

December 30th, 2025

Dear Dr. Rammig,

On behalf of all the co-authors, we thank you for the opportunity to submit revisions to our manuscript *bg-2024-3338*, entitled '*Physicochemical and urban land-use characteristics associated with resistance to precipitation in estuaries vary across scales*'. We also thank the two anonymous reviewers for their thoughtful and constructive comments, which helped improve the clarity and overall strength of the manuscript.

In the revised manuscript, we have:

- Adjusted co-author's last name due to name-change
- Strengthened the abstract to more clearly convey the significance of the study
- Added details on the characteristics of the selected estuaries and monitoring locations to the Methods section and the Supplementary Materials
- Included an additional analysis (PCA) to support results obtained from the linear regression analyses
- Expanded the Discussion section and incorporated a conceptual framework describing expected resistance to precipitation based on estuarine characteristics
- Added a new figure summarizing this conceptual framework
- Revised language throughout the manuscript to provide more clarity

We attest that all authors are aware of the changes to the manuscript. We appreciate your time and consideration and look forward to hearing from you.

Sincerely,

Anna Turetaia & Emily Graham, corresponding authors

Reviewer 1: Thank you for recognizing the importance of this study and for taking the time to review it. Your input is invaluable, and your comments will help improve our manuscript. Below, we provide our responses (in blue font) following each reviewer comment (in black font).

The follow-up point-by-point revisions addressed in the manuscript are presented in *italic* font.

General comments:

This paper looks at how major precipitation events influence dissolved oxygen changes—an integrative measure of estuarine resistance to disturbance—in the NERRS estuaries across the US. There are not many comparative estuarine studies that leverage the network of NERRS data, so this paper fills an important research gap in that respect. The synthesis of the input dataset is a feat in and of itself. Additional strengths of the work are the graphical synthesis of complex results (Figure 5) and a detailed discussion.

Thank you for the encouraging remarks.

However, the paper also has major weaknesses that deserve further attention in a revision. The biggest weakness is the attempt to infer drivers of resistance across a very small number of estuaries through bivariate correlations. As the authors acknowledge in lines 395-397, resistance is associated with myriad specific factors, and these factors interact. Potential multicollinearity within the dataset between percent urbanization and other factors such as watershed contributing area, flushing time, tidal influence, etc. makes it challenging to infer how urbanization influences resistance on the basis of a bivariate correlation. Ideally, one would address collinearities in potential predictors and construct a generalized linear model to account for covariates and isolate contributions of factors like urbanization to resistance in order to draw inferences. However, with this small dataset, this is probably not an option.

We agree that multicollinearity between variables can be problematic for statistical analysis, particularly in the case of some multivariate analyses. Because of that, we previously examined correlations between all variables and provided a correlation matrix in the supplemental material (Fig. S8). Most variables were largely uncorrelated. To clarify this, in the revised manuscript we will add a statement to the methods that multicollinearity was assessed with reference to the supplemental figure.

Also, we note that some multicollinearity is typical in environmental datasets and that collinear variables do not pose an issue for univariate analyses. However, they complicate the construction and interpretation of some multivariate models. For example, temperature and salinity are often

highly correlated, and yet they both have important independent impacts on estuarine dynamics (e.g., through rate kinetics/growth vs. stress tolerance mechanisms). In the multivariate approach proposed by this reviewer, one variable should be omitted from the model because including multiple collinear predictors reduces model performance. In cases where two collinear variables show a similar relationship, we cannot infer if one or both of the variables might be a mechanistic driver.

In univariate models, both can be kept, allowing readers to view results regarding the predictor most relevant for their system. For example, relationships between salinity and resistance may be more interesting to managers of more exposed coastal estuaries with large tidal influences, while relationships with temperature may be more interesting to those working in estuaries cut by deep rivers. We therefore think it is valuable to present independent analyses for all possible relevant parameters even if two variables are correlated (which occurred infrequently in this dataset).

Additionally, as described in lines 139-146 and 239-242, National Estuarine Research Reserve (NERR) water quality data were collected at different intervals (i.e., 15-min time series versus monthly), which means that we would not be able to include all predictive variables into the same model without collapsing them to the same resolution/time interval. This would result in a loss of substantial amounts of information for sensor-based (15-min interval) measurements. In other words, statistical approaches like the Generalized Linear Model or the Principal Component Analysis for this particular dataset cannot investigate physicochemical variables like salinity, water column depth, turbidity, temperature, nutrients, chlorophyll-*a*, and LULC collectively without losing information.

Also, the reviewer's example of collinearity between urbanization and the watershed contributing area is not clear to us. For correlations, we reduced the watershed area by using a defined zone (10-km radius) around monitoring stations. This allowed us to keep realistic the area of the watershed that could contribute to the water quality at a monitoring site within short time scales, and made the analysis more comparable area-wise. To clarify the exact breakdown of LULC within each watershed at each estuary, we will include an additional supplemental table in the revised manuscript.

We added the statement addressing multicollinearity and the robustness of the statistical method we used (i.e., linear regression analysis) to the Methods section (please see text below). We also added Table S2 with LULC breakdown in each watershed. Please see supplementary materials.

"To ensure the robustness of linear regression analysis, we assessed the dataset for multicollinearity (Fig. S7) and conducted principal component analysis (PCA) with Varimax rotation on loadings (Fig. S8). For PCA, we used sensor-based, 15-minute interval measurements (temperature, salinity, turbidity, water column depth) and omitted the nutrient data collected at monthly intervals, to keep most data points in our analysis while remaining consistent with

continental-scale linear regressions. Most variables were largely uncorrelated and the PCA results were in agreement with continental-scale linear regressions.

I instead recommend a few options to address this issue:

1. Quantitative approach: Fully characterize the set of potential drivers of resistance hypothesized to be important and how they vary across estuaries (and potentially across sites, being careful to avoid pseudoreplication—inclusion of sites as multiple datapoints when they all correspond to one independent variable like percent urbanization). This should likely include variables related to estuarine circulation, like flushing time and stratification indices, and potentially watershed area.

We agree with the reviewer that estuarine circulation expressed through metrics like flushing time and stratification indices could impact estuarine processes. However, flushing time and stratification indices are not standard NERR metrics, and they are not widely available in NERR metadata files or literature. To recognize the importance of estuarine circulation, in the revised manuscript we will add discussion on flushing time and stratification that were not considered in the analysis but may influence estuarine resistance to precipitation. We will also add estimated ranges for residence time, accompanied by citations, for each site to Table S1.

While we were unable to locate comparable data for circulation across all five estuaries, we note that the NERR dataset provides a fairly comprehensive assessment of key estuarine variables, as determined through a series of workshops and careful consideration among staff members. Data includes water quality variables (water temperature, depth, salinity, sp. cond., DO, pH, turbidity, chl-*a*), nutrient variables (N-species, PO₄⁻³, other optional species), and weather variables (air temperature, precipitation, humidity, pressure, PAR, wind speed and direction). Also, NERR sample collection and processing is standardized, including the placement of sondes within the water column. The value of such a data product is that it allows direct comparisons across different estuaries. Additional site and estuary notes including average channel width and depth, generalized land-use description surrounding each site, equipment placement, equipment maintenance history, notable historical developments (i.e., site history), site-altering events, etc. are available in metadata files that can be requested at <https://cdmo.baruch.sc.edu/get/landing.cfm>.

We now incorporate flushing/residence time and stratification as factors that influence estuarine resistance to precipitation into the newly added conceptual model (Fig. 6 in the manuscript, also shown in comment below) and section 4.5 that discusses it (see text below). We also added the literature-supported estimated ranges for residence time for several estuaries and sites and enhanced site characteristics (please see Table S1 in supplements).

“4.5. Conceptual model for resistance to precipitation based on estuary characteristics.

Through observed relationships between resistance and physicochemical and land-use factors, we propose the following conceptual model for expected resistance based on estuarine characteristics (Fig. 6, Table S1). We suggest that the highest resistance could be expected in tidal/ marine-dominated or urban-influenced estuaries that are well-mixed and have relatively short residence time, similar to SFB. In such estuaries, the disturbances to DO dynamics driven by precipitation events, riverine freshwater inputs and/or terrestrial-aquatic exchange across mixed land uses (e.g., changes in salinity, turbidity, and/or nutrients), are mediated by tidal mixing. In contrast, the lowest resistance index could be expected in enclosed, shallow, poorly-mixed (i.e., stratified) estuaries with long residence time, strong influence from river-systems, and/or surrounded by agricultural LULC, similar to WKB, Pellicer Creek (GTM), or Pokegama Bay (LKS). In such estuaries, the abrupt disruptions to ambient salinity, turbidity, and/or nutrient concentrations driven by precipitation events would be long-lasting and cause large fluctuations in DO, which in turn would result in low resistance.

Because estuaries are characterized by a continuum of interacting variables, we expect that many estuaries will show moderate resistance that varies with precipitation events of different sizes. In particular, we expect medium-high resistance indexes in well-mixed estuarine systems with engineered flow, short residence time, and periodic nutrient loading conditions (e.g., CBM, remaining LKS and GTM sites), while medium-low resistance could be more common in partly-mixed estuaries, with periodic nutrient loading and moderate residence time.

Although numerous estuary-specific interactions can produce different responses to stressors, our results provide a framework for understanding generalizable responses to precipitation based on measurable characteristics, while also highlighting the importance of system variability in determining estuarine resistance. We recognize that additional scales of investigation (e.g., regional) and other ecological, hydrological and environmental factors could further refine predictions of estuarine resistance. Incorporating these elements in future studies could strengthen our ability to anticipate estuarine responses to disturbances.”

Then conduct a principle components analysis followed by a Varimax rotation to identify how the predictor variables group together and how the estuaries vary with respect to each other and the predictor variables. The Varimax rotation makes each factor more interpretable.

Thank you for this suggestion. We agree that multivariate approaches, like PCA, can be powerful tools. Unfortunately, for this study, data were collected at different intervals which restricts the PCA analysis for the full range of predictive variables used in this study (see discussion above).

Yet, to demonstrate the robustness of our results, we performed the PCA analysis with and without Varimax rotation using the simultaneously-collected sensor-based measurements only (salinity, turbidity, water column depth, and temperature). This analysis is consistent with the data subset used in the linear regressions presented in Figure 3 in the manuscript. We found that the results between PCA and linear regression analysis were in agreement (please see Figure R1 below). Particularly, with PCA when applied for all estuaries regardless of the site or salinity level (i.e., no grouping into low- and high- salinity), we found that salinity had the least influence

on either PC1 or PC2, unlike temperature, depth, and turbidity loadings. In parallel, our continental-scale (i.e., all estuaries combined and regardless of salinity) linear regression analysis between resistance and the four variables showed the existence of significant relationships (dotted green lines) between resistance with turbidity, temperature, and depth, while the relationship between resistance with salinity was not significant.

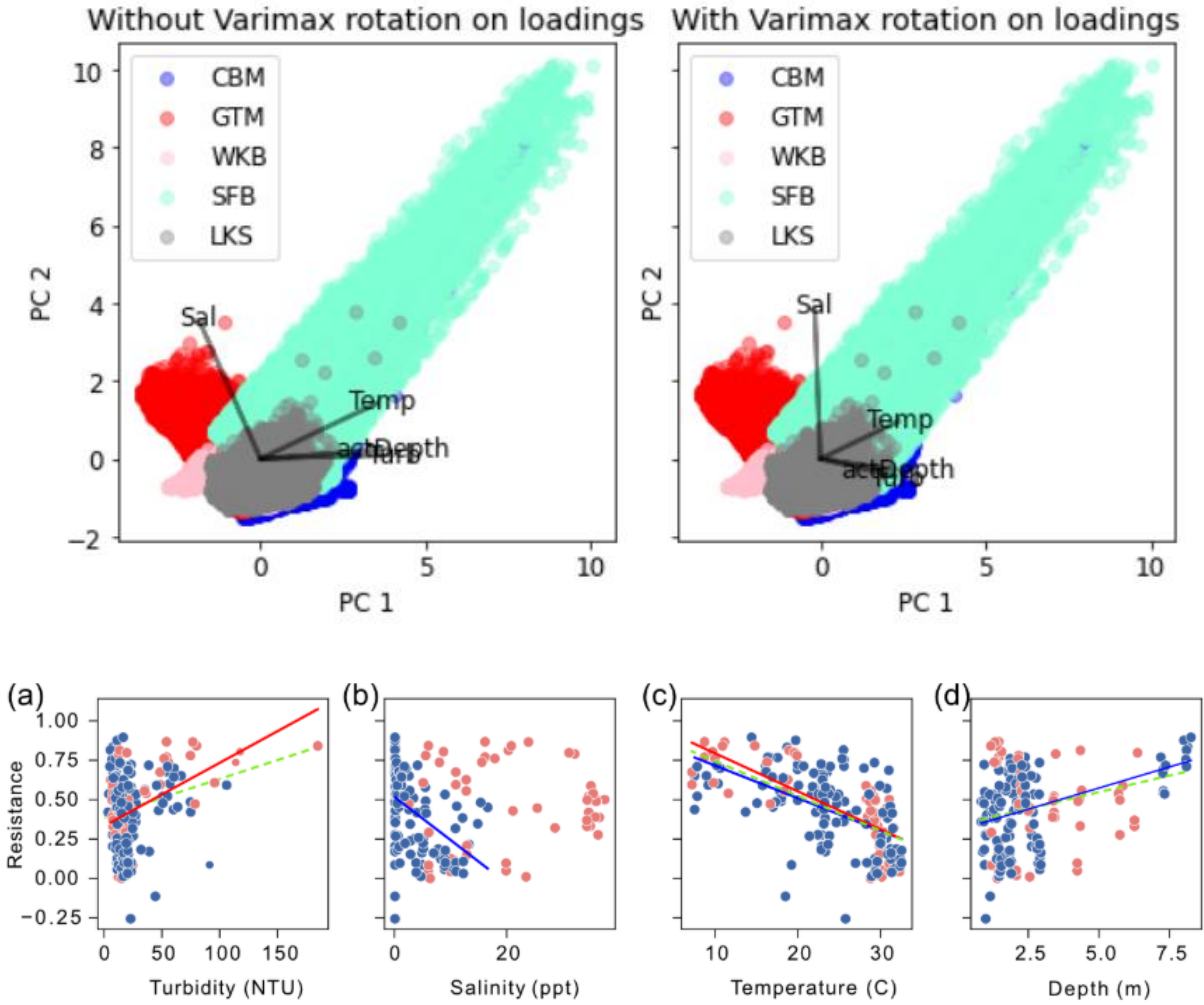


Figure R1. (top panel) Principal component analysis without and with Varimax rotation. (bottom panel, from Figure 3 of the manuscript) Relationships of continental-scale and salinity-based resistance with physicochemical factors. Continental-scale regressions considered all monitoring locations across all estuaries. Significant relationships ($p < 0.05$) are shown in dotted-green, solid red, and solid blue lines for continental-scale, high-salinity and low-salinity estuaries, respectively.

After considering the issues raised by different time intervals and by collinearity (please see the comment above), and by examining the results obtained with PCA versus linear regression

analysis shown in Figure R1 above, we feel that our overall statistical approach is robust and informative. We will add the PCA plots to the supplemental material.

We added the PCA analysis to the Methods section and the results to supplementary materials (see Fig. S8).

Then, plot the factors from the Varimax rotation against resistance, or consider how resistance differs among different groups that emerge from the factor analysis.

Please see the comment above.

2. Qualitative approach: Alternatively, eliminate the cross-estuarine correlations from the analysis and take a case-study approach to elucidate how storm events impact resistance in different types of estuaries. For this approach to be successful, the case-study discussions should be tied to hypothesized detailed mechanisms of how storm events would impact resistance in different types of estuaries.

Understanding what factors are most likely involved in estuarine resistance to storms regardless of the type of estuary is important for large-scale models and for informing management decisions regarding estuarine water quality. Because the aim of the current study is to identify generalizable physicochemical and land-use factors that relate to estuarine resistance to storm events, we intend to keep cross-estuarine correlations.

Nonetheless, while our study is focused on generalizable physicochemical and land use factors that relate to estuarine resistance to storms, we recognize that many estuarine differences could lead to variation in responses to storms (please see lines: 29-31; 341-344; 373-374; 406-411; 437-447; 531-525). To further highlight how storm events impact resistance in different types of estuaries, in the revised manuscript we plan to enhance the discussion and add a conceptual-model figure as suggested by the reviewer in the comment below.

We added section 4.5 to the discussion on the effects of storm events on resistance in different types of estuaries (please see comment above).

Regardless of which option is chosen, I recommend moving some of the excellent literature review in the Discussion to the Introduction and synthesizing it to present a coherent conceptual model of the different ways in which physicochemical variables and storm events are expected to interactively influence resistance. A conceptual figure would be nice as well. Without this theoretical underpinning to orient readers at the outset, the detailed and understandably messy dataset and results are challenging for readers to wade through.

Thank you for your suggestions. To aid the readership, in the revised manuscript we will present an additional figure– a conceptual model– describing the interaction between physicochemical variables, storm events, and resistance.

We now provide a conceptual model accompanied by additional discussion. Please see section 4.5 in the comment above.

High Resistance • Tidal-dominated • Well-mixed • High salinity • Short residence time • Varying depth • Varying urbanization • Moderate nutrient loading	Medium-high Resistance • Engineered flow • Well-mixed • Low salinity • Short residence time • Deep • Urbanized • Periodic nutrient loading
Medium-low Resistance • River-dominated • Partly-mixed • Low salinity • Moderate residence time • Deep • Varying urbanization • Periodic nutrient loading	Low Resistance • Enclosed / Lagoon • Poorly-mixed • Abrupt change in salinity • Long residence time • Shallow • Agricultural • High nutrient loading

Fig. 6. Conceptual model for expected estuarine resistance to precipitation events based on estuarine characteristics.

Another big-picture factor to consider further is that some of the estuaries may be less impacted by precipitation events than by flow events controlled by upstream reservoirs. One factor that should probably be discussed is whether some estuaries may appear more resistant to rain events because upstream reservoirs act as flood-detention buffers.

Thank you for drawing our attention to this detail. In the revised manuscript, we will expand the discussion on factors other than precipitation events that could control DO dynamics including upstream reservoirs and residence time.

Briefly, upon reviewing NERRS metadata files (<https://cdmo.baruch.sc.edu/get/landing.cfm>), three estuaries noted that there were upstream dams and/or other structures but that they were unlikely to influence site hydrology (see the information from NERRS metadata sheets below).

(1) At Lake Superior NERR (LSNERR), the Oliver Bridge monitoring site is reported to be located 12 miles downstream of the Fond de Luc dam. Although the site is hydrologically influenced by Lake Superior seiche and St. Louis River discharge, the potential influence of discharge-regulating dams on dissolved oxygen at this site has not been characterized.

(2) At Guana Tolomato Matanzas (GTMNERR), the hydrology of the GTM system is reported to be ‘somewhat’ altered by a dam across a portion of the Guana River, dikes, drainage ditches, and inland wells. However, the potential influences of upstream structure on resistance at GTM is not evident from our results (see Figure 2). Compared to, for example, SFB– a highly urbanized estuary– the resistance at GTM is lower.

(3) At San Francisco Bay (SFBNERR), the Suisun Bay which incorporates First and Second Mallard (FM and SM, respectively) monitoring sites, is equipped with a marsh salinity control gate. However, there is no mention in the metadata files that the gate was operated preceding, during, or after the rain events selected for this study (i.e., we assumed that the gate had no impact on the measurements used for this manuscript).

We expanded the discussion about impacts of upstream structures on DO dynamics and residence time, and included these processes into the conceptual model (please see the comments above). We also added the following text:

“Similarly, power-generating dams and other large reservoirs often present in urban estuaries can strongly influence DO dynamics through their regulation of flow conditions, salinity, temperature, microbial processes, and solute residence time (Abbott et al., 2022; Ferencz et al., 2021b, a).”

In general, a table and/or text providing a more detailed characterization of the estuaries (beyond land-use) is a needed addition.

To address the reviewer’s suggestion, we will use any available information (i.e., NERR metadata files, literature, reports) to enhance site characterization in the revised manuscript. Specifically, we will:

- 1)** Add columns to Table S1 which will contain:
 - a) Approximate mean tidal fluctuation
 - b) Tidal regime (e.g., minimally tidal, microtidal, moderately tidal)
 - c) Residual current type (e.g., well-mixed, partially mixed)
 - d) Tidal flow type (e.g., diurnal tidal flow; mixed, semi-diurnal tidal flow)
 - e) Site characteristics (e.g., presence of upstream/downstream structures, WWTPs, submerged vegetation, dominant sediment type) and estimated residence time.
- 2)** Add a supplemental figure showing temporal DO at each site during wet and dry years.

We also would like to draw the reviewer's attention to the supplemental material, which contains a wealth of additional information on the estuaries we investigated. In particular, Figures S1-S3, S6-S8, as well as Figure 1 and Table 1 that provide detailed information on long- and short-term precipitation patterns across broader area and within each estuary, temperature dynamics at each monitoring location, nutrient concentrations (i.e., DIN, PO_4^{-3}) and N:P at each monitoring location.

We amended Table S1 with detailed site characteristics, and added Figure S4 showing temporal DO at each site during wet and dry years (please see supplementary material). We also added a brief description of the five estuaries to the methods section which reads:

“Briefly, LKS NERR is a freshwater estuary situated at the confluence of the St. Louis River and Lake Superior, that includes four continuous water quality monitoring locations influenced by lake seiche: Blatnik Bridge, Oliver Bridge, Pokegama Bay, and Barker’s Island. CBM NERR at Jug Bay, is a semi-diurnal minimally tidal estuary. Jug Bay is located in the upper tidal reaches of the Patuxent River, it is dominated by tidal freshwater marsh, and it comprises Railroad Bridge, Iron Pot Landing, and Mataponi Creek monitoring locations. WKB NERR is a partially-mixed (i.e., lagoonal/ semi-isolated), diurnal micro-tidal estuary located on the eastern shore of the Mobile Bay. WKB comprises Fish River, Weeks Bay, Middle Bay, and Magnolia River monitoring locations. SFB NERR estuary is a mixed, semi-diurnal tidal system comprising four monitoring locations across two embayments. The locations include China Camp and Gallinas Creek in the San Pablo Bay embayment within the China Camp State Park, and First Mallard and Second Mallard in the Suisun Bay embayment within the Rush Ranch Open Space Preserve. GTM NERR is a mixed, semi-diurnal tidal estuary associated with the Tolomato and Guana River estuarine systems to the north and the Matanzas River estuary to the south. Monitoring locations include Pine Island, Fort Matanzas, San Sebastian, and Pellicer Creek, with the latter site noted to experience stratification (i.e., salt-wedge).

Upstream reservoirs are reported for several monitoring locations across the set of estuaries (Table S1).”

If a PCA is attempted as suggested in #1 above, it would be ideal to include variables that characterize hydrologic differences among the estuaries or across storms, such as a normalized increase in inflow (if available) and statistics about storm durations, which could be another driver of cross-estuary differences in resistance.

For the use of PCA and availability of estuarine circulation metrics (i.e., flushing time and stratification indices), please see the comments above.

Also, we note that we regressed precipitation amount (reported in Table S2) against resistance values at each estuary. The only significant relationship between precipitation and resistance was observed for Guana Tolomato Matanzas (GTM) estuary (reported in Figure S11).

Specific comments:

The abstract should more specifically state the big-picture implications of these results. What matters about them and why?

In the revised manuscript, we will expand the abstract to include more information on why it is important to understand the factors that associate with estuarine resistance to precipitation and their generalizable patterns.

We now clarify the importance of considering generalizable patterns and factors that relate to estuarine responses to extreme precipitation, and the importance of our findings by enhancing the abstract:

“This knowledge gap complicates our ability to identify estuaries that are more likely to undergo major shifts in ecosystem services and predict the effects of urban and precipitation disturbances on estuarine water quality.”

“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.”

Line 133-136: Is the 10-km lengthscale, then, the spatial scale expected to drain to the point of interest over the sensitive timescale of days? How the two parts of this sentence link is not entirely clear. If runoff generation length scales are smaller, a larger proximity zone would presumably add noise to statistical relationships.

We agree that the ideas presented in the sentence were poorly connected. We will rewrite this sentence in the revised manuscript.

The paragraph now reads:

“Further, because the resistance index was calculated for precipitation events across short time-scales (days), large watershed areas could overrepresent hydrologic contributions to water quality at monitoring locations (watershed area range: 114 – 11,704 km², Table S2). To better match the temporal scale of precipitation responses, we restricted watershed characterization to a 10-km proximity zone surrounding each monitoring location. This approach captures watershed areas most likely to influence water quality over short time scales, and improves comparability among estuaries (Table 1). LULC and population density were quantified within these proximity zones. For the SFB NERR watershed, separate 10-km proximity zones were delineated for San Pablo and Suisun embayments to account for different hydrologic dynamics.”

Line 176: Should mention atmospheric rivers for CA

We will add the atmospheric rivers of California that result in precipitation events during the cool season to the revised manuscript.

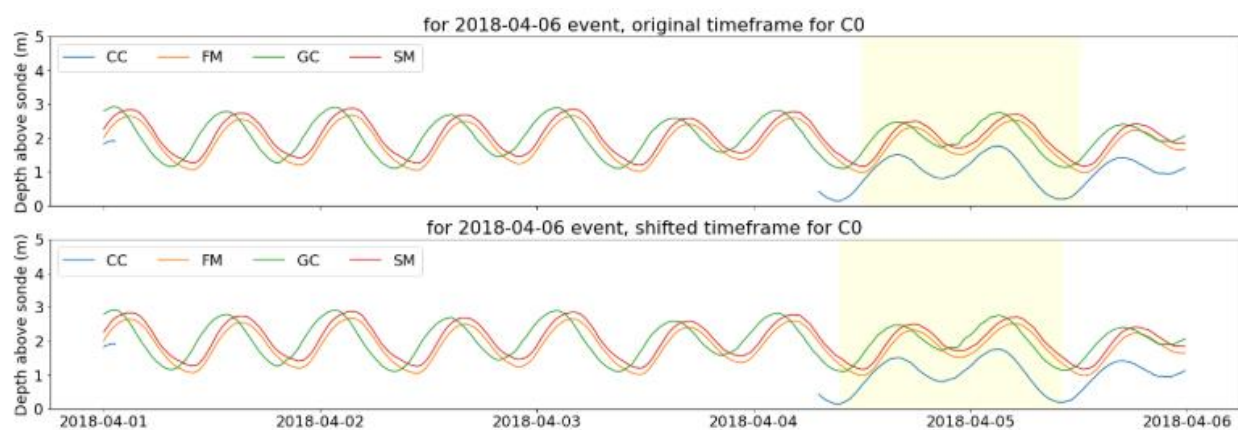
The sentence now reads:

“Specifically, because the definition of ‘major’ precipitation events is hard to quantify and it varies across estuaries, we first considered hurricanes, tropical storms, Nor’easters, atmospheric rivers, and other major storm events noted within NERR metadata sheets when selecting precipitation events.”

Line 220-221: Was the tidal cycle accounted for in selecting the window of time for averaging? Averaging over partial tidal cycles may skew results in a way that could produce spurious differences among sites in the same estuary or across estuaries.

When selecting the timeframe for calculating average C_0 values we were unable to consider the exact tidal cycle at each monitoring location due to non-uniform timing of the tide across stations. Please see the temporal change in depth at each monitoring station and the lag between the arrival of the tides at SFB in Figure R2 below.

Overall, the timeframes selected for the C_0 calculations incorporate most of the tidal cycles. To assess this reviewer’s concern, we re-evaluated C_0 for three events for monitoring locations at the San Francisco Bay (SFB) estuary by shifting the original timeframes to coincide with the tidal cycle. We selected the SFB estuary because it experiences largest tidal fluctuations from the set of estuaries used in this study. The resulting C_0 with shifted timeframes were virtually unchanged from the original values (please see Table R1 below). We will keep our approach for calculating C_0 values.



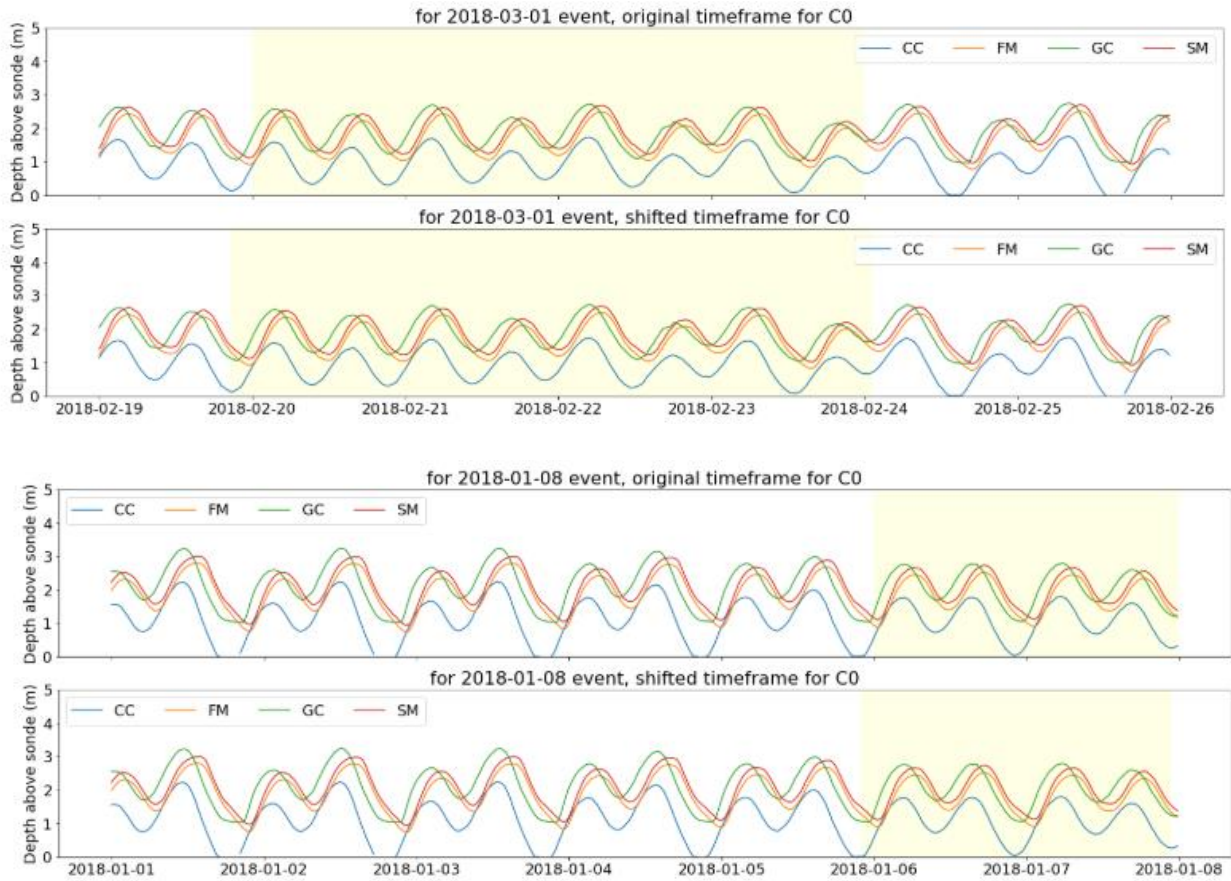


Figure R2: Examples of time delay between tides at monitoring locations at the San Francisco Bay estuary and the original and shifted timeframes used for calculation of average C_0 values.

Table R1: Average C_0 with original and shifted timeframes for three precipitation events at monitoring locations at San Francisco Bay (SFB) NERR.

Monitoring location at SFBNERR	Average C_0 for event: 2018-04-06		Average C_0 for event: 2018-03-01		Average C_0 for event: 2018-01-08	
	Not accounted for the extent of the tidal cycle	Accounted for the extent of the tidal cycle	Not accounted for the extent of the tidal cycle	Accounted for the extent of the tidal cycle	Not accounted for the extent of the tidal cycle	Accounted for the extent of the tidal cycle
China Camp	9.06	9.04	9.30	9.32	8.234	8.231
Gallinas Creek	8.58	8.61	9.71	9.73	7.6041	7.6046

First Mallard	6.49	6.46	8.067	8.064	7.45	7.44
Second Mallard	7.37	7.35	NA	NA	8.82	8.79

Line 231-232: Provide a table of predictor variables

Thank you for the suggestion. While the predictor variables are reported in Figure 3 and Table S4, to aid the readership, we will add the list of predictor variables to the methods in the revised manuscript.

We added a sentence with the list of predictors to the Methods section:

“Specifically, we tested the relationships between resistance and turbidity, salinity, water temperature, water column depth, DIN, PO_4^{3-} , N:P, Chl-a, percent trees, percent crops, percent built area, and population density. For linear regressions that involved land-use factors, we used LULC and population density from the 10-km proximity zone (Table 1). Because of discrepancies in the temporal intervals at which measurements were collected, we conducted separate regressions involving turbidity, salinity, water temperature, water column depth (collected at 15-minute intervals) vs. DIN, PO_4^{3-} , N:P, and Chl-a (collected at monthly intervals) predictors.”

Line 479: N loading and low DO are not always associated. San Francisco Bay is one place where they are not, so this estuary is not the best one to highlight earlier in the paragraph.

The reviewer is right regarding the lack of association between N loading (as DIN) and low DO in the San Francisco Bay estuary, although studies suggest that this might not always have been the case. The reduction in primary production, which affects DO, was previously shown to relate to changes in N species entering the SFB estuary. Particularly, the reduction in primary production in SFB was related to increase in ammonium, which inhibits the uptake of nitrate. The authors attribute the shift in N species loading to changes in wastewater treatment practices in San Francisco (Dugdale et al., 2007, Parker et al., 2012).

Nonetheless, we acknowledge that the message in the manuscript is misleading. We will revise this paragraph.

- Dugdale, R. C., Wilkerson, F. P., Hogue, V. E., and Marchi, A.: The role of ammonium and nitrate in spring bloom development in San Francisco Bay, *Estuar. Coast. Shelf Sci.*, 73, 17–29, <https://doi.org/10.1016/j.ecss.2006.12.008>, 2007.

- Parker, A. E., Hogue, V. E., Wilkerson, F. P., and Dugdale, R. C.: The effect of inorganic nitrogen speciation on primary production in the San Francisco Estuary, *Estuar. Coast. Shelf Sci.*, 104–105, 91–101, <https://doi.org/10.1016/j.ecss.2012.04.001>, 2012.

We revised the text which now reads:

“Relatively high levels of ambient N and low ambient DO in urban estuaries may also facilitate comparatively small DO fluctuations in response to precipitation. Here, estuarine inorganic N concentrations were related to urbanization and also were a major predictor of resistance at the continental-scale (Figs. 4 and S16). While moderate levels of N support biological metabolisms (Howarth, 1988; Howarth and Marino, 2006; Vitousek and Howarth, 1991; Zhang et al., 2021), nutrient loading, including N, is a significant problem for urban aquatic environments (Beman et al., 2005; Bernot et al., 2010; Bettez et al., 2015; Black et al., 2011; Hopkinson and Vallino, 1995; Mulholland et al., 2008; Reisinger et al., 2016). For urban estuaries, where N loading is associated with chronically low DO availability, this could mean that precipitation-driven increases in DO under simultaneous high N input would be small, which would result in higher resistance. Nitrogen limitation, in contrast, is prevalent in coastal marine systems and can negatively impact overall estuarine health by constraining biological activity (Elser et al., 2007; Guildford and Hecky, 2000; Paerl, 2018; Paerl and Piehler, 2008). Relationships of resistance with N and urbanization were particularly evident in more coastal (high-salinity) estuaries where we found positive relationships between resistance, N:P, and built area (Fig. 4). Thus, altered N dynamics in urban estuaries may be key to understanding their comparatively low change in response to precipitation.

While the mechanisms behind positive relationship between resistance and N are not clear, changes in concentrations of NH_4^+ were previously suggested to regulate algal blooms in the San Francisco Bay estuary (Dugdale et al., 2007; Parker et al., 2012). Elevated NH_4^+ concentrations resulting from changes in water-treatment practices in San Francisco were shown to inhibit NO_3^- uptake and suppress algal blooms, thereby altering a major control on DO dynamics in SFB. Therefore, the prevalent N species and shifts in DIN composition following precipitation events should be considered in attempts to explain the underlying mechanisms behind the positive relationship between N and resistance.”

Line 532-534: Please rewrite this paragraph with a more coherent narrative. The topical sentence, focused on variation within single estuaries, is not supported by the following sentences, focused on a comparison between two estuaries (CBM and GTM). The topical sentence also focuses on relationships between physicochemical factors and resistance, whereas the supporting sentences focus on the response of physicochemical factors to precipitation.

Thank you for pointing this out and apologies for the confusion. We will rewrite this section in the revised manuscript.

The section now reads:

“The substantial differences in physicochemical factors linked to resistance across individual estuaries highlight the need to consider both generalized and local estuarine patterns when predicting and managing the effects of major precipitation events and watershed urbanization on water quality (Fig. 5). Individual estuaries may require consideration of factors beyond water temperature, water column depth, turbidity, and Chl-a—identified here as generalizable at the continental scale—and be mindful of differences in relationship directionality between physicochemical factors and resistance among estuaries. For example, we found that resistance at CBM is related to one factor (water column depth), while at GTM, resistance is related to five factors (salinity, water temperature, Chl-a, PO_4^{3-} , and N:P), from which three factors were not identified at the continental scale. Similarly, although resistance and salinity are positively associated at GTM and SFB, at WKB this relationship is negative. Likewise, while the relationship between resistance and water column depth is negative at SFB, at CBM and LKS this relationship is positive.

Variabilities in responses to stressors, at both the system and individual factor levels, is common. Understanding how individual physicochemical factors respond to precipitation broadly and within each system provides insight into the observed relationships between those factors and resistance. For example, Chl-a and dissolved inorganic phosphorus have been shown to respond more strongly to storms in some estuaries than in others, due to differences in light availability, grazing, and nutrient concentrations (Chen et al., 2015; Cloern, 2001; Cloern and Jassby, 2010; Dix et al., 2013, 2008; Liao et al., 2021; Zhang et al., 2022). Likewise, water temperature and salinity also have variable responses to precipitation (Buelo et al., 2023; Chen et al., 2015; Dix et al., 2008), leading to differences in biological processes and phytoplankton activity across estuaries (Apple et al., 2008). System dependencies on groundwater discharge—as a driver of nutrient inputs and a regulator of DO dynamics (Brookfield et al., 2021; Kornelsen and Coulibaly, 2014)—or on microbial community structure (Cheng et al., 2021) should also be appraised when evaluating factors associated with urban estuaries’ resistance to precipitation.”

Technical comments:

Line 87: Reverse the order of the clauses in the previous sentence, since this sentence references the later study, which is in the former part of the sentence (could be confusing!).

Done. The text now reads:

“While Ombadi & Varadharajan (2022) report contrasting effects of urbanization on salinity during flood events when regional dynamics are considered, a continental-scale study by Kaushal et al. (2018) suggests that anthropogenic activity is associated with increasing salinity in waterways. However, Kaushal et al. (2018) recognize that regional, weather-related, LULC, and geologic variabilities also influence salinization patterns.”

Line 105: Add “of” after “understanding.”

Done.

Line 205: Replace “infer” with “be related to”

Done.

Line 241: Alway --> always

Done.

Reviewer 2: Thank you for recognizing the relevance of this study and for your thorough evaluation. Your comments offer important perspectives that will enhance the quality of our revised manuscript. Below, we provide our responses (in blue font) following each reviewer comment (in black font).

The follow-up point-by point revisions addressed in the manuscript are presented in *italic* font.

The manuscript studies the resistance of estuaries to changes in dissolved oxygen following rainfall events. The study made a number of counterintuitive findings such as that resistance to change was higher in urbanised estuaries.

I thought the study was well presented in terms of the organisation and coherence of the text and the quality of the figures. I think the study is potentially important because it uses large datasets across many estuaries to make generalisation about how estuaries response to anthropogenic changes. I note I am not an expert on the statistics, but reviewer 1 has covered this point.

Thank you for the encouraging remarks.

My interest is really in the biogeochemistry of estuaries and what the term resistance to change really means. To my mind this was not a useful metric of estuarine function. As the authors themselves acknowledge, if an estuary is in an unhealthy state (ie low DO) before an event, and quickly returns to this, then it would be classified as resistant to change, which isn't really meaningful. I suggest, %DO saturation un-untransformed for resistance would be more useful as a response variable.

Fundamentally, the resistance index is a normalized value that generally describes the concept of a system's shift from a baseline in response to a perturbation, and one of its strengths is that it is not a system-specific index. We provide the definition of the resistance index (lines 188-189). The resistance index is a common and widely-used framework in various fields of ecosystem science for assessing the ability of an ecosystem to maintain its structure and function in response to a disturbance.

We reiterate that the resistance index can not convey information about the overall state of the system (i.e., healthy or not healthy), it can only indicate if a process variable– indicative of ecosystem function– had shifted relative to the baseline as a result of a disturbance. In the manuscript, we frame the resistance index as a tool for: 1) comparing ecosystems' stability responding to precipitation events; and 2) investigate factors that associate with stability. We state the limitations associated with the resistance index (lines 202-207), and reflect on the dependency of the resistance index on the baseline and on the subjectivity in establishing a baseline (line 248). We also present Figure 2 a–e containing information about DO at each site before and after precipitation, which elucidates ambient DO levels, direction of change in DO, and the absolute magnitude of the change. This figure

complements the resistance index to reveal possible implications of each estuaries' response to precipitation (Figure 2 f–j).

We also thank the reviewer for suggesting to use DO (%-sat.) instead of concentration (mg L^{-1}). We previously performed the calculation and checked the resistance index calculated with DO measured in %-sat. against calculations that use DO in mg L^{-1} (please see Figure S5). The resulting resistance indexes are virtually identical, with slightest differences possibly arising due to flagging/not-flagging of some data points during the QA/QC process, or missing values of variables used for internal conversion from %-sat. to mg L^{-1} . We state that the resulting resistance index calculated using DO (%-sat) and (mg L^{-1}) yielded equivalent results on lines 224–225.

In addition to events, I would also have undertaken the analysis to look at how catchment variable such as tree cover, built area etc influenced estuarine response variables such as chlorophyll a, turbidity and nutrient concentrations and how some of the response variable relate to each other. There are other studies of this nature and I think the biogeochemical and ecological implications of this potentially interesting study would be much more straight forward and higher impact than using what I regard as a rather abstract and inappropriate metric for a study of this nature.

We echo the reviewer's suggestions about the importance of including the analysis showing the relationships among variables and draw their attention to Figures S8 and S13. Particularly, Figure S8 shows a correlation matrix with Pearson's correlation coefficients of all variables (resistance index, physicochemical parameters, and LULC). Figure S13 shows the relationships between estuarine response variables (i.e., DIN, Chl-*a*, and turbidity) and LULC (i.e., catchment variables).

We also acknowledge the significance of catchment characteristics on the response variables and their joint implication on estuarine ecology. We address these implications by discussing the effects of these variables (i.e., DIN, turbidity, Chl-*a*) on the directionality of DO change following storms and their influence on DO baseline (see section 4.1, lines 406–436).

To address the reviewer's suggestion, in the revised manuscript we will expand the discussion to include the relationships between population density with turbidity, and between percent trees with PO_4^{3-} that had some of the highest Pearson's correlation coefficients shown in Figure S8.

The text now reads:

*“We also found that turbidity was positively related to built area, Chl-*a* was negatively related to population density, and PO_4^{3-} concentration was negatively related to tree-cover (Fig. S7, Fig. S15). Tree-populated riparian zones, often reduced or absent in urban environments, can help regulate phytoplankton overgrowth and DO dynamics by significantly reducing PO_4^{3-} concentrations (Keller and Fox, 2019).”*