaries surrounded by agricultural land in this study. Yet, despite these differences, several estuaries exhibited similar patterns in DO responses to precipitation. Precipitation generally reduced DO concentrations at WKB, SFB, and CBM (Fig. 2a–e), whereas LKS, the estuary with the lowest proportion of urbanized land cover, experienced an overall increase in DO concentration following precipitation.”

- Line 516-517: Again, this seems to be an overstatement, looking at Figure 3, where the red regression line seems to be highly influenced by a few points with high leverage. Without the fitted trendlines, there would not appear to be much relationship at all within this scatterplot.

Agreed. We revised the passage, which now reads:

Lines 526-529: “Relatively high levels of ambient inorganic N concentrations and lower baseline DO in urban estuaries may also contribute to comparatively smaller DO responses to precipitation. Here, estuarine inorganic N concentrations were positively associated with urbanization and were significantly, but weakly, related to resistance at the continental -scale (Fig. 3, Fig. S15).”

- Line 561-573: Importantly, deeper estuaries are less likely to develop stratification, and stratification would be associated with a strong tendency to develop low DO.

Thank you for highlighting the role of stratification in regulating DO dynamics. We have revised the paragraph to clarify that. We note that although greater depth may buffer

short-term hydrologic perturbations through dilution and other mechanisms, it can also promote vertical stratification and reduce oxygen replenishment to bottom waters, therefore increasing susceptibility to hypoxia. We also expanded the discussion to emphasize that the influence of water column depth on resistance depends on interactions among stratification, hydrodynamics, and watershed characteristics. The revised text now reads:

Lines 573-587: “Water column depth can also influence estuarine resistance to precipitation through its effects on DO dynamics. Through dilution, deeper estuaries may show a more buffered response to short-term hydrologic changes following precipitation by attenuating changes associated with freshwater inflow, nutrient loading, turbulence, and gas exchange. Similarly, deeper estuaries generally have longer equilibration time with environmental conditions and less diel variability in parameters like temperature (Caissie, 2006; Macan, 1958). These characteristics can contribute to a more stable DO baseline conditions and more moderate responses to precipitation. However, greater depth can also enhance vertical stratification and reduce oxygen replenishment to bottom waters, potentially increasing susceptibility to hypoxia (Cloern, 2001; Cloern and Jassby, 2010). Deeper estuarine channels are frequently associated with urbanization, which shows high resistance in this study, because channel incision, dredging, and altered sediment transport are more common in urban and agricultural watersheds (O’Driscoll et al., 2010; Simon and Rinaldi, 2006; Walsh et al., 2005). Accordingly, water column depth appears to be an important factor influencing the estuarine resistance to precipitation, although its effects on DO dynamics depend on interactions with stratification, hydrodynamics, and watershed characteristics.”

Anonymous Referee #2

My overall impression of the manuscript remains unchanged. The work is technically competent and the authors have broadly responded well to reviewer 1s comments.

As noted in my first round of review, I am struggling to understand what the work means and gain any new insights from it. The tweaks to the text did not really address my broader concern.

I appreciate the authors efforts to apply existing approaches in ecology in a novel way, but I don't think this case study progresses our understanding of estuaries the way it is currently framed.

The authors state that resistance to change conveys no information about the state (health) of the system, but the abstract states

"The capacity of an estuary to resist changes in function in response to precipitation events is a key component of maintaining estuarine health in our changing world"

To me this seems to contradict this. Going back to the example of DO, a highly channelised and stratified estuary can return to an anoxic state quite quickly after a flow event, and hence be resistant to change, but I don't think this is very meaningful. I also think the limited number of estuaries (5) negates the need for such a reductionist approach, and also reduced the generalisability of the conclusions.

Effectively, the end of the abstract seems to underscore my concerns

"These findings suggest that the relationships between urbanization and estuarine stability are complex and context-dependent, and thus management strategies need to consider both broad generalizations and local conditions."

We thank the reviewer for their thoughtful assessment of this study, and for acknowledging the technical quality of the work and our responses to prior comments. We understand the concern that the framing of our study did not clearly communicate the broader conceptual contribution. While revising our work and in parallel with suggestions provided by the anonymous reviewer #1, we took this comment seriously. We now highlight throughout the manuscript that while the cross-scale analysis revealed significant factors that associate with resistance, most associations had low explanatory power, with strong site-specific divergence.

We also recognize that the reviewer has a point regarding contradicting messaging between the two statements: "*The capacity of an estuary to resist changes in function in response to precipitation events is a key component of maintaining estuarine health in our changing world.*" and "*These findings suggest that the relationships between urbanization and estuarine stability are complex and context-dependent, and thus management strategies need to consider both broad generalizations and local conditions.*". This was an oversight. We revised the definition of resistance (below) and related wording throughout the manuscript to avoid implying that more

resistant estuaries are necessarily healthier. We replaced 'estuarine health' with 'estuarine function' or 'estuarine condition' throughout the manuscript.

Lines 18-20: "The capacity of an estuary to resist changes in function in response to precipitation events is an important descriptor of ecosystem response dynamics, but it should be interpreted in the context of baseline system condition and ecological state."

We believe that the changes following the combined comments from both reviewers substantially improve the clarity of the conceptual contribution of the manuscript.